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A STRUCTURAL AND PETROLOGICAL STUDY
OF THE
GRANITIC AND ASSOCIATED ROCKS
OF MID-STRATHSPEY

by

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1
ABSTRACT

A variety of granitic and high grade metamorphic rocks underlies the whole of Mid-Strathspey.

A petrographical description of the rocks of the Moine Series is given and the petrology of minor tourmaliniferous and semi-calcareous rocks discussed. The distribution of migmatisation in rocks of the Moine Series and its relationship to the structure are demonstrated petrographically and structurally.

Description and petrological discussion have been given of previously unrecorded metamorphosed basic igneous rocks in the Moine Series. Emphasis is laid on the relationship between the time of intrusion and that of the peak of metamorphism in the surrounding rocks.

The petrography and the field relations of the rocks of the Grantown Group, and of the granitic rocks within the Group, are described in some detail. Petrological and structural considerations combine to suggest that carbon dioxide released during the metamorphism of the impure limestones has played a major role in the recrystallisation, mobilisation and granitisation of the upper members of the Group. A brief review of comparable Scottish migmatite complexes and their problems is given.

A detailed statistical study of the macroscopic

and megascopic fabric of the foliated rocks has been made and a kinematic interpretation attempted. After a brief petrographic description of the Grantown Granite the structure of its numerous inclusions is compared with the structure of the enclosing country rocks. The inclusions are found to have been displaced, haphazardly on a small scale but regularly on a large scale, during the post-tectonic emplacement of the granite. The possible physical and chemical conditions that attended the formation of the granite and its emplacement are discussed. A study is made of the orientation of the post-tectonic acid veins in the south of the area. The control exerted by pre-existing structures on the localisation of all post-tectonic acid rocks is considered.

The grade of metamorphism, as determined from the five main rock types, is found to be the same over the whole area. The various acid and basic plutonic rocks are compared and contrasted with particular regard to their respective times of formation, modes of origin and emplacement, and structural controls over emplacement.

It is inferred from the evidence now available that metamorphic and metasomatic processes have played a major part in the production of most of the granitic and associated rocks of Mid-Strathspey.

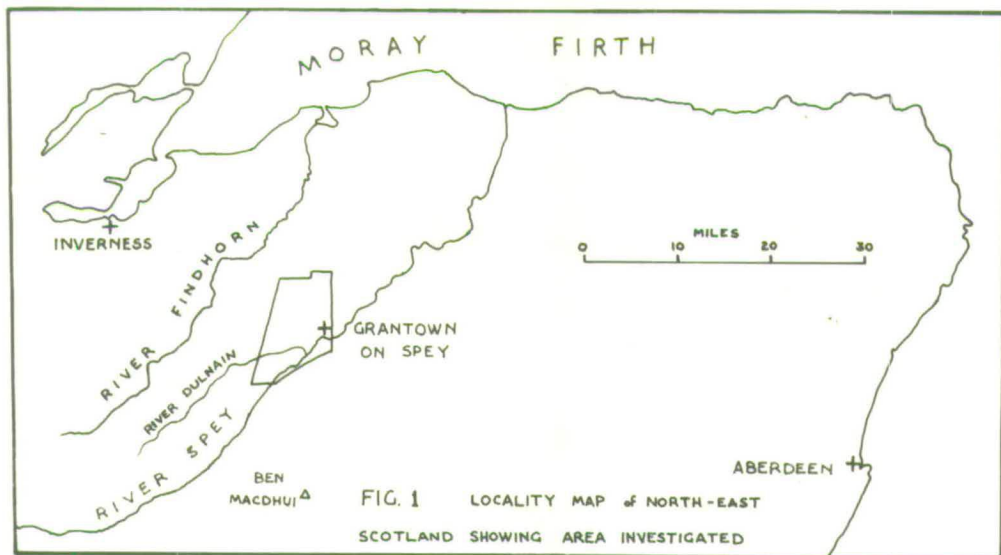


Fig. 1

INTRODUCTION

(a) Aim and scope of Study

This investigation in Mid-Strathspey was commenced with a three-fold aim in view, namely:

(1) to study the structure and petrology of the Grantown Granite in order to obtain evidence bearing on the problems of its mode of emplacement and origin;

(2) to study in detail the structural geology of the Moine Series to the north and west of Grantown; and

(3) to examine the migmatitic rocks of the Spey-Dulnain watershed with a view to elucidating the relationship in time and space between metamorphism, migmatisation and folding.

Further problems which presented themselves during the course of the study were the petrology of calc-silicate nodules in rocks of the Moine Series; the petrology of the Grantown Group with particular reference to the granitic rocks of Craig Revack; and the description of previously undescribed metamorphosed basic igneous rocks exposed near Lochindorb.

The area under investigation covers some 48 square miles and lies towards the heart of the Scottish Highlands, 25 miles to the ESE of Inverness and 55 miles to the WNW of Aberdeen; the northern part of the area is in Morayshire and the southern part in Inverness-shire (see Fig. 1).

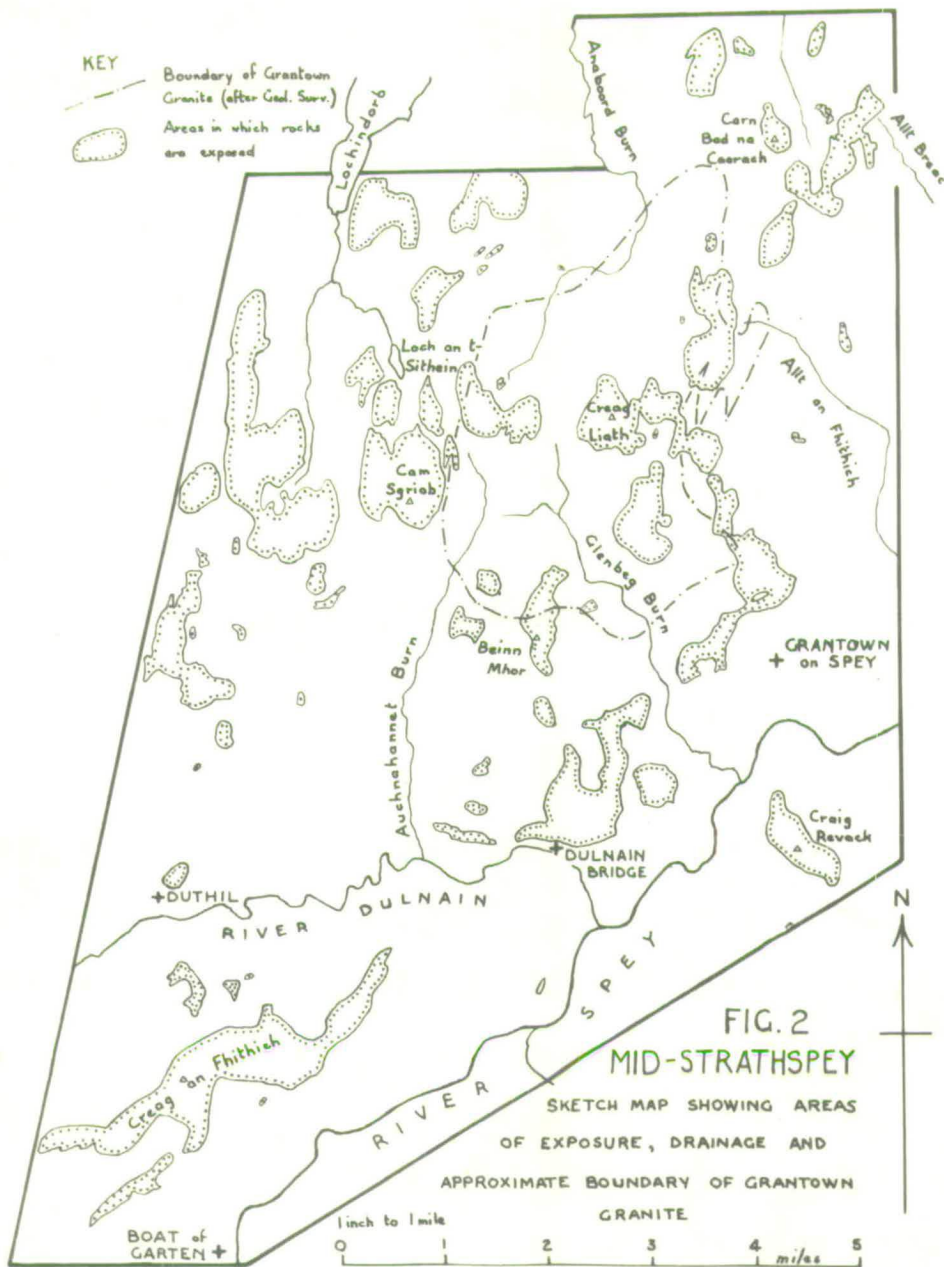


Fig. 2

It is situated entirely in Strathspey and Strathdearn - the valley of the River Findhorn - immediately to the NW of the stretch of the River Spey between Boat of Garten and Spey-bridge, except for a small well-exposed area at Craig Revack on the SE bank of the river. The western boundary runs from Kinveachy near Boat of Garten in the south to the southern end of Lochindorb. A line from Lochindorb to the head of the Allt Breac has been selected as the northern boundary, while a line from the latter point to a point just east of Craig Revack is taken as the boundary on the east.

(b) Drainage and Topography

The area is divided into two unequal parts by the watershed separating the tributaries of the Spey, which drain four-fifths of the area, from those of the Findhorn which are fed by the most northerly part of the area. The watershed follows a sinuous NE-SW course across the north of the area; at its lowest point, where crossed by the Grantown-Forres road and railway, it is some 1050 feet above sea-level. At its highest point - Cam Sgriob - it rises to almost 1600 feet (see Fig. 2).

The gentle northern slope of the watershed is drained partly by the Allt Loch an t-Sithein through the loch of that name to Lochindorb and the Findhorn, and partly by the Anaboard Burn which flows to the Findhorn from the bleak

expanses of Dava moor.

South of the watershed, the Spey flows to the NE in a valley 600-650 feet above sea-level. The most important left bank tributary of the Spey is the eastwards-flowing Dulnain which enters the former obliquely near Dulnainbridge. Minor tributaries draining south and SE include the Glenbeg Burn, the Allt an Fhithich and the Allt Breac running directly to the Spey and the Auchnahannet Burn flowing into the Dulnain.

Most of the high ground occurs on or a little to the south of the main watershed, where several hills such as Cam Sgriob and Creag an Rìgh in the west, Beinn Mhor in the middle and Carn Bad na Caorach in the NE rise above 1500 feet. In the middle of the area is a large tract of undulating moorland above 1250 feet with summits at Creag Liath, Gorton Hill, Creag Bheithe and Carn Luig.

An isolated ridge running NE-SW and culminating in Creag an Fhithich at 1325 feet forms the Spey-Dulnain watershed. On the east bank of the Spey at Revack the bare hill of Craig Revack trends NW-SE across the valley, from which it rises some 400 feet.

Wide tracts of broken drift-covered ground occur at a height of 700-1000 feet above sea-level. Such tracts are found west of the Auchnahannet Burn in Strathdulnain.

immediately north and NE of Grantown in Strathspey and at Dava moor in strathdearn.

The maximum relief is about 1000 feet, but that part of the area underlain by granite to the NW of Grantown is dissected to a depth of only 650 feet. The topography can be accurately described as rolling moorland with a few prominent summits - the northern foothills of the great Cairngorm massif, which lies outwith the area here being considered.

Much of the rough drift-covered land has been afforested, but even more is open grouse moor. Cultivation is sparse but is locally carried as high as 1250 feet. Lines of communication are confined to the valleys, apart from the north-south Grantown-Forres road and railway in the NE of the area.

(c) Sketch of the Geological History of the Area

As is to be expected in a Central Highland area the predominant rock-types are schists and gneisses of high metamorphic grade, cut here and there by post-orogenic granitic rocks. The metamorphic rocks include quartzo-feldspathic gneisses, biotite- and kyanite-gneisses and schists, calc-silicate rocks and marbles, hornblende-schists and amphibolites.

The quartzo-feldspathic gneisses and biotite-gneisses, in places migmatized, are generally considered to belong to the Moine Series, a group of metamorphosed sediments, possibly of continental origin, which originally consisted for the most part of thicknesses of impure sandstones with occasional argillaceous layers. Modules and thin layers of marl intercalated in the sandstones are now represented by calc-silicate granulites interbanded in the gneisses. The Moine gneisses occupy the western half and the NE corner of the area. Near Lochindorb in the NW of the area slightly metamorphosed basic intrusions - now amphibolites - are disposed along a narrow NNE-SSW belt in the Moine Series.

Dominantly pelitic rocks occupy a north-south belt from Broomhill northwards to Dava. Within this area are the biotite- and kyanite-gneisses and the marbles and calc-silicate rocks which were grouped together by the Geological Survey and named the Grantown Series. The calcareous members trend ENE-WSW across the Spey from Dulnain-bridge to Speybridge. The sediments which gave rise to these rocks were more or less impure limestones, with calcareous and aluminous shales.

During an orogenic phase - presumably Caledonian - the above-mentioned rocks were folded together about axes which now plunge approximately 30° to the SE. Small folds

and lineations are well developed in the rocks and are all parallel to this direction. In the south the movements were accompanied by migmatization. The prevalent dip of the foliation is up to 40° towards east or SE, a feature which results in many hills having a steep 'scarp' slope to the west or NW.

Within the pelitic rocks to the NW of Grantown there was emplaced after the above movements a medium-grained, pink, biotite-granite known as the Grantown Granite. This mass underlies roughly 6 square miles (see Fig. 2) and encloses many blocks, large and small, of the country rocks. Narrow veins of granite and pegmatite penetrate the gneisses over the whole of the area under investigation. Following the emplacement of the granite there was slight faulting along its NE margin.

In common with the rest of Scotland, Strathspey and Strathdearn suffered severe glaciation during the Pleistocene epoch. From evidence displayed outwith the area Bremner (1934b) inferred that there were three phases of glaciation separated by two interglacial periods. The ice-moulded ridges aligned north and south are conspicuous features of the countryside as can be clearly seen on aerial photographs. The movement of the ice concerned was from the south. Thick boulder clay was deposited as ground moraine

in the valleys while the hill-tops were scoured bare.

The last ice-sheet left its main impress in its retreat phenomena, wide spreads of terminal and lateral moraines with later fluvioglacial sands and gravels being deposited over the valley floors and on slopes up to a height of about 1300 feet; such sands and gravels lie astride the Spey-Findhorn watershed half-a-mile west of Craig Liath at a height of 1150 feet.

Differing levels of the ice between one strath and the next and between one embayment and another in the same valley caused the ponding-back of melt waters which cut overflow channels across watersheds and spurs of convenient height. Such channels are to be seen at Beun a' Ghladheimh, Greag Liath, Cam/Sgriob, Carn nan Gabhar, Allt an Fhithich and at the headwaters of the Rychraggan Burn. Flow in these channels was generally to the north, east or NE.

River-terraces of post-glacial date are developed at two levels along the banks of the River Dulnain and at four levels along the Spey.

Peat has formed extensively in the area where the gradient has been sufficiently low, particularly at Drynach and Shillochan in Strathdulnain and on the southern part of Dava moor.

As a result of these extensive superficial deposits

formed during and after the Third Glaciation exposures in the area are generally poor (see Fig. 2). Some 80% of the area is covered by continuous spreads of drift; the remaining 20% is very imperfectly exposed. The best exposures are to be found on the watershed hill-tops. Exposures made by quarrying and along road and railway cuttings are relatively few in number.



REVIEW OF PREVIOUS WORK

For well over a century geological investigations of a wide variety of topics have been carried out in Mid-Strathspey. The authors have been numerous, the calibre of their contributions variable. During the nineteenth century observations were of a brief and general nature, but advances in the development and application of geological techniques have encouraged more detailed studies to be made in the last few decades.

Among the earliest geological records of Mid-Strathspey were three maps (Necker, 1808; Boue, 1820; Rhind, 1842) on which the different rock types of the area were not distinguished, all being shown as undifferentiated schist or gneiss.

The first written record, by Martin, appeared in 1837. He stated that the upper, or southern, part of Morayshire was formed of "grey gneiss associated with porphyry and mica slate".

In his "Sketch of the Geology of Moray" Duff (1842) made brief mention of the metamorphic rocks and granites which occupy the southern part of the county. He described the characteristic "wavings and contortions" of the gneisses and mentioned that "metamorphic or primitive limestone" was to be found at Speybridge, a mile SE of Grantown. It is interesting

to note his postulated mechanism for the emplacement of granite. He envisaged a mush of crystals, derived from primary granite, being lubricated by a little water and forced into the cover-rocks under great pressure but at low temperature. Primary granite was, in his opinion, the lowest rock in the stratigraphical column.

Nicol (1844) in a "Guide to the Geology of Scotland" noted the generally low angle of dip of the Strathspey gneisses. Grey gneisses and mica-schists, veined by granite, continue "through the whole upper part of Morayshire but with nothing of great interest". On the geological map which accompanied his "Guide" Nicol indicated the rocks [migmatites] of the ridge between Duthil and Beat of Garten as granite.

Murchison (1860), in the light of his knowledge of the rocks of the North-West Highlands, considered that most of the gneiss of Moray and Banff belonged to the "Younger Gneiss" (now renamed the Moine Series) although he admitted to the possibility that "some of the fundamental gneiss [Lewisian] and older granite may . . . be there partially exhibited".

Following the publication of Murchison's work no further geological researches on the area appeared in print until 1901 when three aspects were discussed by different authors. Geikie (1901) briefly described the features of

the drift deposits to be seen along the line of the Aviemore-Ferres railway; Heddle (1901) gave a long list of minerals to be found in the marbles and calc-silicate rocks at Spey-bridge and Dulnainbridge, as well as the accessory minerals of the Boar of Garten granite; and Hinxman (1901) investigated the variations in gradient of the River Spey. In order to explain the presence of 40 miles of relatively low gradient - 5 feet/mile - above Grantown in the middle reaches of a river whose average gradient is 12 feet/mile, he postulated post-glacial uplift in the Grantown district, causing a ponding-back of the river water in the middle reaches.

The map in Stanford's Geological Atlas (1907), which was presumably compiled from all the available information and thus represents the actual state of geological knowledge of the area at the time of its publication, showed gneiss underlying the whole area except for a single tract of granite on either side of the railway two miles north of Grantown. This tract, one presumes, represents the Grantown Granite, whose northern part is well exposed in the railway cuttings north of the town.

The first accurate and comprehensive account of the geology of the whole area appeared in 1915 as the Mid-Strathspey and Strathdearn Memoir of the Geological Survey

of Scotland; this work was written by L. W. Hinzman and E. M. Anderson and was accompanied by brief petrographical notes by J. S. Flett. The Grantown Series of 'paragneisses', which dip generally SE, were described and were distinguished from the surrounding rocks which were considered to belong to the Moine Series. The metamorphosed equivalents of limestones, shales, calcareous shales and sandstones were found. Structurally the rocks of the Grantown Series were considered to be either an outlier or inlier of the 'Banffshire or Central Highland Series' [Dalradian Series], whose main outcrops occur some ten miles east and SE of Grantown. There was believed to be a slide along the base, i.e. along the western margin of the Grantown Series. An attempt was made to place the rocks of the district in a stratigraphical succession. The quartzite and fine-grained pelitic 'granulite' of the Grantown Series were considered to be intermediate in age between the calcareous rocks of that series and the Moine Series; but the age of the Grantown series relative to the Moine Series was left an open question. The petrographic similarity of two members of the stratigraphical column of the Moine Series suggested to the authors of the Memoir the possibility that there were two phases of folding, the earlier resulting in recumbent folds, which were gently arched by the later phase.

The 'paragneisses' of the Moine Series were also described. They are mainly 'granulites' which are "granitic in character" over much of the country to the west of the Grantown Granite. A lineation, or 'direction of stretching', was found to be parallel over wide areas and was considered to be related to the nullion-structure found in the North-West Highlands. The production of this lineation was regarded as contemporaneous with or later than the 'isoclinal' folding of the gneisses. The 'isoclinal' folds were considered to have sub-horizontal axes trending NN; hence the fingering of the outcrops on the Survey maps.

A brief description of the Grantown Granite - a Newer Granite - was given, particular attention being directed to the nature and widespread occurrence of inclusions and compound pegmatites. As no steep contacts were seen in the area it was suggested that a granite mass underlies the whole district at no great depth below the present surface.

In the petrographic chapter Flett described the principal types of granite and schist. He recorded a graphite-schist from Laggan Hill and the abundance of members of the tremolite-actinolite series in the calc-silicate rocks of the Grantown Series. The kyanite and sillimanite found in rocks of the Grantown Series were considered to be products of the high temperature which

prevailed during the regional metamorphism rather than products of thermal metamorphism at granite contacts.

The 1-inch map (Sheet 74) which accompanied this Memoir gives an accurate and detailed representation of both solid and drift geology. It is unfortunate, however, that drift covers so much of the district, making practically all the boundaries conjectural.

The Mid-Strathspey Memoir was soon followed by the Memoir on the Lower Findhorn and Lower Strathnairn (1923) by Horne, in which was described the geology of Sheet 84 - adjoining the north side of Sheet 74 - in whose SE corner part of the thesis area is included. As in the earlier Memoir general descriptions were given of the various rocks of the Moine Series which occupy large areas of the Sheet. The 'paragneisses' were described and the general evidence for the sedimentary origin of these Moine rocks was discussed, particular attention being paid to the production of the zoisite-granulites from calcareous sandstones. The evidence consisted of, firstly, a chemical composition such as is only found in sediments; secondly, the preservation of sedimentary structures and pebbles in the gneisses; and lastly, the layers of heavy accessory minerals which frequently lie oblique to the foliation.

The pelitic rocks east of Lochindorb, stretching

north to the Knock of Braemoray, were equated with the pelitic gneisses in the Grantown Series to the south; and therefore with the Dalradian rocks. As before, a tentative stratigraphical column was given, but it was, and is still, not certain whether the column is right way up or not. Two structural hypotheses are founded on this column, the first assuming one episode of relatively simple folding, the second requiring two phases of folding, the first phase of which resulted in recumbent folds.

A short petrographic description of the Grantown Granite was given. No foliation was observed in the granite, which is cut by later veins of a strongly coloured pink granite. The granite mass was seen to contain many large inclusions of country rock up to half a mile from the margin. The larger inclusions preserve the strike of the country rocks, but the smaller fragments are haphazardly oriented. No light was thrown on the nature and origin of the mass.

A full description of the sill-like basic intrusion at Carn nan Gabhar was given. The rock was originally an ophitic gabbro. The effects of the metamorphism die away inwards; original pyroxene is preserved in the interior of the mass, while at the edges the rock is an amphibolite. Flett considered that the mass was intruded either at an early stage in the metamorphism and by some unspecified means

escaped the high degree of metamorphism of the surrounding rocks, or was intruded in the late stages of the metamorphic process and therefore only suffered a slight degree of change.

On Sheet 84, the 1-inch map accompanying this Memoir, the solid and drift geology are accurately depicted.

In his work on the heavy accessory minerals from almost all of the Newer Granites of the Grampian Highlands, carried out in connection with his provenance studies on Scottish sandstones, Mackie (1928) ignored the Grantown Granite. No reason for this omission is known.

In 1934 there appeared two classic papers on the glaciation of the district (Bremner, 1934a and b). The first dealt with the magnificent retreat phenomena displayed along the edges of the basin of the Abernethy Forest, which bounds the area on the SE; in the second was considered the evidence for three glaciations and the direction of ice movement in each. Overflow channels along the Spey-Findhorn watershed within the thesis area were also described in this second paper. Ice-flow in the second glaciation, which was the most effective in causing erosion, was towards the north and gave rise to the many north-south trending features of the area.

Incorporated in a general account of the Moine Series (Green, 1935) are two tentative suggestions as to the

stratigraphical position of the Grantown Series. The latter was considered to be either the equivalent of the Findlater Flags (Dalradian) of the Banffshire coast or an inlier of Lewisian gneiss lacking typical 'orthogneiss'. The second suggestion reminds one of the possibility voiced by Murchison (1860) that Lewisian gneiss might be found in the district.

In the British Regional Geology handbook on the Grampian Highlands (Read, 1948) the name "Central Highland Granulites" was given preference for those rocks SE of the Great Glen, whose correlation with the Moine Series of Ross and Sutherland is accepted by most geologists. Brief mention was made of the lithology of the Central Highland Granulites which, with associated pelitic gneisses, underlie most of Strathspey. The deceptive general dip of the Central Highland Granulites was attributed to 'isoclinal' folding.

It is of interest to note here that Anderson (1947) has correlated the rocks of the Grantown Series with calcareous rocks in the Moine Series at Kinlochlaggan 35 miles to the SW.

In the Mineral Resources Memoir of the Geological Survey on "The Limestones of Scotland" Robertson (1949) reported that the metamorphic limestones of the Grantown Series "are not of sufficiently good quality to be of present economic value".

In 1951 McIntyre published a general study of the tectonics of a wide area between Grantown and Tomintoul. Using the methods of the Alpine tectonicians Lugeon, Argand and Wegmann, he determined the lineation of the area as a b-lineation and on this basis constructed a structural profile perpendicular to the average lineation direction. Unfortunately he gave statistical structural data on the Grantown Series alone. The profile showed the rocks of the Grantown Series to be large tectonic inclusions isolated in the Moine Series and plunging at about 30° to the SE. The profile is some seven miles deep and extends up to the relatively high level of the Dalradian rocks at Tomintoul, which appear to have suffered the same deformation as the underlying Moine Series. All contacts are tectonic; the upper layers appear to have moved towards the SE relative to the lower.

McIntyre (1951^b), in a thesis on "Alpine Tectonics and the Study of Ancient Mountain Chains", gave a diagram showing the relationship between the Newer Granites and the regional structure of Mid-Strathspey. The granites do not appear to have disturbed the structural trends developed in the non-granitic areas; the relatively wide sheaf of lineations from included blocks in the Grantown Granite, however, indicate a degree of mobility within the granite not found in the surrounding schists.

In a petrofabric study of the orientation of calcite in naturally deformed marbles McIntyre and Turner (1953) analysed the fabric of a marble from Goldhome quarry, near Dulnainbridge, and deduced directions of tension and compression. Fabric and field evidence agree; the resultant of the last stresses acting on these rocks was found to be sub-horizontal and transversely across an axis plunging 30° to the SE.

The late-glacial history of the area has recently been summarised by Charlesworth (1955) in a regional study.



THE ROCKS OF THE MOINE SERIES

Schists and gneisses, which are generally acknowledged to belong to the Moine Series, underlie by far the greater part of Mid-strathspey. The rocks have a regional dip to the east and SE. In hand specimen and in thin section three main rock types can conveniently be recognised, namely, (a) quartzo-feldspathic and (b) pelitic or semi-pelitic rocks, (a) and (b) being about equally abundant with (c) subordinate calc-silicate bearing rocks, representing siliceous, aluminous and slightly calcareous sediments respectively. Intercalated horizons of amphibolite are considered to be derived from basic igneous rocks and are described and discussed later (p. 56 ^{seq} et seq).

Quartzo-feldspathic gneisses are almost entirely confined to the western part of the area, in a belt from Lechindorb in the north to the Spey-Dulnain watershed in the south. Thin intercalated pelitic and semipelitic layers are quite common in the quartzo-feldspathic gneisses, particularly in the southern part of the belt, which is also characterised by intense migmatisation. Elsewhere in the area migmatisation is much less severe and tends to be confined to the pelitic rocks.

In the east and NE of the area pelitic and semi-pelitic rocks predominate. They contain frequent, thick

quartzo-feldspathic and thin calc-silicate bearing intercalations. Within this area of pelitic and semipelitic rocks there occurs the Grantown Granite.

(a) Field Relations

1. Quartzo-feldspathic gneisses

The quartzo-feldspathic rocks present the same outward characters over a very wide area. Distinct horizons of quartzite can in places be mapped in the monotonous tracts of gneiss. Continuous gradation in mineral composition and a certain amount of intercalation in the field make it difficult to draw a satisfactory dividing line between the quartzo-feldspathic and semipelitic rocks, a difficulty which is illustrated by the fact that the "Siliceous Schist and Granulite" on Sheet 74 (1915) is continued northward on sheet 84 (1923) as "Undifferentiated Schists and Gneisses".

Isolated exposures of quartzite occur in the Auchernack Burn near Craig Revack. The banding of the rock dips SE but the relationships with the surrounding rocks are obscured by drift, and the quartzite has been included in the Moine series.

On Beinn Mhor, 2½ miles due west of Grantown, the officers of the Geological Survey mapped four lenses of quartzite surrounded by pelitic rocks, three lenses trending

SE and one small lens trending NE. The pelitic rocks are shown bounded by granite on the north side and by quartzo-feldspathic rocks on the other sides. Re-mapping has shown that there are three areas of quartzite - one of which is the small lens mapped by the Survey - trending NE and one, in which the foliation is steep or vertical, trending SE. This last area corresponds to the middle lens of southeasterly trending quartzite mapped by the Survey. Moreover, on the ground there seems to be little evidence for the small body of Moine siliceous 'granulite' interposed on the Survey 1-inch Sheet between the largest quartzite and the granite. A re-mapping of the junction between quartzo-feldspathic and pelitic rocks at Ochnoir is described on p. 82.

2. Pelitic and semipelitic gneisses

The rock types included under this head comprise migmatitic mica-gneisses - with minor augen gneisses - , garnetiferous mica-gneisses, mica-schists and granulitic gneisses. The two first named types are distinctive enough to form locally mappable horizons.

On the Geological Survey 1-inch Sheet 84 a narrow tongue of rocks is shown to extend south from Loch an t-sithein for a distance of one mile. The writer has found, however, by reference to the Geological Survey 6-inch sheets (unpublished) that his mapping is in agreement with that of

the survey, in that both show this tongue to consist almost entirely of amphibolite and hornblende-gneiss (see p. 56 and Fig. 5, end pocket). North of Loch an t-Sithein, on Carn Ruigh Chorrach, the survey map indicates an alternation of bands of pelitic and siliceous rock trending NNE. Exposures are here extremely poor and do not justify the detailed lines laid down on the 1-inch sheet; the detailed disposition of the rock types unfortunately remains obscure.

Within the boundary of the Grantown Granite the survey recognised twelve discrete inclusions of country rock, eleven of them pelitic. Their total surface area comprises a very small fraction of the surface area of the granite. The present mapping shows that the granite is practically nowhere without inclusions, most of which are pelitic in composition, although blocks of all the country rock types - including migmatites - have been observed. The surface area of the inclusions constitutes a large proportion of the area of the Grantown Granite Complex at the present level of erosion. The dip of the foliation and the plunge of the linear structures in the inclusions are generally consistently to the NW, in contradistinction to the regional structures outwith the granite (see p. 161 ^{seq} et ~~seq~~). Large inclusions of coarse pelitic gneiss, in places bearing garnet and occasional tourmaline, can be mapped in an east-

west belt on Greagan na h-Othaisge and in a north-south belt from Gorton Hill to Creag Bheithe Mhor and thence to Creag Bheithe Bheag. Contact metamorphic effects of the granite on the inclusions are totally absent in hand specimen (Plate VIII).

Outside the eastern contact of the Grantown Granite scattered exposures of distinctly pelitic rocks have been mapped from Auchnafearn Wood northwards to Camerory, Carn Luig and Carn na Croiche, whereas on Sheet 84 these rocks are not differentiated from other Moine rocks. Within these pelitic rocks a distinctive zone of migmatitic mica-gneiss has been found on the east side of Carn Luig and can be traced northwards to Carn na Croiche, a distance of one mile (Plate I).

In the north-eastern part of the area the pelitic and semipelitic rocks have many quartzo-feldspathic intercalations which are not, however, sufficiently large to be mapped on the 6-inch scale. On Carn Bad na Caorach steeply inclined pelitic and semipelitic rocks can be mapped in a broad band trending SSE parallel to the strike. On the low hill NW of Carn Bad na Caorach the quartzo-feldspathic bands preponderate over the pelitic rocks in which they are intercalated and dip SE at moderate angles. Thin quartzose bands on the two above hills contain structures which are considered

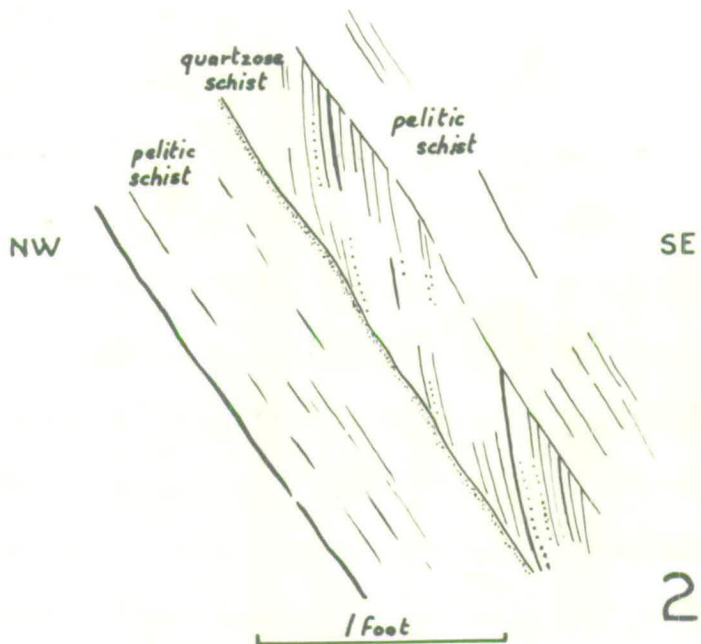
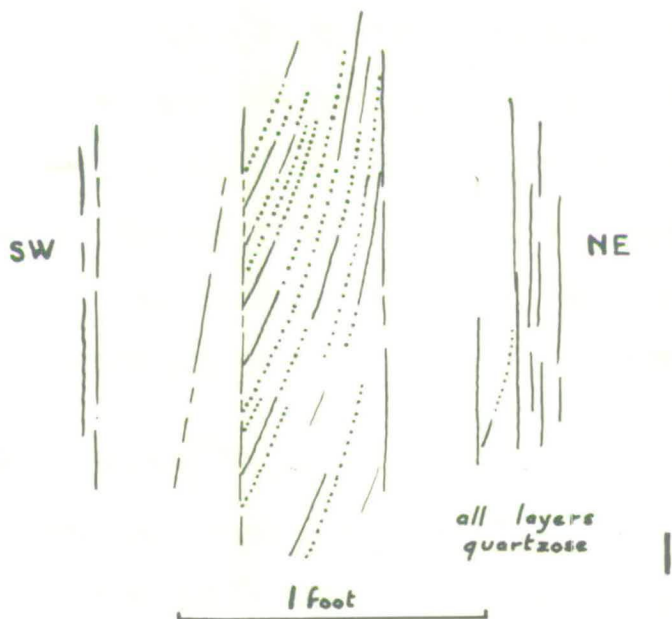


Fig. 3 Current bedding in quartzo-feldspathic layers in the Moine Series.

1. 100 yards SE of top of Carn Bada na Caorach.
2. 1200 yards NW of top of Carn Bada na Caorach.

to represent current bedding (Fig. 3), believed to be the first examples recorded from the Moine Series of this part of the Highlands. Sparsely exposed pelitic and semipelitic rocks south of the River Dulnain have been assigned to the Moine Series proper rather than to the Grantown Group on grounds of lithological similarity (p. 83).

3. Calc-silicate 'granulites'

These rocks are widespread, having been observed in the more quartzose layers which are intercalated throughout the pelitic and semipelitic rocks, but they also occur, though less commonly, in the quartzo-feldspathic rocks in the west of the area. They are not mentioned in the Geological Survey Memoir for Sheet 74, but two instances from localities in the north of the area are reported in the Sheet 84 Memoir (pp. 39,57). The rock occurs as thin impersistent bands and lenses up to five inches in thickness interbedded with either pelitic or siliceous rocks, or as nodules and lenses never greater than 9 by 12 inches in section, found in quartzo-feldspathic layers (Plate II). The longer axes of the nodular bodies are parallel to the banding of the surrounding rock. The foliation of the enclosing rock does not bend round the nodule; where the nodule is sufficiently rich in mica, the foliation continues unchanged in attitude through the nodule.

so scattered are these bands that they do not mark a distinctive horizon or zone. They have been found in the included blocks within the Grantown Granite and they have been observed in rocks of the Moine Series over a wide region outside the area.

The bands and nodules weather distinctively. The bands have prominent outstanding margins and a less resistant, weathered-away interior, particularly when the latter is calcitic (Plate III); the nodules have a deeply weathered bounding zone, while the interior, which sometimes shows several concentric zones, stands out.

(b) Petrography

The schists and gneisses of the Moine Series receive only brief mention in the petrographic chapters of the Memoirs on Sheets 74 and 84. The descriptions given below apply equally to the rocks outside the Grantown Granite and to those included within it.

1. Quartzo-feldspathic gneisses

In hand specimen these fine to medium grained rocks are pale pink, pale grey or white in colour and are usually banded. There are occasional micaceous partings parallel to the banding, and in some bands porphyroblastic lenses of feldspar are common. Quartz, feldspar, biotite and muscovite

TABLE 1

Modal analyses of quartzo-feldspathic rocks of the
Moine Series.

Thin section no.	239	453	0.14	165	23	427	461
Quartz	77	75	48	47	43	57	25
Plagioclase	16	3	35	40	20	8	56
Microcline	-	16	6	1	30	31	3
Biotite	5	-	9	12	6	3	14
Muscovite	-	6	-	-	-	-	1
Accessory	3	-	1	-	1	-	-
Points counted	1600 in each case						

239. Quartzite, 1000 yards SE of Auchernack Farm.

453. Quartzite, 500 yards SE of the top of Gam Sgriob.

0.14. quartzo-feldspathic gneiss, Ochnoir.*

165. quartzo-feldspathic gneiss, 400 yards SSE of the top of Creag an Fhithich.

23. quartzo-feldspathic gneiss, 300 yards SW of Torispardon.

427. quartzo-feldspathic gneiss, 500 yards SSW of Ryndian.

461. quartzo-feldspathic gneiss, 400 yards NE of the top of Creag an Righ.

* Specimen presented by Dr D.B. McIntyre.

can all be identified in hand specimen, while macroscopic red garnet is rarely seen. Linear structures are uncommon in these rocks but the quartzite on Beinn Mhor has a faint lineation formed by the parallelism of small narrow ribbons of quartz seen on weathered foliation surfaces. This lineation is parallel to the regional fold axis and is not to be confused with the broad parallel ribbons of quartz in true granulites.

A series of modal analyses* are given in Table 1

* All modal analyses were made on a Swift Point Counter and are therefore volumetric estimates. 1100 to 2100 points were counted, depending on the coarseness of the rock. The traverses were made 1 mm. apart, individual points in the traverse being 0.16 mm apart. The proportions were calculated to the nearest one per cent. All the thin sections analysed were cut perpendicular to the foliation of the rock. That the method of modal analysis is applicable to metamorphic rocks has been demonstrated by Shaw and Harrison (1955)

to show the range in mineral composition of the rocks, particularly the wide variation in the relative abundances of plagioclase and microcline, and the sympathetic variation between plagioclase and biotite. The analysis of 461 indicates the approximate upper limit of mica with the

concomitant high proportion of plagioclase. A typical example is shown in Plate XII .

Quartz is always found as xenoblastic crystals, equigranular to poikiloblastic in habit, and up to 5 mm in length. Granular or sutured margins are ubiquitous and undulose extinction is very common. Differences in extinction position of up to 20° have been observed in a single strained crystal. The smaller granules, however, are not strained. Large, very irregularly shaped crystals have apparently formed by coalescence of several smaller crystals during recrystallisation (Plate XII). In the quartzites of Beinn Mhor the quartz crystals are characteristically elongate, with the longer axis of their ruptural strain shadows (Hietanen, 1938) parallel to the foliation. In the less quartzitic rocks the tendency for crystals to be elongate parallel to the foliation is less marked. In one or two thin sections there are crystals of quartz which are slightly biaxial and have the appearance of incipient cross-hatching between crossed nicols. Quartz with undulose extinction always accompanies the biaxial quartz and the development of biaxial characteristics in this mineral is therefore considered likely to be the result of strain.

Xenoblastic crystals of plagioclase up to 3 mm across are found in most specimens. The crystals form

porphyroblasts with concave margins towards crystals of other minerals. Twinning on the albite law is common; twinning on two laws is sparse; the twin lamellae are relatively narrow. In the quartzites - highly deformed rocks - the plagioclase twin lamellae are bent and displaced. Zoning is uncommon and takes the form of a narrow sodic rim to the crystals. The composition of plagioclase from 36 specimens fell in the range An_{23} to An_{37} , the majority being near An_{30} *. Some specimens show patchy

* Throughout this thesis the composition of plagioclase has been estimated by the method of maximum symmetrical extinction angles in albite twins.

albitisation of plagioclase while others contain ragged patches of microcline enclosed within plagioclase (Plate XIII). Blebby quartz was observed in the plagioclase crystals of a few specimens. Alteration of the plagioclase is typically to secondary mica, although small secondary clinozoisite crystals were occasionally observed within plagioclase.

Microcline is rare in the plagioclase-rich types, but generally becomes common when plagioclase is low (239 being an exception). It occurs as fresh xenoblasts or porphyroblasts up to 6 mm in length, the porphyroblasts containing rounded inclusions of quartz. Boundaries between

microcline crystals tend to be sutured or granular. Microcline-microperthite is commonly found and takes the form either of a system of very thin albite veins, often en echelon, in the untwinned interior of a microcline crystal (as in Plate XIV), or of much larger ragged stringers and veins of oligoclase-andesine throughout the microcline; the latter type of intergrowth is rare. Areally, and therefore volumetrically, there is a complete gradation from plagioclase with a few % included microcline to microcline with a few % included plagioclase. This gradation is not, however, seen in all specimens. In the quartzites the microcline crystals (absent in 239) are lensoid in outline, their longer axes being parallel to the foliation.

The disposition of small quantities of tabular crystals of biotite usually gives the rocks a foliation, but the quantity is seldom sufficient to form discrete layers. The crystals, which have a maximum length of 3 mm, are often partly or entirely chloritised and are occasionally bent. The pleochroic scheme is: X = yellow-brown; Y, Z = dark brown or red-brown.

Less common than the biotite (except in 453) and usually absent, the muscovite crystals range up to 2.5 mm in size. The crystals are commonly bent, irregular in outline, and have their cleavage traces oblique to the

foliation. Occasionally (as in 453) there is enough muscovite present for it to form discrete foliation in the rock.

Accessory minerals, which together never exceed 4%, have been found in great variety in these rocks and include (in approximate order of abundance) pink garnet, pale yellow epidote with occasional orthite cores, zircon, iron ore, apatite, green hornblende, rutile and green tourmaline. The crystals are idioblastic or hypidioblastic. Garnet, which is sometimes altered to chlorite along cracks, and magnetite are exceptional in being occasionally as much as 3 mm across. The more usual upper limit of size amongst the accessory minerals is that of epidote which does not exceed 0.7 mm across. The gneisses at Drumroy near Lochindorb are unusual in that certain foliation planes are crowded with porphyroblasts of magnetite up to 3 mm across. Oxidation of the mineral by weathering gives the foliation planes a purplish or rusty colour.

2. Pelitic and semipelitic gneisses

Dark in colour, the rocks vary from fine to coarse in grain size. They are well-banded or foliate rocks, the coarser varieties commonly having small quartzo-feldspathic eyes, lenses and layers. Where thin pelitic and quartzo-feldspathic rocks are interbanded the former tend to have a

TABLE 2

Modal analyses of pelitic rocks of the Moine Series.

Thin section no.	64	102	156	408
Quartz	19	22	13	21
Plagioclase	21	28	42	26
Microcline	15	18	-	-
Biotite	31	29	40	32
Muscovite	14	4	5	18
Garnet	-	-	-	3
Accessory	-	-	1	-
Points counted	1800	1500	1700	1500

64. Biotite-gneiss, Staac an Toisich.
102. Biotite-gneiss, 900 yards north of the top of Gortan Hill.
156. Granulitic biotite-gneiss, Broomhill Quarry.
408. Garnetiferous biotite-gneiss, 500 yards NW of the top of Creag Bheithe Mhor.

NOTE

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foliation oblique to the layering. Biotite, muscovite, quartz and feldspar can readily be identified in hand specimen. Dark red garnet crystals up to 10 mm across are sparsely distributed and are typical only of certain bands in the rocks. Some of the coarser gneisses contain thin quartzo-feldspathic bands and lenses in which occur idioblastic, well-formed crystals of black tourmaline, with a maximum length of 40 mm, accompanied by crystals of red garnet. A lineation of mica crystals on the foliation planes of the finer grained rocks is the only visible linear structure. Garnet is always porphyroblastic while plagioclase is only sometimes so. Plates XIII, XIV show typical pelitic and semipelitic rocks in thin section.

The most abundant mica is biotite whose tabular crystals are ubiquitous, forming discrete layers in most specimens, and reaching a maximum length of 3 mm. Many crystals which are apparently large in ordinary light are seen between crossed nicols to consist of several crystals in parallel growth. The crystals are occasionally bent. In general the grain size of biotite is about the same as that of the other minerals in the rock. Pleochroic haloes surrounding small inclusions are common. The typical pleochroic scheme is: X = straw yellow; Y, Z = rich red-brown. Biotite is altered to pale green chlorite which

contains occasional grains of iron ore along the cleavage planes.

Normally muscovite is less abundant than biotite; unlike biotite, its crystals reach a maximum length of 4 mm and are commonly bent through angles of up to 20° . The crystals are thick, rather irregular in outline, and often lie with their cleavage traces oblique to the foliation as defined by biotite. Some of the muscovite, however, is in parallel growth with biotite. Wide variation in the grain size of muscovite within a single thin section is usual.

Quartz is always present, the equidimensional xenoblasts reaching a maximum diameter of about 2 mm. Undulose extinction is everywhere characteristic except in the small rounded crystals included in feldspars, and in the smaller granules. Sutured boundaries between quartz crystals are common. As in the quartzo-feldspathic rocks slightly but definitely biaxial quartz is occasionally encountered.

The typical feldspar of the rocks is plagioclase with a composition range of An_{23} to An_{37} , the majority of crystals having a composition of about An_{30} . The plagioclase forms xenoblasts which are equidimensional in the finer grained rocks and tend to be porphyroblastic or poikiloblastic in the coarser. The usual maximum size of porphyro-

blasts is 6 mm, except in the tourmaline-bearing bands where they are up to 12 mm across. Twin lamellae are not strongly developed and are relatively narrow; twinning on two laws in one crystal is rare. Pinit zoning is common, many of the smaller crystals being zoned but not twinned. In all the zoned crystals in which the composition range could be estimated zoning was towards a sodic margin. Up to three distinct zone boundaries have been observed in a single crystal; they are normally roughly parallel to the crystal margin but some are irregular in outline. In crystals that are both twinned and zoned the twin and zone boundaries cross each other undisturbed. Bending of the twin lamellae is rare. The plagioclase is occasionally altered to secondary mica and dusty material. As in the quartz-feldspathic rocks the plagioclase of the coarser rocks is sometimes albitised in irregular patches, or alternatively contains irregular areas of microcline (Plate XIII). It is often difficult to decide whether plagioclase or microcline is the host mineral. The porphyroblastic crystals contain inclusions of other minerals, particularly micas, oriented with their longer axes parallel to either or both of the two visible cleavage traces of the plagioclase.

Less common than plagioclase (and sometimes absent as in 156 and 408 in Table 2) is microcline whose

xenoblastic crystals range up to 3 mm across. Microcline-microperthite is also present (Plate XIV). Microcline does not occur in rocks which bear garnet. Normally the crystals conform to the average grain size of the rock. Occasionally the microcline crystals contain small rounded inclusions of quartz. In contrast to the quartzo-feldspathic gneisses the crystals do not have granular margins nor do they show cataclastic structures such as bent or broken twin lamellae.

Although they form only a small proportion of the rocks, porphyroblasts of garnet are prominent in certain layers (408). The crystals are equidimensional, their maximum diameter in thin section being 5 mm. Typically the crystals are pink in colour and are spongy, with inclusions of quartz, muscovite and biotite in that order of abundance. The tabular included minerals are sometimes seen to be concentrically arranged within the garnet. A biotite-poor zone surrounds many of the porphyroblasts, around which the foliation is deflected. Alteration to chlorite along the cracks has been observed in a few specimens.

Large tourmaline porphyroblasts occur in certain quartzose layers of the coarser gneisses, and lack a preferred orientation in these layers. In thin section the idioblasts are seen to be slightly spongy and olive or green-

brown in colour, which varies a little within the crystal. Absorption is strong; $O > E$. Small inclusions of quartz, muscovite and sometimes biotite are arranged with their longer axes parallel to the crystallographic c-axis of the tourmaline.

Idioblastic or hypidioblastic crystals of several accessory minerals are found in these rocks. The minerals include iron ore, apatite, sphene, garnet, zircon, and clinozoisite, and they tend to be concentrated along biotite-rich folia. The size of the crystals is seldom above 0.5 mm. Where sphene is a common accessory mineral the biotite is dark brown rather than red-brown in colour, a fact which indirectly bears out Hall's (1941) correlation of red-brown colour in biotite with high titania content. There appears to be no correlation between plagioclase composition and the colour of biotite when sphene is present. Iron ore forms ragged crystals, often along the cleavage planes of biotite.

Augen-gneisses constitute a minor proportion of the pelitic and semipelitic gneisses, and are confined to certain thin layers. They have not been found in the extreme Ng of the area. The augen-gneisses differ little in petrography from the other pelitic and semipelitic rocks, the following facts being exceptions to the general similarity. The quartz crystals of the augen-gneisses tend to be

elongate parallel to the foliation and reach a maximum length of 6 mm; blebby quartz is sometimes found in the plagioclase crystals. The 'eyes' are not composed of a single crystal but consist of an equigranular mosaic of any or all of quartz, microcline and plagioclase, the mosaic seldom being coarser than the average grain size of the gneiss.

3. Calc-silicate 'granulites'

The bands and less frequent nodules of these rocks are medium to fine in grain, are pale in colour and are studded with pink or brown garnets and with elongate parallel streaks of dark minerals, hence the name "Blotch-Rock" given by Barrow (1904, p.410). The lineation formed by parallelism of the streaks can, in a few favourable exposures, be shown to be parallel to the regional fold axis. The larger nodules are concentrically zoned, showing varying degrees of garnet concentration while the country rock for a distance of an inch or two outside the nodule is dark in colour and has a content of biotite above the average.

Along both sides of the belt of basic rocks between Carnloch and Carn nan Gabhar, near Lochindorb, the pelitic and semipelitic schists and gneisses contain small flattish nodules of calc-silicate bearing rock. These nodules, which are seldom more than three inches thick

TABLE 3

Modal analyses of calc-silicate 'granulites' in the Moine Series

Thin Section No.	222	246	248	251	253	254	255	276	282	304	306	339	438
Quartz	36	47	45	32	45	44	45	56	23	39	42	33	32
Plagioclase	5	34	15	33	4	45	-	24	50	27	41	15	35
Clinozoisite	24	11	27	25	47	2	36	16	5	9	8	31	21
Garnet	5	2	4	6	2	2	-	2	5	3	4	15	-
Hornblende	4	2	-	-	2	1	-	-	9	11	4	4	11
Calcite	24	-	3	-	-	-	-	-	2	8	-	-	-
Biotite	-	4	3	4	-	5	4*	-	4	2	-	-	-
Muscovite	-	-	-	-	-	-	14	-	-	-	-	-	-
Sphene	2	1	2	1	1	-	1	2	3	1	1	2	1

Points counted

1200 to 1600 in every case

*chlorite

222. Carn Bad na Caorach
 246. NE. of Carn Bad na Caorach
 248. NW. of Auchnagallin
 251. Carn a' Ghille Chearr
 253. Carn a' Ghille Chearr
 254. Carn a' Ghille Chearr
 255. South of Carnloch

276. SW. of Creag an Fhithich
 282. Pityoulish Hill
 304. Tromie Bridge
 306. Creagan na h'Othaisge
 339. South of Carnloch
 438. South of Carnloch

and are fine in grain, stand out prominently on weathered surfaces and the larger ones are zoned from a pale pink interior to a pale green or grey margin. The thinner nodules contain only the pale green or grey zone.

The usual mineral assemblage, whether in band or nodule, is quartz-plagioclase-clinozoisite (or epidote)-hornblende-garnet with occasional small amounts of biotite, muscovite, calcite and sphene. Table 3 shows the overall unity of the group, 255 being an exceptional type. Plagioclase and clinozoisite tend on the whole to rise and fall reciprocally. The typical features of rocks of this group are seen in Plate XV .

Quartz, plagioclase or clinozoisite may be the most abundant mineral in a particular specimen but of these it is generally quartz which makes up the major proportion of the rocks. The crystals are xenoblastic and equidimensional, and usually have undulose extinction.

Individual specimens may contain up to 54% of plagioclase, which forms xenoblastic crystals with a maximum length of 1 mm. Twin lamellae are sparse and narrow; zoning to a sodic margin is slight but distinct in many crystals. Most of the crystals are slightly altered to mica or clinozoisite. The composition range of plagioclase in thirty specimens is An_{27} to An_{60} , with two distinct

maxima at approximately An_{35} and An_{60} . There appears to be no correlation of plagioclase composition with mode of occurrence, geographical position or distinctive mineral content, such as the presence of clinozoisite within the plagioclase.

Colourless crystals of clinozoisite are common, occurring either as a network around the quartz and plagioclase or in clumps and patches which represent (in part) the dark streaks of the hand specimen. (Hornblende and biotite are also found in the dark streaks.) The crystals are up to 1 mm across and between crossed nicols are commonly seen to be zoned. In many specimens the clinozoisite occurs within crystals of plagioclase, which it has possibly replaced; these plagioclase crystals are no more or less calcic than the rest.

garnet always appears conspicuous in hand specimen but in thin section the porphyroblasts are found to be so poikiloblastic or even skeletal in habit that the proportion of garnet in the mode is low. Crystals of the mineral are pale pink or colourless, up to 3 mm across, and usually have inclusions of quartz with lesser amounts of clinozoisite and calcite. Crystal faces are seldom developed.

Small, sparse, ragged poikiloblasts of green hornblende are found in most specimens. The mineral, whose

crystals are too small for measurement on the Universal Stage, occurs in association with biotite and clinzoisite. The pleochroic scheme is: X = pale green; Y = green; Z = bluish-green, the colours being sometimes paler than these. The blue-green colour suggests that the hornblende contains the hastingsite molecule.

Biotite is occasionally present in essential proportions. The tabular crystals are small, having the pleochroic scheme: X = colourless; Y, Z = rich light brown. Chlorite is the most common alteration product of biotite.

Equidimensional crystals of well-twinning calcite have a maximum diameter of 0.5 mm. The mineral has been detected in only a few specimens (e.g. 222, 248, 282, 304) and its presence has no effect on the mineral assemblage developed.

The accessory minerals include ubiquitous pinkish-brown sphene in small idiomorphs forming up to 3% of the rock; occasional microcline in small xenoblastic crystals; and sparse shreds of muscovite which are sometimes secondary after plagioclase.

There are two notable exceptions to the description given above. Firstly, in the migmatitic quartzo-feldspathic gneisses of Stac an Toisich near Boat of Garten there have been found a few thin calc-silicate bearing bands (276). The

bands are coarse in grain and light in colour, sparse garnet and sphene being the only dark minerals present. Plagioclase is predominant but is usually altered to carbonate and secondary mica; clinzoisite occurs as coarse xenoblastic crystals which sometimes form a network in which the quartz and feldspar are set. This rock type resembles thin bands found in the pelitic gneisses of Craig Revack (see ~~notes on p.~~ ^{Table 18}). The second exception is the type of fine-grained equigranular rock found as nodules in the Lochindorb district (339,438). The middle of each nodule is a mass of small brown garnet crystals, the interstices between which are filled by quartz and clinzoisite, and this grades outwards into an intermediate zone rich in clinzoisite (or epidote), poor in garnet and bearing coarse shreds of a colourless amphibole; which zone, in turn, grades into an outer zone either rich in poikiloblasts of blue-green hornblende with, in addition, plagioclase ($An_{55}-An_{60}$), quartz and clinzoisite, or consisting of the assemblage quartz-clinzoisite-muscovite-chlorite (255), the two last named minerals probably being alteration products of plagioclase and biotite respectively. Outside this zone the enclosing granulitic quartz-andesine-biotite rock is found. Occasionally, in the smaller nodules, the innermost,

garnetiferous zone is lacking (438). Nodules of this type are always found in fine-grained pelitic or semipelitic rocks, and, although their texture differs from the more usual and more widespread calc-silicate bands, they have the same mineral assemblage.

Intercalated in quartzo-feldspathic gneisses at Drumroy, near Lochindorb, are a few thin bands of a rock whose mode of occurrence and appearance in hand specimen closely resemble those of the calc-silicate 'granulites'. In thin section, however, these are distinctive and unusual hornblende rocks which can be grouped with neither the basic nor the calcareous rocks. A modal analysis gave the result: hornblende, 37%; epidote, 26%; plagioclase(An_{40}), 26%; quartz, 7%; sphene + apatite, 3%. The crystals of epidote, sphene and apatite are idioblastic, the other minerals being xenoblastic in habit. Consideration of the mineral content has made possible an estimation of the relative abundance of oxides in the rock, thus: silica > alumina > iron oxides > lime > magnesia > soda. The origin of the bands is obscure.

(c) Discussion of Origins

A high content of plagioclase and/or microcline characterises the quartzo-feldspathic gneisses (Table 1), which have an average s.g. of approximately 2.7. An extreme

rock type (461) containing 56% by volume of plagioclase of composition AN_{30} (S.G. = 2.7), would theoretically contain about 3.8% soda by weight, and another extreme (23) with 30% by volume of microcline (S.G. = 2.6) and 6% biotite (S.G. = 2.95) would contain about 5.1% potash. These maximum values for soda and potash in the quartzo-feldspathic gneisses both lie within the corresponding ranges for analysed arkoses (Pettijohn, 1949, p.259) and the mineral compositions of the rocks fall within the arkose field (Pettijohn, 1949, p.258). Redistribution of some material in situ during metamorphism is indicated by the occurrence of porphyroblasts of feldspar, garnet and magnetite. Parallelism of the present banding with the original bedding appears to be indicated in some thin sections by the parallelism of lines of rounded zircons with the biotite foliation. The intergrowths shown by the feldspars indicate the action of either of two processes: (1) the exsolution of a homogeneous (Na,Ca,K) feldspar into its plagioclase and alkali feldspar components on cooling from a high temperature, or (2) a low temperature replacement of plagioclase by microcline and vice versa, involving the small-scale transport of soda and potash. These intergrowths are also found in the feldspars of the temperature-sensitive pelitic and semipelitic gneisses, which do not, however, show a development of high-temperature

minerals; therefore the second alternative is much to be preferred. There is little evidence either for or against the large scale introduction of soda and/or potash. The quartzo-feldspathic gneisses are therefore considered to have formed either by the metamorphism of arkoses or by the metamorphism and alkali metasomatism of more quartzose sediments.

The petrography of the pelitic and semipelitic rocks is consistent with the production of these rocks from argillaceous sediments. The conditions of formation of plagioclase were such that twinning was not favoured, while continuous zoning was. If twinning be considered a result of stress, as is commonly held to be the case (see for example Harker, 1904, pp.124-125; Alling, 1936, pp.155,157; Harker, 1954, p.269), then the plagioclase finally crystallised under low stress. Muscovite, judging by its usual obliquity to the foliation, appears likely to have formed when directed stress was low or had ceased. As in the quartzo-feldspathic rocks there are intergrowths between plagioclase and microcline whose origin appears to be in some doubt. Origin by replacement is preferred to one by exsolution, as the mineral development of the rocks does not indicate a high-temperature of formation.

It could be argued that the restriction of

tourmaliniferous gneisses to within the boundary of the Grantown Granite suggests that the tourmaline bands are apophyses of the granite. As the tourmaline-bearing bands are parallel to the gneissic foliation and occur also as isolated lenses and pods along the line of the main band, and as the gneissic foliation has been moulded around the pods just as it has around porphyroblasts, and the veins which can be seen to connect with the granite are cross-cutting and parallel-sided, then it is clear that the origin of the tourmaliniferous bands is bound up with that of the gneisses and not with that of the granite. The constituent which controls the formation of tourmaline is boric oxide, and argillaceous sediments contain up to 0.1% of that oxide (Rankama and Sahama, 1950, p.491; Goldschmidt, 1954, p.286). Tourmaline contains approximately 10% boric oxide by weight and therefore, without introduction of B_2O_3 from some outside source, metamorphosed sediments are likely to contain up to 1% tourmaline by weight.* The

* The pelitic gneisses of the Grantown Group (S.G. approx. 3.0) contain up to 1% by volume - and therefore roughly 1% by weight - of disseminated tourmaline (see p. ¹⁰¹105).

proportion of tourmaline (1-2%) in the bands on Creagan na h-Othaisge and Creag Bheithe is such as would require the

migration and concentration of B_2O_3 and other oxides from a maximum distance of only a few inches, provided the original sediment contained 0.1% boric oxide. The presence of sparse garnet porphyroblasts in the surrounding rock testifies to the occurrence of diffusion in these rocks, on the scale of metamorphic differentiation.

The bands and nodules of calc-silicate 'granulite' show a remarkable consistency of mineral composition over a wide area. The nodular, zoned occurrence at some localities suggests that the nodules represent original calcareous concretions in the quartzose bands, concretions whose content of lime decreased outwards. This hypothesis is supported by the fact that the foliation planes of the gneiss sometimes pass through the nodule and that the presence of a nodule does not result in an increase in the thickness of the layer in which it lies (Plate II). The examples of current bedding in the same district indicate that the original sedimentary structures are preserved in the rocks even at a high grade of metamorphism. The calc-silicate bands therefore, by analogy, represent original calcareous layers.

From their mineralogy the small zoned nodules from the Carnloch-Carn nan Gabhar area would appear to have been more lime-rich and less sandy than the foregoing bands.

But to contain relatively large quantities of minerals rich in alumina (garnet, clinozoisite and labradorite) the original concretion must have been calcareo-aluminous and rich in lime towards the interior. This is hardly surprising in view of the fact that these nodules are found in pelitic and semipelitic layers. They are therefore the homologue in pelitic rocks of the usual calc-silicate 'granulites' which tend to be found in quartzose layers. To the best of the present writer's knowledge similar nodular rocks have not previously been described from the Moine Series. The mineral content of all bands and layers allows the average lime content of these rocks to be approximately estimated at about 10%. This compares favourably with chemically analysed calc-silicate bearing rocks from other regions (Flett, 1912; Pettijohn, 1940; Kennedy, 1949).

The mineral proportions in several modal analyses were converted to the approximate proportions of oxides, making allowance for the different S.G. of different minerals and the range of composition in minerals which form solid solution series. By this method the chemical composition of the calc-silicate 'granulites' can be summarised thus: silica \ggg alumina $>$ lime $>$ iron oxides \approx magnesia $>$ soda $>$ potash.

Lenticular bands of calc-silicate 'granulite'

have been described from all parts of the Moine Series since Gunn and Teall (1898, p.41) first recognised these rocks, in Ross-shire. The first detailed petrographic description to be accompanied by a chemical analysis appeared in the Ben Wyvis Memoir (Flett, 1912, pp.42-45). Flett (in Horne, 1923, p.55) considered the calc-silicate 'granulites' - derived from calcareous sandstones - to be one of the distinguishing features of the Moine Series.

James (1955, Pl.I, Fig.3) has figured and Pettijohn (1940) has described from the Precambrian rocks of the Great Lakes region concretions which are structurally and petrographically similar to those found in Mid-Strathspey. Pettijohn concludes that the nodules represent calcareous concretions (doggers) which formed in sandy rocks after their deposition but prior to their metamorphism. A chemical analysis of one such nodule shows it to have a lime content of 9%. Similar examples from the Gold Coast have recently been described by Conybeare (1951).

Kennedy (1949) has demonstrated the changes brought about in calc-silicate 'granulites' by progressive metamorphism. Two specimens from the boundary between Kennedy's zoisite zone and anorthite-hornblende zone at Lochailort show textural features and mineral assemblages identical with those seen in the calc-silicate bands of

Mid-Strathspey. The Lochailort rocks contain the assemblage quartz-plagioclase (An_{60})-clinozoisite-hornblende-garnet with accessory sphene and calcite. This is taken by Kennedy to indicate a grade of metamorphism corresponding to that of the kyanite zone in pelitic rocks, i.e. to the lower amphibolite facies; in Mid Strathspey the kyanite isograd is seen to be attained by all rocks (see p.193). Calcite in essential proportions in some of the rocks of Mid-Strathspey suggests that this mineral persists to a higher grade than Kennedy has postulated. Its presence can be accounted for by considering that all the alumina originally present has been used to produce clinozoisite, etc., and the temperature has not risen high enough for the production of a non-aluminous calc-silicate such as wollastonite.

Where rocks with intercalated calc-silicate bands have undergone migmatization the assemblage developed is quartz-plagioclase-clinozoisite (or epidote) with accessory garnet and sphene. This holds true for bands in both the migmatized quartzo-feldspathic gneisses of Stac an Toisich and the migmatized pelitic gneisses of Craig Revack (see p.107). This new assemblage does not necessarily indicate a higher grade of metamorphism than elsewhere in the area but rather a different metamorphic environment in which hornblende and biotite were both unstable. From the literature on the

Highlands the only description comparable to that given above is by Teall (in Horne, 1910, p.81), who described calc-silicate 'granulites' from the migmatitic rocks of the Fannich Mountains.

(d) Migmatisation

Throughout the area, and particularly in the SW along the Spey-Dulnain watershed, the rocks of the Moine Series have suffered deformation and migmatisation. The intensity of deformation can be shown to be closely related in time and space to the intensity of migmatisation (p.55). Both quartzo-feldspathic and pelitic rocks are migmatized in the SW but elsewhere the tendency is for the pelitic and semipelitic rocks alone to show evidence of migmatisation. Blocks of migmatite are included within the Grantown Granite.

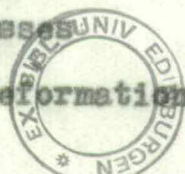
At various localities - apparently distributed at random - the quartzo-feldspathic rocks are granitic in character. They are pink in colour and contain randomly oriented, scattered mica flakes, as was noted in the Geological Survey Memoir (1915, p.21).

The gneisses are seen to contain coarse quartzo-feldspathic bodies parallel to the foliation or banding S_1^* .

* Throughout this thesis the mineral banding of the rocks is denoted by S_1 , the foliation in micaceous bands which is

oblique to S_1 is called S_2 , and surfaces of slip or incipient slip at a high angle to S_1 are S_3 (see also p.161).

and in the form of lenses, layers, knots, rods, and veins all of which are either elongate parallel to, or contain a linear structure parallel to, the regional fold axis. The gneisses and the quartzose layers have, therefore, been folded together, and S_1 curves around the coarse masses. Coarse quartz-rich pygmatic veins are also found along S_1 . On Greag Mhor the quartzose layers show intrafolial folding in the gneisses. Where S_1 is steep or intensely folded (Plate III) the quartzose bodies are most abundant and conspicuous as they commonly occur in the crests of small folds, but even where S_1 is gently dipping, as at Craig Garten, there are many coarse quartz-feldspathic lenses parallel to S_1 . Small quartz-feldspathic eyes characterise many but not all of the micaceous layers. Every gradation in size is found from quarter inch thick eyes to large lenses of up to one foot thick. The most common occurrence of the quartzose bodies is as single or inter-connecting groups of lenses, sometimes haphazard in distribution, sometimes confined to a particular layer. The non-transgressive nature of the quartzose bodies and the parallelism of their linear and planar structures to the structures in the gneisses indicate that the lenses were produced during the deformation



and assumed structural features controlled by that deformation.

The petrographic description given in the following paragraph applies equally to all migmatitic rocks of the area. The lenses and rods consist for the most part of quartz accompanied by considerable but lesser proportions of feldspar (microcline, microcline-perthite and calcic oligoclase). Biotite, muscovite and small red crystals of garnet are occasionally found. Some of the more feldspathic pods have biotite-rich margins (Plate X).

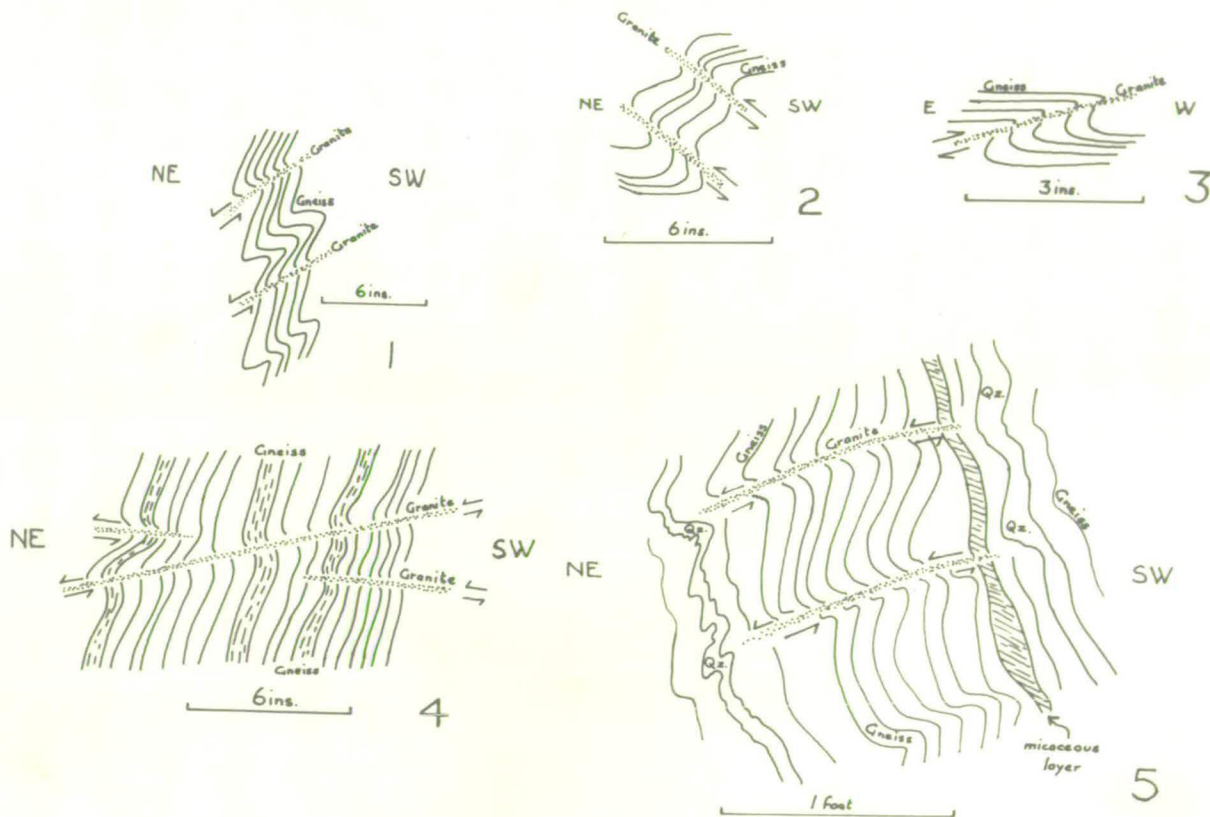
In thin section the thinner quartzose layers are seen to contain the same minerals that are found in the gneisses but in different proportions and as much larger crystals. Quartz and feldspar make up the greater part of the layers. Some layers contain oligoclase to the exclusion of microcline and vice versa. The plagioclase crystals are usually well altered to secondary mica and it is difficult to establish their composition; in the few available fresh crystals the composition was calcic oligoclase. Some plagioclase crystals contain small blebs of quartz. Lenses in which oligoclase and microcline are found together tend to have intergrowths of microcline in plagioclase while the larger microcline crystals contain in their untwinned areas tiny albitic stringers. Granular

Fig. 4 Thin granite sheets along S_1 and S_3 in the migmatitic rocks of the Spey-Dulnain watershed.

1,2. Creag an Fhithich.

3. Creag Mhor.

4,5. Stac an Toisich.



margins between crystals are common in microcline-rich bands. The sparse muscovite and biotite are indistinguishable in size and optical properties from the muscovite and biotite of the gneisses. The lenses do not invariably have biotite-rich margins; however, closely contiguous layers are usually separated by a thin biotite-rich wall.

A further effect of migmatization is seen in the thin impersistent sheets of granitic rock which are developed along slip surfaces (S_3) oblique both to S_1 and S_2 and usually at a high angle to the former (Fig. 4; cf. Ramberg, 1952, Fig. 121). These sheets are only found south of the Dulnain and are best displayed in the steeply dipping gneisses of Creag an Fhithich and Stac an Toisich. The sheets dip gently SE but are not strictly planar, as the granite is irregularly developed and sometimes tends to be located for a little distance along the quartzose S_1 planes, leaving biotitic septa projecting from the gneiss into the granite (Plate IX). The maximum dimensions of the sheets are one inch in thickness and three feet in lateral extent, the observed extension parallel to the fold axis being about five feet. Nowhere have the sheets parallel to S_3 been seen to cross the quartzose layers parallel to S_1 . In only one example was a sheet of granite observed to be parallel to the axial plane of a small fold. The relative

displacement of S_1 on either side of S_3 is slight; the displacement dies out laterally, non-displaced folia being found on either side of the layer containing S_3 . Many S_3 surfaces, however, are not recognisably displaced, neither do they contain granite. S_1 and S_3 intersect in a line which is close to the regional fold axis; the folds which define S_3 have axes parallel to the regional fold axis. The displacement about S_3 has been used in the kinematic interpretation of the structures of these rocks (see p.170 and Fig.19).

Petrographically the material of these thin granitic sheets consists of a mosaic of quartz, hypidic-blastic oligoclase, some microcline and very small quantities of muscovite and red-brown biotite. These minerals are indistinguishable from the chief constituents of the gneisses except that the plagioclase of the granite is slightly more sodic in composition and more highly altered than the plagioclase in the nearby gneiss; the granite is slightly coarser in grain than the gneiss. Throughout Mid-Strathspey the migmatitic rocks are quite distinct from the abundant and widespread persistent parallel-sided transgressive granite and pegmatite veins (see p.185 et seq.).

As with the larger quartzose bodies the structural evidence clearly shows a close relationship in time between

the deformation of the gneisses and the formation of the thin granite sheets. Petrographic evidence indicates a close similarity in mineral content between the pegmatitic and granitic rocks and the surrounding gneisses. A large development of acid material in the gneisses can be directly correlated with a high degree of deformation. Slightly deformed and non-migmatized rocks (containing sedimentary structures) are found in the north of the area but not in the south. The combined evidences therefore suggest to the present writer that the simplest and most adequate hypothesis to account for the various migmatitic rocks described above is to suppose that quartzose and feldspathic material segregated from the gneisses under the stimulus of metamorphism and deformation and crystallised in localities where, possibly because of lower stress, the environment was suitable. Migmatization was, therefore, syntectonic. During the period of this investigation time has not permitted speculation as to the nature of the fundamental processes which were responsible for recrystallisation and deformation.

30

THE METAMORPHOSED BASIC IGNEOUS ROCKS

IN THE MOINE SERIES

Several lenses and sheets of hornblende rocks (epidiorites) lie concordantly in the Moine Series at various localities in Mid-Strathspey. Near Lochindorb basic rocks occupy a discontinuous belt which trends NNE and is about two miles long and up to 200 yards broad. Small lenticular bodies of hornblende-schist are found on the SW slope of Craig Kevack and in the River Dulnain near Muckrach Lodge. The basic rocks of Carn nan Gabhar in the Lochindorb belt alone are indicated on the Geological Survey 1-inch maps and are the only occurrence which has been previously described.

Flett (1923, pp.44,58-60) has furnished an excellent description and discussion of the basic rocks of Carn nan Gabhar. His description is equally applicable to those which outcrop immediately south of Gabhar but for which there is no published map or description. He considered that the original basic rocks were derived from ophitic gabbros which were broken down first to flaser gabbro and finally to amphibolite containing phacoids of the original minerals. Flett visualised pressure as the main cause of the change and considered it likely that the rocks were intruded at a late stage in the regional meta-

morphism. The present study has revealed new evidence relating to the origin and history of the rocks and has, in addition, made possible an amplification of the sequence of changes noted by Flett.

In the field several distinct rock types can be recognised, comprising hornblende-schist, hornblende-gneiss, massive amphibolite with relict igneous texture, garnetiferous amphibolite and fine-grained granulitic amphibolite.

(a) Field Relations

1. Lechindorb belt

Remapping on the 6-inch scale by the writer (see Fig.5, end pocket) has shown that (a) at Gabhar there are several large and small lenses of basic rock and not a single Y-shaped outcrop as indicated on the unpublished survey 6-inch map; and (b) between the head of Loch an t-Sithein and the NW slope of Cam Sgriob there is, similarly, a series of lenses and not the plane parallel sheet shown on the survey 6-inch map. Other detailed changes include the omission of the areas of granite reported to lie close to the basic rocks both at Gabhar and Cam Sgriob (Fig.5, end pocket).

The basic lenses are parallel to the foliation of the enclosing rocks and sometimes have a foliation dipping, and a lineation plunging, parallel to the same structures

outside the lenses. The large lenses have outcrops of up to 200 yards by 100 yards and are invariably massive with relics of ophitic texture towards the interior. They are usually flanked by zones containing either or both hornblende-gneiss and small discrete lenses and layers of amphibolite, sometimes garnetiferous (Plate IV).

Associated with the belt of basic rocks are pelitic and semipelitic gneisses bearing calc-silicate nodules which occur on either or both sides of the belt. The contacts of the large masses with the country rocks dip eastwards, except for the southern body at Carnloch, whose south-western contact dips steeply SW. Locally the contacts intersect the foliation of the country rocks at a low angle.

There is wide variation in both texture and grain size within the basic masses. The relict ophitic texture can be detected at most localities (Plate IX) but is best displayed at Gabhar where in hand specimen black pyroxene crystals are seen to be rimmed by green amphibole. An original parallelism of feldspar crystals in the gabbro is seen immediately north of Carnloch; the platy structure dips gently east parallel to the foliation of the country rock.

The massive amphibolite has crude, widely spaced

joints and weathers to hummocks which have a rough knobby surface, the upstanding knobs having cores of resistant pyroxene or garnet. Locally the massive amphibolite may contain macroscopic flakes of biotite, or may be pale green and schistose. Porphyroblasts of feldspar are sparse. Hornblende and biotite form the foliation of the hornblende-gneisses, which are poorer in hornblende than the amphibolites. The garnet porphyroblasts which are typical of some of the amphibolites and hornblende-gneisses usually have an envelope or a pressure shadow of quartz-feldspathic material. The porphyroblasts are often ragged in outline and are up to 10 mm across; they are not found in rocks with recognisable ophitic texture.

Throughout the massive amphibolite there are small sheets and irregular patches of hornblende-'granulite' which sometimes contain feldspar and biotite (Plate IV). In the sheets the margin of the granulitic rock cuts sharply across the ophitic texture of the enclosing rock. The sheets are vertical and are up to 6 inches in width, while patches of up to one foot square have been noted. South of Carnloch such a patch is bounded by a narrow coarse zone rich in feldspar and biotite. Granulitic rock is also found at the upper, that is, eastern margin of the easternmost lens at Gabhar. Hornblende-'granulite' has been found

only within the massive amphibolites. There is no field evidence to indicate whether the granulitic rock represents an originally fine-grained xenolith or portion of the basic rock, or a post-intrusion development from a homogeneous gabbro.

The basic rocks contain thin ramifying quartzo-feldspathic veins which are usually planar and probably follow old joints which were not parallel to the present joints. Cutting the thin veins are occasional irregular patches of leucocratic rock containing quartz, feldspar and biotite; these patches grade into the basic rock and appear to be an integral part of it (Plate V). There occur thick transgressive veins of pegmatite which resemble the pegmatites of the country rocks. Close to the margins of the larger masses small, rusty-coloured tabular inclusions of schist have been sparsely found. There are occasional small round inclusions of a coarse granitic rock. Neither inclusions nor bordering country rocks have a hornfelsed aspect, despite the fact that both are pelitic in composition and therefore thermally sensitive. In a layer of country rock between two lenses of basic rock near Carnloch there is a sheet of true granulite some 9 inches thick. Ribbons of quartz are set in an equigranular quartzo-feldspathic matrix and plunge SE parallel to the regional

TABLE 4

Modal analyses of metamorphosed basic rocks in the
Moine Series.

Thin section no.	266	265	257	429	350	236
Augite	20	-	-	-	-	-
Hornblende	32	53	60	39	68	48
Plagioclase	40	23	16	31	25	19
Biotite	1	4	6	8	5	17
Iron ore + sphene	2	1	6	5	2	1
Epidote	3	19	-	-	-	10
Quartz	2	-	6	13	-	5
Garnet	-	-	5	4	-	-
Accessories	negligible in every case					

Points counted 1200-1300 in every case

266. Amphibolite with relict ophitic texture, 200 yards SW of top of Carn nan Gabhar, (stage I).
265. Amphibolite with relict ophitic texture, 200 yards south of top of Carn nan Gabhar, (stage II).
257. Garnetiferous amphibolite, 500 yards SSW of Carnloch, (stage III).
429. Garnetiferous hornblende-gneiss, 600 yards south of top of Carn nan Gabhar.
350. Hornblende-'granulite', 600 yards south of Carnloch.
236. Hornblende-schist, 75 yards SW of top of Craig Revack.

fold axis.

2. Valleys of the Spey and Dulnain

Discovery has been made of two small and previously unrecorded masses of hornblende-schist. One, a lens about 15 yards long by three yards broad, occurs on the slopes of Craig Revack and has an upper contact marked by a quartzose pegmatite with occasional hornblende crystals up to one inch in length, and the other, a sheet about 10 yards long and one foot in thickness, outcrops in the River Dulnain at Muckrach Lodge. In both bodies macroscopic hornblende and biotite form a crude foliation and lineation parallel to the foliation and lineation of the country rocks. Garnet is absent from these schists in contrast with the basic rocks of the Lochindorb belt.

(b) Petrology

As the original ophitic texture and gabbroic minerals are well preserved in some of the basic rocks it is possible to study the stages of chemical and physical readjustment in the direction gabbro \rightarrow garnetiferous amphibolite. The series of modal analyses in Table 4 give an indication of the mineralogical changes and the composition of some of the unusual rock types. The optical properties of some of the minerals from the various stages

TABLE 5

Universal stage data on the amphiboles and pyroxenes
of the basic rocks on the Moine Series.

AMPHIBOLE

Thin section no.	266		349		432	
	2Vz	Z [^] c	2Vz	Z [^] c	2Vz	Z [^] c
	100	10	100	14	108	16
	94	12	116	26	104	16
	104	26	102	22	86	19
	98	23	92	20	102	14
	90	20			96	16
Average	97	18	102	21	99	16

Thin section no.	448		295	
	2Vz	Z [^] c	2Vz	Z [^] c
	116	18	104	18
	110	18	104	20
	98	16	102	23
	112	20		
Average	109	18	104	20

PYROXENE

Thin section no.	266	
	2Vz	Z [^] c
	60	47
	44	35
	50	40
Average	51	41

266. Amphibolite with relict ophitic texture, 260 yards SW of top of Carn nan Gabhar (stage I).
349. Amphibolite, 600 yards south of Carnloch, (stage II). [(stage III)]
432. Amphibolite, 300 yards north of Carnloch.
448. Garnetiferous hornblende-gneiss, 600 yards NW of top of Cam Sgrìob.
295. Hornblende-schist, 75 yards SW of top of Craig Revaack.

are given in Table 5.

1. Stage I - original ophitic
pyroxene present

Rocks from this stage are restricted to the interior of the large lenses.

In only one thin section (266) are fresh ophitic pyroxene and euhedral plagioclase to be seen in contact. This pyroxene is free from dark inclusions and has a prominent (100) cleavage; the plagioclase is twinned on the albite law, has a composition of labradorite continuously zoned towards a more sodic margin and contains many small crystals of apatite and myriads of minute dark inclusions. Usually pyroxene and plagioclase are separated by a zone of hornblende. The tabular crystals of plagioclase have a maximum length of 5 mm; their composition range in all the specimens from this stage is from An_{35} to An_{55} . The pyroxene is an augite with the (100) cleavage strongly developed (see Table 5) and ophitic areas up to 10 mm across are in optical continuity. Sparse iron ore occurs and is probably original.

The augite shows two types of alteration, namely, (a) to sparse aggregates of small granules which have poorly developed cleavage and which are not necessarily surrounded

by hornblende, and (b) marginal alteration to hornblende which forms at first an optically continuous rim. This first-formed amphibole is found within 0.5 mm of the remaining augite and has the pleochroic scheme: X = pale brown; Y,Z = green-brown. It cannot be distinguished otherwise from the second amphibole which forms outside the first and which has the pleochroic scheme: X = colourless; Y,Z = pale green. Both the first and second formed amphiboles are hornblendes with ϵ_c below 20° and all thin sections with original pyroxene are characterised by pale hornblende. Augite, marginally altered to hornblende, contains many small dark inclusions which in places have coalesced to give a crystal of iron ore ^{as in} (Plate XVII) thus indicating that the hornblende is poorer in iron than the parent augite. At an advanced stage of alteration masses of dark inclusions and wisps of augite remain within the hornblende. In turn the large single hornblende crystals give way to a mass of small, more strongly coloured crystals which form first at hornblende-plagioclase boundaries.

Meanwhile four types of change can be recognised in the plagioclase, namely, (a) further development of apatite crystals within the original crystals, (b) occasional development of a second set of twin lamellae approximately normal to the first, (c) alteration of the

original crystals, particularly in their interiors, to secondary mica, clinozoisite and dusty material, and (d) recrystallisation of the large original crystals to a mosaic of equigranular grains which have lost the myriads of small dark inclusions typical of the least altered crystals. Signs of cataclasis are rare.

Crystals of iron ore, probably original, are rimmed by a zone of granular sphene, the lime for which was probably supplied by the change in composition of the plagioclase from more calcic to more sodic. Small quantities of red-brown biotite are commonly associated either with hornblende or around the iron ore crystals.

The rocks also contain, in accessory quantity, quartz, apatite and rutile rimmed by sphene. In one thin section small colourless garnet crystals are developed between areas of hornblende and plagioclase. The presence of garnet in rocks of this stage is, however, exceptional.

2. Stage II - ophitic outlines formed by hornblende alone

The rocks of this stage are found in the large lenses. The augite and the early pale hornblende have now been completely superseded by a hornblende with the pleochroic scheme: X = pale brown-green; Y = brown-green; Z = bluish-

green, and with α_c above 20° . A mosaic of large anhedral and small euhedral crystals of hornblende pseudomorphs the original ophitic augite crystals. Some of the larger crystals still contain specks of iron ore inherited from the augite and tend also to contain small inclusions of quartz. Most of the plagioclase (composition range An_{30} to An_{50}) now forms an equigranular mosaic of sparsely twinned crystals with faint zoning sub-parallel to the crystal margins. The boundaries of the ophitic areas have become irregular and there is a tendency towards the production of a hornblende-plagioclase mosaic with an average grain size of approximately 0.3-0.5 mm, a reduction from the average granularity of the rocks of stage I. See Plate XVII A further reduction in grain size would give the granular hornblende-plagioclase rock regarded by Flett as a hornfels. The phacoids or augen reported by Flett have not been observed.

In general the proportion of quartz has increased (but not in the modal analysis given) and myrmekitic quartz-plagioclase intergrowth is sparsely found. There is also an increase in the proportion of red-brown biotite, much of which surrounds the sphene which in turn mantles the iron ore. The abundance of sphene - in individual clusters and strings of small crystals - increases in proportion as more lime is released from the plagioclase and combines with

titania from the ilmenitic iron ore. Occasional idio-
blasts of clinozoisite are closely associated with both
altered plagioclase and chloritised biotite.

The accessory minerals include zircon, apatite,
rutile and colourless garnet.

3. Stage III - amphibolite without trace of ophitic texture

With the loss of traces of ophitic texture the
basic rock becomes more or less schistose and the grain
size tends to increase (Plate XVII). The rocks of stage
III are medium grained and are found either in small lenses
or at the margins of the large ones.

Biotite and sphene are the only idiolastic
minerals present. The hornblende is strongly coloured
(pleochroic scheme: X = pale green or brown; Y = brown-
green; Z = blue-green); the plagioclase lies in the com-
position range An_{30} to An_{65} ; while colourless or pale
pink garnet porphyroblasts up to 5 mm across occur in the
middle of areas in which plagioclase, hornblende and biotite
are finely intergrown. The plagioclase is less abundant
than in stage II, is well-twinned and shows an increasing
tendency to be myrmekitically intergrown with quartz.
Quartz and biotite are slightly more abundant than in
stage II, the biotite sometimes forming discrete folia in

the rock.

Crystals of sphene still form occasional clusters around crystals of titaniferous iron ore or rutile, but are more often found without such nuclei, while magnetite commonly occurs as small spongy crystals without associated sphene. There are pleochroic haloes around some of the small sphene crystals included in hornblende. Idioblasts of epidote and clinozoisite are common where the plagioclase has suffered secondary alteration. Apatite is a common accessory mineral.

There are occasional feldspar porphyroblasts up to 12 mm long and streaks of quartz-feldspathic material. In thin section a few 'porphyroblasts' are seen to be areas of plagioclase mosaic. The decrease in proportion of plagioclase throughout the series suggests that it contributes material to those minerals whose proportion increases, viz. hornblende, biotite, garnet and quartz.

4. Minor rock types.

Hornblende-gneisses border some of the lenses. These coarse grained rocks are banded and contain more quartz-feldspathic material than do the amphibolites. The rocks consist of quartz, plagioclase (composition range An_{27} to An_{37}), biotite, hornblende (pleochroic

scheme: X = brown-green; Y = green; Z = blue-green) and garnet. The plagioclase is invariably crowded with small inclusions of quartz or of microcline crystals in optical continuity with each other. The accessory minerals include rutile, apatite, epidote, clusters of sphene and spongy crystals of iron ore.

The patches and sheets of hornblende-'granulite' have an average grain size of 0.1-0.2 mm and contain hornblende similar to that in the rocks of stage II, plagioclase (composition range An_{35} to An_{55}), red-brown biotite, iron ore and sphene (Plate XVIII). There are occasional quartzo-feldspathic streaks and plagioclase porphyroblasts up to 3 mm long. The equigranular condition of the hornblende-'granulite' is incipiently seen in stage II, and does not appear to be a physical breakdown but an extreme stage of the general recrystallisation, possibly favoured by local inhomogeneities in the gabbro. Perhaps this granular rock, which is rich in hornblende (see Table 4), is the complementary metamorphic differentiate of the irregular patches and veins of plagioclase (An_{30}) and biotite which occur in the rock. The thick transgressive acid veins are rich in microcline and microcline-perthite and cannot be distinguished from the cross-cutting pegmatites in the country rocks.

The small inclusions within the basic rocks are fine-grained granulitic schists containing quartz, plagioclase, sometimes porphyroblastic, and biotite which is red-brown and ragged in outline. The round coarse grained inclusions of granitic aspect consist mainly of quartz and microcline-perthite with a little plagioclase and biotite resembling those of the schistose inclusions. These inclusions cannot be matched with any of the exposed granites of the district; their source is therefore unknown.

The hornblende-schists of Craig Revack and the River Dulnain are medium grained, thoroughly reconstituted rocks. All the minerals are xenoblastic except biotite and sphene. Hornblende forms the bulk of the rocks and has the pleochroic scheme: X = yellow-green; Y = green; Z = bluish-green, and is accompanied by lesser amounts of plagioclase in the range An_{40} to An_{47} . Clinzoisite and quartz are the remaining constituents. The lens at Craig Revack is bordered on its upper side by a quartz-rich pegmatite which also contains certain minerals - hornblende, clinzoisite and sphene - which are found to be optically identical with, and in some cases optically continuous with, the corresponding minerals of the hornblende-schist. It is therefore considered that this pegmatite formed more or less in situ by the mobilisation of the materials of the

hornblende-schist, possibly aided by the passage of carbon dioxide such as has ~~already~~ ^{by the writer} been inferred to have passed through the surrounding rocks (see pp. 113-118).

(c) Discussion

The origin of the basic rocks of the Lochindorb belt as a gabbroic or doleritic intrusion more or less confined to a particular horizon in the Meine Series is not in doubt. Flett considered the sequence of changes observed in thin section to be the result of pressure breaking up the original texture and promoting the recrystallisation of old minerals and the growth of new ones. Although pressure undoubtedly had an effect on the rearrangements in the rocks the evidence presented above indicates that temperature and/or chemical environment were much more potent factors than pressure. The mineralogical and textural rearrangements were the results of the tendency of a high temperature assemblage to reach equilibrium at a lower temperature. Yet the difference in temperature between the igneous rock and the country rock was insufficient to produce hornfelses in the latter. Flett's claim that hornfels was produced in the basic rocks by a later granite does not appear justified; in fact, no such granite has been detected.

The thin planar acid veins in the basic rocks possibly represent an acid residuum which crystallised in the joint planes of the parent gabbro (as in Campbell and Lunn, 1927, Plate I, Fig.1). Later, there occurred segregation of plagioclase and biotite into irregular patches which are possibly the complementary metamorphic differentiates of the hornblende-'granulites'.

The combined field and petrographic evidence essentially supports Flett's view that the intrusion of the gabbro took place late in the metamorphic history of the country rocks, while the country rocks were still at a relatively high temperature. Moreover, the lensoid shape of the basic bodies and the lack of complete reconstitution and of cataclastic structures strongly suggest that the masses were intruded as a series of lenses along the foliation of the country rock rather than as a sheet which was subsequently sheared into lenses. Subsequent changes gave rise to a progressive series of rocks culminating in garnetiferous amphibolite.

The late-metamorphic basic rocks of the Lochindorb belt therefore contrast with the pre- or syntectonic basic rocks of the valleys of the Spey and the Dulnain some four miles to the SE. The Lochindorb rocks are part of an unusual province which lies along the south side of the Moray

Firth and in which the metamorphosed basic rocks contain distinct relict igneous structures and textures despite the high metamorphic grade (Read, 1923; Wiseman, 1934). The existence of this province athwart the Moine-Dalradian boundary is indirect evidence supporting the hypothesis that the Moine and Dalradian Series were recrystallised and folded at the same time. It is possible that the Moray-Banff province is also distinct chemically. In his regional study of the epidiorites Wiseman (1934, p.392) considered that the epidiorites of the kyanite zone lack biotite; in fact he considered that the presence of biotite in basic rocks at this grade indicated a sedimentary origin (p.397). For comparison with Mid-Strathspey the writer examined thin sections of kyanite zone epidiorites from Upper Strathspey and Portsoy, in Banffshire. Thin sections from the former district lacked biotite; those from the latter contained biotite and closely resembled in many respects the basic rocks of Mid-Strathspey. It thus appears that the basic rocks of the late-metamorphic province are richer in potash than the pre- or syntectonic basic rocks from further south.

Sutton and Watson (1951) have given thought to the problem of the retention, in several regions, of original textures by dolerites (and gabbros) which have

been variously metamorphosed to low grade amphibolites (SW Highlands), to high grade amphibolites (NW Highlands and Benff) and to pyroxene granulites (Adelie Land). They regard these three end-products as representative of three of the possible types of regional metamorphism, one of which is metamorphism with development of Barrovian zones. From their discussion of the nature of the types of metamorphism they reject variation in stress as a significant factor and have recourse to variation in the "threshold" temperature of reaction to account for the different trends. But Sutton and Watson did not take into consideration such factors as time of intrusion of the dolerites and the metamorphic grade of the country rocks at the time of intrusion. Late-metamorphic intrusions in high-grade rocks would not pass through the low-grade stages of metamorphism yet they would in all probability revert to an assemblage stable at the temperature of the country rocks insofar as time was available before the regional temperature fell and the rate of reaction was greatly reduced. The higher the grade, and therefore the temperature, of the country rocks the more the new assemblage in the dolerite would approach the magmatic assemblage of the original dolerite. Consideration of the time of intrusion therefore accounts for many of the apparently anomalous facts. The hypothesis, however, would

be strengthened by the discovery of closely contiguous (and recognisable) pre-metamorphic and late-metamorphic basic rocks in a high-grade region.

IMPERIAL
PANCHANG
NOTICE



THE GRANTOWN GROUP*

(a) Introduction

The name Grantown Group was given (1915) to a distinctive group of metamorphic rocks which underlie an elongate area in the Spey valley between Grantown in the NE and Broomhill in the SW. Included in the Grantown Group was the so-called Beinn Mhor Pelitic Group whose members are so similar to rocks of the Moine Series that they are omitted from this discussion. The Geological Survey officers regarded the Grantown Group as the equivalent of certain units in the Dalradian Series, then known as the Banffshire or Central Highland Series. Although it will later be demonstrated that the Grantown Group is an integral part of the Moine Series it is convenient to retain the name without attaching stratigraphical significance to it.

* The term Grantown Group was used in the Geological Survey Memoir (1915) by Hinxman and is preferable to the name Grantown Series used by Anderson in the same volume to denote the same rocks.

The rock types comprise marbles and calc-silicate rocks, biotite- and kyanite-gneisses, and granulitic

biotite-schists.

In general the rocks dip east, SE or south at moderate angles. Small folds and lineations plunge consistently to the SE at moderate angles. The outcrops of marble at Leggan Hill and Goldhome define a broad open synform while the calc-silicate rocks at Wester Leggan show the arch of the adjacent antiform, both structures plunging SE. At Craig Revack there is a broad antiform with a steep south-western limb.

Marbles and calc-silicate rocks lie along the north-western boundary of the Group and are followed eastward, that is, structurally upwards, by biotite- and kyanite-gneisses, above which are further calc-silicate rocks with thin marbles followed by coarse biotite-gneisses. The drift deposits of the Spey valley cover the rocks immediately overlying the uppermost gneisses. The rocks above the gneisses are very poorly exposed and, in most parts of the area, after a considerable interval typical rocks of the Moine Series outcrop to the east.

Detailed mapping of this Group on the 6-inch scale shows that some revision of the Geological Survey's 1-inch Sheet 74 and unpublished 6-inch sheets is necessary. In particular a new area of calc-silicate rocks and marble has been discovered on the NW slope of Craig Revack on the

77
east bank of the River Spey (see Fig.6, end pocket).

(b) Field Relations

1. Marbles and calc-silicate rocks

Marbles and calc-silicate rocks are exposed in seven discrete tracts within the area. Accurate correlation of outcrops from one tract to another is prevented by the mantle of peat and drift lying between the tracts.

The paucity of calcareous rocks in this part of the Highlands has resulted in every marble outcrop having been worked for agricultural lime in the past. Exposures are therefore always in quarries or pits. In general the marbles are interbanded with green calc-silicate rocks, the bands and lenses of marble varying from a few inches to about 20 feet in thickness. Individual bands can be traced for as much as 400 yards along the strike, as at Goldhome Quarry, where the thickest visible marble in the area has been wrought.

A small lens of marble is indicated on the Survey 1-inch map at a point on the east side of the Glenbeg Burn 800 yards due west of Grantown West Station. Despite an intensive search no outcrops were seen at or near this locality.

Goldhome The Survey, on the 1-inch Sheet 74.

indicate at Goldhome Quarry three beds of marble surrounded by predominantly pelitic rocks. During the present study it was found possible to map four distinct beds of marble enclosed in and separated by beds of calc-silicate rock and not pelitic rock as mapped by the Survey. The nearest exposures of pelitic rocks are 200 yards SE of the quarry.

Laggen Hill At Laggen Hill two superposed bands of marble, each 6-10 feet in thickness, are found. These are again over- and underlain by calc-silicate rocks, not pelitic gneisses as on Sheet 74. Here the foliation dips south and kyanite-gneiss first occurs 30 yards south of the marbles. To the north of the marbles, on the NW slope of the hill, all the exposures are of calc-silicate rocks except for a narrow strip of kyanite-gneiss not shown on the Survey 1-inch sheet. The exposures west of Laggen Hill and north of Goldhome are insufficient to justify the large tongue-shaped outcrop of calc-silicate rocks which is reputed to lie there. To the east of Laggen Hill the Survey map shows an area of pelitic rocks with a small rectangular area of quartzo-feldspathic rocks of Moine type, at its eastward end. Pelitic rocks are clearly seen to dip under the calc-silicate rocks, but above the latter no trace of pelitic rocks has been discovered. Semipelitic granulitic rocks are exposed over a

small triangular area and are apparently inter-banded with the neighbouring calc-silicate rocks. The foliation planes are parallel in both rock types. One presumes that this area of semipelitic rocks represents the rocks of Moine type shown on the Survey map. Furthermore, thin bands of calc-silicate rock occur in the pelitic gneisses low down on the east side of the hill, thus emphasising the intercalation of the two rock types.

Achnagonalin On the east bank of the River Spey at Achnagonalin Quarry a band of fairly pure marble about 20 feet in thickness was formerly worked, but the workings are now filled by water and debris. The granulitic biotite-schist which overlies the marble and dips SE at 30° is not indicated on the 1-inch Sheet.

Gaich Wood Along the north side of Gaich Wood the Survey officers mapped a single thin band of marble dipping southwards and overlain by a belt of calc-silicate rocks whose outcrop is 200-300 yards in width, the southern part of the wood being underlain by an unbroken tract of pelitic gneisses. Re-mapping indicates that in Gaich Wood there are two distinct bands of marble, each about 5 feet in thickness. The more northerly can be traced for 600 feet along the strike and the other band for 500 feet. Each marble has calc-silicate rock above and below it to a width

of some 400 feet across the strike. Separating the two calcareous belts are coarse kyanite-gneisses, whose outcrop is about 200 feet in width, while the upper calcareous rocks are overlain by coarse biotite-gneisses containing eyes and lenses of pegmatitic material. A break in exposures separates the lower calcareous rocks from the kyanite-gneisses of Laggan Hill to the NW.

Wester Laggan At the farm of Wester Laggan bands of marble were quarried. On Sheet 74 two bands are indicated, enclosed by pelitic rocks which are immediately succeeded eastwards by calc-silicate rocks. The present study has shown that here three bands of marble exist, each being bordered by calc-silicate, not pelitic, rocks. Moreover, NW of the marbles and dipping below them and above the kyanite-gneisses of Finlarig Wood, an area of distinctive greenish, micaceous and intensely crumpled rocks can be mapped.

Between Wester Laggan and the south end of Finlarig Wood the Survey indicate an arcuate belt - intercalated between pelitic rocks - of calc-silicate rocks with a curving outcrop convex to the south. The western end of this arcuate belt can now be shown to bifurcate, the structurally lower but topographically higher extension consisting of the distinctive micaceous rock mentioned

above. This is separated by coarse biotite-gneiss from the structurally upper extension of green calc-silicate rocks which, by virtue of the configuration of the ground, curve abruptly south before the scattered outcrops die out to the west.

Craig Revack Finally, on the north-western slopes of Craig Revack a new area, about 8 acres in extent, of calc-silicate rocks and marble has been discovered and mapped. In the Memoir on Sheet 74 it is noted that "on the lower slopes of the hill [Craig Revack] the rock has a greasy feel, possibly due to the presence of talc." (p.28) During the revision it was found possible at this locality to map impure marble, medium to coarse grained, banded green calc-silicate rock, and fine grained greenish granulitic schist. These rock types underlie a roughly triangular area bounded to south and east by coarse pelitic gneiss and granite, and to the NW by drift deposits. Along the south-western margin of the triangle the foliation is vertical in both calc-silicate rocks and bounding gneisses, and trends SE. Along the eastern margin the calc-silicate rocks dip gently SE beneath the gneisses. On the north-western side of the triangle numerous very thin bands of impure marble are seen to be intercalated in the calc-silicate rocks, in which are also found the fine grained

greenish schists mentioned above. The joints in the marble bands are intensely slickensided in many directions. At this locality, as nowhere else in the calc-silicate rocks, there are small concordant veins and lenses of quartz.

2. Biotite- and kyanite-gneisses

Pelitic rocks are found in five of the tracts named in the previous sub-section. Coarse biotite-gneisses are confined to the southern tracts of Wester Laggan, Gaich and Revack, while kyanite-gneisses are mainly found in the NW of the Group.

South of the River Dulnain the Geological Survey show a large wedge of pelitic rocks whose southern apex divides at Ochnoir into three branches mutually separated by siliceous Moine rocks. The easternmost branch is wider than the others and extends further to the south. The writer's detailed mapping shows that near Ochnoir three horizons of garnetiferous biotite-gneiss dip SE conformably with the surrounding quartzo-feldspathic gneiss. There is, however, no evidence either to confute the suggestion that the pelitic rocks are normal intercalations in the Moine Series, or to support the idea that the pelitic outcrop widens northwards. The area at Ochnoir where the wide eastern outcrop shown by the Survey should be located lacks exposures. Moreover, at Toum, where no pelitic rocks are

shown on the 1-inch Sheet, there is a considerable outcrop of garnetiferous biotite-gneiss.

At the quarry of Broomhill, also south of the Dulnain, there are medium grained granulitic biotite-gneisses which also closely resemble typical rocks of the Moine Series.

The arguments presented by the Survey to support the continuation of the Grantown Group south of the Dulnain depends on the assumed continuation of the rocks for a distance of two miles over ground devoid of exposures, and on the supposed lithological similarity of the rock types north and south of the river. The pelitic rocks at Broomhill and Ochnoir are not of a "markedly different type" (1915, p.27) from the rocks of the Moine Series, as was maintained by the Survey. There is, therefore, no justification for separating the pelitic rocks south of the Dulnain from the Moine Series proper.

In Finlarig Wood and along the southern slopes of Laggan Hill, as previously noted, the outcrop of kyanite-gneisses is more restricted than that mapped by the Survey. On the NE side of Laggan Hill the foliation in the narrow east-west outcrop of pelitic gneisses dips SE. Kyanite-gneiss has been mapped in Gaich Wood, the outcrop seldom being more than 200 feet wide across the strike.

At Craig Revack, outwith the granite and the wedge

of calc-silicate rocks, pelitic rocks alone have been mapped. Pelitic rocks in the most easterly exposures tend to be less coarse in grain than on the rest of the hill. Rocks of the usual Moine type have not been observed on the ground immediately east of the hill. Well-exposed pelitic gneiss at the gate of Revack Lodge suggests that the outcrop on the 1-inch map could be extended some 200 yards to the north. There is little justification for the wedge of pelitic rocks marked by the Survey as extending SW from the hill. The area thus mapped was then and is now entirely cultivated.

Near Dulnainbridge there is, on the north bank of the Dulnain, an elongate area of exposed rocks, marked pelitic on the 1-inch Sheet, in which it has been found possible to map three rock types. The rocks dip southwards at moderate angles. At the western end of the Dulnainbridge plantation and 1000 feet up from the mouth of the Finlarig Burn there are coarse pelitic gneisses of the same type as those seen between Dulnainbridge and Revack, three miles to the east. The coarse pelitic gneisses dip beneath and grade into medium grained pelitic gneisses which can be traced in an east-west belt from Dulnainbridge almost to Muckrach Lodge. Above these, in the bed of the Dulnain and a little to the north, there lies a narrow belt of semipelitic

flaggy gneisses of typical Moine type. The distance across the strike between this last rock and the coarse gneiss structurally below is about 200 yards. Therefore the grain size of the pelitic rock decreases markedly both upwards and outwards from the calc-silicate rocks. This decrease is illustrated in Plate XI.

(c) Petrography

1. Previous work

Previous petrographic descriptions of rocks from the area have been brief. In the Geological Survey Memoir (1915, p.27) Anderson, on the evidence of hand specimens, divided the calc-silicate rocks into coarse tremolite rocks and granulitic zoisite-bearing rocks corresponding roughly to two of the four divisions listed in the following paragraph. Flett, in the same volume (p.53), described the mineral content of the calc-silicate rocks of Laggan Hill. These rocks are rich in tremolite-actinolite together with white augite (malacolite), phlogopite, epidote, zoisite, sphene, quartz, alkali feldspar, and some carbonates. More recently Williams, Turner and Gilbert (1954, p.239) used a marble from the Grantown Group containing calcite, quartz, biotite, clinozoisite and sphene to illustrate a typical marble of the amphibolite facies.

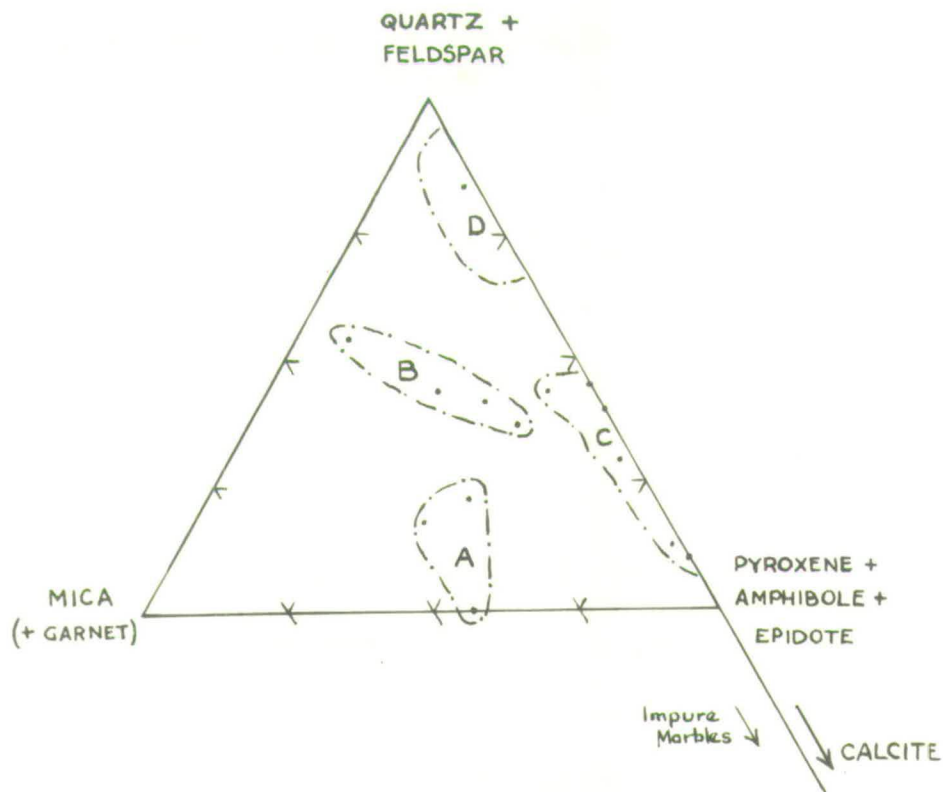


FIG 7 Plot of modal analyses of calc-silicate rocks of the Grantown Group.

- Calc-silicate rocks {
- A - Micaceous type
 - B - Granulitic type
 - C - Amphibolitic type
 - D - Field of granulitic calc-silicate rocks of Maine Series. Point represents epidote-bearing rock from biotite-gneisses, Craig Revack.

(+GARNET) refers only to granulitic calc-silicate rocks of the Maine Series.

2. Petrography of the calc-silicate bearing rocks

The calc-silicate rocks of the Grantown Group can be subdivided into four types, recognisable in hand specimen and distinctive in thin section. They are (a) impure marble, (b) micaceous type, (c) granulitic type, and (d) amphibolitic (and diopsidic) type. These types represent compositional variants of the original sediments (p. III) and it is not therefore surprising that the types grade into each other. The distinctions and gradations are well seen on the triangular diagram (Fig. 7) on which are plotted modal analyses of the rocks. In particular the boundary between the granulitic type and the amphibolitic type is rather arbitrary. The micaceous and calcareous types are more distinct both from each other and from the two foregoing types. It is possible to find two of these types interbanded in the field, individual layers ranging in thickness down to a few mm. Each such layer has, however, a distinctive mineral assemblage. Modal analyses have been made on slides which contain one type only.

A. Impure marbles

In hand specimen the impure marbles are compact, medium grained, banded rocks. The mineral banding probably

TABLE 6

Modal analysis of impure marble, Goldhome Quarry,
Dulnainbridge.

<u>Thin section no.</u>	<u>173</u>
Calcite	62
Phlogopite	9
Tremolite	25
Diopside	4
Accessory	1
<hr/>	
<u>Points counted</u>	<u>1800</u>

NOTE

PARCHMENT

IMPERIAL

represents original bedding. Although weathered surfaces are usually buff in colour, fresh surfaces are pale green, grey or buff. The calc-silicate minerals are in prominent thin bands. The only dark mineral which can be recognised with confidence is a bronzy mica occurring in thin layers or in small flakes scattered throughout the rock. Some specimens have a mica lineation.

Calcite is the main constituent of the rock. The crystals tend to be elongate, with a maximum length of 1.5 mm parallel to the foliation, and are usually well twinned (Plate XVIII). Occasionally concordant thin bands of very fine grained equigranular calcite are found; the larger crystals in these bands have bent twin-lamellae. The bands are probably due to slight cataclasis at a low temperature; they occur in a heavily slickensided rock (p.82)

Amphibole is normally present in variable proportions, which, however, exceed the proportion of diopside. The crystals are colourless and show good prismatic form, cross-sections being up to 0.4 mm in diameter. The larger crystals are poikiloblastic, while the smaller are arranged in strings and clusters in the calcitic matrix. Measurements on the Federov 4-axis Universal Stage indicate that the optical properties are not constant even in the same thin-section. The average

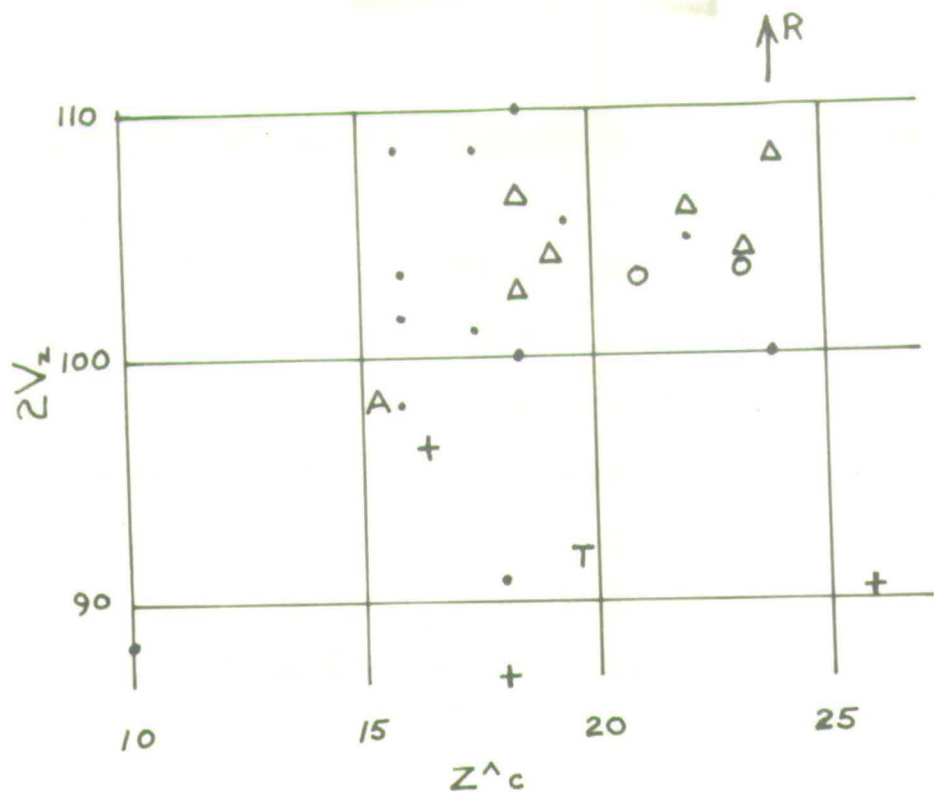


Fig. 8 $2V_z$ plotted against Z^c for 24 amphiboles from calc-silicate rocks of the Grantown Group. T=tremolite, A=actinolite, R=richterite. + = amphiboles from impure marbles, ○ from micaceous rocks, Δ from granulitic rocks, • from amphibolites.

values of $2Vz$ and $Z^{\wedge}c$ (Table 7) correspond with the tremolite cited by Winchell (1951). (See also Fig.8.)

Pyroxene is normally present in variable proportions. The crystals are colourless and roughly equidimensional, up to 1.0 mm across but with irregular outlines; they are sometimes poikiloblastic. The smaller crystals are in strings or closely clustered aggregates. Closely spaced (100) cleavages are common in the crystals of rocks characterised by the occurrence of shear bands in the calcite matrix.

While repeatable for any one crystal, values of $2Vz$ and $Z^{\wedge}c$ vary from one crystal to another within a single specimen (Table 7); when plotted against each other, however, the values are seen to have a linear relationship over a considerable range (Fig.9). The values indicate a range of composition from diopside to hedenbergite.

Mica is usually present in small quantity. The crystals are pleochroic with X = colourless; $Y = Z$ = pale golden brown. They are not markedly tabular, their length being rarely more than 0.2 mm. In some rocks they occur as isolated crystals, in others they form small clumps and thin layers. In composition the mica is probably a phlogopite.

Clinzoisite, occurring as colourless, xenoblastic

TABLE 7

Universal stage data on the pyroxenes and amphiboles
of the impure marbles.

Thin section no.	173		173		371	
	amphibole		pyroxene		pyroxene	
	2Vz	Z ^ c	2Vz	Z ^ c	2Vz	Z ^ c
	86	18	52	36	70	50
	90	27	70	50	84	51
	96	16	60	45	66	47
			68	45	90	56
					62	40
Average	91	20	62	44	74	49

173. Coldhome Quarry, Dulnainbridge.

371. West side of Craig Nevack.

NOTE

PARCHMENT

IMPERIAL

crystals, is usually found in small quantity. Cleavage is poorly developed in the crystals, which seldom exceed 0.4 mm in length and show anomalous blue interference tints. In bands rich in calc-silicate minerals clinozoisite tends to be interstitial.

Microcline is occasionally found in thin layers as a granoblastic mosaic of equidimensional grains up to 0.4 mm in diameter.

Accessory minerals comprise small xenoblastic crystals of pyrite and, more commonly, well-formed small crystals of sphene which shows pleochroism from Z = pale pinkish brown to Y = nearly colourless, and small crystals of quartz.

B. Micaceous calc-silicate rocks

These rocks are well-foliated, grey-green, faintly colour banded and generally rather fine grained, and commonly show small folds and crumples even in hand specimens. Mica plates, amphibole needles, quartz rods and small folds form a parallel linear structure in the rock. Calcite has not been found in this type. (See Plate XIX.)

Mica (33-42%) is common to abundant in all specimens (Fig.7). The tabular flakes vary from 0.1 mm to 1.2 mm in length, the larger crystals being more platy than the smaller. The pleochroic scheme is: X = colourless;

TABLE 8

Modal analyses of micaceous calc-silicate rocks.

Thin section no.	91	242	468
Phlogopite	42	42	33
Tremolite	57	37	43
Quartz	-	20	15
Plagioclase	-	1	8
Accessory	0.5	-	1
points counted	1200	1300	1700

91. Calc-silicate rock, 300 yards south of Easter Laggan Farm.
242. Calc-silicate-schist, 150 yards NW of Wester Laggan Farm.
468. Calc-silicate-schist, 350 yards west of Wester Laggan Farm.

NOTE

PARCHMENT

IMPERIAL

Y, Z = pale golden brown. Measurement on the Universal stage shows that there is optic axial darkness over a range of 8-9° suggesting a value of $2V_z$ close to this figure. Extinction is straight, parallel to the cleavage. In composition the mica appears to be close to phlogopite. In some specimens the micas occur in rod- or lens-shaped aggregates while in others the crystals tend to form a continuous micaceous 'matrix' to crystals of other minerals.

Amphibole (43-57%) is always present in rocks of this group, the proportion varying inversely to that of the mica. The amphibole forms colourless crystals which are normally needle-shaped with good prismatic form. Cross-sections are up to 0.3 mm across; longitudinal sections have a maximum length of 1.0 mm.* Crystals are normally

* In all the amphibole-bearing rocks the amphiboles are needle-shaped. Therefore throughout the thesis the maximum dimensions will be given by the sizes of the largest cross-section and the longest length.

too small for measurement on the Universal Stage, but two large crystals gave the values:

Thin Section 91	Average		
$2V_z$	104°	104°	104°
$Z \wedge c$	23°	21°	22°

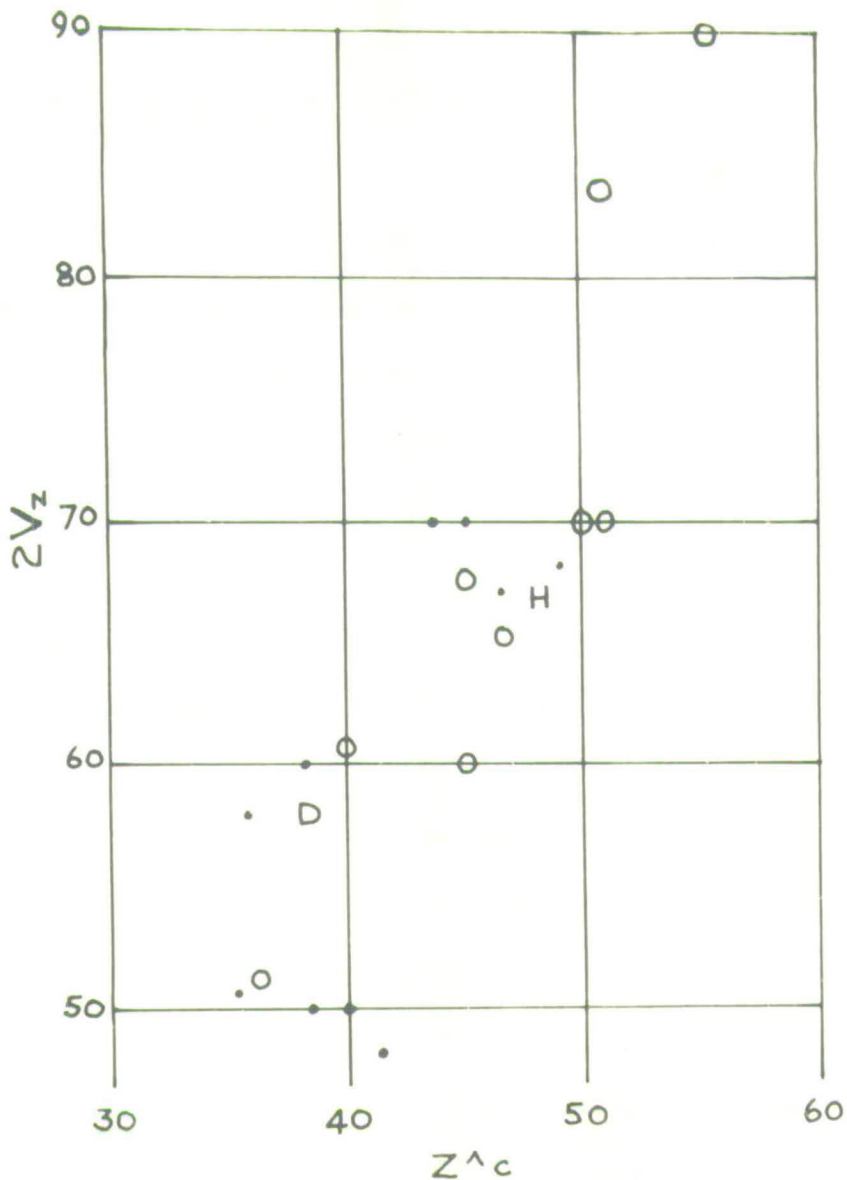


Fig. 9 $2V_z$ plotted against Z^c for 19 pyroxenes from calc-silicate rocks of the Grantown Group. D = diopside, H = hedenbergite. ○ = pyroxene from impure marble; ● = pyroxene from amphibolite.

Quartz (0-20%) is occasionally present. The crystals are equidimensional, interstitial, lack undulose extinction and are rarely as much as 0.4 mm across.

Plagioclase (0-8%) is sometimes present, as crystals lacking good form and usually about 0.1 mm in diameter. Most of the crystals are dusty and altered to secondary mica, but in one fresh example the composition was estimated at An_{30} .

Microcline is seldom seen and then only in small quantity, the crystals being xenoblastic and about 0.1 mm across.

Several specimens contain up to 10% of a colourless chlorite in small flakes up to 0.3 mm in length. The birefringence is low, with mean R.I. about 1.60; the crystals are length-fast and show one good cleavage and straight extinction.

Accessory minerals include the following:- muscovite in aggregates of small flakes; sphene as small ragged crystals; small ragged crystals of iron ore, some of which can be identified as hematite; graphite as small flakes occasionally included in the amphibole; and sparse apatite in small idiomorphs.

C. Granulitic calc-silicate rocks

In hand specimen these are compact grey or green

TABLE 9

Modal analyses of granulitic calc-silicate rocks.

Thin section no.	107	177	231	232
Quartz	3	41	43	18
Plagioclase	10	-	13	26
Microcline	24	-	-	-
Phlogopite	16	30	34	26
Muscovite	-	5	-	-
Tremolite	45	-	-	25
Epidote	-	24	8	2
Accessory	1	0.5	2	3
Points counted	1100-1300			

107. Calc-silicate rock, 350 yards
NW of top of Graig Revack.

177. Calc-silicate rock, 350 yards
SE of top of Laggan Hill.

231. Calc-silicate rock, 350 yards
SW of Revack Lodge.

232. Calc-silicate rock, same
locality as 107 above.

NOTE

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rocks, well banded but imperfectly foliated, with alternating light and dark bands. Small folds and crumples are seldom seen. The rocks are fine to medium in grain, and mica, quartz and needle-shaped amphibole can be recognised with the hand lens. Where the amphibole crystals are conspicuous, they are seen to form a lineation. The modal analyses (Table 9) show the wide variability in the abundances of even the main constituents.

Quartz (3-43%) is always present. It forms equidimensional granules which lack undulose extinction and are up to 0.2 mm in diameter.

Plagioclase (0-26%) forms small xenoblastic crystals with a maximum diameter of 0.4 mm, while in a few specimens poikiloblasts up to 1.0 mm across occur sparingly. The crystals are equigranular, commonly altered to mica or dusty material and twinned on the albite law, the twin lamellae being relatively narrow. Many crystals show patchy albitisation both at the edges and in the interior. Fine continuous zoning is sometimes visible. Two specimens gave a composition of about An_{35} .

Microcline (0-24%) is not present in every specimen. The crystals are xenoblastic, interstitial and irregular in outline, few having a diameter above 0.5 mm and none above 2.0 mm. The larger crystals tend to be

TABLE 10

Universal Stage data on the amphiboles of the gran-
ulitic calc-silicate rocks.

Thin section no.	294		366	
	2Vz	Z ^ c	2Vz	Z ^ c
	104	23	103	18
	108	24	106	22
	104	19	106	18
Average	105	22	105	19

*X = colourless

Y = very pale green

Z = " " "

X = very pale green

Y = pale green

Z = pale blue-green

* This pleochroic scheme is much the more
common.

NOTE

PAROCHMENT

IMPERIAL

poikiloblastic. In rocks with a high content of microcline, perthitic intergrowths in the form of very thin stringers of albite in the microcline are found.

Mica (16-34%), probably phlogopite, is always present. The tabular crystals have a maximum length of 0.3 mm, their pleochroic scheme being: X = colourless; Y, Z = pale golden brown or pale olive-brown. The crystals are too small for measurement on the Universal Stage. Where amphibole is abundant the mica crystals are noticeably more ragged than is usual.

Amphibole (0-45%) is usually present. The crystals are idiohedral with a maximum size of 0.7 mm in cross-section and 2.5 mm in length. The larger crystals tend to be poikiloblastic. Measurements made on the Universal Stage show the amphibole to have the composition of sodic tremolite-actinolite in accordance with the blue-green shade seen in the more strongly coloured crystals.

Epidote (0-24%) is nearly always present, the proportion decreasing almost to zero in rocks rich in amphibole. The epidote forms hypidioblastic or xenoblastic crystals, up to 0.2 mm in cross-section and 0.5 mm in length, which are colourless or very pale yellow (Plate XIX). The birefringence and $2V_z$ are high; the mineral is optically negative. Simple twins are occasionally seen. In one

TABLE 11

Modal analyses of amphibolitic and diopsidic calc-silicate rocks.

Thin section no.	96	175	205	228	229	355
quartz	4	14	18	3	24	-
Plagioclase	6	8	19	23	19	13
Microcline	-	22	6	13	-	-
Phlogopite	-	1	7	-	-	1
Tremolite	75	47	48	60	54	2
Diopside	-	21	-	-	-	78
Epidote	13	1	-	-	-	6
Muscovite	1	-	-	-	-	-
Accessory	1	-	2	1	3	1

Points counted

1200-1700

96. Calc-silicate rock, 200 yards SW of top of Leggan Hill.
175. Calc-silicate rock, 100 yards north of Goldhome Quarry.
205. Calc-silicate rock, 150 yards NE of top of Gaich Hill.
228. Calc-silicate rock, 500 yards NW of top of Craig Revack.
229. Calc-silicate rock, 400 yards SW of Revack Lodge.
355. Calc-silicate rock (diopsidic band), same locality as 228 above.

example the epidote crystals adjacent to accessory pyrite are greenish-yellow and strongly pleochroic whereas the epidote elsewhere in the slide is colourless.

The most abundant accessory mineral is sphene. The idioblastic crystals are up to 0.7 mm in length and occur in clusters. The larger crystals are pleochroic from pinkish-brown to colourless. Very small quantities of muscovite in sparse short shreds are found in some specimens. Iron ore is seldom encountered; where found it is usually pyrite in small xenoblastic crystals. Small idioblastic needles of apatite occur sparsely.

D. Amphibolitic and diopsidic calc-silicate rocks

Although in hand specimen the amphibolitic rocks are the most typical and distinctive of the calc-silicate bearing rocks the modal analyses show a gradational change towards the granulitic type (Fig.7). In hand specimen the rocks are compact, evenly banded, the bands being mainly green but also grey, white and occasionally pink. The grain size varies from fine to coarse. With the hand lens fibrous amphibole is easily recognised together with mica, feldspar, quartz and occasionally sphene. The amphibole needles, up to 10 mm long, usually form a lineation.

The amphibolitic rocks contain occasional persistent diopsidic bands up to three inches thick. The bands -

TABLE 12

Universal stage data on the amphiboles of the amphibolitic calc-silicate rocks.

Thin section no.	96		110		175	
	2Vz	Z [^] c	2Vz	Z [^] c	2Vz	Z [^] c
	104	16	88	10	110	18
	98	16	92	18	108	17
	102	16				

Thin section no.	204		362	
	2Vz	Z [^] c	2Vz	Z [^] c
	106	18	102	17
	106	22		
	100	18		
	108	16		
	100	24		

NOTE

PAROCHMENT

IMPERIAL

which form only a small proportion of the rock - are pale green or white in colour and are parallel to the foliation of both the calc-silicate rocks and the enclosing mica-gneisses (p. 81) and to the contact between these two rock types. A typical modal analysis of one of these bands is given in Table 11 (355) and a photomicrograph in Plate XXI . The constituent minerals have the same optical properties and textural features as the minerals of the amphibolitic rocks and a separate petrographic description is therefore unnecessary.

The table of modal analyses (Table 11) shows the rocks to be poor in micas but generally rich in feldspar and sometimes in quartz.

Amphibole (47-75%), the characteristic mineral of these rocks, is always present and its proportion is only low where pyroxene is very high. The crystals are generally idioblastic, especially the smaller ones. Above 1.0 mm long - up to 6.0 mm long - the crystals are xenoblastic and tend to be poikiloblastic. The needles normally lie in the foliation plane, but are occasionally oblique. Simple twins are rare. Some crystals are colourless but the majority have the pleochroic scheme: X = colourless; Y,Z = very pale green. Thirteen crystals were examined on the Universal Stage. 2Vs varied from one crystal to another

TABLE 13

Universal stage data on the pyroxenes of the amphibolitic and diopsidic calc-silicate rocks.

Thin section no.	175		204		355	
	2Vz	Z [^] c	2Vz	Z [^] c	2Vz	Z [^] c
	70	44	66	46	60	38
	50	40	50	39	52	36
	48	41	70	45	57	36
			68	49		
Average	56	42	63	45	56	36

NOTE

PAROCHMENT

IMPERIAL

over the range 88° to 110° and $Z \wedge c$ from 10° to 24° . When $2Vz$ is plotted against $Z \wedge c$ there is a scatter of points around $2Vz = 102^\circ$ and $Z \wedge c = 17^\circ$, values which suggest a mean composition close to sodic actinolite (Fig.8). (See also Plate XX.)

Pyroxene (0-21%) is seldom present, the crystals being colourless in thin section. The size of crystal varies from 0.1 mm to 3.0 mm, the smaller being hypidioblastic whereas the larger have a poikilitic xenoblastic habit. Many of the larger crystals can be seen to be formed of a mass of small interlocking xenoblasts with almost the same optical orientation. It is not clear whether the poikiloblasts are breaking up or forming by aggregation. Closely spaced (100) cleavages are common in many crystals.

Data from the Universal Stage on 10 crystals show a wide range of values, $2Vz$ varying from 48° to 70° and $Z \wedge c$ from 36° to 49° . As shown on Fig.9 these values are in two concentrations around $2Vz = 55^\circ$, $Z \wedge c = 38^\circ$ and $2Vz = 67^\circ$, $Z \wedge c = 47^\circ$, corresponding to compositions of diopside and hedenbergite.

Plagioclase (6-23%) is present in variable proportion. In most examples the mineral is completely altered to secondary mica, dusty material and occasional calcite. Crystals lack good form and are interstitial; they vary in

TABLE 14

Universal stage data on epidote minerals, amphibolitic
calc-silicate rocks.

110		355		362	
2Vz	Z [^] 001	2Vz	Z [^] 001	2Vz	Z [^] 001
104	28	94	24	108	23
104	23	88	20		

NOTE

PARCHMENT

IMPERIAL

size from 0.1 mm (equidimensional) to 0.7 mm (poikiloblastic). since fresh crystals are rare it was possible to measure the composition accurately in only two specimens: An_{25} and An_{37} .

Microcline (0-22%) is found in about half of the specimens, its abundance being unrelated to that of the other minerals, including plagioclase. The crystals are interstitial or poikiloblastic, and are occasionally up to 4.0 mm across but normally are about 0.5 mm. Patches of secondary mica in the microcline suggest that the latter originally contained plagioclase, i.e. was perthitic.

Epidote minerals (0-13%). Both epidote (-, high birefringence) and clinozoisite (+, low anomalous birefringence) are found, sometimes in the same thin section. Crystals of both minerals are colourless or a faint brown. Those of clinozoisite are generally small and interstitial, but larger ones - exceptionally up to 1.0 mm - tend to be more irregular in outline. Simple twins are rare. The angle $Z \wedge (001)$ was measured on the Universal Stage for several crystals and the values ranged from 16° to 20° . The epidote crystals, also up to 1.0 mm long, are more variable in size and sometimes show hypidioblastic form. Measurement of five crystals on the Universal Stage shows that $2Vz$ varies from 94° to 108° and the $Z \wedge (001)$ from 23° to 28° (Table 14).

Quartz (0-24%) is usually present. Most of the crystals are small and equidimensional and, apart from a few of the larger crystals (>0.5 mm across) which are strained, they lack undulose extinction. Exceptionally the quartz crystals reach 1.3 mm across, and in one thin section were found to contain thin fibres of rutile.

Mica (0-7%) is sparse and is usually found in thin layers in the rock. The crystals are small, thick plates up to 0.5 mm long and have a pleochroic scheme: X = colourless; Y,Z = pale golden brown, pale red-brown or pale brown. When in thin layers the mica tends to alter to a very pale green chlorite with low normal birefringence. Muscovite is found occasionally in clumps of small crystals.

Sphene, pleochroic from pinkish-brown to colourless, is the most common accessory mineral and usually occurs as small idiomorphic crystals (0.1-0.5 mm) but in the coarse rocks larger ragged crystals (to 1.0 mm) are found. Some have cores of rutile. Iron ore is sparse, and forms small interstitial crystals which can sometimes be identified as pyrite. Interstitial calcite is sometimes sparsely present.

The chemical composition of these calc-silicate rocks has been summarised (as on p.47) and contrasts with that of the calc-silicate 'granulites' thus: silica » lime » magnesia > iron oxides » alumina > potash » soda. Notably

TABLE 15

Modal analyses of kyanite-gneisses.

Thin section no.	98	338
Quartz	40	42
Plagioclase	-	3
Biotite	27	42
Muscovite, primary	-	4
" , secondary	19	4
Kyanite	11	5
Accessory	3	1
Points counted	1500	1800

98. Kyanite-gneiss, 450 yards
NW of Easter Laggan Farm.

338. Kyanite-gneiss, 200 yards
north of top of Gaich
Hill.

NOTE

PARCHMENT

IMPERIAL

the alkali ratio is reversed, alumina is much lower and silica is slightly lower, while the basic oxides have increased in proportion.

3. Petrography of the pelitic rocks

In hand specimen the pelitic rocks can be divided into: (a) kyanite-mica-gneisses without quartzo-feldspathic layers and lenticles, and (b) mica-gneisses with marked quartzo-feldspathic layers and lenticles. The latter are found immediately SE of the Revack-Gaich-Wester Laggan belt of calc-silicate rocks and marbles in a zone varying from 250 yards wide across the strike at Dulnainbridge to over 600 yards at Revack.

A. Kyanite-mica-gneisses

These rocks are coarse grained and flaky with large plates of biotite and muscovite prominent on the crude foliation planes. On weathered surfaces elongate prisms of blue-grey kyanite are prominent. The prisms, which have a maximum length of 30 mm, generally lie roughly sub-parallel to each other in the plane of the foliation forming a crude lineation. The biotite-gneisses associated with the kyanite-gneisses differ only in absence of kyanite.

Biotite (27-42%) is always present in flakes up to 3.0 mm across, but usually much smaller. The pleochroic

scheme is: X = pale yellow-brown; Y, Z = rich golden brown. Alteration along the cleavages is common, resulting in a pale green chlorite (with low normal birefringence) and minor amounts of iron ore.

Muscovite (8-19%) occurs commonly as plates which are relatively thicker than those of biotite and reach a maximum length of 2.0 mm. Much of the muscovite, however, forms either sheaths of small crystals surrounding the kyanite or ovoid to sub-rectangular patches (the shimmer-aggregate of Barrow) probably completely replacing kyanite. Such muscovite has been recorded as secondary in the modal analyses (Table 15). Some thin needles suspected to be sillimanite were observed in the aggregates but their identity could not be confirmed.

Kyanite (5-11%) occurs mainly as bladed crystals, up to 3.0 mm across and 30 mm long, which are usually well formed and surrounded by thin sheaths of small muscovite crystals. One example contains kyanite which tends to be spongy and poikiloblastic, each embayment containing its complete muscovite sheath (Plate XXI). Further, in this example the parts of the spongy crystal are not quite in optical continuity, up to 12° difference being seen in the extinction positions of the different parts. The minerals occurring in the interstitial spaces of the spongy kyanite

crystals are much smaller in grain size than the crystals of the same minerals in the mass of the rock.

Quartz forms about 40% of the rocks. The crystals lack good form, are up to 3.0 mm long and are slightly strained. Intergranular boundaries are smooth and unsutured.

Plagioclase (up to 3%) is usually found in the varieties which contain spongy kyanite. The crystals are interstitial and xenoblastic, up to 4.0 mm long. They tend to have small rounded inclusions of other minerals, particularly quartz, biotite and muscovite. The crystals are fresh and well-twinned with relatively narrow twin lamellae. The composition range is An_{20} to An_{30} .

Accessory minerals have not been observed to exceed 3% of the rock. Tourmaline is the most common, occurring in idiomorphic pleochroic olive green prisms up to 0.2 mm long. The absorption scheme is $O > E$. Small colourless crystals of garnet up to 0.3 mm in diameter are found in some specimens; and sparse ragged crystals of iron ore, probably liberated during the alteration of biotite, also occur. Small idiomorphs of rutile, apatite and zircon complete the list of accessories.

B. Mica-gneisses

These rocks are coarse grained and dark grey in

TABLE 16

Modal analyses of mica-gneisses and schists.

Thin section no.	108	360	455	457	201
quartz	39	34	37	33	17
plagioclase	21	26	8	35	41
Biotite	17	14	22	17	38
Muscovite	20	22	29	15	-
Accessory	3	4	4	-	3
Points counted	1500-1600 in each case				

108. Mica-gneiss, 400 yards SE of the top of Craig Revack.
360. Mica-gneiss, 350 yards NW of the top of Craig Revack.
455. Mica-gneiss, top of Gaich Hill.
457. Mica-gneiss, 100 yards up from the mouth of the Finlarig Burn, Dulnain-bridge.
201. Biotite-schist, above marble, Achnagonalin Quarry.

NOTE

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colour, crudely foliated and sometimes faintly banded. The banding is probably original and is not always parallel to the foliation (see p. 162). The foliation surfaces are intensely rough and crumpled. Muscovite, biotite, quartz and feldspar can be distinguished with a hand lens. The rocks typically contain lenses, pods and thin layers of coarse quartzo-feldspathic material (Plate XI).

On the scale of an exposure the rocks are seldom without rods and lenses of quartz and pegmatite, or infolded narrow discontinuous pegmatites. The pegmatitic parts of the rock are usually concordant with the foliation but cross-cutting examples up to two feet in width are seen. The quartz rods are up to 1 foot by 2 feet in cross-section (Plate V) while the concordant pegmatite sheets range up to 3 feet in thickness. The margins of some infolded pegmatites are richer in mica than the country rock (cf. Plate X) and Greenly (1923), Figs 4,5,6).

The resulting rock assemblage (Plate VI) is unique within the area and indeed among the Moine Series of an extensive part of the Highlands. The rocks show remarkable consistency in modal composition, apart from the schist which overlies marble at Achnagonalin (Table 16).

Muscovite (15-29%) is commonly in parallel growth with biotite, over which it predominates slightly in most specimens (Plate XXII). The plates are well-formed,

up to 3.5 mm long and are usually thicker than biotite crystals of the same size in the rock. The crystals are often bent, sometimes through angles of 20-30°. The total mica content (32-51%) is here sufficiently high for continuous layers of mica to have developed through the rock.

Biotite (14-38%) forms plates up to 2.5 mm long, which are usually well-crystallised, even around the crests of small folds. Bent crystals are occasionally found. The smaller crystals tend to be irregular in outline. Some plates which appear large in ordinary light are actually composed of several crystals in parallel growth. In general the larger crystals are less irregular in outline than the smaller. The usual pleochroic scheme is: X = straw yellow; Y,Z = dark brown or olive-brown. The most common alteration products of the biotite are chlorite (with anomalous purple interference colours) and lesser amounts of iron ore. In some slides the alteration of biotite is complete over small areas.

Quartz (17-39%) has two modes of occurrence, as large xenoblastic crystals up to 3.0 mm long with prominent undulose extinction, the crystals tending to be elongate parallel to the foliation; and as small equidimensional crystals up to 0.7 mm across, usually forming a granoblastic mosaic over areas of the same size as crystals of the first

type. These small crystals lack undulose extinction and in some cases are seen at the margins of the large strained crystals. It would therefore appear that the mosaics of small crystals were formed by the break-down and re-crystallisation of the large crystals.

Plagioclase (8-41%) forms xenoblastic crystals, the larger ones tending to be irregular in outline. In most specimens the size of the crystals is not above 1.5 mm but exceptionally crystals up to 4.0 mm long are found. Twinning is sparse and the twin lamellae are narrow. Most crystals show faint continuous zoning to a more sodic margin. The composition ranges from An_{20} to An_{35} . The most common type of alteration is to secondary mica in the outer parts of crystals. Partial alteration to carbonate and an unknown dusty material have also been observed. Zeisitisation of plagioclase has not been observed.

An extensive suite of accessory minerals occurs, the proportion of any one mineral and of the total accessory minerals seldom exceeding 1% and 4% respectively. Pale yellow hypidioblastic crystals of epidote occur up to 0.5 mm in length. Cores of brown orthite are common; unrimmed orthite is also found. Garnet almost attains to essential proportions in many specimens. The crystals are colourless or pale pink, rounded and hypidioblastic and up to 0.5 mm

across. skeletal crystals up to 1.2 mm in size are sparse. Garnet is often altered to chlorite along cracks. Crystals of iron ore of various sizes up to 1.0 mm are commonly scattered through the rocks. Small crystals tend to be more idiomorphic than the larger. Scattered small idiomorphs of apatite and idiomorphic prisms of grey-green or red-brown tourmaline occur sparingly.

At Achnagonalin the pelitic rocks overlie the marble directly, there being no intervening band of calc-silicate rock. Thus this tract differs in two ways from the others, firstly in the absence of calc-silicate rocks and secondly in the absence of a cover of coarse mica-gneiss.

Within the coarse pelitic gneisses are two minor rock types which both occur as bands and layers up to a few inches thick. The bands are infolded with and grade into the gneiss and are usually but not always parallel to the foliation in the gneiss. The bands frequently thin out after a few feet and are occasionally seen to suffer boudinage (fig.12). They are practically absent at Dulnain-bridge but increase in abundance towards the east at Revack. Presumably they represent original competent beds in the rock. In hand specimen the rocks are compact, medium to fine in grain, equigranular, grey or pink in colour; quartz, feldspar and biotite can be made out with the hand lens.

TABLE 17

Modal analyses of plagioclase-gneisses.

Thin section no.	354	388
Quartz	20	15
Plagioclase	53	60
Biotite	21	18
Accessory	6	7
Points counted	1700	1700

354. Plagioclase-gneiss band in coarse mica-gneiss, 500 yards NW of the top of Craig Revack.
388. Plagioclase-gneiss band, 500 yards SE of the top of Craig Revack.

NOTE

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When the last-named is lacking garnet and a pale green mineral can be made out. Biotite is not in discrete layers but is scattered through the rock. Microscopically two types are distinguishable.

(1) Plagioclase-gneisses

These rocks are found in bands up to 4 inches thick. Modal analyses are given in Table 17; a photomicrograph is shown on Plate XXII.

Plagioclase crystals (53-60%) are xenoblastic or hypidioblastic, with a maximum length of 2 mm and an average length of 0.5-1.0 mm. Twinning is uncommon or absent; most crystals show slight continuous zoning parallel to their margins. The composition ranges from An_{23} to An_{35} ; most crystals have the composition An_{27} . Sericitisation and dusting are common, particularly towards the margins of crystals.

Quartz (15-20%) is interstitial and normally occurs as patches of mosaic formed of equidimensional grains up to 0.7 mm in diameter. The larger crystals have slightly undulose extinction while the smaller show no such signs of strain.

Biotite (18-21%) is present as relatively thin, sub-parallel flakes with a maximum length of 1.5 mm and an average length of about 0.5 mm. The edges of the flakes tend

TABLE 18

Modal analyses of plagioclase-epidote rocks.

Thin section no.	240	390
Quartz	40	31
Plagioclase	45	52
Epidote	10	14
Accessory	5	3
Points counted	1200	2100

240. Granulitic layer in coarse mica-gneiss, 50 yards west of top of Craig Revack.

390. Granulitic layer in coarse mica-gneiss, 75 yards south of top of Craig Revack.

NOTE

PARCHMENT

IMPERIAL

to be ragged and irregular, and very small irregular crystals - in optical continuity with the larger biotites - are often embedded in plagioclase close to the larger biotites. The pleochroic scheme is: X = colourless; Y,Z = dark brown or olive-brown. Alteration to pleochroic green chlorite along the cleavages is occasionally seen.

The commonest accessory mineral is muscovite which occurs as bent plates of up to 0.5 mm in length. Pale yellow or colourless epidote forms xenoblasts with a maximum length of 0.8 mm. The crystals sometimes have cores of brown orthite and occur in association with the micas. Sparse crystals of hematite are present, the smaller crystals being hypidioblastic, the larger ragged. Small xenoblasts of microcline have been observed. Idioblastic crystals (all 1.0 mm across) of sphene, apatite, zircon and garnet complete the list of accessories. The total accessory content is 6-7%.

(ii) Plagioclase-epidote rocks

These rocks occur as bands which are never more than about an inch thick, are pinkish in colour and are practically lacking in biotite. They have been found only at Craig Revack. (See Plate XXIII.)

Plagioclase (about 50%) is the most abundant constituent in all examples. The crystals are xenoblastic

and slightly poikiloblastic, up to 1.0 mm long. A narrow outer sodic zone is developed on most crystals; twinning is more common than in the plagioclase of the plagioclase-gneisses. The crystal to crystal composition range is An_{27} to An_{40} . The crystals are commonly partly altered to secondary mica, clinozoisite, or unidentifiable dusty material in various combinations. The twin lamellae are often bent. It is noteworthy that the composition of the plagioclase is more calcic than in the plagioclase- and mica-gneisses, and that the alteration products are also correspondingly different.

Quartz (about 30%) forms interstitial patches of mosaic, the grains of which are unstrained and up to 0.4 mm across. Where quartz crystals are included in plagioclase they tend to be rounded in outline.

Epidote (about 15%) is found in all slides and is faintly pleochroic from colourless to pale yellow. The form is idio- or hypidioblastic and the crystals are up to 1.0 mm long. They are either evenly distributed through the band or concentrated towards the middle.

Garnet, however, is generally found towards the margins of a band, independent of the distribution of epidote. Garnet is included with accessories in the modal analyses (Table 18). The sparse idiomorphs are pink, are up

to 0.8 mm across, and tend to lie in strings sub-parallel to the margins of the band outwith the central zone which always contains epidote.

Accessory minerals include irregularly shaped plates of biotite (pleochroic from X = pale yellow to Y,Z = dark olive-brown), often altered to chlorite; thin flakes of muscovite; xenoblastic interstitial crystals of iron ore, some being pyrite surrounded by thin zones of hematite; and pinkish brown, pleochroic, xenoblastic crystals of sphene. Accessories seldom exceed 3% of the rock.

At the junctions of the bands of plagioclase-epidote rocks with the enclosing gneiss the latter is relatively richer than usual in dark brown biotite, skeletal garnet and small idioblastic epidote crystals.

(d) Discussion of Origin

There is no evidence to suggest that large-scale introduction of material from outside sources to the rocks of the Grantown Group has taken place. Further, the varied assemblage of rock types within the Group indicates that little homogenisation has occurred. Modes of the rocks give an indication of the types of sediment from which the calc-silicate bearing rocks were derived.

Owing to the lack of chemical analyses the mutual

relationships of the rock types cannot be shown on a conventional von Wolff or similar diagram. However, it has been found that if the modes of the rocks are plotted on a triangular diagram whose co-ordinates are [quartz + feldspar], [mica]* and [diopside + tremolite + epidote] the

* In the plagioclase-epidote rocks and the calc-silicate 'granulites' of the Moine Series garnet partly takes the role of phlogopite in the calc-silicate rocks of the Grantown Group. Therefore mica and garnet are plotted together in modal analyses of the two first-named rock types.

relationships of the rocks to one another are clearly displayed (Fig.7). The total proportion of quartz and feldspar in a rock can be taken as a rough index of the abundance of silica; similarly the mica-feldspar line represents alumina, and the calc-silicates lime and magnesia. Calcite is not shown on this triangle but, as it does not occur in association with significant amounts of quartz and/or feldspar, it would lie on a continuation of the silica-lime side of the triangle. The impure marbles thus fall outside the particular triangle here being used.

The impurity in the original slightly magnesian limestones, now marbles, was largely siliceous rather than

aluminous as is shown by their content of tremolite and diopside.

The sediments represented by the plots of three micaceous rocks (A) were composed of a calcareous and aluminous mixture, that is, were calcareous shales. Granulitic calc-silicate rocks (B) were formed from sediments with a fairly constant amount of sandy material but with wide reciprocal variation in lime and alumina. At the calcareo-magnesian end of field B the aluminous impurity is very low and the rocks grade into the amphibolitic calc-silicate rocks (C). The latter rocks lie along the [quartz + feldspar] - [calc-silicate] line, their position depending on the original lime content in what were essentially calcareous sandstones. This type is the most common in the area. Therefore the sediments which gave rise to the calc-silicate bearing rocks of the Grantown Group were mainly calcareous sandstones with minor sandy limestones and calcareous shales, all being slightly magnesian.

Field D is defined by plots of modal analyses of calc-silicate 'granulites' of the Meine Series - metamorphosed slightly calcareous sandstones (see p.37 et seq.). The modal analyses of thin plagioclase-epidote-garnet bands (Table 18) found in the coarse gneisses were plotted on the triangular diagram (Fig.7) and the points fell in field D. As calc-

silicate 'granulites' are abundantly found in both pelitic and quartzo-feldspathic rocks of the Moine Series the evidence given above shows that it is likely that the coarse gneiss with epidotic bands was produced from a sediment of 'Moine type'.

The coarse kyanite-gneiss would appear to be the normal result of high-grade metamorphism of pelitic sediments. The partial replacement of kyanite by muscovite, however, shows migration and fixation of potash after the peak of the metamorphism had been passed. Minerals containing significant amounts of soda are not found in the kyanite-gneisses and it is therefore impossible to say whether soda has migrated with the potash or not; at least it has not been fixed.

The mica-gneisses of the Dulnainbridge-Reveck belt are so unusual as to suggest that their formation was controlled by a factor not normally active in the genesis of the other rocks of the area. Any reasonable hypothesis must take account of all the significant facts. These gneisses are very much coarser than any other pelitic rocks in the district (p.102). The belt of gneisses everywhere structurally overlies calc-silicate rocks of considerable thickness (p.76). The rocks exposed at Dulnainbridge show that the grain size in pelitic rocks decreases markedly outwards and upwards from the zone of calc-silicate rocks (p.85).

contained in the gneisses are considerable bodies of quartzo-feldspathic material which are virtually absent from the underlying calc-silicate rocks (pp.82,102). The gneisses, bearing the assemblage quartz-oligoclase-muscovite-biotite (pp.103,104), are of the same metamorphic grade as the surrounding rocks. Contained in the gneisses are thin, medium grained layers rich in epidote and layers very rich in oligoclase. The epidote is stable in the presence of calcic oligoclase (pp.106-108).

The process required for the formation of the gneisses is therefore one which increases the grain size but not the metamorphic grade of the rock; which promotes mobility of quartzo-feldspathic material; and which becomes less effective with increasing distance from the calc-silicate rocks, i.e. upwards. That this process can be correlated with the presence of calc-silicate rocks is well supported at Achnagonalin where the pelitic rock overlying an almost pure calcite marble is a schist lacking the quartzose layers and the coarse grain size of the mica-gneisses (p.105).

During the metamorphism of impure calcareous sediments the reactions between calcite and the impurities to form calc-silicate minerals release large volumes of CO_2^* .

* For properties of CO_2 at geological temperatures and

pressures see Kennedy (1954).

which, "migrating upward into zones of lower temperature, may there play an important part in metasomatism." (Turner and Verhoogen, 1951, p.482). Turner (1948, p.145) regards much of the calcite of greenschists and the calcitic veins in other low grade rocks as the product of CO_2 rising from the higher grade regions of the crust. On the same topic Weeks (1956, p.255) says, "The rock overburden is likely to be semipermeable to gases and water vapour so that CO_2 can 'diffuse' away from regions of high CO_2 pressure (reaction sites)." A considerable volume of the impure calcareous rocks of the Grantown Group has been converted almost entirely to calc-silicate minerals. Assuming a volume of rock 4 km by 4 km by 80 m (average figures from field data) converted entirely to tremolite with 10% CaO , the volume of CO_2 released would be $1.536 \times 10^{17} \text{ cm}^3$ at N.T.P. or $2.174 \times 10^{14} \text{ cm}^3$ at 500°C and 2000 atmospheres pressure, the P-T conditions of the amphibolite facies (Walton, 1955).

Comparison of the high proportion of muscovite in these rocks with the muscovite-free schist at Achnagonalin (Table 16), and the evidence already presented that potash migrated into and was fixed in the kyanite-gneisses, jointly suggest that some potash was also introduced to the mica-gneisses during their formation. Similarly the high proportion

of oligoclase in the intercalated plagioclase-gneisses suggests that soda was introduced (from a source not yet identified) and was stabilised in the quartzo-feldspathic layers rather than in those of pelitic composition.

It is generally considered that the presence of volatiles has an important effect in increasing the grain size of rocks, and may be the primary factor concerned. Yet no chemical trace of the fluxes need remain if they acted only as carriers or catalytic agents and themselves remained unfixed in the environment prevailing during and shortly after their release.

It is therefore suggested that the large volume of CO_2 given off from the calc-silicate rocks entered the overlying normal pelitic rocks as a flux, thereby allowing them to reach a distinctively coarse grain size and also assisting in the mobilisation and differential fixation of potash and soda. Further, the passage of such mobile fluxes charged with alkalies made possible the formation of coarse patches of quartzo-feldspathic aggregates in suitable areas. In no other hypothesis known to the writer has the source of the migmatizing and granitizing fluxes been so confidently traced to the escape of CO_2 from impure limestones into the overlying rocks, nor has this particular concept been previously applied to high grade rocks.

Recently much work has been carried out on the influence of CO_2 pressure on various equilibria in metamorphosed impure limestones (for reference see Weeks, 1956). Only Weeks, however, discusses the escape of CO_2 into cover rocks; even so, he is very cautious on the matter. At high grades of metamorphism such as are found in Mid-Strathspay "the release of CO_2 due to progressive carbonate reactions will be quite slow. However the permeability of the rock (at least in deeply buried regions) will probably be low." (p.295). There would probably exist, therefore, a strong pressure gradient outwards and upwards from the calc-silicate rocks and presumably migration of the CO_2 would take place in response to this gradient.

Several writers (Knopf, 1929; Hess, 1933; Read, 1934; Haapala, 1936) have discussed the role of CO_2 in the formation of mineral deposits such as gold, magnesite and talc. Some consider that the CO_2 is of 'magmatic' or 'hydrothermal', i.e. hypothetical, origin while others are more cautious and admit that the source of the CO_2 -bearing solutions which reacted with the ultrabasic rock masses to produce magnesite and talc is unknown. In each of these cases of formation of magnesite or talc the rocks have been partly replaced by carbonate deposited from solutions. Further, the paragenetic evidence indicates that CO_2 became

fixed as carbonate only at late, low temperature stages in the process, although it may reasonably be presumed to have been present during earlier stages. In the example from Grantown, however, there is a prolific source for CO_2 but no visible carbonate mineralisation, only the results of what appears to have been mainly a fluxing effect, such as feldspathisation, sericitisation and coarsening of grain. One presumes that the temperature was relatively high and that carbonate mineralisation would therefore only begin at a much higher level in the crust. This level has now long been eroded from the district. The upward dissipation of the volatiles is shown by the upward diminution of the presumed fluxing effects at Dulnainbridge.

Although vaguely admitting the possibility of such a process, Turner and Verhoogen (1951, p.482) cite no examples. Accounts of the geology of areas of high grade metamorphic rocks where calc-silicate rocks underlie pelitic rocks are few. Of outstanding interest, therefore, are Read's papers on the geology of Unst in the Shetlands (1934, 1937), where some 500 feet of calc-silicate rocks of the Westing Group dip gently beneath coarse, tough pelitic gneisses whose lower 300 feet consists of "massive biotite gneisses with innumerable eye-shaped patches and stripes of quartz-feldspathic material" and in which "pegmatite sheets and stripes

are locally well developed." (1934, p.646). The upper zone of the gneisses recalls to Read the permeation gneisses of the great Sutherland complexes. Elsewhere in Unst "injection gneisses" are associated with pegmatites whose origin Read considers to be magmatic.

The resemblance of the Unst sequence to that seen at Grantown is remarkable and it is tempting to suggest a similar origin for the pegmatite-bearing gneisses at both localities. Related examples from other Scottish complexes are characterised by the association of granitic rather than the quartzo-feldspathic material discussed above; they will therefore be considered later (p. 136).

The hypothesis outlined above appears to be unique in the light of the geological literature known to the writer, who hopes that it may prove capable of application to metamorphic terrains in which pelitic schists overlie calc-silicate rocks.

(e) Status of the Grantown Group

Anderson (1915) suggested that the Grantown Group was a mass of the Dalradian Series lying in the Moine Series and entirely bounded by tectonic contacts or 'slides'.

In his tectonic analysis of a wide area McIntyre (1951a), although re-interpreting Anderson's work, considered

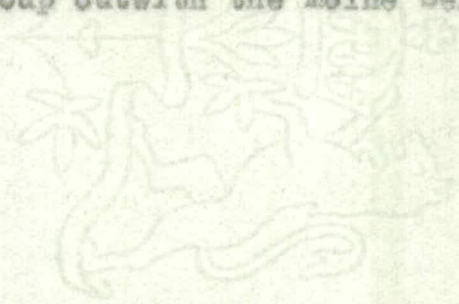
the Grantown Group to be a large tectonic inclusion in the Moine Series.

Exposures of the contact of the Grantown Group with rocks of the Moine Series are poor. At Laggan Hill rocks of the two formations, i.e. rocks of two lithological types, are interbanded and the contacts are no more tectonic than those between any other pairs of adjacent rock layers in the area.

Evidence presented above (p.112) suggests that epidotic bands in the coarse gneisses at Craig Revack are comparable to the calc-silicate 'granulites' of the Moine Series. Moreover, at Dulnainbridge the coarse gneisses pass gradually upwards into flaggy semipelitic gneisses of Moine aspect. Thin lenses of hornblende-schist occur both in migmatitic rocks at Craig Revack and in normal country rocks at the mouth of the Finlarig Burn (p.61). Therefore Anderson's "prima facie case for regarding them [the Grantown Group] as belonging to a different group [from the Moine Series]" (1915, p.27) must be rejected.

It therefore appears to the writer that the available facts are not inconsistent with the interpretation that the Grantown Group is an integral part of the Moine Series. The unusual assemblage of rocks within the Group and the differences that distinguish them from typical members of the Moine Series are to be ascribed to the action

of a localised agency during the course of the metamorphism rather than to such fundamental differences in age and facies as would be implied by placing of the Grantown Group outwith the Meine Series.



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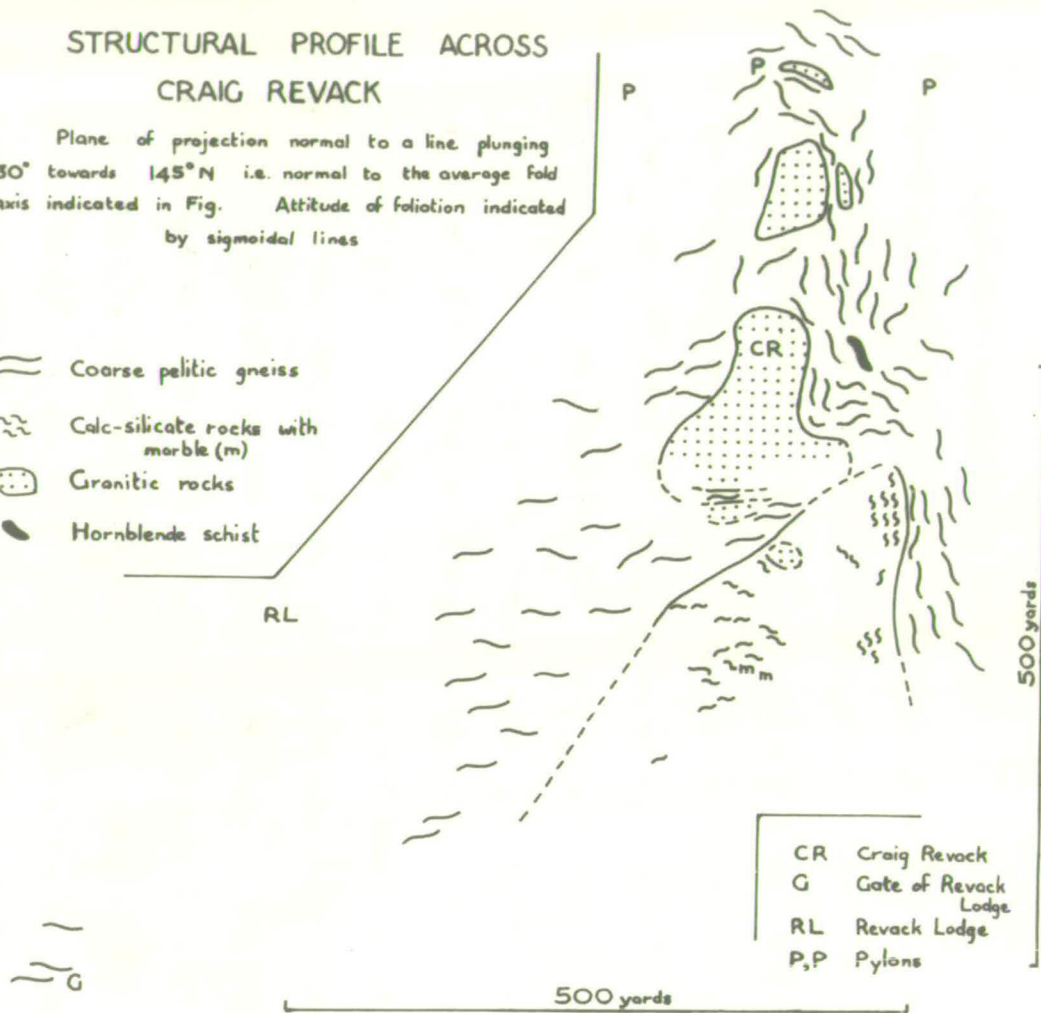
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Fig. 10

STRUCTURAL PROFILE ACROSS CRAIG REVACK

Plane of projection normal to a line plunging
30° towards 145°N i.e. normal to the average fold
axis indicated in Fig. Attitude of foliation indicated
by sigmoidal lines

-  Coarse pelitic gneiss
-  Calc-silicate rocks with marble (m)
-  Granitic rocks
-  Hornblende schist



CR Craig Revack
G Gate of Revack
Lodge
RL Revack Lodge
P, P Pylons

THE GRANITIC ROCKS OF CRAIG REVACK(a) Field Relations - Larger Granitic Masses

Along the crest of Craig Revack within the Grantown Group several types of granitic rock are exposed to view. There are several masses of a coarse pegmatoid granite which is almost entirely surrounded by the pegmatite-bearing coarse biotite-gneisses described above (pp.101 et seq.). In plan the granitic bodies are elongate NW to SE parallel to the strike of the country rocks (Fig.6, end pocket).

The largest mass, 200 feet by 800 feet in surface area, lies mainly in mica-gneiss but abuts against the calc-silicate rocks on its north-western side where the contact is nowhere clearly seen; the few available exposures indicate an interfingering of the granite with the gneiss immediately above the calc-silicate rocks. Elsewhere the contact can be accurately mapped and the granite is generally seen to cut across the foliation of the gneiss. The plane of contact dips outwards, steeply - but parallel to the steep foliation of the gneiss - along the SW margin of the granite and more gently on the SE and the NE. No effects of contact metamorphism were observed in the gneisses close to the granite.

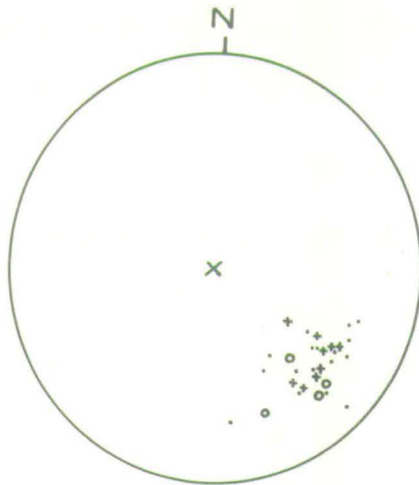


Fig. 11 Structure of Craig Revack. Profile (Fig.10) constructed normal to the average fold axis. Equal area lower hemisphere projection (as are all projections in this thesis). Circles, β -axes (4); crosses, small folds (9); points, lineations (17).

The granitic bodies never contain inclusions of gneiss, but have occasional lenses of quartz several inches across. The general form and distribution of the granitic rocks are well shown on the Geological Survey 1-inch Sheet 74. Only one exposure of granite has been found in the calc-silicate rocks and it lies close to their upper, that is, their south-eastern margin.

All along the south-western side of the granite and at a few points on the NE side the gneisses have vertical foliation trending SE. North of the granite the gneiss dips gently SE. To the east and SE of the granite the dip is south-easterly, the strike tending to curve around the granite mass and the dip concurrently becoming steeper until on the SW side it is vertical. Therefore the granite is almost entirely confined to the crest of an asymmetrical antiform. The relationships of the granite to the structure of the gneisses are best seen on a profile (Fig.10). The plane of projection of the profile is perpendicular to the average direction of foldaxes, lineations and β -axes in the gneisses (Fig.11).

(b) Field Relations - Minor Granitic Bodies

The pelitic gneisses of Craig Revack abound in small layers, veins, lenses and irregular bodies of granitic

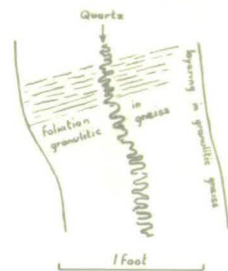
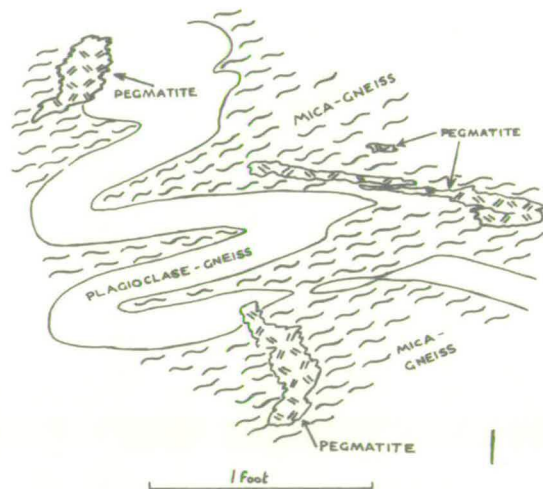


Fig. 12 Profiles of structures in the pelitic gneisses of Craig Revack.

1. plastic style in folded plagioclase-gneiss; irregular patches of pegmatite.
2. Ptygmatic quartz vein parallel to layering.
3. Boudins of plagioclase-gneiss in mica-gneiss.

or quartzose rock which show great variation in grain-size and mode of occurrence. These bodies can readily be distinguished from the small lenses described above (p.102). Medium grained splite in concordant layers up to several yards long and 6 inches thick is commonly found. Quartz rods and lenses up to 1 foot by 2 feet in cross-section and elongate parallel to the regional fold axis are often found lying en echelon (Plate V). Ptygmatic quartz veins are found lying parallel to the banding of the more granulitic rocks. Pegmatites occur as gently infolded parallel-sided veins up to 4 inches in thickness and sometimes as cross-cutting veins up to two feet in width, but their most common mode of occurrence is as irregularly shaped knots or intensely infolded discontinuous veins (Fig.12). Many of the pegmatitic bodies, including offshoots from the larger granite masses, do not have parallel margins. Both pegmatites and aplites occasionally have gradational margins; those of the pegmatites are sometimes rich in mica (cf. Plate X).

The calc-silicate rocks contain occasional concordant and cross-cutting quartz veins and lenses; pegmatite is noticeably lacking.

(c) Petrology

As all the granitic rocks, whether granite,

TABLE 19

Modal analyses of granitic rocks of Craig Revack.

Thin section no.	109	374	375	356
Quartz	32	32	31	41
Plagioclase	38	54	58	45
Microcline	23	-	8	-
Muscovite	8	12	3	14
Accessory	-	2	-	-
Points counted	1700-2000 each			

109. Granite from the largest mass, top of Craig Revack.
374. Granite, 100 yards NW of the top of Craig Revack, same mass as 109.
375. Granite, 70 yards NW of the top of Craig Revack, same mass as 109.
356. Pegmatite vein infolded with mica-gneisses, 400 yards NW of the top of Craig Revack.

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splite or pegmatite, have similar mineral compositions and show the same microscopic structures only one petrographic description is necessary. The main exception to the general description is that the smaller bodies of granitic rocks are usually free from microcline, or nearly so. Other minor exceptions are given in the appropriate places.

The granitic rocks are pink, and variable in grain size, but usually very coarse. No directional structure was detected. Large crystals of quartz, feldspar and muscovite are prominent; with the hand lens several specimens are seen to contain many thin closely-spaced persistent veins parallel to the main NE-trending joint plane in the rock.

Quartz (31-41%) is always anhedral; the largest crystals are 3 mm across and have strong undulose extinction. Most crystals are, however, much smaller in size, lack undulose extinction and form a granoblastic mosaic in large patches interstitial to the feldspars. In some thin sections the edges of strained quartz crystals are bounded by small granules which, because they are unstrained, are considered to have formed by recrystallisation of the strained crystals.

Plagioclase (38-58%) is abundant - ranging in

size from 0.5 mm to 15.0 mm - the crystals being always the largest of any minerals present. Subhedral or anhedral in shape, with ragged boundaries, the crystals show many signs of cataclasis. The twin lamellae are severely bent and displaced in all specimens. The lamellae are of two types, the first being relatively broad but ill-defined and having very ragged and irregular margins which are seen in places to have been produced by displacement along many small shears in the crystal (Plate XXIV). This type of twin lamella is occasionally cut across by the relatively narrow well-defined twin lamellae of the second type (Plate XXIV) which are themselves broken and displaced (Plate XXIII) but not to the same extent as the first. The second type appears to be later than the first. The composition of the plagioclase ranges from An_{10} to An_{37} , the majority of the crystals having compositions of An_{25} or An_{30} . Zoning is relatively rare and when found is of the normal continuous type, with only a few very faint zone boundaries occasionally being discernable.

In many plagioclase crystals are found groups of small irregular microcline crystals which are in optical continuity with each other and generally have one of their twin axes parallel to the albite-twin axis of the plagioclase. The microcline is quite fresh even when the

surrounding plagioclase is highly altered to secondary mica. Both minerals are occasionally broken and sheared. In some crystals the microcline forms a solid but ragged core merely rimmed by plagioclase (Plate XXV). Elsewhere large plagioclases have a discontinuous rim of small microcline crystals. The textural relationships suggest that in most examples the microcline has partly replaced the plagioclase. Myrmekitic quartz is found in a few plagioclase crystals. The plagioclase has been altered to secondary mica and the alteration is intense in many cases; crystals of secondary colourless mica are up to 0.5 mm in length. Alteration of the plagioclase to dusty material is uncommon and to zoisite is rare.

The plagioclase, like the other crystals in the rock, is penetrated by a system of narrow parallel veins, usually of quartz but sometimes of microcline or muscovite. In section the veins are elongate lensoids, either confined to one crystal or crossing several crystal boundaries; occasionally within a single crystal there are short parallel veins arranged en echelon. The veins are undeformed and cross all cataclastic structures in the rock; they are parallel to a set of well developed joint planes in the rock. From this evidence it is considered that the veins were formed under tension at a late stage in the meta-

morphic history of the rock.

Microcline (0-23%) is not always present. In particular it is noticeably absent or sparse in the in-folded pegmatites and thin granitic layers of the gneisses. When present its proportion is less than that of plagioclase. As noted above, some ragged microcline crystals are found within plagioclase crystals. The bulk of the microcline occurs as anhedral irregularly shaped crystals, which have a maximum length of 9 mm but which usually measure less than 3 mm. Boundaries between adjacent microcline crystals tend to be crudely sutured. Many crystals have bent, broken or sheared twin bands (Plate XXV). In one thin section there are several small microcline crystals separated from each other by quartz. They can be reconstructed to form a single crystal which was broken into several fragments between which quartz later grew. As in the plagioclase, many crystals are crossed by thin parallel quartz veins. In some thin sections the large microcline crystals contain ragged stringers of albitic plagioclase forming a microcline-microperthite. Myrmekitic quartz is found in the microcline crystals of some specimens (Plate XXVI).

Muscovite (3-14%) is always present except in one of the small concordant aplitic layers in the gneiss. It occurs in some specimens as small secondary crystals

(up to 0.5 mm long) in the plagioclase, but in general the mineral forms large plates which are usually bent and are up to 5.0 mm long. The smaller crystals occur in clumps or strings. Thin quartz veins are found along the muscovite cleavage only where the latter is oriented parallel to the narrow vein system of the rock.

Not all thin sections contain accessory minerals. Of these clinozoisite is the most common (up to 2%), forming fresh anhedral and occasionally euhedral crystals up to 0.7 mm in length. The crystals are occasionally clustered but they usually occur singly, associated with clumps or layers of muscovite. Iron ore occurs as sparse, small, ragged crystals which can usually be identified as hematite, which sometimes has a core of pyrite. Crystals of dark brown biotite, brown rutile and pinkish sphene have been detected but are rare.

The mutual relationships of the minerals in the granitic rocks described above make it possible to outline a time-sequence of events during and after the emplacement of the rocks. Not all of these events are necessarily recorded in every specimen; but the events that are recorded are always in the same order. Moreover, the sequence holds good for all rocks whatever the occurrence and whatever the aspect, granitic, aplitic or pegmatitic.

The one exception is that the smaller bodies lack the quartz-filled joints found in the larger masses.

The first recorded event was the crystallisation of the plagioclase and the formation of the broad, now ragged, twin lamellae. Deformation resulting in the breaking of these lamellae, and the formation of the second, relatively narrow, set of lamellae followed. Later some of the plagioclase was replaced by microcline one of whose twin axes coincided with the albite-twin axis of the plagioclase. It would seem likely that most of the microcline in the rocks crystallised at this stage. While deformation and replacement were affecting the plagioclase, primary muscovite crystallised, followed by some quartz. The crystallisation of the last two minerals, however, cannot be related in time to the sequence of events taking place in the plagioclase.

All the minerals being now in crystalline form, a second phase of deformation left an ubiquitous imprint in the form of broken and bent twin lamellae in all feldspars, bent mica, strained and partly recrystallised quartz and many granulated intercrystal boundaries. This deformation, however, does not seem to have been intense.

Subsequent to the second deformation there was sericitisation and "dusting" of plagioclase, recrystallisation

of quartz, and possibly chloritisation of biotite, all taking place while the rock was under little appreciable stress.

The final stage in the sequence of events was the opening of NE-trending tension cracks and joints which were filled by quartz accompanied by lesser amounts of microcline and muscovite, presumably derived from still mobile, or mobilised, material. This stage is not represented in the minor bodies. The granitic rocks have thus suffered three recorded periods of deformation of which the second and third were probably less severe than the first.

(d) Discussion of Origin

The Revack granitic rocks are distinct among the granitic rocks of the district in that they are not seen to penetrate the rocks structurally beneath the coarse containing gneisses in which they are emplaced. These gneisses are themselves unusual (p.102) and it appears not unlikely that the origins of the granitic rocks and the gneisses are closely inter-related and, at least partly, contemporaneous. This conclusion is strongly supported by the restriction of the coarse pegmatoid granitic rocks to the crest of an antiform in the coarse pegmatite-bearing gneisses, by the

absence of contact metamorphism around the granitic rocks and by petrological and structural evidence. The complex consists of two rock types of 'igneous' and 'metamorphic' aspect and is therefore a migmatite complex (Sederholm, 1907).

Close to the main body of granite the gneisses contain a high proportion of quartz-feldspathic material, much of it concordant with the foliation of the gneiss, and most of it generated during the folding and metamorphism, as for example were the quartz rods and ptygmatic veins (Fig.12). Irregularly shaped patches of pegmatite (Fig.12) and pegmatites which have been gently infolded with the gneisses are petrographically similar to the larger granitic bodies, both concordant and cross-cutting. A pegmatite found at the junction between hornblende-schist and mica-gneiss contains large crystals of hornblende identical with those in the schist (see p.69). Therefore much of the pegmatitic material was formed essentially in place by a process involving replacement or segregation or both. These pegmatitic and aplitic bodies are up to several feet in thickness and are not found in the underlying calc-silicate rocks. The enclosing gneisses form an asymmetrical antiform plunging SE, the vertical limb being on the SW side (Fig.10). Small folds and lineations in the gneisses

lie in a close sheaf (Fig.11), parallel to the fold axis in the non-granitic rocks of Mid-Strathspey (p. 164). These structural trends have therefore not been disturbed by the emplacement of the granite.* Rather the granitic

* Unlike the post-tectonic Grantown Granite. See pp.173-178.

bodies have inherited the same structural trend as the country rock. The main body of granite has on two sides steep cross-cutting contacts with the enclosing gneisses but there is no visible feeder in the underlying rocks nor any evidence pointing to a mechanism whereby the pre-existing country rock could have been removed. Towards the lower margin of the main granite mass there is evidence of interfingering of granite with gneiss. On the microscopic scale cataclastic structures are widespread in the granites. The granitic rocks show considerable variability in grain size and there is evidence of late replacement of plagioclase by microcline. Contact metamorphic effects are totally lacking, indicating that the granitic rocks formed at a temperature close to or lower than the temperature of metamorphism of the country rocks.

It has previously been postulated (pp.112-118) that the large volumes of CO_2 given off during the metamorphism of the impure limestones of the Grantown Group

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assisted in the production of the coarse gneisses with their small quartzo-feldspathic lenses. The evidence relating to the granitic rocks of Craig Revack strongly suggests that, aided by these abundant fluxes and by introduced soda and potash, a considerable volume of quartzo-feldspathic material was segregated* in the

* Throughout this thesis 'segregation' is used in the sense of a setting apart, a separation, a metamorphic differentiation, in which acid material is more easily mobilised and transported than relatively basic material.

gneisses and migrated particularly to the crest of the growing Revack antiform where, presumably, the stress was lower than elsewhere, thus favouring accumulation and crystallisation of the mobilised material. Concomitantly, smaller quartzo-feldspathic bodies formed both by replacement and by segregation in the nearby gneisses and were involved in the same sequence of deformations as the larger granitic masses. Silica was mobile throughout the sequence from the peak of deformation onwards. The resulting bodies were composed essentially of quartz, plagioclase and some muscovite. As folding further proceeded and the temperature was still relatively high the large plastic granitic mass was deformed so that it

penetrated the overlying, also plastic, gneisses. That pegmatite was still forming at this stage, however, is shown by the small pegmatitic offshoots from the granite into the gneiss. The movements leading to the penetration of the overlying gneisses by the granite can be tentatively correlated with those responsible for the breaking of the first set of twin lamellae in the plagioclase crystals of the granite. The influx of mobile material continued until adequate potash had passed into the main masses to replace some plagioclase by microcline. This influx is tentatively correlated with the late slight potash metasomatism in the kyanite-gneisses of Laggan Hill to the west (p.99). Later slight movements caused microscopic deformation structures to form in both granite and gneiss. Joints, now mainly quartz-filled, were the last structures to form in the granite. They are roughly parallel to the ac plane of the country rock fabric.

If this differentiation into quartzo-feldspathic and pelitic fractions occurred with the minimum metasomatism the original rock must have been more quartzose than the present pelitic gneiss, in which case it may have corresponded roughly in composition to the semipelitic gneiss exposed at the River Dulnain, the nearest non-mobilised country rock. However this may be, it is clear that once again a

hypothesis involving metasomatism and metamorphic differentiation, aided by abundant volatiles adequately explains the observed facts. Again the passage of CO_2 , the predominant distributive agent, is marked by coarseness in grain.

The patchy nature and non-parallel margins of many of the smaller pegmatitic bodies suggest an origin by replacement while their mica-rich margins give many pegmatites a bulk composition not far removed from that of the enclosing gneiss. Therefore small scale metasomatism nearly in situ thus probably aided the main large scale metasomatism, mobilisation and plastic flow in the formation of the granitic rocks of Craig Revack. In fact it is likely that "These geochemical migrations . . . would no doubt enhance the mobility of the rocks and assist in the development of the fold." (Reynolds, 1942, p.62).

The presence of kyanite in the pelitic gneisses of Gaich Hill and Laggan Hill indicates that the temperature during crystallisation was of the order of 450°C (James, 1955, pp.1468,1485) i.e. in the field corresponding to that of the lower amphibolite facies. It has recently been shown by Ramberg (1949, 1952) that many quartzofeldspathic rocks in metamorphic terrains bear mineral

assemblages indicative of P-T conditions below the field of magmatism. As acid silicates saturated with H_2O begin to form melts only at about $600^\circ C$ (Goranson, 1932) and the Grantown Group gneisses, which lack signs of contact metamorphism, appear to have been formed at about $450^\circ C$ it is instructive to examine the mineral assemblages of the Craig Revack granitic rocks in the light of Ramberg's findings. The presence of muscovite and microcline in the granitic rocks indicates that about $600^\circ C$ was not exceeded during crystallisation while epidote in equilibrium with plagioclase of composition An_{25} to An_{30} indicates a temperature of formation of the order of $400-450^\circ C$ (Ramberg, 1949, p.33; 1952, p.137). Further, the several types of surrounding gneisses contain epidote which is in stable equilibrium with oligoclase-andesine (pp.99-109). Such rocks cannot be considered other than metamorphic in origin. If Ramberg's inferences be accepted as valid the above evidence constitutes strong support for the metamorphic-metasomatic origin of the Craig Revack granitic rocks.

(e) Comparative studies in the Highlands

Many have been the reviews (and reviews of reviews) on the nature and origin of migmatites since Sederholm (1907) introduced the term to geological

literature. There is therefore little need for a general discussion of migmatites in this thesis. However, a brief study of the so-called "Injection Complexes", or areas of syntectonic migmatisation, which cover such wide areas of the Scottish Highlands is appropriate in view of the present findings in Mid-Strathspey. At the outset the great variation in scale and intensity must be emphasised. The intensely migmatised Sutherland occurrences studied by Read cover about 700 square miles, while the migmatitic gneisses of the Grantown Group cover less than a square mile in a district where migmatisation is only locally severe.

The earliest description of granitic gneisses was given by Barrow (1892, 1893) who studied the rocks of North Angus. He considered the non-foliate potassic pegmatites to be the sweated out portion of the foliate sodic granite-gneiss which was itself considered to be a representative of the 'Older Granites' formed prior to or during the movements and metamorphism. The granite-gneiss is variable in texture and Barrow noted that "The gneissose structure . . . is developed only when the outcrops have a breadth of 100 yards or more . . ." (1893, p.331). Most of the rocks studied by him are well-crystallised and lack cataclastic structures.

Because of the intimate association of granite and coarsely crystalline gneiss in Eastern Sutherland Horne and Greenly (1896) found it difficult to believe that the granite was "wholly foreign matter" (p.647). They realised that both rock types formed at the same high temperature and that there were many examples "where lenticles of granite occurring in the schists could not be seen to have any communication with any other granite masses" (p.650). Greenly (1903) elaborated on the above work, noting that the permeation phenomena are found in a "flaky or wavy biotite gneiss" (p.210). He favoured formation of the granite "by quiet diffusion rather than by forcible injection" (p.212).

In a paper on the metamorphism around the Ross of Mull granite Bosworth (1910) described the infolded thin granite veins in the coarse kyanite- and sillimanite-bearing gneisses at the contact of the granite with the rocks of the Moine Series. Scattered through the gneisses up to a distance of two miles from the contact and intimately connected with the folding are irregularly shaped patches and veins of pegmatite which sometimes contain large kyanite and tourmaline crystals. There is a complete gradation between these pegmatites and the quartzo-feldspathic streaks which are elsewhere found in the gneisses.

Bosworth therefore considers that "these pegmatites are due to segregation of the more mobile constituents present in the original sediments rather than to intrusion of material from an underlying source." (p.391). It would now seem likely that the Ross of Mull granite was emplaced in the rocks of a high grade migmatite complex and had little contact metamorphic effect as we now understand it. (Bosworth was influenced by Barrow whose views on regional and contact metamorphism are well known.)

The complex of Cromar, Deeside, (Read, 1927) contains several features comparable with the rocks of the Grantown Group. The thick impure Deeside Limestone dips north below the 'injected' rocks which are in the sillimanite zone of metamorphism. Found in the 'injected' rocks are relict layers of siliceous, calcareous and hornblendic composition. Pegmatites occur much more abundantly in the 'injected' rocks than in the country rocks, but the rocks of the complex "vary from those possessing dominant country-rock characters to those with dominant igneous characters" (p.321). Sillimanite crystals are surrounded by 'shimmer aggregates' of muscovite, believed by Read to be produced during the 'injection' process. Read postulated that at the end of the general metamorphism more volatile constituents separated from the 'magma body' and penetrated

the pre-existing rocks along their foliation planes. The keynotes of this movement phase - keynotes which were recognised by Horne and Greenly in 1896 - were that the country rocks were at a high temperature, that the region was under strong stress, and that 'intrusions' were concordant.

Read (1931) made a further contribution to the subject when he described the great 'injection complexes' of Loch Choire and Strath Halladale in the Geological Survey Memoir for Central Sutherland. The former complex contains an abundance of pelitic rock as host to the granitic members. A zone of Veins at garnet-staurolite grade underlies a Zone of Injection at sillimanite grade. The Zone of Veins contains cross-cutting and thick concordant granitic layers, while occasionally the rocks merge into masses of granite. Within the injection zone bands of rock in which the host is dominant alternate with rocks rich in granitic material. Many of the 'injections' have selvages rich in biotite. The injected pelitic rocks are much coarser than the pelitic rocks outside the complex. The Grantown Group rocks differ from the above in that they are all at the same grade of metamorphism whether rich or poor in granitic material. Moreover, at Grantown concordant granitic layers are more common than cross-cutting veins.

Read considered that the injection took place under conditions of high temperature and stress, the injected material representing the volatile-rich sodic phase, i.e. oligoclase and quartz, from a granodioritic magma which lay down-dip to the east. Potassic solutions became active only at a late stage and to a lesser degree than their sodic precursors. Metamorphic differentiation in situ by itself is rejected by Read as a tenable hypothesis, as some influx of material must have been involved. Myrmekitic quartz in plagioclase and muscovite rims around sillimanite are taken to represent late influxes of soda and potash respectively, presumably after the rock was solid. The hypothesis put forward by Read covers some of the phenomena observed by him but does not explain others. There seems little doubt that there was some addition of potash and soda but that the source should be regarded as having been directly down-dip seems highly unsatisfactory when it is remembered that the zone of cross-cutting veins underlies the injection zone. It appears more likely that many of the veins with biotite-rich margins would be formed by reconstitution and differentiation of the host rock in the presence of a flux; those rocks in which granitic material is dominant may originally have had a quartzo-feldspathic rather than a pelitic composition. The high metamorphic grade within

the complex need not have been directly due to the injection process, because sillimanite-and kyanite-bearing rocks of the Moine Series are found to the east of the injection complexes. A series of chemical analyses are given to illustrate the role of soda in the permeation of the pelitic rocks but such is the scale and distribution of the permeation phenomena that these analyses give no more than a general indication of the role.

A detailed re-investigation of the Duchray Hill Gneiss, one of Barrow's Older Granites from Glen Shee, was carried out by Williamson (1935). The gneiss occurs in the Ben Lui Schist and again a limestone, the Loch Tay Limestone dips below the 'injection complex'. Intercalated in the gneiss are "xenoliths, thin strips or thick masses" (p.390) whose longest dimension is parallel to the foliation and which presumably represent siliceous, calcareous and hornblende layers in the country rocks. The injected rocks are coarse in grain but appear to be at the same metamorphic grade as the country rocks, namely, in the garnet and kyanite zones. For the concordant pegmatites and aplites Williamson rejects formation by rearrangement in place. There is evidence for introduction of potash but at which stage is not clear. He considered that the injection metamorphism post-dated the regional metamorphism. Williamson

concludes (p.418) that

" . . . the Older Granite, or Duchray Hill Gneiss, was generated by the invasion of the pelitic fraction of the Ben Lui Schist by oligoclase-quartz magma, with the production of composite oligoclase-muscovite-biotite-gneiss, bearing siliceous, lime-silicate and Older Basic rocks, which had been avoided by the invading magma."

In its intercalations, which compare closely with the undoubtedly non-xenolithic layers in the Grantown Group, this example is similar to the rocks of the latter. It therefore appears that this Older Granite is partly syntectonic; whether its foliation is magmatic or metamorphic is a moot point.

As noted above (p.117) Read (1934, 1937) has described "injection gneisses" from Unst, Shetland. The same general theory of origin is applied here as to Central Sutherland and Cromar; but in Unst there are abundant calc-silicate rocks to provide volatiles at a low level in the structural pile.

Fernando (1941) elaborates on the origin of the pelitic gneisses of Unst described by Read. These are the rocks which overlie a belt of thick calc-silicate rocks (the Westing limestone). The particular augen-gneisses described by Fernando overlie a "well developed talcose zone", and have suffered "local and sporadic" feldspathisation. He postulates a permeation of the rocks by

alkaline solutions of magmatic origin percolating along the foliation planes, but admits the difficulty of accounting for a sequence of solutions appropriate to the sequence of chemical alterations inferred from thin section evidence.

A detailed petrochemical study of a small area within the north Sutherland complex was carried out by Cheng (1943) who showed that the migmatitic rocks resulted from the continued percolation and passage of alkaline solutions through a varied sequence of Moine rock types. Pelitic rocks suffered soda-metasomatism and semipelitic rocks potash-metasomatism, while in the channels along which most alkali was transferred discrete granitic bodies formed. The material introduced to the rocks was, therefore, in a very tenuous form, but of "magmatic and anatectic" derivation. Cheng did not attempt to relate the migmatization to the main metamorphism but it seems likely from his account that migmatization was contemporaneous with, or slightly after, the regional metamorphism. This study is valuable in that it shows how little material need be added to change radically the aspect of the rocks. He considers that some of the metasomatic potash was released by reactions going on in the rock and was not necessarily introduced from without.

A useful summary of the distribution of the

migmatitic complexes of the Northern Highlands has been given by Plemister (1948). Migmatitic rocks are now seen to cover large tracts of North Argyll, Western Inverness-shire and South Ross-shire. He rightly urges caution in the use of genetic terms to describe these rocks. In Ross-shire the early Survey workers were divided as to the origin of the quartzo-feldspathic augen and folia in the gneisses - e.g. whether they were segregations or injected pegmatites. It is suggested by Plemister that the presence of an invading magma would have assisted in the production of the folds in the gneisses. The injecting 'magmas' are tentatively correlated with those thought to be responsible for the Older Granites of the Grampians, and it is considered possible that the injections represent the first phase of Caledonian igneous activity; later this activity culminated in the production of the Newer Granites after movements associated with the metamorphism had ceased.

In discussion of the metamorphism of the Moine Series north of the Great Glen, Macgregor (1932) considered that the "Older Granite" migmatization, the thermal zoning and the folding were penecontemporaneous, and Caledonian in age, the "Older Granite" injection causing the thermal zoning. In a recent paper Flinn (1954) has described a localised permeation which took place later than the regional

metamorphism of the Delting area of Shetland. He claims that permeation by recrystallising solutions had the effect of thermally metamorphosing the regionally metamorphosed rocks with the production of sillimanite and andalusite. The area is free from discrete granitic bodies but the permeating agents have been responsible for the growth of abundant microcline in the rocks. A thick, but rather pure, marble is found in the rock succession of the area.

A critical survey of work on Scottish migmatite complexes shows that in the past too genetic - and therefore hypothetical - a terminology has been used in descriptions that should be strictly objective; e.g. injection gneiss, permeation gneiss, anatexite, imbibition rock, and so forth. The use of the more purely descriptive terms such as migmatite (mixed-looking rock), granitic rock, veined gneiss or pegmatitic gneiss keeps the reader free from the bias that is inevitably engendered by the previous terms. The use made of structural and geometrical criteria has so far or hitherto been slight. Many examples of vein systems (e.g. Read, 1931, p.111) create so serious a space problem as to suggest that the veins must be, at least in part, of replacement origin. There has been little work showing the relationship between migmatitisation and structures visible

in the field and none on the microfabric of the so-called injection rocks. There is consequently still great difficulty in assigning to the foliation of granitic gneisses an unequivocal origin. Too often it has been tacitly assumed that the foliation has been the result of flow in a magma when both flow and magma were purely hypothetical concepts. In many cases appeal has been made to the injection of a 'magma' when mere rearrangement in place with the addition of a few mobile constituents would suffice to account for the rock types concerned. In many examples a source of distributive volatiles in impure limestones can be proved or inferred. Furthermore, even these introduced active materials coming from deeper parts of the mountain chain are as likely to be of metamorphic as of magmatic origin. There has also been too rigid a separation of granitic rocks into Older and Newer. Among the Older Granites there has been confusion between the syntectonic granites and the pre-tectonic granites. Nor is there any reason why granite should not form at any time during the wax and wane of the metamorphic process and take on characters appropriate to that time.

Many of the areas detailed above show resemblance to Mid-Strathspey, and in particular to the rocks of Craig Revack. No single migmatite complex appears to be exactly

homologous to the Grantown Group. Several complexes show a few of the main features, such as a previously existing underlying source of abundant volatiles (Gromar, Glen Shee, Unst), evidence of potash and soda metasomatism (Sutherland, Gromar, Glen Shee), resistant relict layers of the original country rock (Sutherland, Gromar, Glen Shee), unusually coarse grain size of the rocks (all complexes), localisation in areas of high metamorphic grade (all complexes), and the presence of segregative and replacive granitic rocks (Sutherland, Ross of Mull).

Various origins have been proposed for the Scottish migmatitic rocks discussed immediately above. Yet in almost every instance there are many facts which are quite unaccountable by the hypothesis proposed, and in almost every hypothesis there is an unnecessary degree of uncertainty introduced, e.g. by the invocation of 'magma'. Detailed study of a small but well-exposed part of the Grantown Group has demonstrated an adequate source of fluxes, a lack of feeders for granitic material, and a structural control of the localisation of granite. The process of migmatitisation and granitisation was here, therefore, an integral part of the metamorphic deformation and recrystallisation. As there is no doubt that metamorphism has taken place there is no need in this case to postulate

exceptional mechanisms to account for the migmatization.

It is unlikely that any one hypothesis can account for all the varied rock suites and rock structures of migmatite complexes, particularly a hypothesis which has been devised to correlate the evidence collected from a small area only. It is uncertain how far the hypothesis here proposed to account for the rocks of Craig Revack can be successfully applied further afield, but the extension of calc-silicate rocks and marbles below the large complexes of Unst, Gromar and Glen Shee supports the hope that this hypothesis may well be applicable to other and larger areas than those so far described in Mid-Strathspey.

NOTE

PARCHMENT

IMPERIAL

THE GRANTOWN GRANITE COMPLEX(a) The Problem and the Method

The salient features of the Grantown Granite and the essence of the problem it presents were summarised by Hinxman (1923, p.50) thus:

"The granite contains many inclusions, large and small, of the surrounding pelitic schists. The larger of these, some of which are more than half a mile in length, preserve the strike of the foliated rocks outside the granite mass; the smaller included fragments are often lying at all angles, having evidently been torn off and carried along with the magma.

"The general parallelism between the strike of the country rock, the main boundaries of the intrusion, and its apophyses and the larger included fragments is a striking feature of the Grantown Granite, as shown upon the map, and may possibly throw some light upon the nature of the intrusion."

Anderson (1915, p.39), in describing the southern half of the mass, recorded that the inclusions "sometimes occur more than half a mile from the margin" and that "the country rock is veined with granite up to a mile from the main mass", thus emphasising the difficulty of drawing a definite boundary to the body.

The problem of the Grantown Granite is to account satisfactorily for the numbers, size and orientation of the included blocks, that is, to elucidate as far as possible what Hinxman has called "the nature of the intrusion", and to suggest an origin for the granite. It is necessary to

determine the source of the blocks and whether they retain their original positions or have moved in the granite. If the blocks have moved one must look for evidence from which it might be inferred how they moved.

The investigations directed towards a solution of these problems require a detailed study of the field relations and petrography of the granite, a comparison of the structure of the country rock with the structure of the inclusions, and a study of the structures within the granite itself.

The lack of a regular joint pattern, and of either foliation or lineation within the granite itself makes the mass singularly unsuitable for study by the methods of granite tectonics devised by Cloos and described in English by Balk (1937). The presence of a large number of inclusions all characterised by the structures common in the country rocks suggested that the geometrical and statistical methods of structural geology would be the most suitable for a study of the interior of the granite. These methods have entailed the accurate measurement of all the available structures and the statistical study of the resulting data with the aid of the Schmidt or equal-area projection, the most satisfactory two-dimensional device for the representation of three-dimensional structural data. These methods are

usually applied to foliated rocks to demonstrate areas of homogeneity of fabric but there is no valid objection to their use to demonstrate degrees of inhomogeneity of fabric.

(b) Field Relations

The Grantown Granite complex lies a few miles to the NW of Grantown-on-Spey and extends for $3\frac{1}{2}$ miles from north to south and for about $2\frac{1}{2}$ miles from east to west. The relief within the granite is about 600 feet. The mass contains many inclusions of a variety of country rocks ranging in size from a few inches across to nearly 100 yards long. The blocks are found throughout the granite and, as stated above (p.23), their total surface area comprises a large proportion of the surface area of the complex.

The contacts of the granite with the country rocks are both concordant with and transgressive to the prominent foliation but do not follow any other directed structure in the country rocks such as axial plane foliation or joint surfaces. Both granite and country rocks are cut by granitic and pegmatitic veins, some of which are seen to be offshoots from the main mass. The outer contact is ill-defined and is only exposed at three localities, Huntly's Cave, Beinn Mhor and Creagan na

h-Othaisge. The reason for the lack of definition lies in the fact that one passes outwards through a zone of contact from rocks with many granite sills to rocks rich in granitic and pegmatitic veins and then to rocks poor in veins. The boundary line of the granite on the text-figures is therefore to be regarded as representing a zone of contact corresponding to the rocks rich in granitic and pegmatitic veins. At Huntly's Cave remapping by the writer shows that a series of thick granite sills dip east along the foliation of the gneiss. The number and thickness of the sills decreases to the east. On Beinn Mhor in the south there are again several sills, dipping SE, which contain numerous inclusions whose foliation has a variable attitude. The outcrop of one extensive mass of quartzo-feldspathic country rock projects for some distance between two of the granite sills. At Creagan na h-Othaisge the western contact zone of the granite is steep.

It is difficult to represent accurately on the 6-inch scale the intricate detail of granite enclosing gneiss; on the Geological Survey 6-inch maps (unpublished) this difficulty has been overcome by the insertion of notes on the map indicating that numerous inclusions are present in the granite. The mapping of very large inclusions by the survey is misleading as it can be seen on the ground

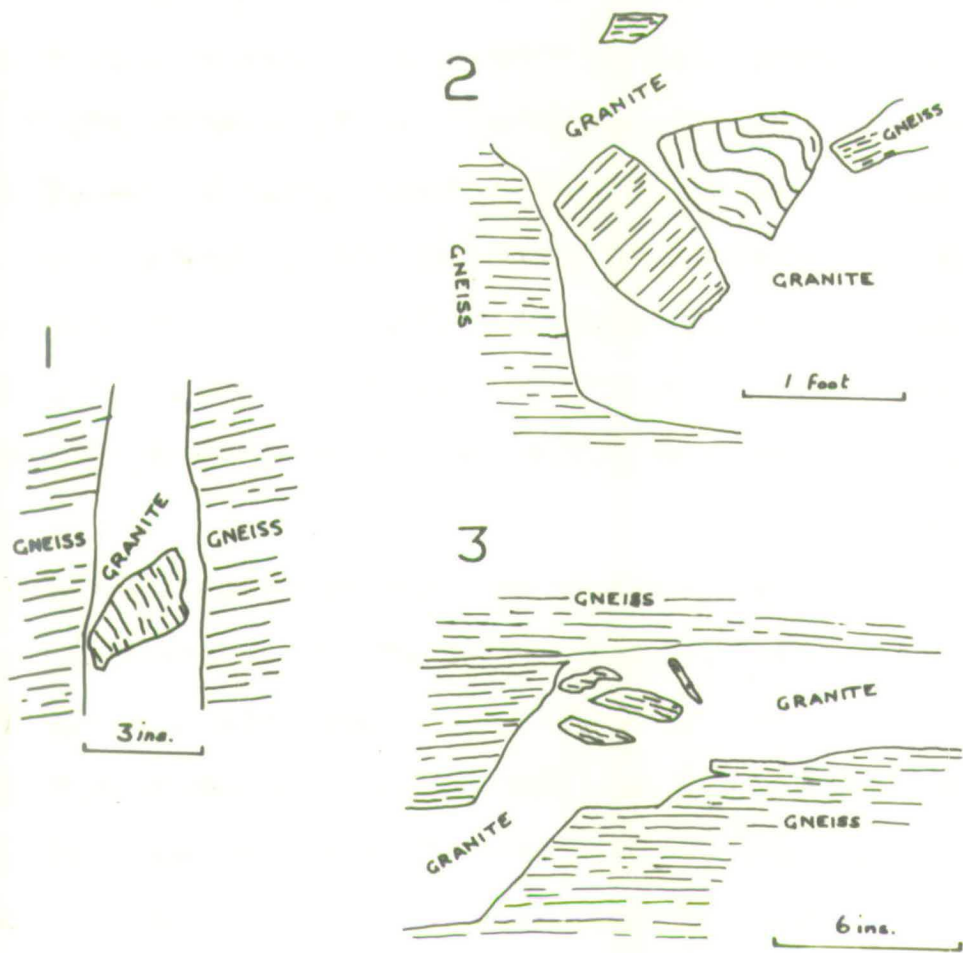


Fig. 13 Displaced blocks of gneiss within the Grantown Granite or its offshoots.

- 1,2. West side of Creag Liath
 3. East side of Creag Liath.

that the blocks do not have the great lateral extent shown on the published (1-inch) maps; the inclusions are much intersected by sheet-like masses of granite and pegmatite. The general pattern of the granite outcrops on both the large and intermediate scales is reticulate, formed by intersecting dykes and sills. There is no evidence to suggest that the dykes and sills formed at different times. The dip arrows on the Survey maps give a rather generalised picture of the attitude of the various inclusions.

On the scale of an exposure several examples have been discovered of small blocks of gneiss embedded in granite adjacent to large blocks, and displaced relative to the large blocks (Fig.13). The displaced blocks are found both in thin veins of granite and in the larger granite bodies. Displacement on this scale was also noted by officers of the Survey (1923, p.50). Large inclusions of gneiss can be shown to be planar parallel to their foliation but of much less horizontal extent than indicated on the 1-inch maps. The largest exposed area of granite is elongate north-south, measures about 300 yards by 100 yards, and is situated on the east slope of Creagan na h-Othaisge towards the middle of the granite complex.

Many of the granitic and pegmatitic veins are seen

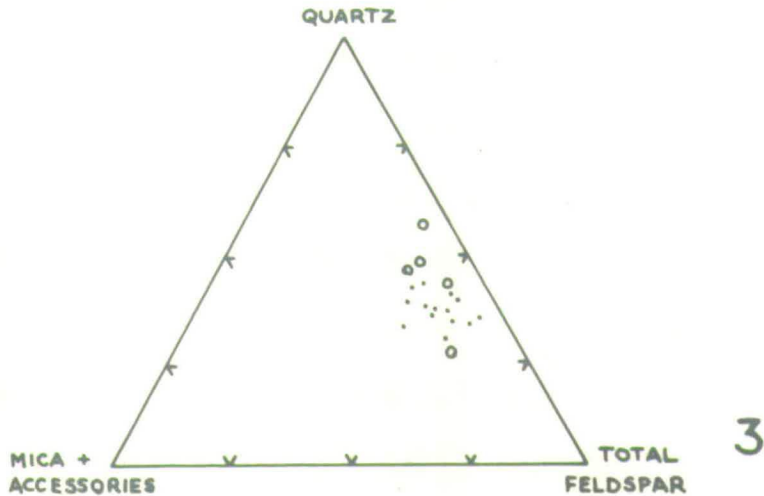
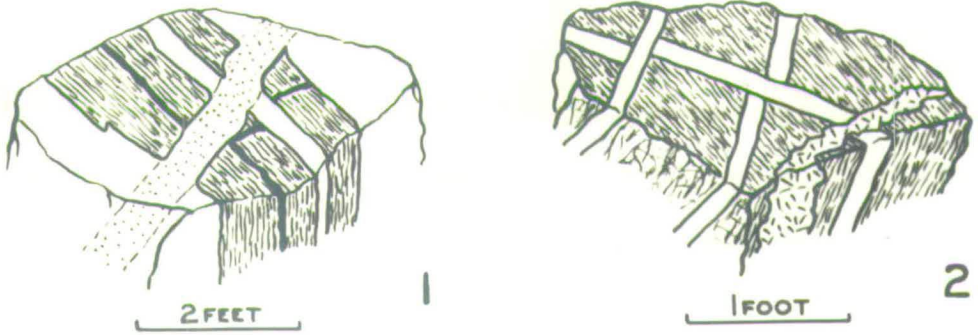


Fig. 14 1,2. Dilation veins of granite in blocks of gneiss, Creag Bheithe Mhor.

3. Plot of 14 modal analyses of specimens of the Grantown Granite (points) compared with five modal analyses of quartzo-feldspathic rocks of the Moine Series (circles). Modes of latter are numbers 0.14, 23, 165, 427 and 461 in Table 1.

to be dilation veins (Goodspeed, 1940; Jaeger, 1951) when the displacement of layers in the country rock by them is studied in three dimensions (Fig.14).

(c) Petrography

In hand specimen the granite is medium grained and is pink or grey in colour; quartz, feldspar, biotite and garnet can be recognised. Joints are common and well spaced, and show little significant pattern (p.179). In thin section quartz, plagioclase, microcline, biotite and muscovite are the most abundant minerals; their texture is equigranular and granoblastic. Unlike the majority of the Newer Granites the Grantown Granite is practically never porphyritic. (See photomicrograph on Plate XXVI.)

The most abundant constituent is quartz, which occurs as anhedral crystals up to 3 mm across. The range of size in a single thin section is considerable, as it is with all the other constituents. The crystals usually show undulose extinction; only one thin section shows granular zones and boundaries and 'deformation lamellae' in the quartz. Intergranular boundaries tend to be sutured. Unstrained quartz is found as inclusions in feldspar crystals while blebs of quartz have been observed in the outer zones of some plagioclase crystals.

The plagioclase crystals are up to 3 mm across and are for the most part subhedral, with square, rectangular or triangular outlines. The crystals are therefore cuboidal in shape. The range of grain size for plagioclase is smaller than for microcline. Plagioclase tends to be concave towards quartz and microcline. Twinning on the albite law is sparse and the twin lamellae are thin; twinning on two laws is rare. The composition range of plagioclase within the mass is An_{20} to An_{30} . Zoning of the normal discontinuous type is common; up to seven zones have been observed in a single crystal. The zone boundaries are sub-parallel to the crystal margins, but most crystals show slight changes of shape with stages of growth. The zone boundaries are not offset by twin lamellae. The evidence in a few crystals indicates that there was rounding of corners and formation of re-entrant angles at an early stage of growth. One crystal contains what appears to be a crack passing through two of the inner zones and filled by material continuous with an outer zone. Other crystals show, by the abrupt intersection of zone with crystal boundaries, that it is likely that they were derived by disintegration of a larger crystal. It is not, however, possible to reconstruct the size and shape of these large crystals owing to the scattered occurrence of the fragments.

In a few crystals it was possible to determine the zonal composition range as from An_{25} to An_{10} from interior to margin. No examples were recorded in which the twin lamellae were confined to a particular zone or zones.

As in so many other rock types in the area, the plagioclase crystals commonly contain ragged, patchy inclusions of microcline, which has one twin axis parallel to the albite-twin axis of the plagioclase. This consistency in optical orientation can hardly be attributable to a chance slice of an irregularly shaped microcline partly embedded in an equally irregular plagioclase, or vice versa. Small plagioclase crystals are occasionally seen in the larger microcline crystals in a relationship the reverse of that described immediately above. Alteration of plagioclase to secondary mica is common, the only distinguishing features of the cross-cutting veins in the granite from the granite itself being the more intense alteration of plagioclase in the veins. There is occasional preferential alteration along zones or less commonly along twin lamellae. Zoisitisation of plagioclase is rare.

The crystals of microcline are anhedral, are up to 3 mm across and show wide variation in size within a single thin section. Approximately half of the specimens

150

contain microcline crystals twinned on the Carlsbad law in addition to the usual albite and pericline laws. The mineral is often found intergrown with plagioclase as described above. As in many other rock types the microcline often contains extremely thin veins of plagioclase arranged en echelon. There occur occasional patches and veins of 'porphyritic' granite whose contact relations are nowhere clear. Petrographically these rocks are similar to the rest of the granite except that each 'phenocryst' is composed of an aggregate of large microcline crystals which show distortion of lamellae and peripheral granulation. At their margins these large microcline crystals contain inclusions of the groundmass minerals. Contiguous large microcline crystals are almost in optical continuity with each other and appear to have formed by the break-down of a much larger crystal. Patchy stringers of oligoclase are common in these microcline crystals. The majority of the crystals are therefore microcline-microperthites.

Biotite occurs as tabular crystals up to 1.5 mm long, with the pleochroic scheme: X = yellow-brown or straw yellow; Y,Z = red-brown or dark brown. Red-brown biotite is twice as abundant as dark brown biotite; there is no correlation with the presence or absence of accessory

sphene as in the pelitic rocks of the Moine Series (p.36). In some thin sections the biotite is slightly chloritised.

Muscovite also occurs as crystals up to 1.5 mm long but is less common than biotite. The crystals are either tabular or anhedral and are occasionally bent, whereas the plates of biotite show no signs of deformation.

The accessory minerals, which do not exceed 1% of the rock, include euhedral garnet, subhedral clinzoisite and epidote, anhedral magnetite, euhedral pyrite, apatite, zircon and sphene, the four last named seldom exceeding 0.2 mm across, whereas the first four accessories have a maximum size of 0.5 mm. The garnet is a pink variety, the ~~clinzoisite~~ clinzoisite is colourless and the epidote pale yellow. Garnet is confined to six of the 40 specimens collected; clinzoisite, epidote, iron ores, apatite and zircon are ubiquitous; sphene is rare. The garnetiferous specimens are all from localities in the north-eastern part of the granite. Euhedral crystals of pyrite up to 10 mm across are found in a specimen consisting almost entirely of microcline from a locality on Gorton Hill. This rock grades into granite of the normal type over a distance of about one foot.

More can be deduced of the history of the plagioclase than of any other mineral in the rock. Plagioclase

crystallised in an environment favourable to zoning. There was little limitation on the development of good crystal form until a late stage in their history, except that during an early stage some crystals suffered embayment by a means as yet unknown. Twinning of the crystals followed growth to their present size. Alteration to secondary mica, internal development of microcline and the breaking of some large crystals all post-dated twinning but in what time sequence cannot be determined from the evidence available. Late outgrowths of plagioclase contain post-twinning blebs of quartz.

Any thin section from the Grantown Granite shows homogeneity in texture and mineral composition, but on the scale of an exposure there is a distinct but variable irregularity in the biotite content of the rock. Sometimes the variation is clearly shown by small planar areas rich in biotite which can be seen to be parallel to each other only over distances of up to several feet. Their orientation over the granite mass as a whole appears to be haphazard. A more vague discontinuity in composition is shown by faint irregular swirl-shaped patches slightly richer in biotite than the surrounding granite. Planar orientation of biotite has nowhere been found.* Fourteen modal analyses

* Petrofabric analysis of two specimens of the granite has

shown that the orientation of c-axes of quartz and of poles to (001) cleavage in biotite are random.

of thin sections from widely scattered localities were plotted on a triangular diagram which has quartz, total feldspar, and mica + accessories at the apices (Fig.14). The analyses all fall within a relatively small area. The ratio of plagioclase to microcline, however, varies from 8:1 to 0.25:1, but in half the specimens the proportions are approximately equal. Mica + accessories do not exceed 20% of the rock. It may be noted that the mineral assemblage and the mineral proportions are closely similar to those of the quartzo-feldspathic rocks of the Moine Series to the west of the granite (Fig.14).

The petrographic evidence throws little light on the problem of the origin of the Grantown Granite, but shows that there was mechanical break-down of some of the feldspars after their crystallisation.

(d) The Structure of the Country Rocks

1. Fabric axes and fabric elements

The structure of rocks can be expressed in terms of planar and linear structural elements, which together constitute the fabric. It is customary to refer the elements

of the fabric to three mutually perpendicular axes, a, b and c, whose orientation is based for convenience on geometrical features of the fabric. In accordance with the usage of Sander (1948, p.125) the penetrative planar structure, whether foliation or banding, is named ab and the most conspicuous linear structure is b; c is normal to ab and a is normal to b in the ab plane. Where b is an axis of flexural folding it is named B. These are descriptive or symmetrological axes (see Weiss, 1955, p.229) which, when the rocks have monoclinic symmetry, coincide with the kinematic axes. The reflection of the symmetry of the deforming movements in the symmetry of the fabric of the deformed rock is a fundamental postulate of structural geology and petrology.

In Mid-Strathspey the prominent mica foliation or mineral banding present in most rocks has been named ab = S₁. Flexural folding of S₁ has given rise to small folds and parallel lineations named F₁ and L₁ respectively. Therefore B = F₁ = L₁. The marked lithological variation normal to S₁ suggests that S₁ represents the original sedimentary layering. The other planar elements are S₂, a foliation which is usually but not always an axial plane foliation, is developed in pelitic layers and is oblique to S₁; and S₃, a slip surface which is steeply inclined to S₁

and usually occurs where S_1 is steep or vertical. S_2 and S_3 both intersect S_1 in a line parallel to B . Unfortunately the nature of the exposures has prevented the measurement and statistical treatment of S_2 and S_3 . S_2 is sometimes seen to be a transposition foliation of closely spaced slip surfaces (Plate VI). As S_2 and S_3 are in the plane containing B they are hOl planes with regard to the fabric axes.* In

* By analogy with crystallography ratios of intercepts on the a, b and c-axes are denoted by the indices h, k and l respectively.

some exposures S_1 , S_2 and S_3 can all be observed (Fig.4). The lineation L_1 is formed by the parallelism of mica crystals, ribbons of quartz, or crystals of hornblende or kyanite depending on the rock type. In pelitic rocks L_1 is formed by the intersection of S_1 and S_2 . Denoted by F_1 are mullions, boudins, quartz rods and folds of all sizes up to several yards in amplitude.

Joints have not been studied in detail but the most prominent are related to the fold fabric. Post-tectonic quartz, granite and pegmatite veins follow joint directions.

With the exception of S_3 all the elements named above are found in the inclusions in the Grantown Granite.

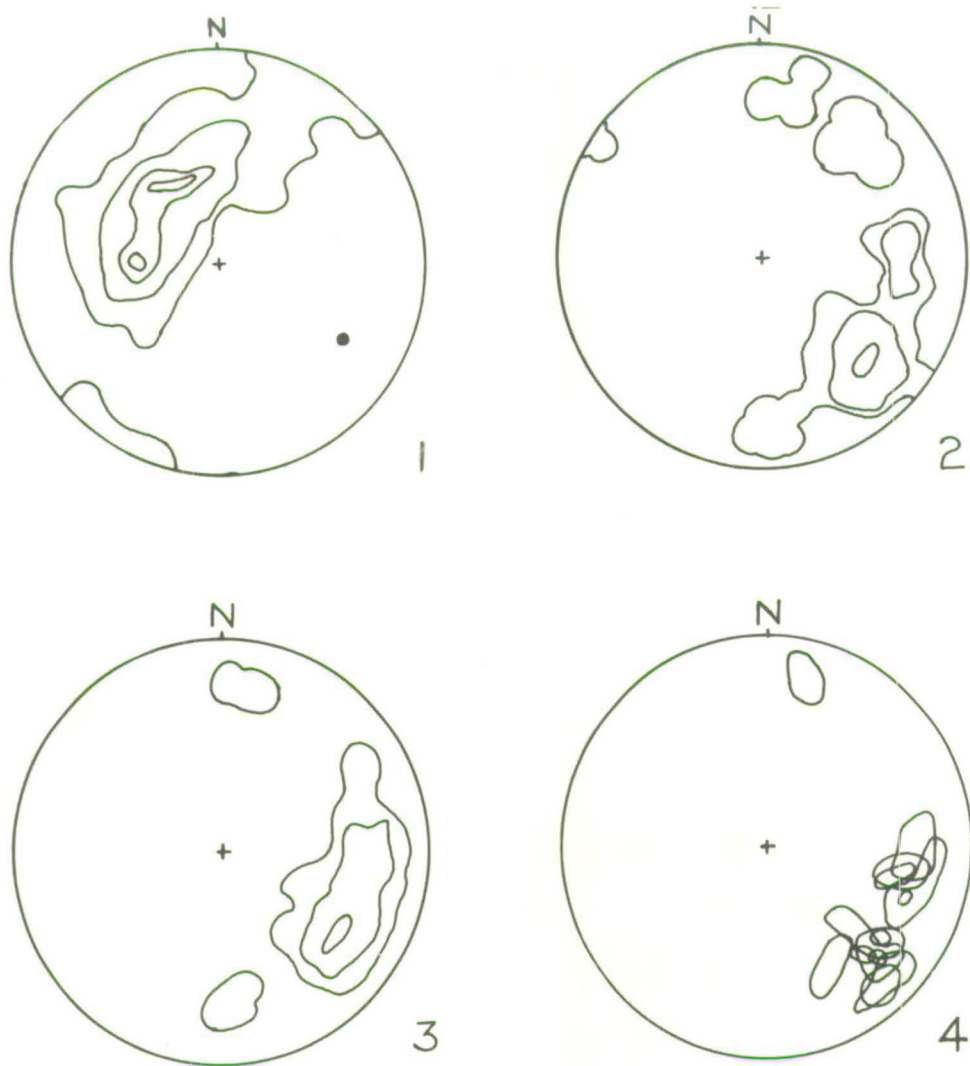


Fig. 16 Structure of the country rocks of Mid-Strathspey.

1. Poles of 785 foliation surfaces; full circle, axis of girdle; contours, 1-3-5-7% per 1% area.
2. Axes of 160 small folds; contours 1-5-15%.
3. Axes of 157 lineations; contours 1-5-15%.
4. Synoptic diagram of 15% contour lines from the 13 β -diagrams of Fig.15.

2. Planar fabric

The orientation of S_1 in the country rocks is given in Fig.16.1, in which the π -poles of S_1 are plotted. The π -poles lie in a girdle about an axis which plunges SE at approximately 30° . The spread of the maximum contour represents the regional dip of S_1 to the east, SE or south depending on locality. So persistent is this regional dip that no indication of the general fold style can be obtained from the diagram (see Weiss, 1954).

In the manner suggested by Wegmann (1929) and Sander (1948) the area has been subdivided into small areas to test the homogeneity of the fabric. If the folds are cylindroidal the intersections of S_1 surfaces in a particular area define a β -axis for that area. The intensity of the β -axes is given by contouring the concentration of intersections. The orientation of the β -axis is then read from the Schmidt net and indicated in the subarea. In Mid-strathspey the β -axes are parallel to the \underline{B} -axes. The β -diagrams from 28 subareas in and around the Grantown Granite are shown on Fig.15 (end pocket), and the results from outside the granite are summarised in Fig.16, on which the β -diagrams are represented by all the 15% contour lines from the diagrams. In an area which has insufficiently variable data for plotting as a β -diagram the average foliation

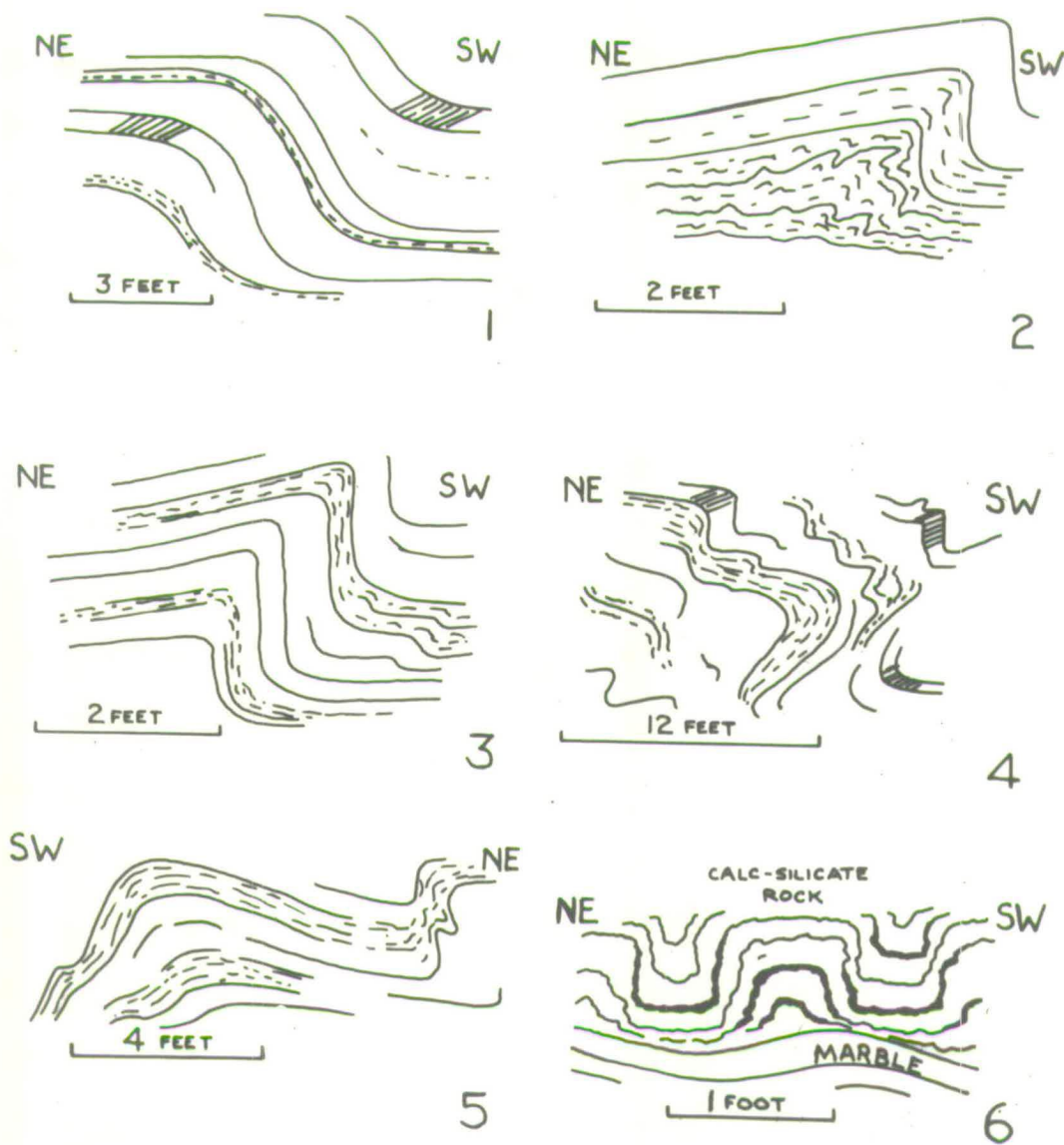


Fig. 17 Fold style in the northern part of Mid-Strathspey.

- 1,2. Headwaters of the Allt Breac.
3. South of Carnloch.
4. Creag Liath, block within granite.
5. Laggan Hill, calc-silicate rock.
6. Wester Laggan Farm.

surface is represented by the great circle drawn normal to the π -pole maximum. The dip and strike of the average foliation surface are then indicated in the appropriate sub-area. In general the β -axes plunge SE, with a swing towards east in the NE of the area and towards south along the Spey-Dulnain watershed. The intensity of the β -axes has a regular variation which is discussed later (p. 188).

Folding of S_1 is common throughout the area, the fold style varying both with rock type and with locality. In general the style is monoclinial, the folds being overturned from the NE. In pelitic rocks and migmatites the style is plastic and the sense of overturning is sometimes difficult to determine. Figs. 17 and 18 show a series of fold profiles from localities selected to show the progressive change of style from north to south. Various rock types are represented including blocks contained in the Grantown Granite. The sense of overturning is the same in the country rocks as in the included blocks. In the NE of the area the style is simple, only the micaceous layers showing disharmonic folding. In the SW, both micaceous and quartzo-feldspathic layers have a plastic style, many of the examples showing an equivocal sense of overturning. The sense of overturning on the largest possible scale in the migmatitic rocks of the Spey-Dulnain watershed is consistent

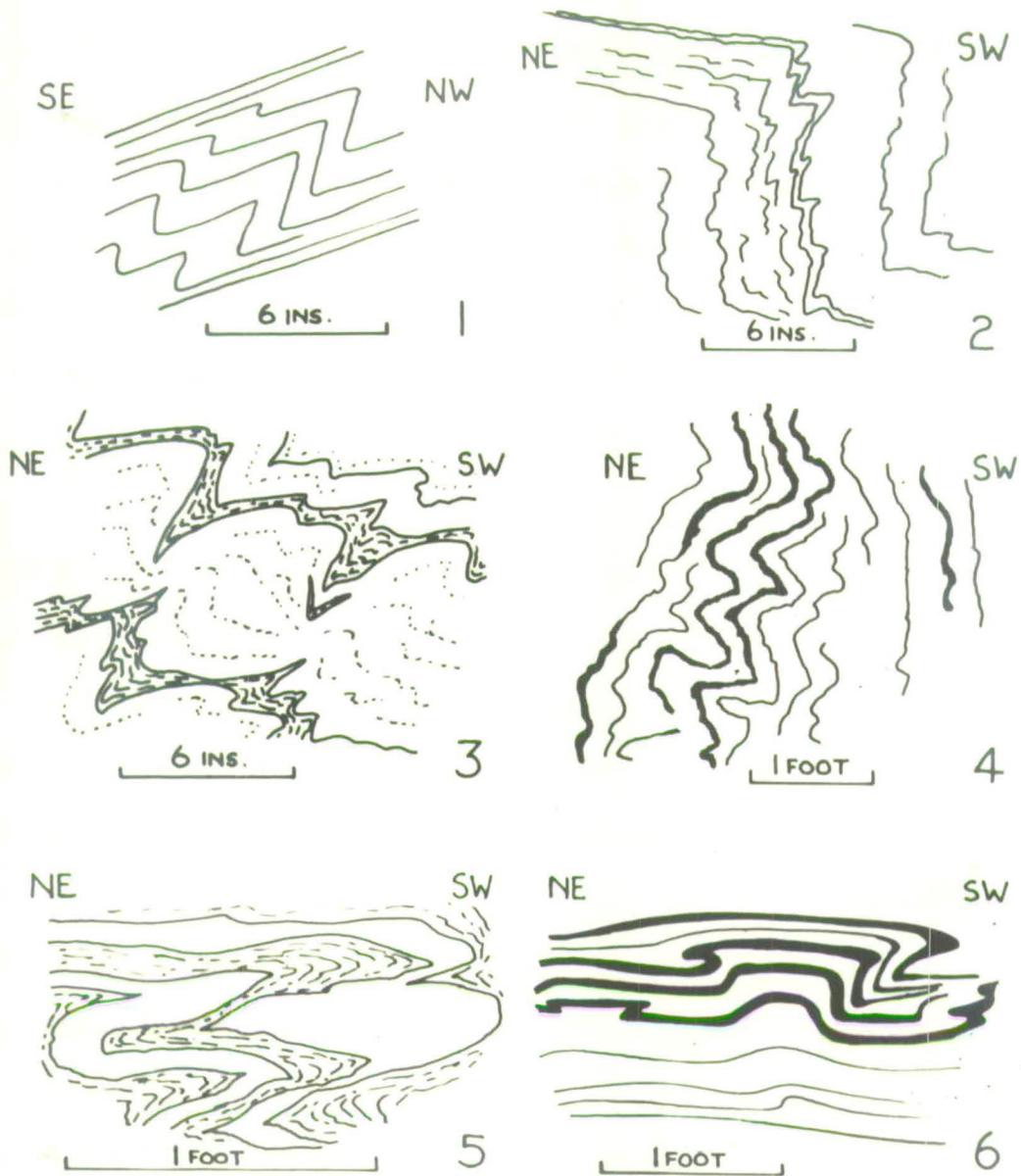


Fig. 18 Fold style in the southern part of Mid-Strathspey.

1. Quartzo-feldspathic gneiss, Carnloch.
- 2,3. Migmatite, Creag an Fhithich.
4. Migmatite, Stac an Toisich.
- 5,6. Migmatite, Creag an Fhithich.

with that shown elsewhere in the area. This fact is only appreciated when the dip and strike of S_1 have been measured over an area of several hundred square yards.

S_2 is nearly always constant in orientation with a dip to the ENE. In some folds S_2 is a transposition foliation parallel to the axial planes of the folds. Throughout the migmatitic rocks the orientation of S_2 is variable, commonly dipping south or SW as in Fig.4. S_2 is diagrammatically indicated in Fig.17.1.4. At Craig Revack S_2 is prominent in the coarse pelitic gneisses (Plate VI) but is variable in orientation, with a tendency to a southerly dip on the SW limb of the Revack antiform and an easterly dip on the NE limb. As with S_3 , S_2 is most conspicuous where S_1 is steep.

The surfaces named S_3 usually dip SE at the angle of plunge of the fold axis, and are only developed where S_1 has a steep dip (Fig.4). S_3 is a surface of actual or incipient slip. Thin sheets of granitic rock are sometimes found along S_3 (see pp. 53-55). Kinematic interpretation of the movements on S_3 can usually be made. The thin sheets have their maximum length parallel to the regional E-axis.

The rocks of the area are well jointed, many of the joints being geometrically related to the fabric. Time

has not permitted an extensive study of the joint pattern. ac joints are everywhere prominent and provide excellent profiles of the folds, besides giving many hills a scarp feature to the NW. The ac joints are best developed where nullion structure is found (Plate VI). hk0 joints are also common, the fold axis intersecting either the acute or the obtuse angle between the joints.

3. Linear fabric

A synoptic diagram of the orientation of fold axes and lineations is shown in Fig.16.2.3. All the lineations are B-lineations parallel to the axes of visible folds and the two elements \underline{F}_1 and \underline{L}_1 can be considered jointly. The maxima for \underline{F}_1 and \underline{L}_1 coincide with the β -axis maximum. The apparent girdle of fold axes and lineations can be accounted for by subdivision of the information according to locality and by consideration of the regional dip of \underline{S}_1 . The coincidence of the plane of the regional dip with the girdle of B-axes shows that all the linear elements lie in the plane of the foliation. The small concentration of southerly plunging axes is found in a small area near Ochnoir on the Spey-Dulnain watershed. The larger concentration of elements with an eastward plunge is found in the NE of the area, to the east of the Grantown-

Forres railway line. Over by far the greater part of the area the axial elements plunge SE at approximately 30° and the local variations mentioned above are irregularities in the regional trend.

There is a small concentration of elements which plunge gently to the NNE. These axes are restricted to three small areas, viz. the summit of Laggan Hill, Easter Duthill and Carnloch, in calc-silicate, migmatitic and quartzo-feldspathic rocks respectively. The style of these folds is identical with that of folds of regional trend in similar rocks nearby. The sense of overturning is consistently from the SE. At Laggan Hill the NE plunging folds form the top of the hill; their relationship to the underlying SE plunging folds is unfortunately obscured. At Carnloch the relationship between rocks with fold axes of SE and NE trend is seen to be a normal interbanding with no evidence of violent tectonic discontinuity between. It must be noted that the axes in adjacent rocks in two of the above cases are approximately 90° apart in the plane of the regional foliation surface and that there are no axes of intermediate trend. There is no evidence to suggest that the folding at such localities took place in two distinct phases.

The necessity for a statistical treatment of folds

and lineations is well shown on Creag an Fhithich where on large exposures some of the small folds die out along their length; F_{-1} is, however, the direction of least change and is sub-parallel over a wide area.

4. Kinematic interpretation

The foliated rocks of Mid-Strathspey have monoclinic symmetry about an ac plane which is inclined steeply NW. This symmetry reflects movement in the plane ab (S_{-1}) and about the B-axis, a being the direction of shortening.

The necessary risk involved in kinematic interpretation and extrapolation has been minimised in this study by attempting as far as possible to treat the material statistically. The text-figures are representative of large numbers of structures in the field. The scale has been continually borne in mind. All the examples here given are found in areas of up to 200 yards square, but usually much less. The picture, however, is so consistent on this intermediate and small scale that it is likely that the movement picture over the area as a whole is similar to that provided by single exposures.

Unless the regional foliation attitude is known the overturning of folds gives a sense of rotation only and not a sense of relative movement. The mode of inter-

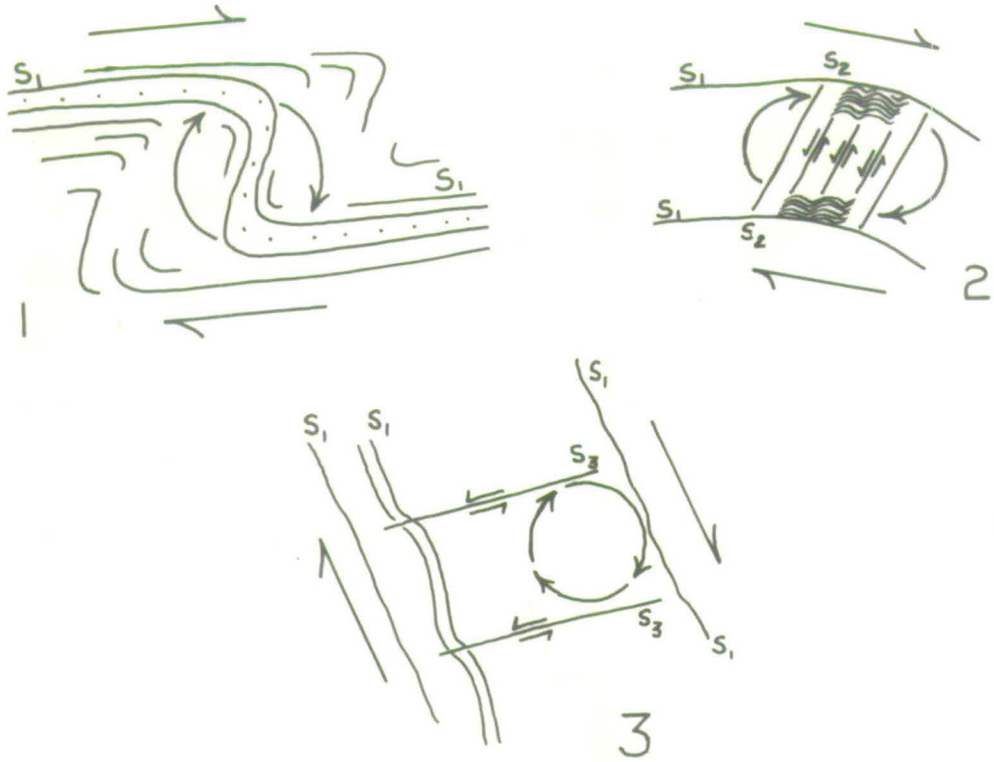


Fig. 19 Methods of kinematic interpretation of structures.

1. Monoclinal folds in S_1
2. Axial plane foliation; S_2
3. Slip surfaces; S_3

pretation of folding of, or slip on, S_1 , S_2 and S_3 is indicated in Fig.19. The presence of a consistent penetrative planar surface on which slip can take place (S_1), the consistent orientation of the axial plane foliation (S_2) and the consistent sense of overturning in monoclinical folds up to the scale of the Revack antiform (Fig.10) show that in the penetrative movements which affected the district the upper layers moved SW relative to the lower layers. In the belt of steep foliation on Creag an Fhithich the south-western layers moved down relative to the north-eastern layers. The sense of overturning of the folds does not necessarily give the sense of tectonic transport. The direction of transport a was sub-horizontal and trended NE, while there was concomitant flexural folding about an axis plunging SE at 30° . There was therefore crustal shortening in the direction NE-SW; this study gives no information about change of shape in any other direction.

Kinematic interpretation of structures in the migmatitic rocks of the Spey-Dulnain watershed has been carried out with caution because, for example, of the equivocal sense of overturning in some folds. S_1 dips steadily SE as far south as Craig Garten and is steep and highly contorted over the whole of Creag an Fhithich and Stac an Toisich. Here S_3 is well developed. Further south

on Docharn Craig S_1 again has a steady dip to the SE. On the largest visible scale at Stac an Toisich the rocks are monoclinical in style and are overturned from the NE indicating slip of upper S_1 layers to the SW relative to the lower and, where S_1 is steep, of south-western layers down relative to north-eastern layers. Axial plane slip surfaces (Fig.4.2) on Craig Garten conform to this movement as does the sense of relative movement inferred from slip on S_3 (Fig.4.3). In the highly folded rocks of Creag an Fhithich S_2 is variable in attitude and is not a reliable guide to movements on a larger scale.

The relatively large areas of steadily dipping rocks without many folds suggests that the transport need not have been large-scale. Nowhere in the area have large movement horizons been located although they are known to exist a short distance to the south (Weiss, McIntyre and Kursten, 1955). Locally small shears and displacements are found but they would appear to be small faults much later in age than the folding.

Movement to form folds which trend NE has also been monoclinic, the upper layers having moved NW relative to the lower (Fig.18.1). The folds of SE and NW trend cannot be shown to be of different ages but some shortening in the NW-SE direction has taken place at least on a small

scale.

The spread of the trend of the B-axes in a girdle from south to NN parallel to the regional foliation surface presents a difficult problem. The geometry suggests one of the following kinematic interpretations: (a) local torsion by a horizontal couple, the effect dying out in depth; (b) marked inhomogeneity in the original sediments leading to complex movements, or (c) movements superposed on a pre-existent markedly oriented structure, that is, complex movements. The occurrence of B-axes of various trends at the same tectonic level suggests that (a) is an unlikely explanation. The absence of steep secondary fold axes characteristic of rocks which have suffered two deformations* suggests that (c) has not been a major factor

* Oral communication from Dr. L. E. Weiss.

unless the fabric before the second deformation agreed in symmetry with the second phase of deforming movements. There is no evidence either for or against (b). The question must remain open. The spread of the sheaf of B-axes in the migmatitic rocks of the Spey-Dulnain watershed can be explained by increased mobility of the rocks during migmatization (see pp.188-191).

There is in this area no evidence to assist in



Fig. 20 Structure of the included blocks in the Grantown Granite.

1. Poles of 266 foliation surfaces; full circle, axis of girdle; contours, 1-3-5-7% per 1% area.
2. Axes of 47 small folds; contours, 2-5-15%.
3. Axes of 36 lineations; contours, 2-5-15%.
4. Synoptic diagram of 15% contour lines from 12 β -diagrams on Fig.15.

the elucidation of the problem of the regional fold axis in the Moine Series. Whether this axis formed in its present position or was rotated into its position by later movements is not clear.

An extrapolation of the kinematic picture here outlined beyond the limits of the area is not justified, as an area of complex kinematics lies immediately to the south (Weiss, McIntyre and Kursten, 1955).

(e) Structure of the Inclusions in the Granite

1. Orientation of the fabric

The fabric of the included blocks is summarised in Fig.20 and given in detail in Fig.15 (end pocket). The π -poles of S_1 form a less well-defined girdle than in the country rocks. There is therefore less homogeneity of fabric within the small area of the Grantown Granite than in the rest of Mid-Strathspey. The full circle in Fig.20,1 marks the approximate axis of the π -pole girdle and corresponds closely with the maxima for folds, lineations and β -axes (Fig.20,2,3,4). When the sub-areas are examined in detail it is seen that the folds, lineations and β -axes which form small concentrations in the SE quadrant lie in the plane of the foliation whose π -poles mark a minor maximum in the NW quadrant. Furthermore, these

south-easterly plunging elements are confined to the north-eastern and southern margins of the granite mass. The style of folding and sense of overturning of folds are identical outside and inside the granite.

The sheaf of β -axes from the inclusions is approximately the same width as the sheaf of β -axes for any area of the same size in the neighbourhood of the granite (cf. Fig.20.4 with Fig.25); the average maximum contour^r value in β -diagrams is slightly less for sub-areas inside the granite than for those outside (Table 20), indicating that on the scale of the sub-area the fabric of the inclusions in the granite is comparatively homogeneous. The comparison of inclusions with country rock is graphically illustrated in Fig.15 (end pocket), where for clarity the information is presented for only a narrow zone of country rock close to the granite boundary. The sub-areas are arbitrarily defined, mainly by absence of exposures beyond their margins, and each contains a large number of inclusions, large and small, separated by granite sheets. As previously described (p.165), in areas of constant foliation attitude an average foliation surface is obtained from the π -pole maximum. The average foliation surfaces within the granite lie in the same plane as the β -axes and \underline{B} -axes for nearby sub-areas. The nature of the exposures

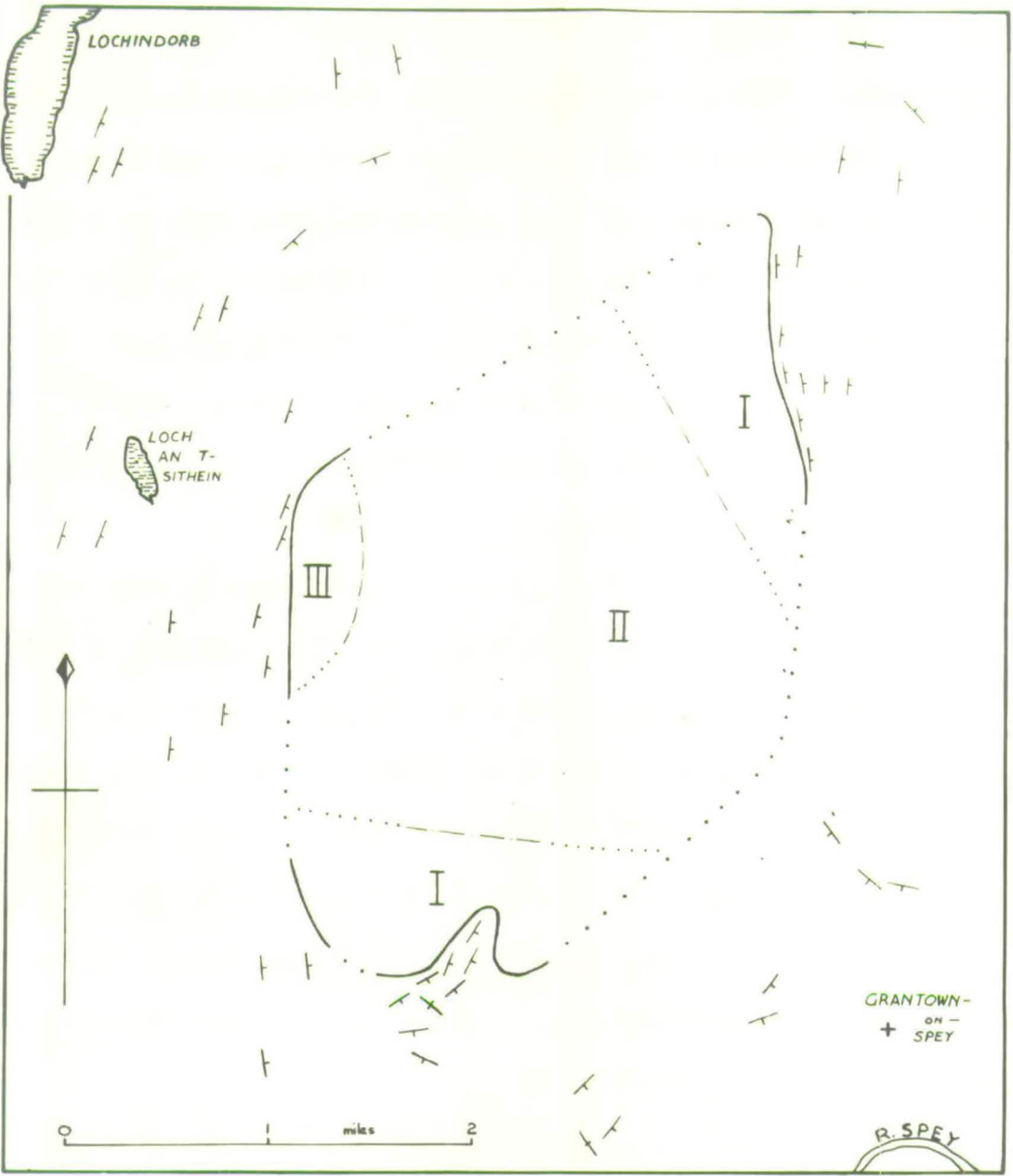


Fig. 21 Zones of orientation of included blocks within the Granttown Granite. Attitude of foliation in the country rocks indicated.

prevents a direct measurement of the degree of rotation suffered by the small inclusions (Fig.13), but does not prevent an estimate of the degree of rotation on a much larger scale. The B-axes for the sub-areas in the granite as a whole are given statistically by Fig.20.2.3; in any sub-area the B-axis conforms closely to the β -axis.

Three zones of orientation can be identified within the granite (Fig.21).

In Zone I the orientation of the B-axis for the blocks is up to about 30° away from the regional B-axis in a vertical plane. This zone is developed along the north-eastern and southern margins of the granite where the contact is usually concordant with the foliation of the country rock and dips east or SE. The B-axes in this zone generally plunge gently SSE but the amount of deviation from this generalisation is shown by a comparison of sub-areas XVIII and XX with the rest.

Zone II, which occupies the larger part of the interior of the granite mass, contains sub-areas whose B-axes plunge NW at angles of up to 30° . These inclusions have been rotated from the regional B-axis by from 30° to 60° in a vertical plane. The average foliation surfaces in the zone dip gently NW or more steeply SW. The sub-areas XII and XIII on Creag Bheithe would appear to be the

continuation within the granite of the steep south-westerly dipping foliation at LynnsGregor. Although structural measurements were made in so many inclusions the homogeneity of fabric in this zone is remarkable, equalling in constancy the sub-areas of the country rocks. Towards the east side of the zone the β -axis is weak indicating increasing departure of the foliation surfaces from the cylindroidal.

Zone III is confined to one sub-area (VI) at the western margin of the granite where the contact is steep. The β -axis and the \underline{B} -axis plunge steeply to the NW and the former has a weak maximum. This β -axis has been rotated by from 60° to 90° from the position of the regional \underline{B} -axis. sub-area V lies astride the granite contact zone and contains a weak β -axis plunging at 45° to the SE. The average foliation surface in sub-areas west of the granite is generally steeper than the regional foliation dip of 30° .

2. Kinematics of the granite

The similarity in fold style, symmetry and therefore kinematics of the foliated rocks inside and outside the granite, the coincidence of areas of similar dip and strike across the granite contact zone at Creag Bheithe, and the fact that nowhere else in Mid-Strathspey

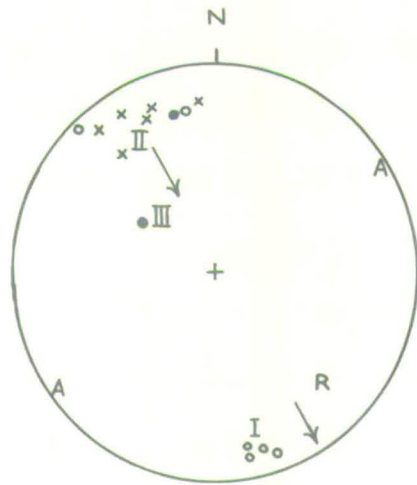


Fig. 22 Generalised geometrical rotation of blocks
in the Grantown Granite.

R, regional β -axis; open circles, β -axes
of Zone I; crosses, β -axes of Zone II;
black circles, β -axes of Zone III; A,
general axis of rotation, sense shown by
arrows.

but in the granite are NW plunging folds to be found all indicate that prior to the formation of the granite the blocks now in the granite were oriented with their B-axes plunging SE at about 30° .

The progressive rotation of the blocks in the granite from their original position is illustrated by the rotation from R through I and II to III on Fig.22. This generalised rotation is about a sub-horizontal axis, A, which trends NE. But rotation is here used in a geometrical and not a kinematic sense. The sense of geometrical rotation in the granite is anti-clockwise to an observer looking NE along the axis, because the upper surface of layers and folds in the country rocks corresponds to the upper surface of layers and folds in the inclusions. Kinematically there was external rotation of blocks in the plastic granite but neither direction nor sense of movement can be inferred from the present data.

There must have been considerable movement in the granite to allow the inclusions, both large and small, to take up their present positions. Moreover, the regular pattern of orientation suggests that the inclusions did not move solely by gravitation in the plastic granite but were carried to their positions by movements in the granite itself, movements which were not, however, sufficiently

strong to disturb the bordering country rocks. Movement in the granite in a plane parallel to the regional foliation surface and therefore parallel to the longer axis of the mass and to the granite sills along the north-eastern and southern margins could account for this lack of disturbance. It is not known to what extent movement of the granite and the inclusions was reciprocal and relative.

The regularity of orientation in Zone II is perhaps due to the fact that the Zone consists of a few very large included blocks separated by thin planar granite sheets along the foliation surfaces, a condition which would result in the maximum of cylindrical homogeneity.

In the absence of a penetrative structural element in the granite the kinematic picture must remain incomplete. The results can be summarised by stating that the displacement in the attitude of blocks was greater to the west side of the mass than to the east. Petrographic similarity of inclusions and country rocks indicates that movement of the blocks in a vertical direction was not great.

(f) Structures within the Granite itself

Nowhere has the granite been seen to contain a

directed structure of its constituent minerals, either by form or lattice orientation. At several localities the granite contains thin impersistent biotite-rich sheets or 'schlieren'. Their orientation was measured and the planes of the sheets are randomly oriented with respect to visible contacts, but over the granite as a whole tend to dip to the southern hemisphere at variable angles. The significance of these sheets in the structural picture is not clear and there is no evidence to suggest that they can be regarded as 'flow planes'.

Joints are common in the granite and their orientation has been measured at many localities. The great majority are steep or vertical with variable trends. Large numbers dip either east or west at intermediate angles. In the road and railway cuttings near Carn Luig and at Tom a' Chaisteil many of the westerly dipping joints contain thin quartz veins on which there are slickensides plunging towards the WNW at 50° . The grooving of the slickensides shows that the planes were reversed faults, the throw being unknown.

The Grantown Granite is therefore unsuitable for study by the Cloos-Balk methods of granite tectonics.

(g) summary of Evidence

The country rocks are characterised by:-

- (i) A regional dip to the SE and east.
- (ii) A regional plunge of linear elements at 30° to the SE.
- (iii) Flexural folding about B. The complexity and plasticity of style and degree of inhomogeneity increases southwards with migmatisation. The style is monoclinal, the folds being overturned from the NE.
- (iv) Movement was of upper layers to the SW relative to lower layers.
- (v) Lack of contact metamorphism by the granite.

The granite is characterised by:-

- (i) An abundance of inclusions of all sizes which retain all the features of the country rocks except orientation.
- (ii) Planar and linear elements in the inclusions tend to plunge NW at increasing angles and with increasing inhomogeneity away from the eastern contact.
- (iii) Petrographic homogeneity and a lack of internal structures.

- (iv) The granite mass is lenticular in outline and has a steep western contact and a gently dipping conformable eastern contact. Internally the granite forms a reticulate pattern of dykes and sills between the inclusions. There is a tendency for the foliation of the country rocks to curve around the granite mass.

(h) Discussion of Origin

The Grantown Granite is a cross-cutting biotite-granite later in age than the metamorphism of the Moine Series, and can therefore be considered to be a Newer Granite, presumably of Caledonian age. It is petrographically homogeneous and is somewhat similar to the other Newer Granites of NE Scotland, but differs from them in that it is seldom porphyritic, is fine in grain and has a unique suite of inclusions - features which lead one to believe that only the upper part of the granite mass is exposed.

Microcline which is in an arrested stage of mechanical break-down forms the sparse phenocrysts (see pp.155 et seq.). Some of the plagioclase crystals have been embayed at about half their present size and have all been zoned throughout their history. Some plagioclase crystals are fragments of larger crystals. This petro-

graphic evidence suggests that there is perhaps some support for the kind of concept propounded by Duff (1942). He considered that granite was emplaced at high pressure and low temperature as a mush of crystals lubricated by a small quantity of water. The crystals were derived from a pre-existing rock.

The inclusions furnish evidence to show that at the time of emplacement the granite was plastic and was at a temperature close to that of the country rock, that is, probably below about 500°C. Granite veins cutting the inclusions show that there was dilation on a small scale; the curving of the strike of the foliation of the country rocks around the mass suggests that there has been dilation on a large scale. Leedal (1952, p.39) considers this feature to be typical of Scottish granites of Caledonian age.

It is concluded that the granite was generated in a place and by a process unknown and that it subsequently moved into its present position along the foliation of the country rock, making room for itself by forcible dilation of the latter. It is visualised that at the time of emplacement the granite consisted of a mush of crystals, some being broken, with a little lubricant (as in Sosman, 1948). There was no tendency for the granite to take on

a directed structure. Inclusions of country rock, some of which are very large blocks, remained throughout at least the upper visible 600 feet of the mass and suffered increasing degrees of disorientation towards the western margin of the granite, but were not greatly displaced in a vertical direction.

If the granite be regarded as a rheomorphic derivative of pre-existing rocks there is a sufficiency of material of similar composition (Fig.14) in the Moine Series to the west and south of the granite. Moreover, the quartzo-feldspathic rocks of the Moine Series are carried below the surface position of the granite by the regional dip and plunge. If rheomorphism is to be invoked, then the major difference between the granite and the quartzo-feldspathic rocks, viz. the zoning of the plagioclase, provides a clue towards deciphering the rheomorphic history of the granite.

The only other recorded complex which resembles the Grantown Granite is that described by Runner (1943) from the Black Hills, South Dakota. The Harney Peak granite contains numerous inclusions which dip radially outwards to form a dome-shaped structure. The granite has a reticulate pattern formed by intersecting sills and dykes along and across the foliation of the inclusions. Runner

considers that the sills and dykes were successively formed and that the inclusions were therefore never totally enclosed by granite which was in the process of formation or emplacement.

Rotated inclusions in granite masses have been recorded from several localities (Lelubre, 1938; Cogne, 1950; Pitcher, 1952) and have been discussed by Roubault (1952) and Perrin (1954, 1956) who has studied some of "the relatively rare cases of so-called displaced inclusions, i.e. with discordant schistosity, suggestive of displacement by a liquid." (1956, p.12). Perrin has devised a series of explanations for displaced inclusions, such as granitisation of a folded migmatite, granitisation of lavas containing inclusions, eruptive breccias or development of new schistosity in the inclusions, yet he has to admit that "there are certain exceptional cases of displaced enclaves, described by authors who have given sketches thereof, that still puzzle me" (1956, p.12). The Grantown Granite furnishes clear-cut examples of displaced inclusions which appear to the writer to be inconsistent with formation of the granite in situ.

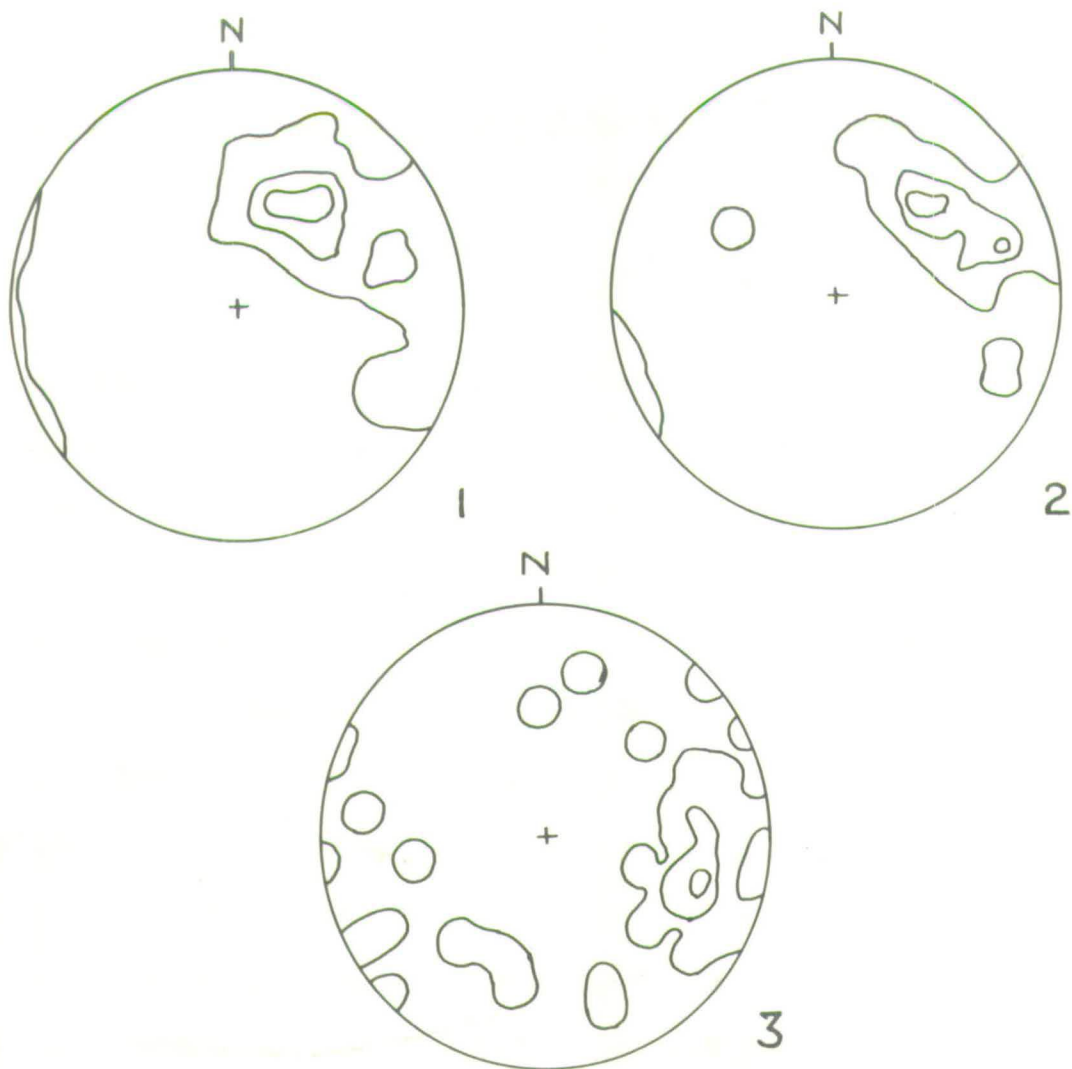


Fig. 23 Statistical treatment of pegmatite, granite and quartz veins, Spey-Dulnain watershed.

1. Poles of planes of 441 pegmatites; contours, 1-5-7%; maxima normal to h0l and hk0.
2. Poles of planes of 51 granite veins; contours, 2-10-15%; maxima normal to h0l and hk0.
3. Poles of planes of 57 quartz veins; contours, 2-10-15%; maximum normal to ac plane.

SOME GENERAL ASPECTS OF THE GEOLOGY
OF MID-STRATHSPEY

(a) Post-tectonic Acid Veins

As part of the investigation of the relationship between granitic rocks and structure in Mid-Strathspey, a statistical study was made of the orientation of the abundant post-tectonic quartz, granite and pegmatite veins which cut the migmatites of the Spey-Dalnain watershed. The results are summarised in Fig.23. The veining is most intense where the migmatisation and the deformation have been strongest, viz. on Greag an Fhithich, but the veins undoubtedly post-date the migmatisation phase. The veins are not visibly connected with any granite mass.

The veins are planar and seldom exceed two feet in thickness. Many can be seen to thin out laterally, only to be succeeded by a further, neighbouring vein en echelon. Most of them are responsible for displacements of structures in the country rock which can only have come about by dilation normal to the plane of the vein (Goodspeed, 1940; Jaeger, 1951). As recorded by Hinxman and Anderson (1915, pp.39,45) many granite veins are found to grade to a pegmatitic margin, and although Anderson (p.39) considered the granite to be a later intrusion along the middle of the

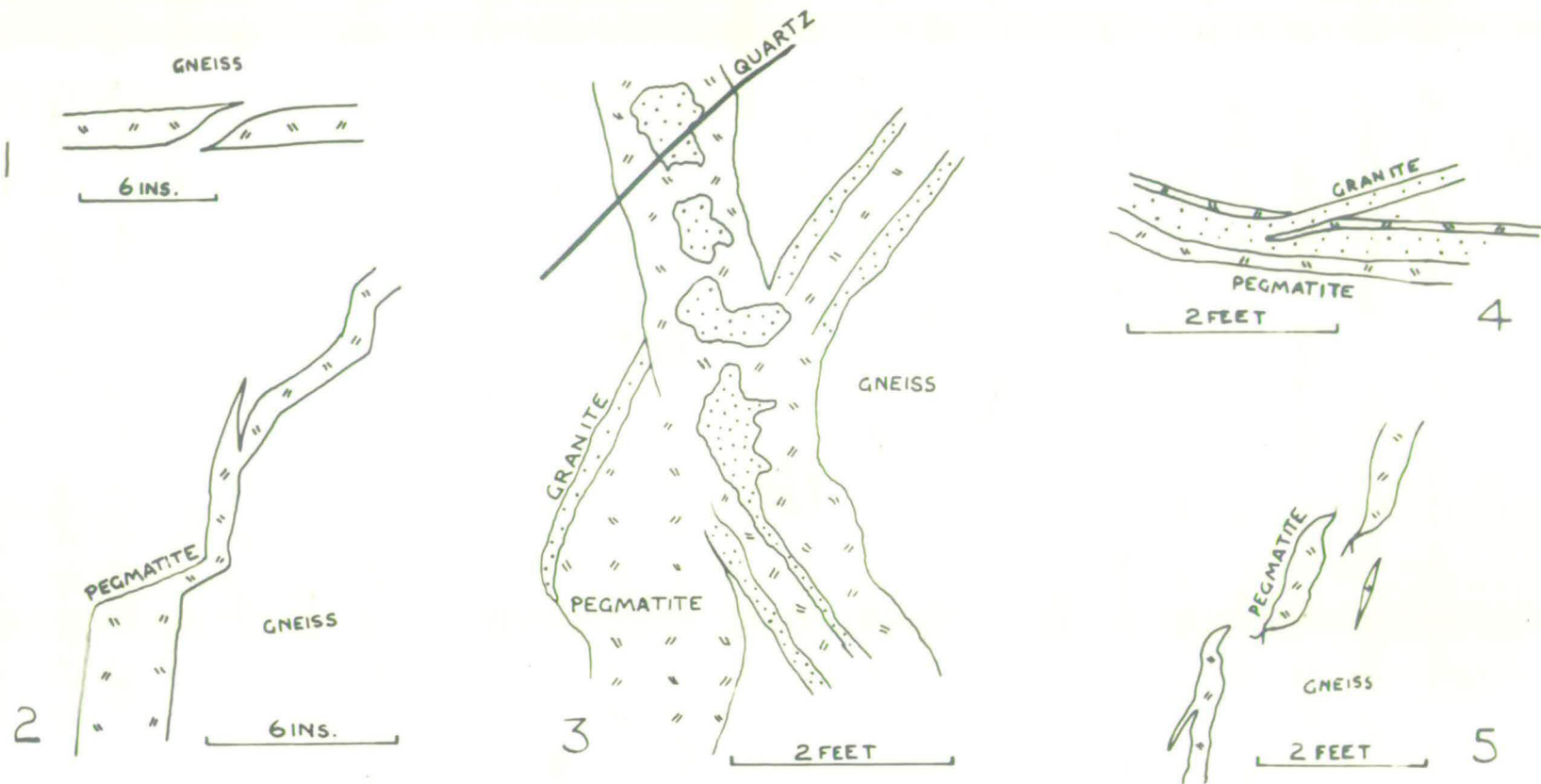


Fig. 24 Plan views of various post-tectonic acid veins of the Spey-Dalnain watershed.

1,5. Craig Garten.
 2,3,4. Creag an Fhithich.

pegmatite, Hinxman (p.45) saw no grounds on which to decide which part of the vein formed first. Ramberg (1956, Plates 1 and 9) has recently figured excellent examples of the same phenomenon which he considers to be the result of pegmatite replacing the pre-existing granite vein. On Greag an Fhithich the writer discovered examples of compound veins with pegmatite developed on one side only, and with one exception the pegmatitic margins occupied the upper sides of the veins. Furthermore, in some compound veins the pegmatite is restricted to the middle, while in many pegmatites the middle is rich in quartz. These compound veins are characterised by complex structures, either the marginal or the internal portions sometimes branching from the main vein into the country rock (Fig.24). The appearance of the large feldspars in some compound veins suggests that they grew in the granitic matrix after emplacement (Plate K).

The pegmatite veins consist of quartz, oligoclase, microcline, biotite, muscovite and occasional euhedral crystals of red garnet up to 5 mm across. The micas are usually concentrated at, and lie with their cleavage normal to, the vein margins. The granite of the veins is pink, medium grained and biotite-bearing and cannot be distinguished from specimens of the Grantown Granite mass.

Statistically the pegmatite and the granite veins have the same orientation (Fig.23.1,2). It has not been found possible to separate compound from simple pegmatites on a structural basis. The stronger of the two π -pole maxima represents veins in planes which are h0l with regard to the regional fabric, while the lesser maximum is normal to an hk0 plane. A few degrees latitude from the ideal is allowed in indexing the plane. In both Fig.23.1 and 2 there is a slight spread of the contours towards an hkl plane which is vertical and trends NNW, and a very weak distribution in the sc plane. By contrast the π -poles of the planes of quartz veins have a strong maximum normal to the sc plane with a slight spread towards an hk0 plane (Fig.23.3).

The field evidence shows that the pegmatite and granite veins are invariably cut by quartz veins. The pegmatite and granite veins transgress the quartzo-feldspathic segregations formed during migmatization (Plate VII). The planar extent of many of these veins and their relationship to the fabric indicates that they filled joints or incipient joints. The close association of the post-tectonic veins with the syntectonic acid segregations suggests, but does not prove, that the later material was formed by a re-working of acid material already present in

the migmatites.

The sequence of events in this district can therefore be summarised as follows:

Movements and planes available	Type and localisation of veins
1. Regional monoclinic movement; slip on S_1 , folding about B ; S_1 and S_3 are planes of structural anisotropy.	Migmatisation; quartzo-feldspathic segregation along S_1 , granitic sheets along S_3 .
2. Stresses leading to opening of planes $h0l$ and to a lesser extent $hk0$.	Dilation of openings and filling by granite and pegmatite; latter possibly formed later by recrystallisation of granite (?).
3. Stresses leading to opening of ac and to a lesser extent $hk0$ planes.	Dilation of openings and filling by quartz.

(b) The Relationship between Migmatisation and Structure

When the first indications of distinct migmatisation of the rocks on a large scale are plotted on a

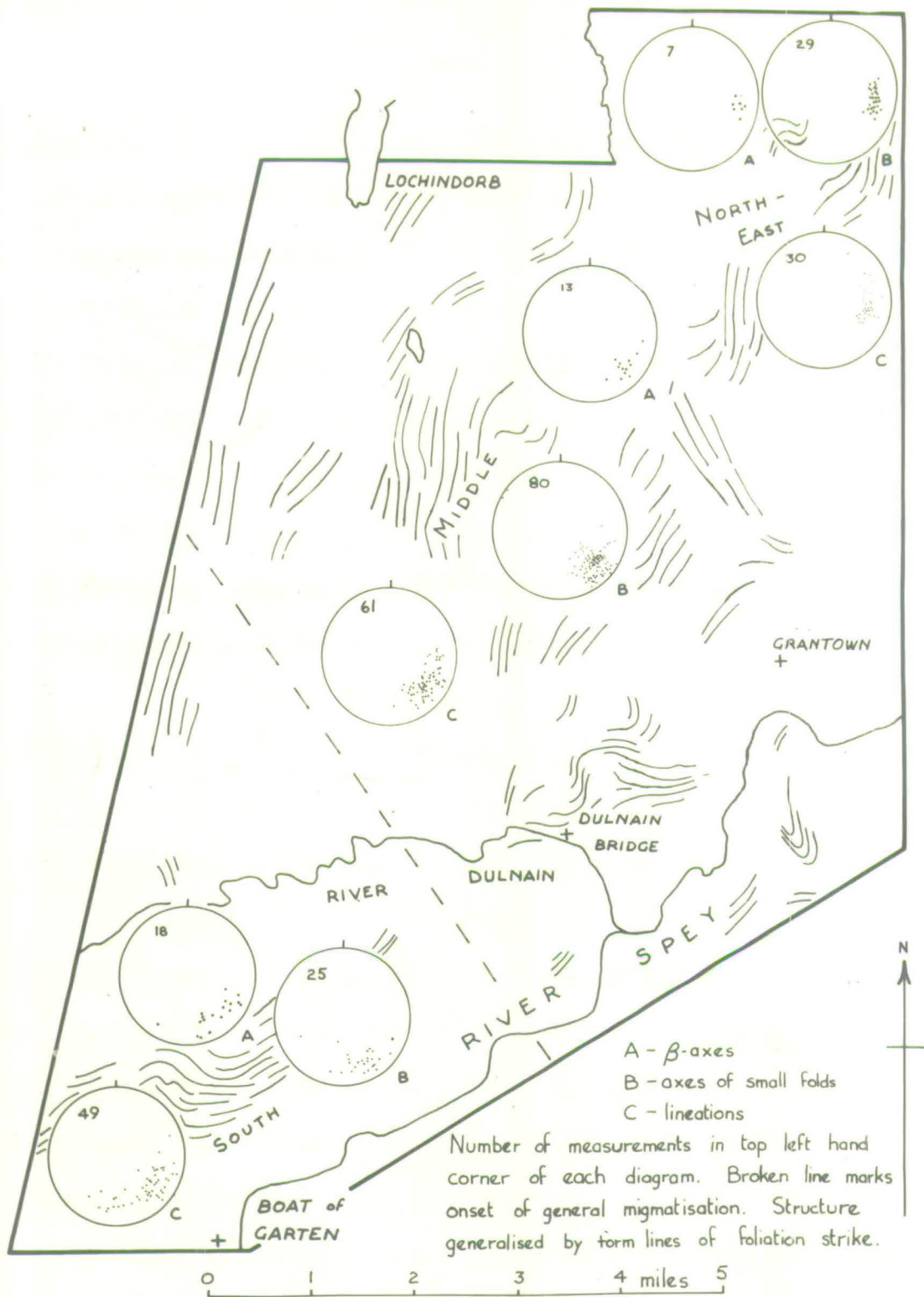


Fig. 25 The relationship between migmatisation and structure in Mid-Strathspey.

structural map of Mid-Strathspey, the migmatite boundary or 'front' is seen to transgress the structural levels obliquely (Fig.25). Therefore migmatisation has not been controlled entirely by tectonic depth, progressively higher structural members being migmatitic towards the SW. Moreover, the unique position of the migmatitic rocks of the Grantown Group is further emphasised. The Revack rocks are outwith the zone of general migmatisation and do not show an increase in structural inhomogeneity compared with their surroundings as do the rocks of that zone to the south (cf. Fig.11 with southern plots on Fig.25). As no metamorphic zone boundary crosses the area it is not possible to determine whether the isograds coincide with the migmatite front or with a particular structural level or with neither.

It has been stated, e.g. by Wegmann (1929, p.106), that increasing mobility of rocks results in an increasing spread of the sheaf of axial elements. No example of such a spread has been recorded in the literature known to the writer. The structural map of the Spey-Dulnain watershed provided by McIntyre (1951) leads one to believe that there the structural homogeneity is as great as in other parts of Mid-strathspey. It has been shown (p.165) that there is a regular increase in plasticity of fold style with the

TABLE 20

Data from structural diagrams on Fig. 25.

District	Number of diagrams	Apical angle, cone of -axes	Apical angle, cone of folds	Apical angle, cone of lineations	Average value of -maxima
North- eastern	7	14°	34°	52°	32%
Middle	13	56°	60°	77°	26%
Southern	18	95°	108°	120°	21%
Blocks in Grantown Granite	15	80°	85°	120°	24%

NOTE

PAROCHMENT

IMPERIAL

increase of migmatization to the south. To demonstrate this statistically the thesis area has been sub-divided into three districts designated north-eastern, middle and southern, for which the Grantown-Ferres railway and the River Pulnain are the dividing lines. By synoptic treatment of the data therein, the progressive decrease of structural homogeneity with increase in migmatization can be shown. The results of plotting the β -axes, small folds and lineations for each district are shown in Fig. 25, and the apical angles of the sheaves or cones of elements as measured on the Schmidt net are given in Table 20. The angular spread of the sheaf of all three elements increases markedly to the south. Furthermore, in each district the β -axes form the closest sheaf, followed in order by the small folds and the lineations. It is thus clear that β -diagrams - representing the attitude of the foliation - are more reliable indicators of homogeneity than diagrams of folds or lineations although the last two give a good indication of the regional fold axis. With the widening of the sheaf of elements to the south so the average value of the maxima in the β -diagrams decreases regularly indicating an increasing departure of the foliation surfaces from the cylindrical. The variation in homogeneity in Mid-Strathpey is not markedly affected by the presence of different

rock types as the middle district contains a wide variety of types both competent and incompetent. The apical angles of the cones are not absolute indicators of inhomogeneity but give a relative indication of the departure of the folds from the ideal. This treatment brings out the close connection in time between folding and migmatization.

For comparison the figures for the conical angle of the sheaves of elements from inclusions within the Grantown Granite are added (see also Fig.20). The inclusions in the granite have an intermediate degree of inhomogeneity between rocks of the middle and southern districts. The cause of the inhomogeneity in the two examples is, however, quite distinct. The inhomogeneity of the country rocks is due to syntectonic migmatization and mobility, while the flowage of the post-tectonic granite has caused the inhomogeneity in the orientation of the inclusions.

The evidence constitutes statistical proof that the dispersion of the π -poles from the great circle increases as the granitization of the rocks becomes more intense. It also gives an approximate measure of the inhomogeneity to be expected in migmatites at the kyanite zone of metamorphism.

(c) Grade of Regional Metamorphism

The mineral assemblages developed in the several rock types have been compared in order to determine the grade and facies of metamorphism attained by the rocks. Furthermore, the standard Barrovian zones in pelitic rocks can be related to the metamorphic facies, a system of classification which applies to all rock types. The rocks of Mid-Strathspey are found to lie within a single metamorphic zone - the kyanite zone - which is the equivalent of the lower amphibolite facies. The presence of the kyanite zone in Mid-Strathspey is not entirely in accord with Kennedy's thermal map of the Highlands (1948, p.230).

1. Quartzo-feldspathic rocks

The most common assemblage is quartz-calcic oligoclase-microcline-biotite-muscovite with occasional garnet; this grouping is also found in most of the granitic rocks of the area. Quartzo-feldspathic rocks of this type are known to be stable over a wide range of P-T conditions. It is therefore difficult to assign them to a particular narrow grade of metamorphism. Ramberg (1952, p.150) has suggested that the zoisite \rightleftharpoons An₃₀ equilibrium be used to define the base of the amphibolite facies. Small amounts of clinzoisite in apparent equilibrium with

plagioclase (An_{30}) occur in the quartzo-feldspathic rocks of the area. This evidence indicates that the P-T conditions under which the rocks formed were approximately at the boundary between the epidote-amphibolite and the amphibolite facies.

2. Pelitic and semipelitic rocks

The pelitic rocks of the area contain the assemblages biotite-muscovite-kyanite-quartz-calcic oligoclase and biotite-muscovite-garnet-quartz-calcic oligoclase and thus can be assigned to Barrow's kyanite zone of metamorphism. Moreover, the presence of An_{30} in the semipelitic rocks also indicates the zone of kyanite or sillimanite (Vogt, 1927).

Correlation of metamorphic facies with Barrovian zones of progressive metamorphism has been attempted by Turner (1948, p.76). If, as is believed for example by Harker (1950, p.224), the staurolite and kyanite zones are more or less coincident, with staurolite equivalent to the lower kyanite zone in rocks of appropriate composition, then the kyanite zone occupies most of the lower part of the amphibolite facies.

3. Semi-calcareous rocks

The standard succession of metamorphic zones in

these rocks has been described by Kennedy (1949) from Western Inverness-shire. The usual development of minerals in the Mid-Strathspey calc-silicate 'granulites' is quartz-plagioclase (An_{30} to An_{60})-garnet-hornblende-epidote with occasional calcite.

As discussed above (p.49) the presence of hornblende, intermediate plagioclase and epidote, and the absence of pyroxene indicate that the rocks are in the kyanite zone and belong to the lower amphibolite facies (1949, pp.50,53).

4. Impure marbles and associated calc-silicate rocks

The marbles contain the assemblage calcite-tremolite-diopside-phlogopite-microcline with occasional quartz. Turner (1948, p.80) and Ramberg (1952, p.150) regard the lower limit of the amphibolite facies as the point at which diopside takes the place of tremolite in presence of calcite. The rocks therefore belong to the lowest part of the amphibolite facies; all the tremolite has not yet been made over to diopside although calcite and quartz are both available in the rocks. Chemically the rocks are rich in lime and magnesia, have intermediate amounts of iron oxides and are poor in silica and alumina; potash is abundant relative to soda.

The non-calcitic calc-silicate rocks have the assemblage tremolite-phlogopite-epidote-plagioclase-microcline-diopside-quartz and are closely associated in the field with the impure marbles. The presence of sparse but stable diopside, and plagioclase (An_{30}) and epidote together, again indicate the lower amphibolite facies.

5. Basic igneous rocks

The occurrence of rocks containing hornblende-plagioclase-biotite-garnet-quartz, as the end-product of the changes in a basic igneous rock, indicates once again the lower amphibolite facies (Turner, 1948, pp.76,82). The presence, at Craig Revack, of a schist with the assemblage hornblende-plagioclase-epidote-biotite-quartz is also consistent with attribution to the lower amphibolite facies (Turner, 1948, p.89). The plagioclase in both the above examples is andesine or labradorite and is in equilibrium with the epidote.

(d) Acid and Basic Rocks - Contrasts and Comparisons

Within the compass of this thesis there have been described several distinct types of acid and basic rocks which can best be compared and contrasted under the headings of time of emplacement, mode of origin and emplacement, and

structural control over emplacement.

Time of emplacement In general it can be said that recrystallisation continued after the main movements had ceased. The completely metamorphosed basic rocks of the valleys of the Spey and Dulnain were emplaced prior to or during the metamorphism. It has been shown above that the migmatitic rocks in the south of the area are syntectonic in age, as are the granitic rocks of Craig Revaek whose recrystallisation, however, continued until late in the movements. The basic igneous rocks near Lochindorb were intruded late in the metamorphism and suffered chemical rather than physical break-down at a relatively high temperature. Both the large granitic mass of the Grantown Granite and the acid veins of the Spey-Dalnain watershed are post-tectonic but their relation to each other in time is not clear.

Mode of origin and emplacement The formation of the migmatitic rocks of the south involved the segregation and rearrangement of quartzo-feldspathic material from the pre-existing rocks into small, irregularly distributed bodies. Small quantities of alkaline fluxes increased the chemical reactivity and physical mobility within the rocks. The granitic rocks of Craig Revaek originated in essentially the same way, but here the presence of copious supplies of

fluxes enhanced the mobilisation of material, the transport of alkalies and the segregation and fixation of moderately sized granitic bodies, all without disturbing the pre-existing structural trends in the parent rocks. Small scale replacement accompanied these segregations. The physical conditions in the above examples were those of high grade metamorphism, namely, moderate temperature and high pressure.

The Lochindorb basic rocks retain undoubted igneous textures and were intruded as lenticular sills, taking up very few fragments of the country rocks. Movement in the country rocks after intrusion was slight but the temperature remained sufficiently high for considerable reconstitution of the basic rocks to take place. The absence of hornfels suggests that the temperature difference between intrusion and wall-rocks was not high.

The post-tectonic granitic rocks were emplaced principally by the dilation of joints in the case of the thin veins and of the foliation in the case of the larger masses. The large, mineralogically homogeneous Grantown mass took up and displaced numerous inclusions of country rock and was therefore in a plastic state at the time of emplacement. The vertical displacement of the inclusions was not, however, great. As with the basic rocks the lack

of hornfels indicates that the temperature difference between granitic and country rocks was not great, but the temperatures were lower than in the basic rocks. It is postulated that the granite was emplaced under considerable pressure. The origin of the granite, however, remains obscure. Some of the pegmatite veins in the south have possibly been formed by a process involving recrystallisation of pre-existing granite veins.

structural control over emplacement

At every stage in the plutonic history of the region the structure has exerted strong control over the localisation of both granitic and basic rocks.

The syntectonic rocks tended to form along surfaces of discontinuity which were then being made available. Segregation was most common where deformation was most intense. At Craig Revaek the granitic rocks occupy the crest of an antiform and were presumably fixed at a site of relatively low stress. They have locally pierced the cover rocks in a diapiric fashion late in the movements. The late-metamorphic basic rocks formed as concordant lenses rather than sills. In contrast the post-tectonic rocks were formed in positions controlled by pre-existent surfaces of structural anisotropy such as joints and foliation surfaces.

SUMMARY OF CONCLUSIONS

(a) The rocks of the Moine Series attained their present condition by the regional metamorphism, without much metasomatism, of a series of siliceous, pelitic and subordinate semi-calcareous sediments. In particular:

1. The foliation and banding are parallel to the original bedding.

2. Tourmaliniferous bands in pelitic gneisses represent a concentration by fixation of boric oxide originally dispersed through the surrounding rocks.

3. Layers and nodular bodies of calc-silicate 'granulites' were formed from calcareous layers and concretions in the original pelitic and siliceous sediments.

(b) The Grantown Group

1. The rocks of this group have been formed from a variety of calcareous and aluminous sediments of which four types can be recognised.

2. The Group as a whole is an integral part of the Moine Series.

3. The coarse gneisses on the west side of the Group are considered to have been formed from normal pelitic and semipelitic rocks by the fluxing action of carbon dioxide released during the metamorphism of the

impure limestones structurally underlying them.

4. The uprising carbon dioxide assisted in the mobilisation and differential fixation of alkalies.

(c) The granitic rocks of Craig Revack within the Grantown Group.

1. These are syntectonic in relative age.

2. No possible feeder for the granitic rocks has anywhere been found.

3. The granitic rocks pierce the overlying gneisses at the crest of the Revack antiform.

4. The origin of the granitic rocks lies in an extension and intensification of the process outlined in (b) 3 and 4 above. The carbon dioxide transported alkalies and, in favourable localities, the distribution of which was controlled by the structures then forming, facilitated the formation of granitic rather than gneissic rocks.

(d) During the regional metamorphism and deformation the Moine Series and the Grantown Group suffered a single monoclinic deformation about a E-axis plunging east or SE. The sense of movement shown by all structures on all scales is of the upper layers moving to the SW relative to the lower layers.

(e) The post-tectonic Grantown Granite was emplaced

in a plastic state at a temperature close to that of the country rocks. Space for the granite was provided by the forcible dilation of the country rocks principally along the foliation. Numerous blocks of country rock were displaced from their original positions by the granite, the amount of displacement increasing towards the west side of the mass. Amongst these blocks the granite forms a complex of thick dykes and sills. It is tentatively suggested that the granite may have been intruded as a mass of crystals which were in part derived from the pre-existing rocks by a rheomorphic process.

(f) The basic rocks in the Moine Series near Lochindorb are slightly metamorphosed gabbros, which were intruded as lensoid sills at a late stage in the metamorphism when the temperature was still high. High temperature rather than pressure appears to have been the governing factor in determining the metamorphic changes suffered by the gabbros.

(g) General aspects.

1. The post-tectonic acid veins in the south of the area were emplaced along joint planes controlled by the regional structural axes.

2. In the Moine Series both plasticity of fold

style and migmatization increase towards the south.

Migmatization was most intense where the deformation was most pronounced. The sheaf of β -axes, folds and lineations becomes progressively wider towards the south, indicating a corresponding increase in the mobility of the rocks. The planes along which migmatized material was preferentially formed were planes of weakness controlled by the structural axes.

3. The mineral assemblages from the five rock types which predominate in the area indicate that the whole of Mid-Strathspey lies within the kyanite zone of metamorphism which is equivalent to the lower amphibolite facies.



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IMPERIAL
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Profiles of migmatitic pelitic gneisses
along the east side of the Grantown
Granite (p.24). Top, top of Carn Luig
looking NW; bottom, east side of Carn
Luig looking SE.

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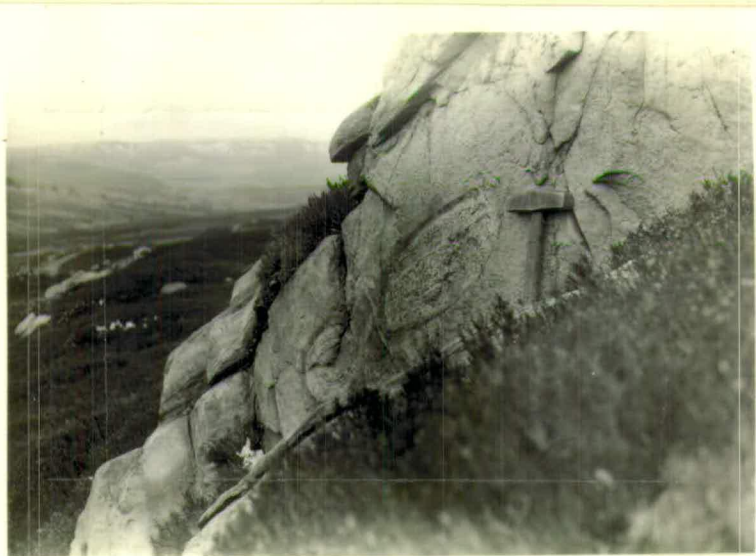


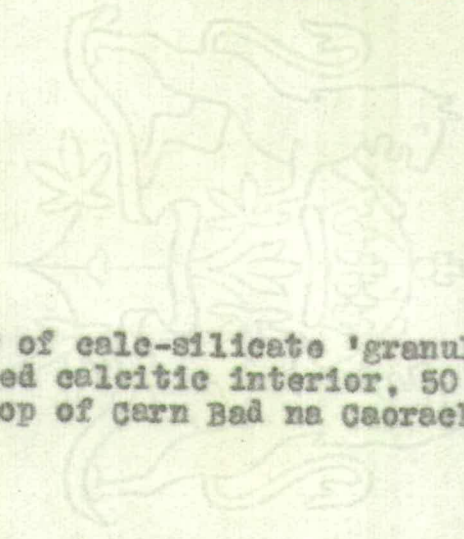
Nodules of calc-silicate 'granulite' in bands of quartzo-feldspathic gneiss, Carn a' Ghille Chearr (p.25). The nodules are concentrically zoned, the outermost zone being relatively rich in biotite. Some bands are characterised by several nodules.

NOTE

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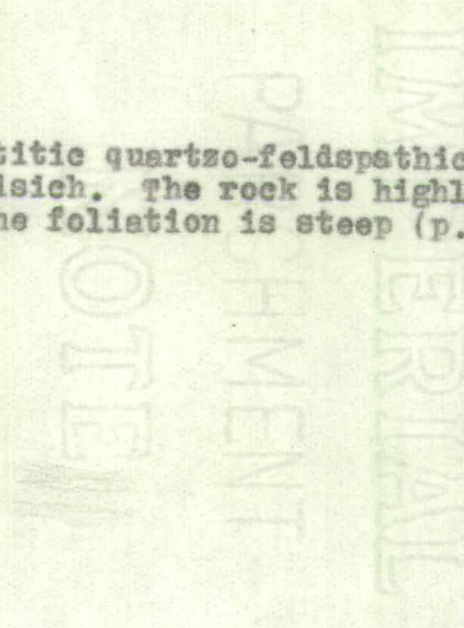
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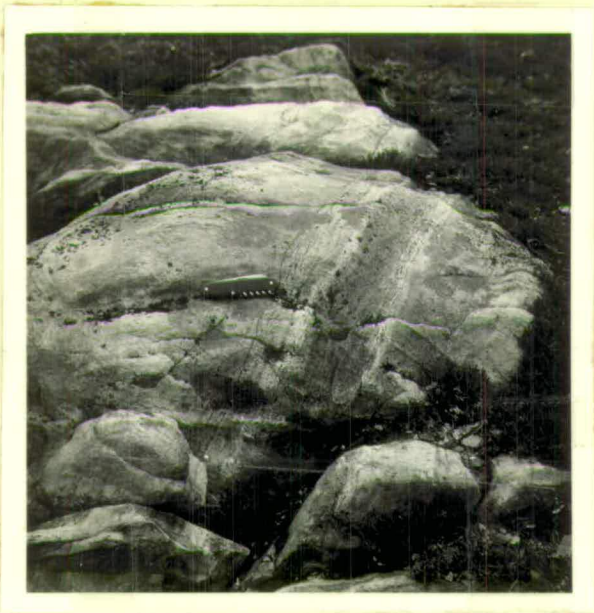





Layer of calc-silicate 'granulite' with a leached calcitic interior, 50 yards NW of the top of Carn Bad na Gaorach (p.26).

Migmatitic quartzo-feldspathic gneiss, Stac an Toisich. The rock is highly contorted and the foliation is steep (p.51).

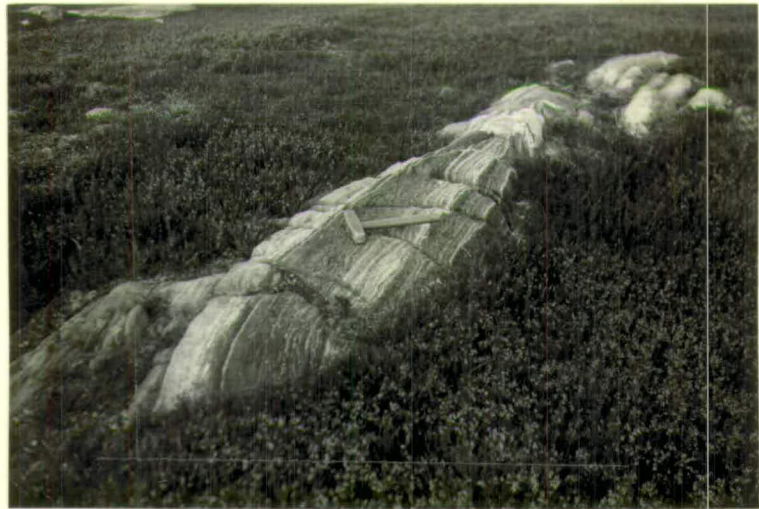


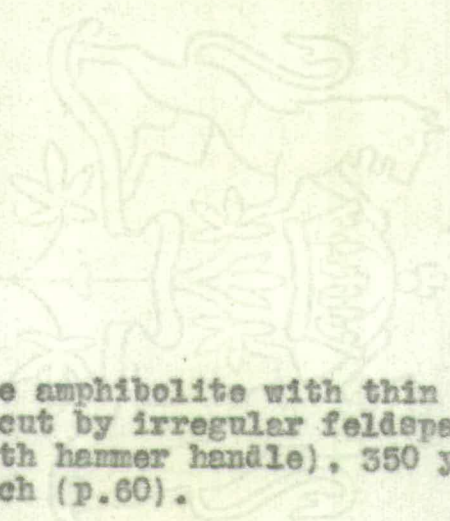




Lens of garnetiferous amphibolite in the zone between massive amphibolite (off photograph to right) and semipelitic gneisses (left), 400 yards south of Carnloch (p.58).

Thin steep sheet of hornblende-'granulite' cutting massive amphibolite, 400 yards south of Carnloch (p.59). The sheet can be seen to contain feldspar porphyroblasts.

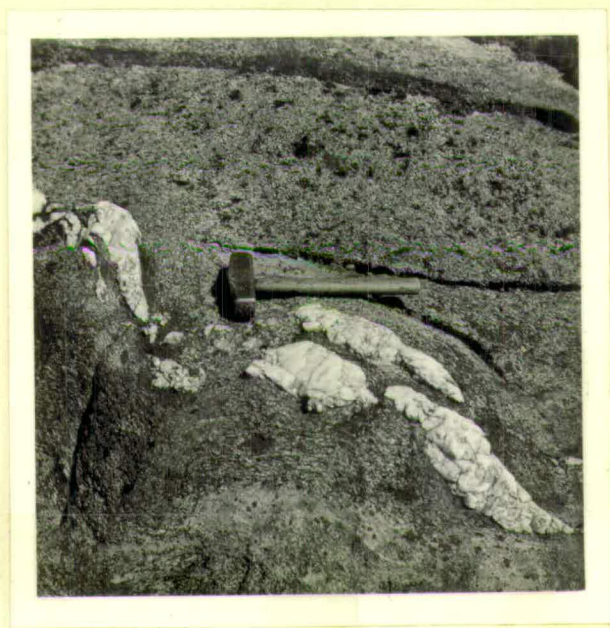





Massive amphibolite with thin planar acid
veins cut by irregular feldspathic patches
(beneath hammer handle), 350 yards south of
Carnloch (p.60).

quartz lenses in coarse pelitic gneiss, west
side of Craig Reveck (p.102).

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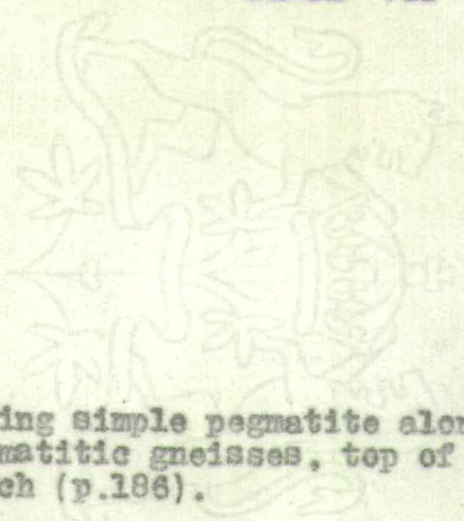




Coarse pelitic gneiss, west side of Craig Revack. S_1 (top left to bottom right) is crossed by steep slip surfaces S_2 (top right to bottom left). (p.166).²Thick pegmatite in background.

Mullion structure in medium grained pelitic gneiss plunging SE at 30° , Broomhill Quarry. ac joints are well developed.





Branching simple pegmatite along the ac plane
of migmatitic gneisses, top of Creag an
Phithich (p.186).

Migmatite containing concordant quartz-feldspar
pegmatite lenses cut by (a) thick post-tectonic
compound pegmatite along h01 plane and (b) thin
post-tectonic quartz vein along ac plane, top
of creag an Phithich (pp.187-8).

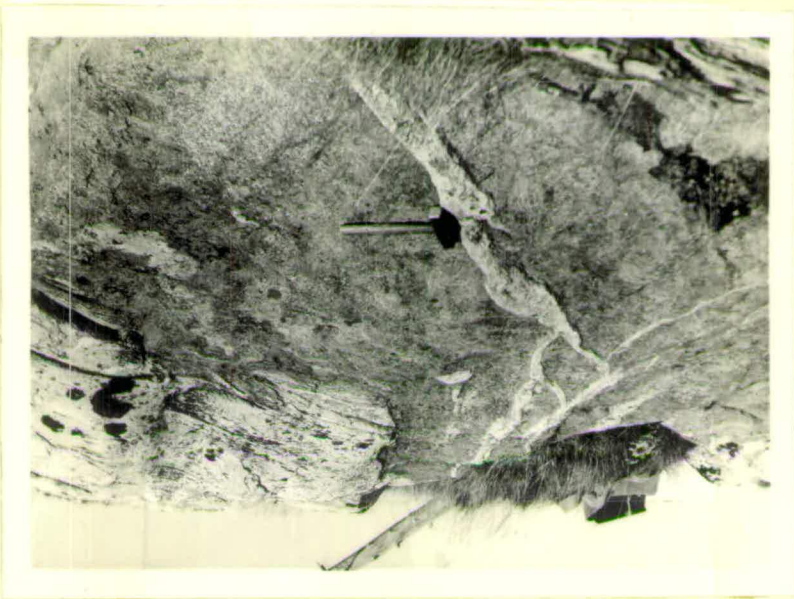
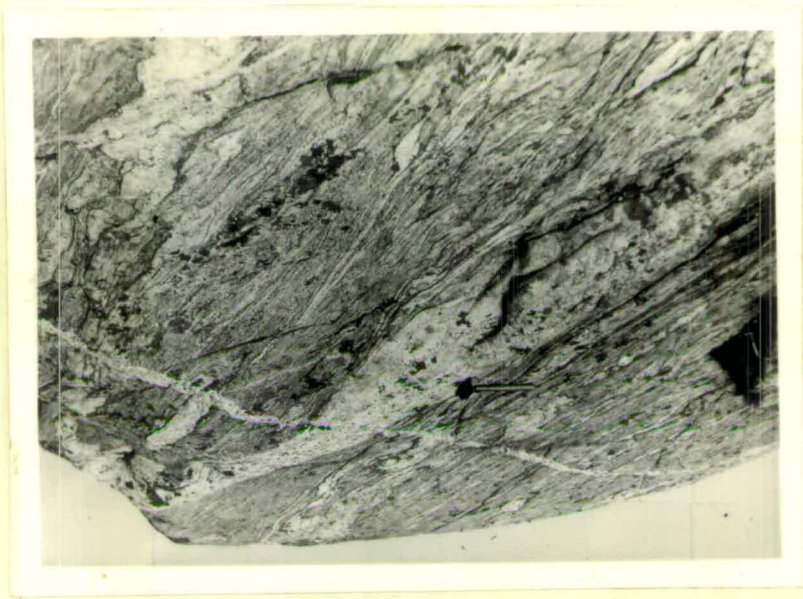


Plate VII




Block of migmatitic gneiss in the medium-grained Grantown Granite. Both gneiss and granite are cut by pegmatite veins (p.154). West side of Creag Liath.

contact of Grantown Granite with banded gneiss (specimen 394) showing lack of contact alteration (p.24). From west side of Creag Liath.

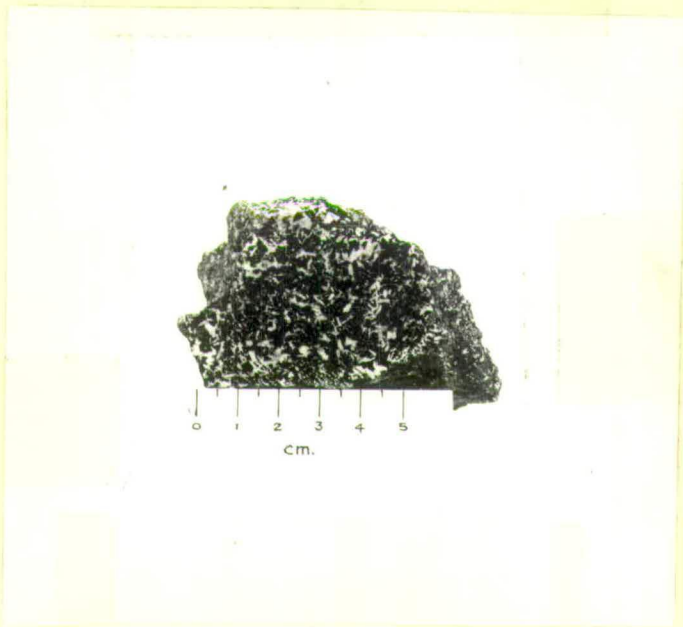
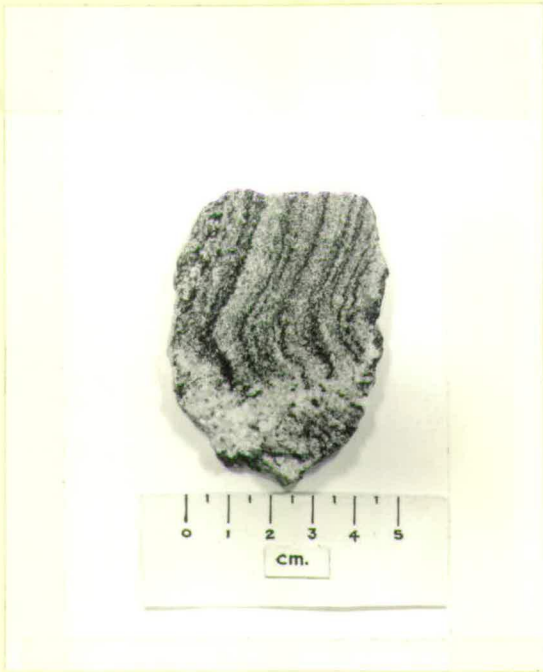
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Irregular sheet of granite along S_2 surface in migmatitic gneiss (137), Staac an Tóisich. Thin biotitic walls project from S_1 into the granite (p.53).

ophitic texture in massive amphibolite (265) from interior of large metamorphosed lens of gabbro, Carn nan Gabhar (p.58).





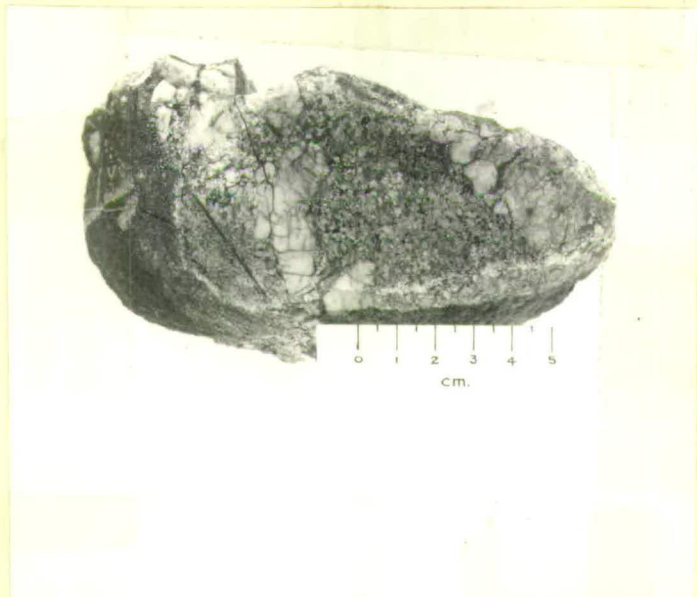
Migmatitic gneiss containing feldspathic pods
with biotite-rich margins, Stac an Toisich
(p.52).

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Compound pegmatite, Stac an Toisich (180).
Large feldspars appear to be porphyroblasts
in the granitic matrix (p.186). Line on
specimen marks contact of vein with country
rock.



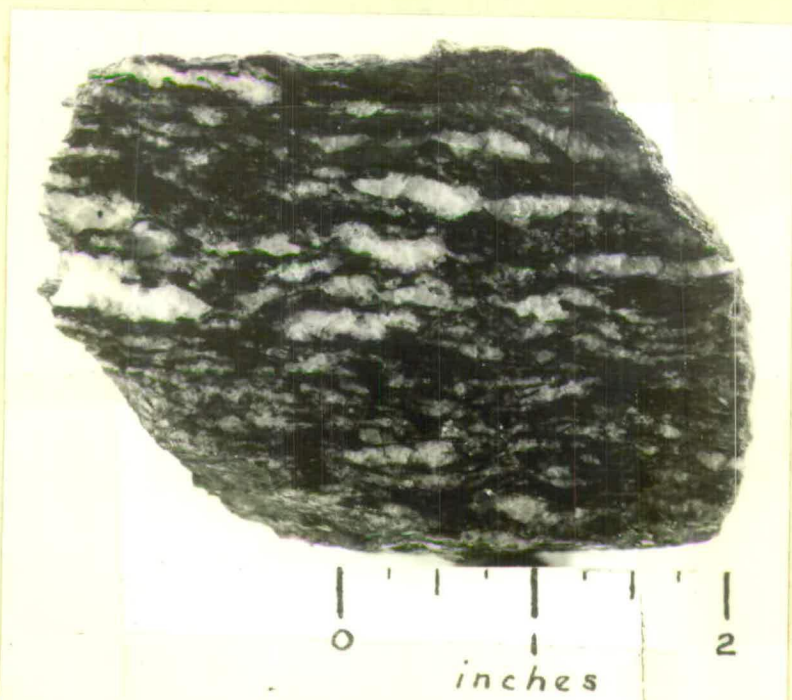
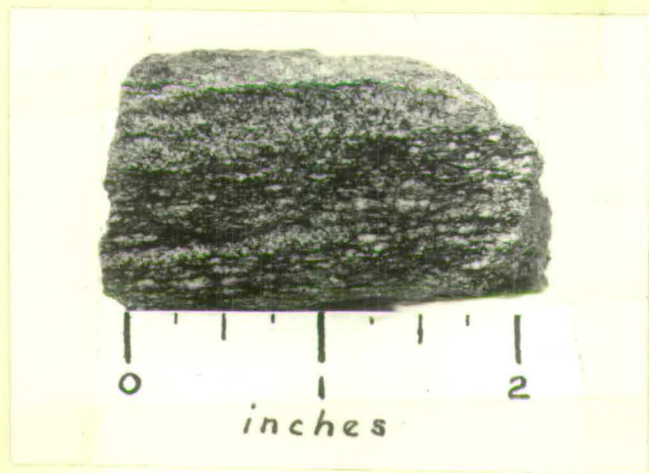
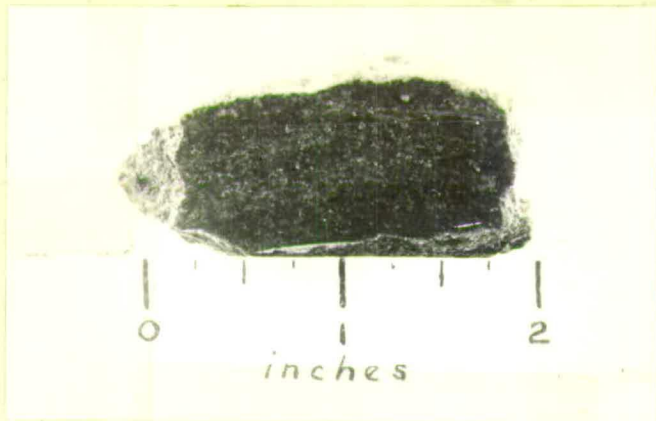


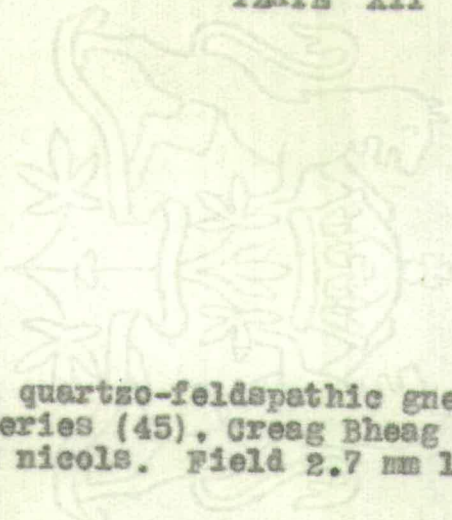
series of specimens to illustrate the upward decrease in grain size and loss of quartzose pods in pelitic rocks of the Dulnainbridge-Reveck belt (pp. 64-5). These rocks overlie thick calc-silicate rocks. Specimens 179, 457 and 458 (reading upwards) are from Wester Laggan, the Finlarig Burn and the River Dulnain at Muckrach Lodge respectively.

NOTE

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Typical quartzo-feldspathic gneiss of the Moine Series (45), Creag Bheag (p.28).
Crossed nicols. Field 2.7 mm long.

Large irregularly shaped quartz crystal in quartzo-feldspathic gneiss (46), Creag Bheag (p.28). Crossed nicols. Field 2.7 mm long.

NOTE
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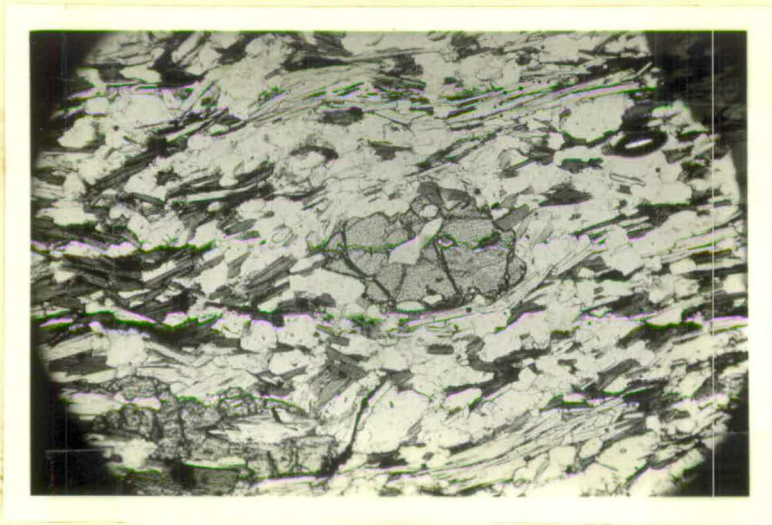


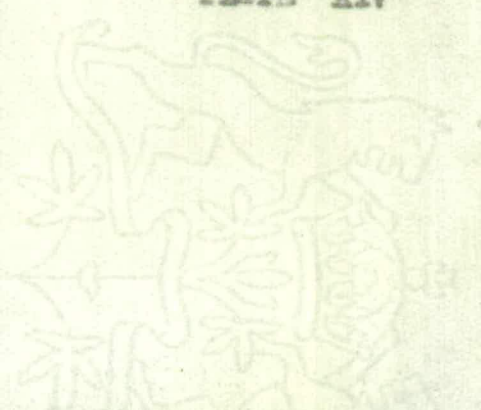


Irregular patches of microcline in optical continuity with one another in a plagioclase crystal (12), quartzo-feldspathic gneiss, Shillochan (p.29). Crossed nicols. Field 2.7 mm long.

Garnetiferous muscovite-biotite-gneiss (224), Ochnoir (p.32). Ordinary light. Field 2.7 mm long.

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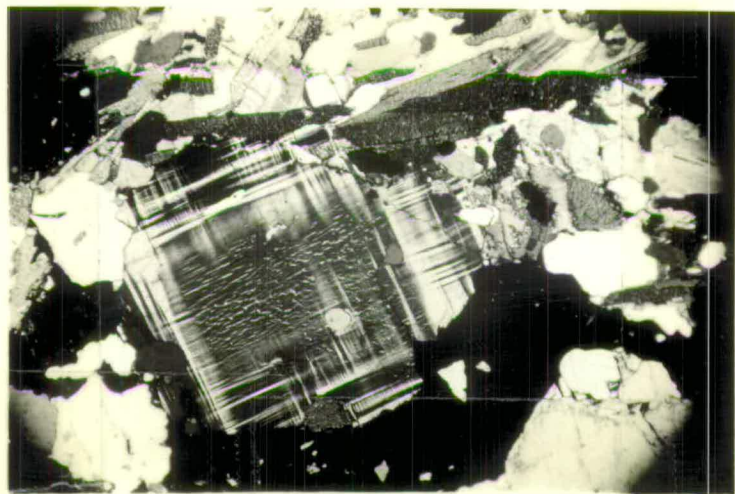
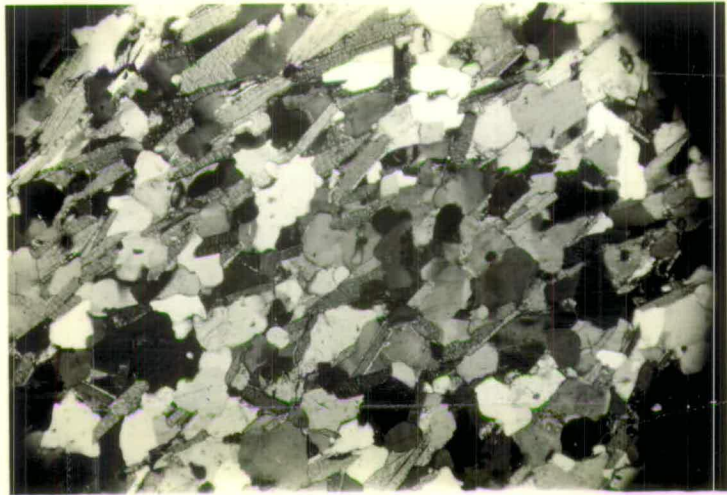





Typical semipelitic gneiss (293) containing quartz, plagioclase and biotite, Carn a' Ghille chearr (p.32). Crossed nicols. Field 2.7 mm long.

Crystal of microcline-microperthite in pelitic gneiss (102), An Creagan (p.35). Thin albitic veins occur in the untwinned interior of the crystal. Crossed nicols. Field 2.7 mm long.

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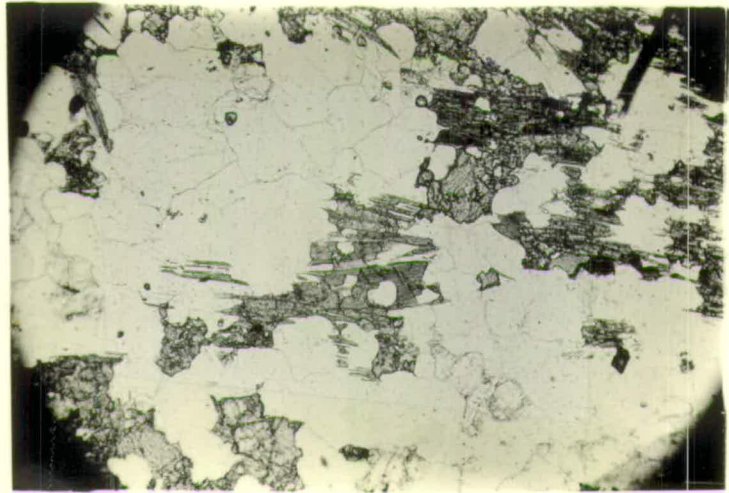




Typical calc-silicate 'granulite' (246), Garn a' Ghille Ghearr (p.38). Clinzoisite, spongy garnet and poikiloblastic hornblende (all high relief) are set in a matrix of quartz and plagioclase. Ordinary light. Field 2.7 mm long.

Relict ophitic texture in amphibolite (266), garn nan gabhar (p.62). Augite with small iron ore inclusions is rimmed by hornblende. Ordinary light. Field 6.5 mm long.

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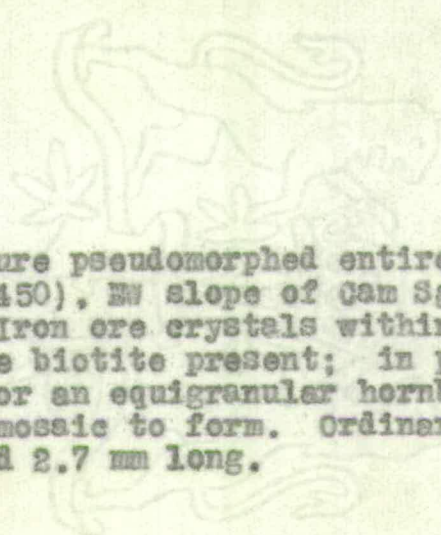
Ophitic texture in amphibolite (266), Garn
nan gabhar (pp.62-4). Field 2.7 mm long.
Top, ordinary light, to show (100) cleavage
in augite; bottom, crossed nicols, to show
granular texture of some of the plagioclase
and of the hornblende away from the augite.

NOTE

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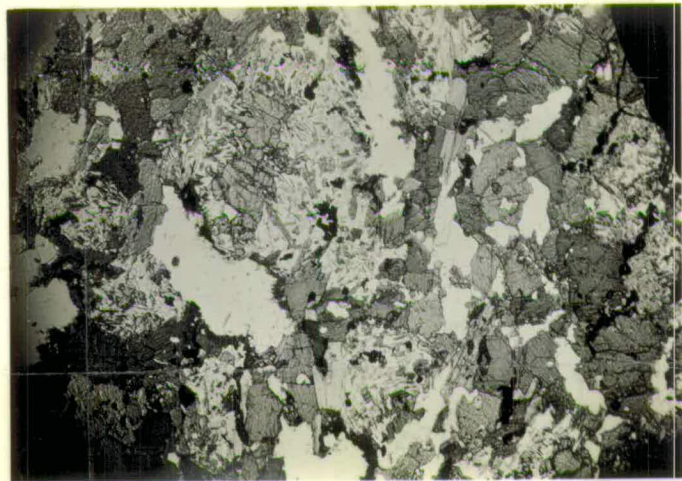
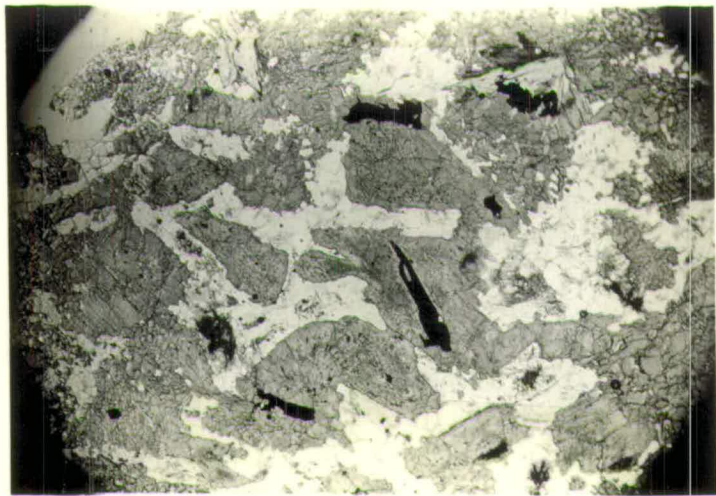


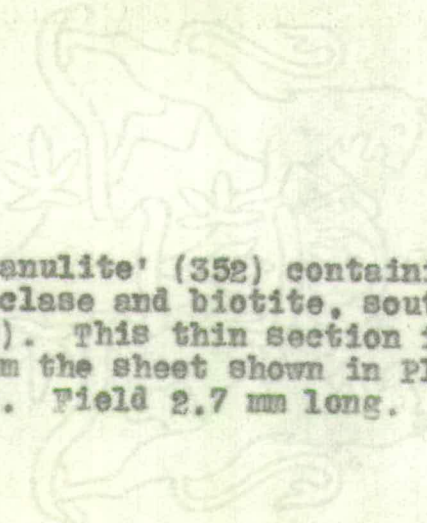


Ophitic texture pseudomorphed entirely by hornblende (450), NW slope of Cam Sgriob (pp.64-6). Iron ore crystals within hornblende; some biotite present; in places a tendency for an equigranular hornblende-plagioclase mosaic to form. Ordinary light. Field 2.7 mm long.

Garnetiferous amphibolite (257), south of Carnloch (pp.66-7). Ragged garnets are surrounded by a zone in which plagioclase, hornblende and biotite are intergrown. Ordinary light. Field 2.7 mm long.

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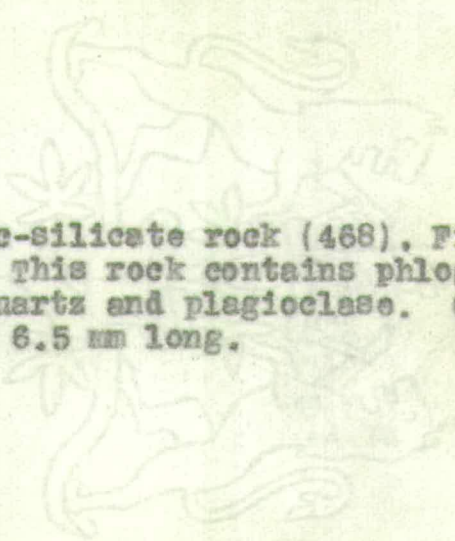
Hornblende-'granulite' (352) containing hornblende, plagioclase and biotite, south of Carnloch (p.68). This thin section is from a specimen from the sheet shown in Plate IV. Ordinary light. Field 2.7 mm long.

Impure marble (93) containing a layer of diopside and tremolite (right) and a shear band of granular calcite (left), Laggan Hill (pp.87-8). Crossed nicols. Field 6.5 mm long.

PERMANENT
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Plate XVIII





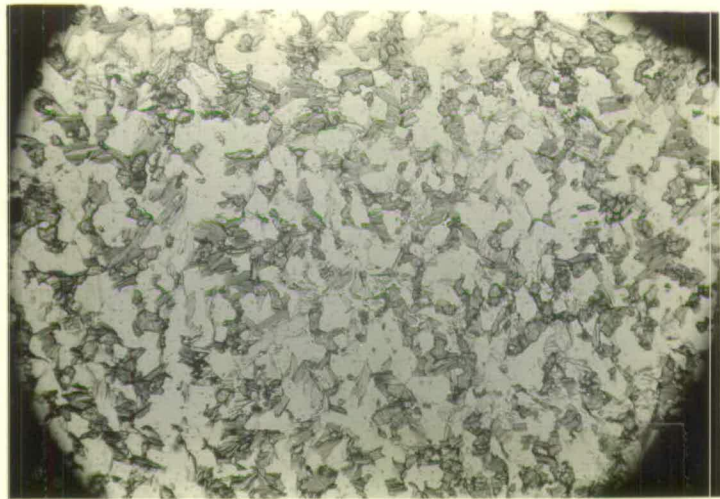
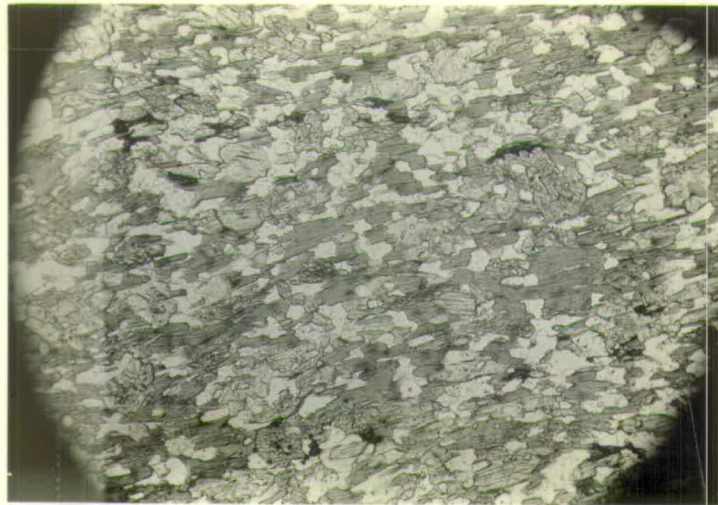
Micaceous calc-silicate rock (468), Finlarig Wood (p.89). This rock contains phlogopite, actinolite, quartz and plagioclase. Ordinary light. Field 6.5 mm long.

Granulitic calc-silicate rock (177), Laggan Hill (pp.92-4). This rock contains quartz, epidote and biotite. Ordinary light. Field 6.5 mm long.

NOTE

APPENDIX

APPENDIX



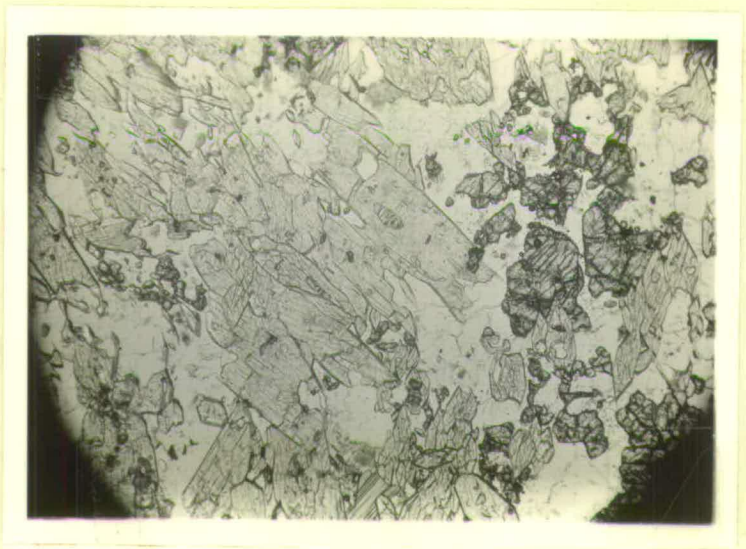


Amphibolitic calc-silicate rocks, consisting
of actinolite, diopside, quartz and microcline.
Top, 110 from Craig Reveck; bottom, 175 from
Goldhome Quarry. Ordinary light. Fields
2.7 mm long.

NOTE

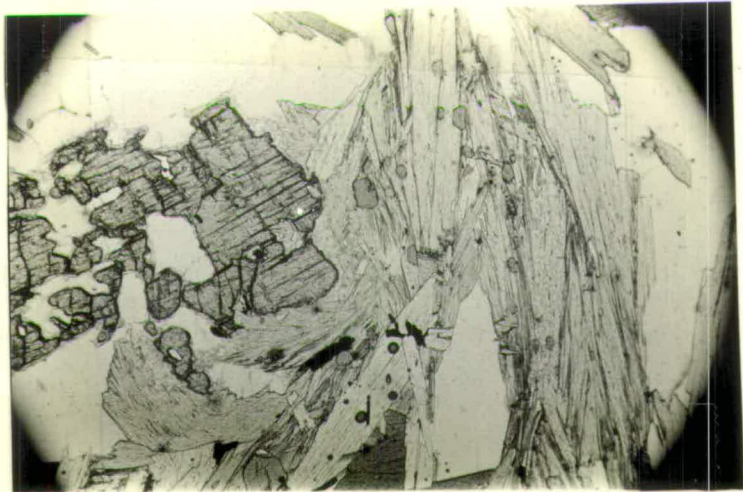
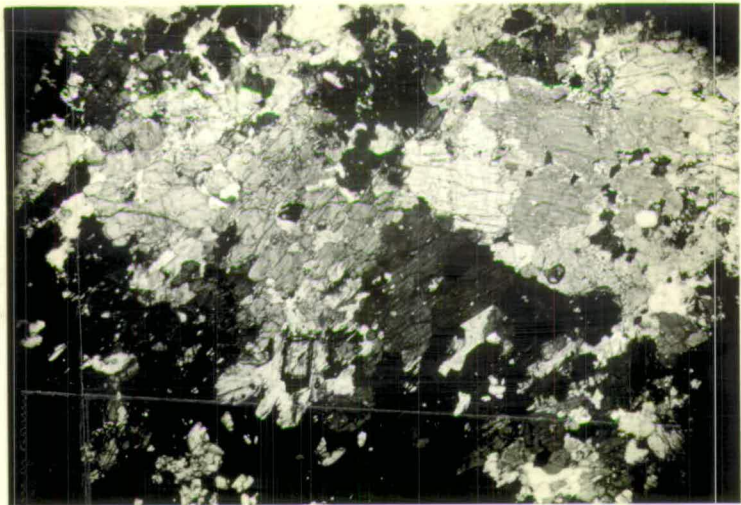
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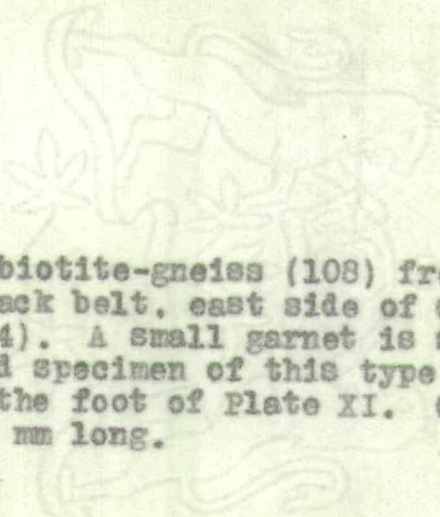
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Diopsidic calc-silicate rock (355), Craig
Revaek (p.95). The irregular poikiloblastic
habit can be seen. Crossed nicols. Field
6.5 mm long.

Kyanite-gneiss (538), Gaich Wood (pp.99-101).
Spongy kyanite is rimmed by muscovite;
biotite encloses small prisms of accessory
tourmaline; quartz forms the remainder of
the rock. ordinary light. Field 2.7 mm long.

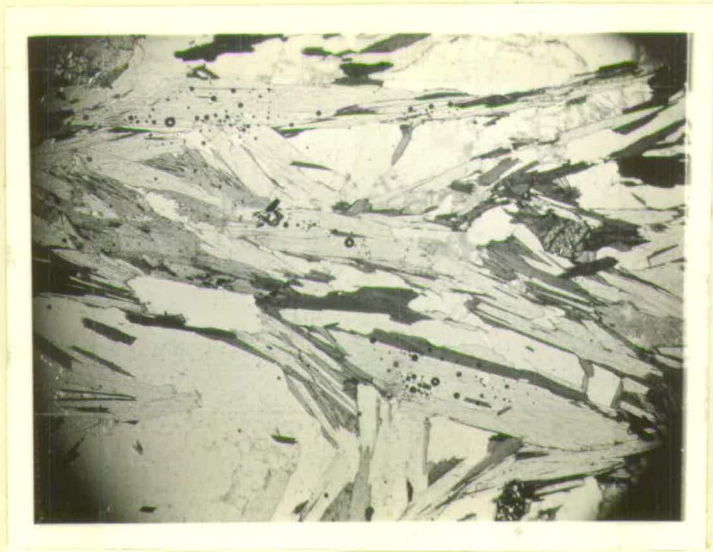


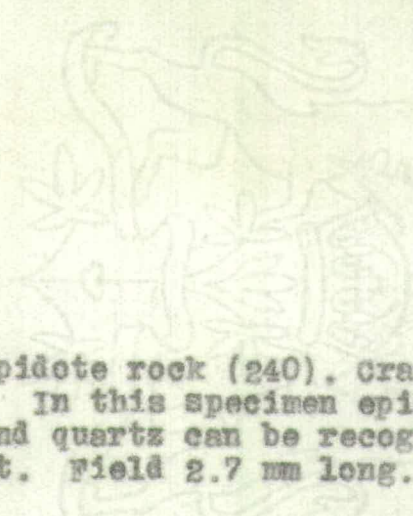


Coarse muscovite-biotite-gneiss (108) from the
Dulnainbridge-Revack belt, east side of Craig
Revack (pp.102-104). A small garnet is seen on
the right. A hand specimen of this type of
rock is shown at the foot of Plate XI. Ordinary
light. Field 6.5 mm long.

Plagioclase-gneiss (358), Craig Revack (pp.106-
107). The rock consists mainly of oligoclase
with lesser amounts of quartz and biotite.
Crossed nicols. Field 2.7 mm long.

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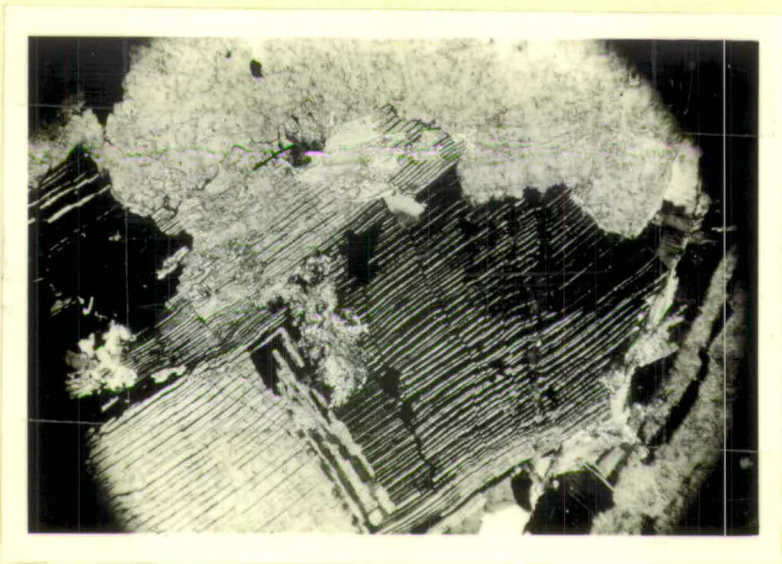




Plagioclase-epidote rock (240). Craig Revaek
(pp.107-109). In this specimen epidote, dusty
plagioclase and quartz can be recognised.
Ordinary light. Field 2.7 mm long.

Broken plagioclase crystal in the Revaek granite
(368) (p.125). The shears do not extend into
the surrounding minerals. Crossed nicols.
Field 2.7 mm long.

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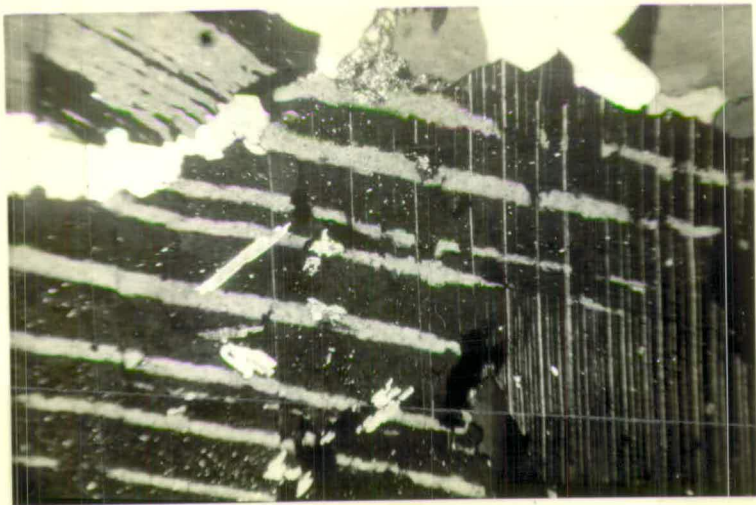
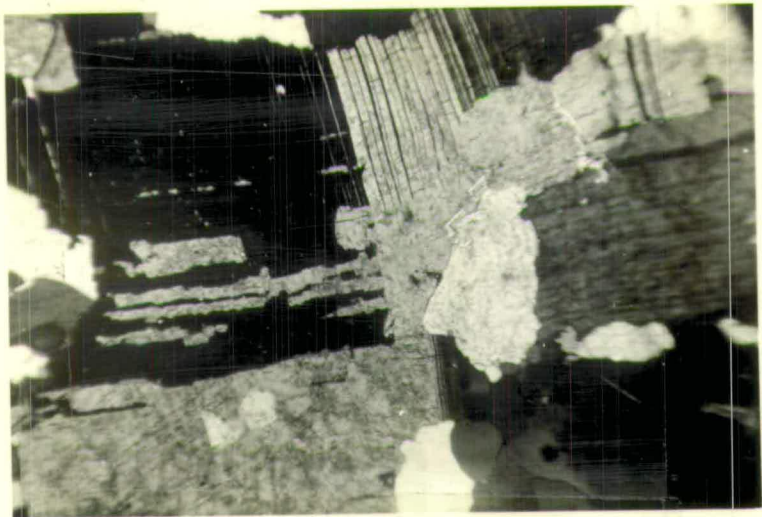


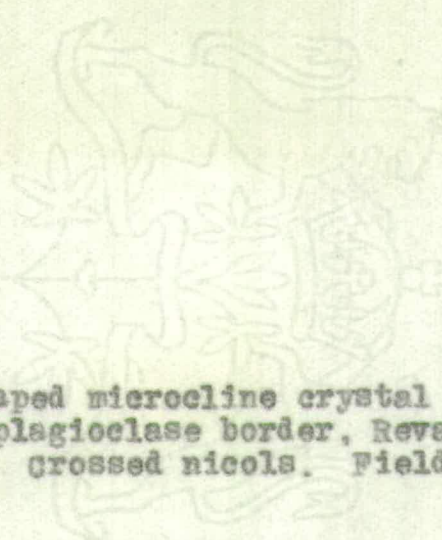
Examples of two sets of twin lamellae developed in plagioclase crystals of the Revack granite (p.125). Top, 368; bottom, 356. The ragged early set of lamellae are displaced by small shears parallel to the later straight lamellae. Crossed nicols. Fields 2.7 mm long.

NOTE

PAROCHMENT

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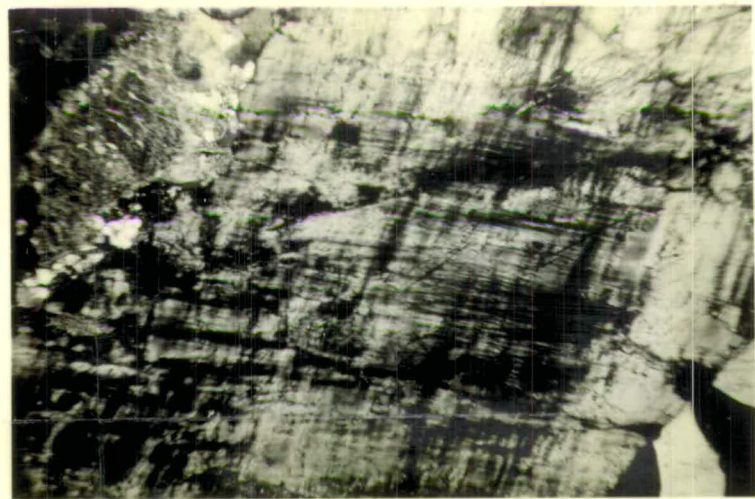




Irregularly shaped microcline crystal with a discontinuous plagioclase border, Revack granite (376) (p.126). Crossed nicols. Field 2.7 mm long.

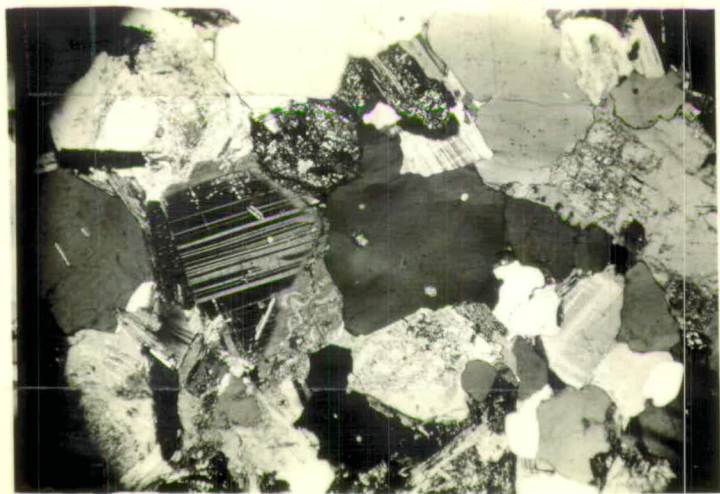
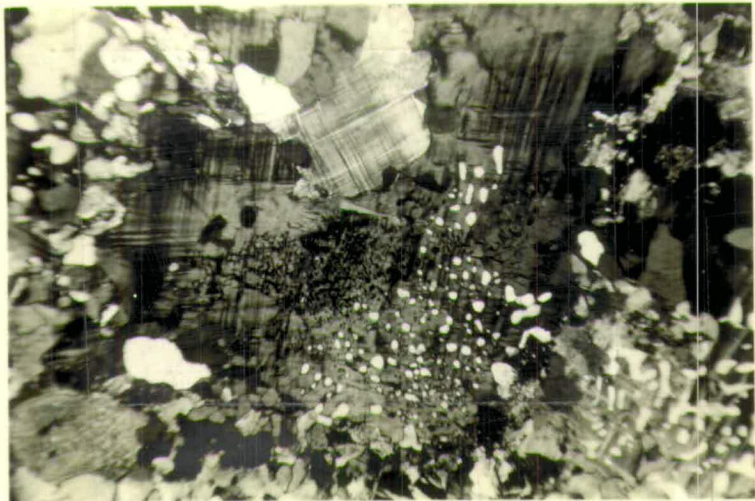
Deformed crystal of microcline in the Revack granite (109) (p.127). Crossed nicols. Field 2.7 mm long.

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Myrmekitic quartz within crystals of microcline
in the Revaek granite, (387) (p.127). Crossed
nicols. Field 2.7 mm long.

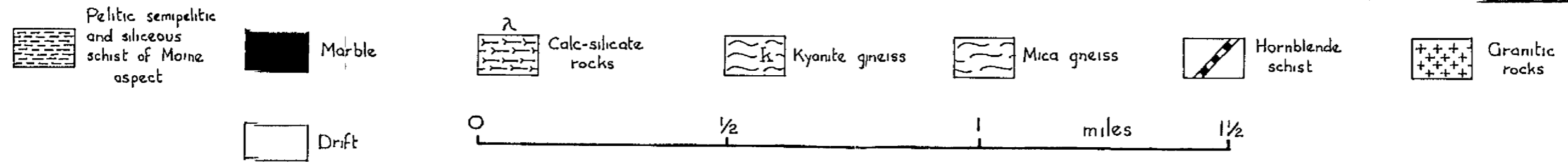
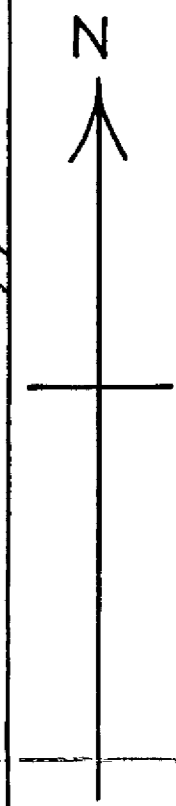
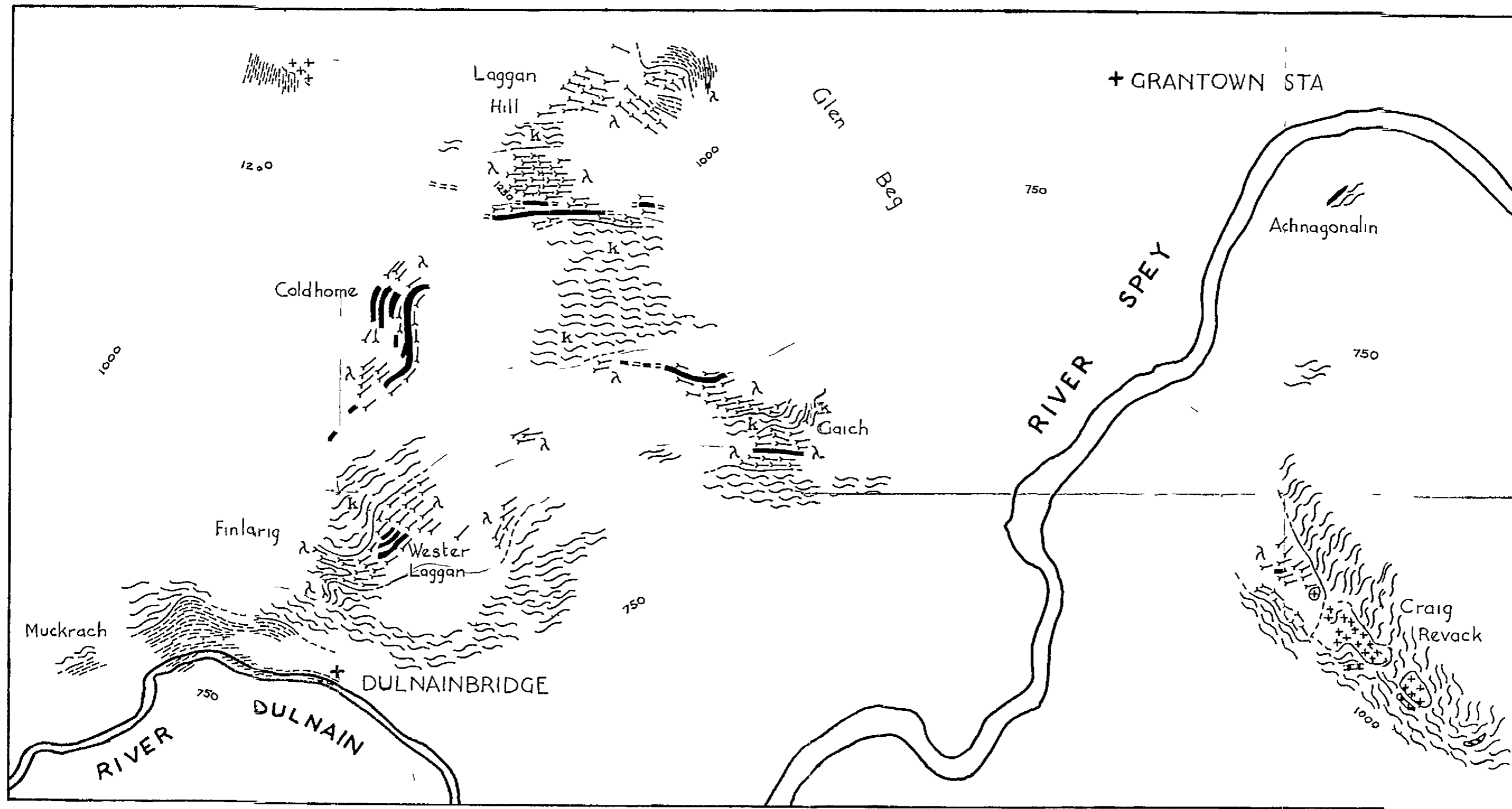
Typical field from thin section of the Grantown
Granite (111), Gorton Hill (pp.155-161).
Subhedral biotite and zoned oligoclase with
anhedral quartz and microcline can be recognised.
crossed nicols. Field 2.7 mm long.

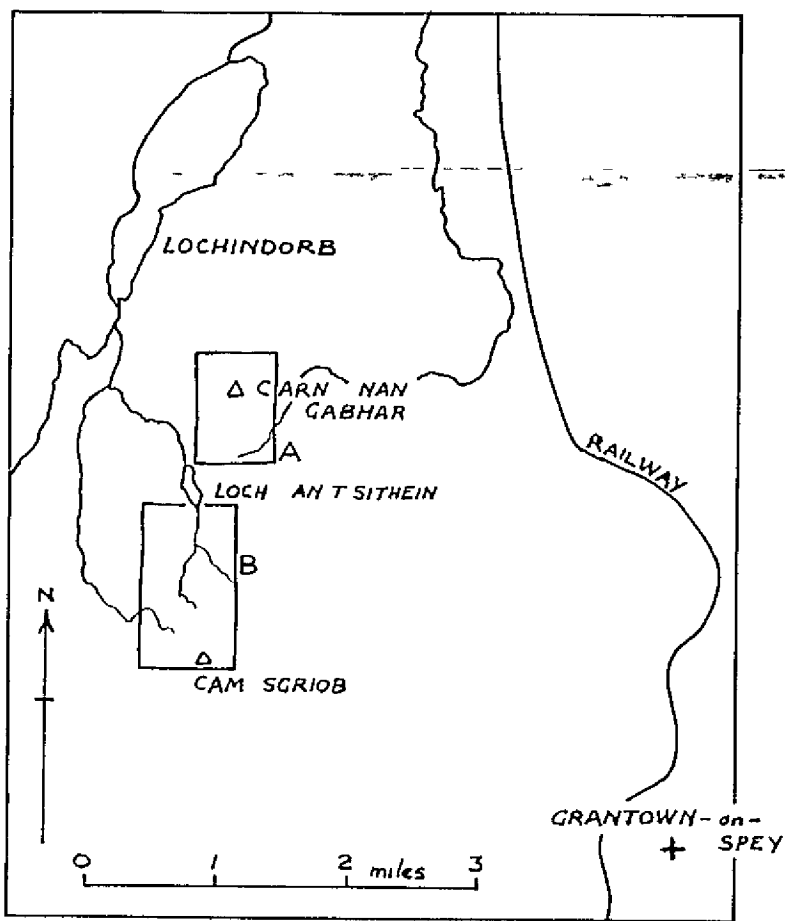


GEOLOGICAL MAP OF THE GRANTOWN GROUP

MID-STRATHSPEY

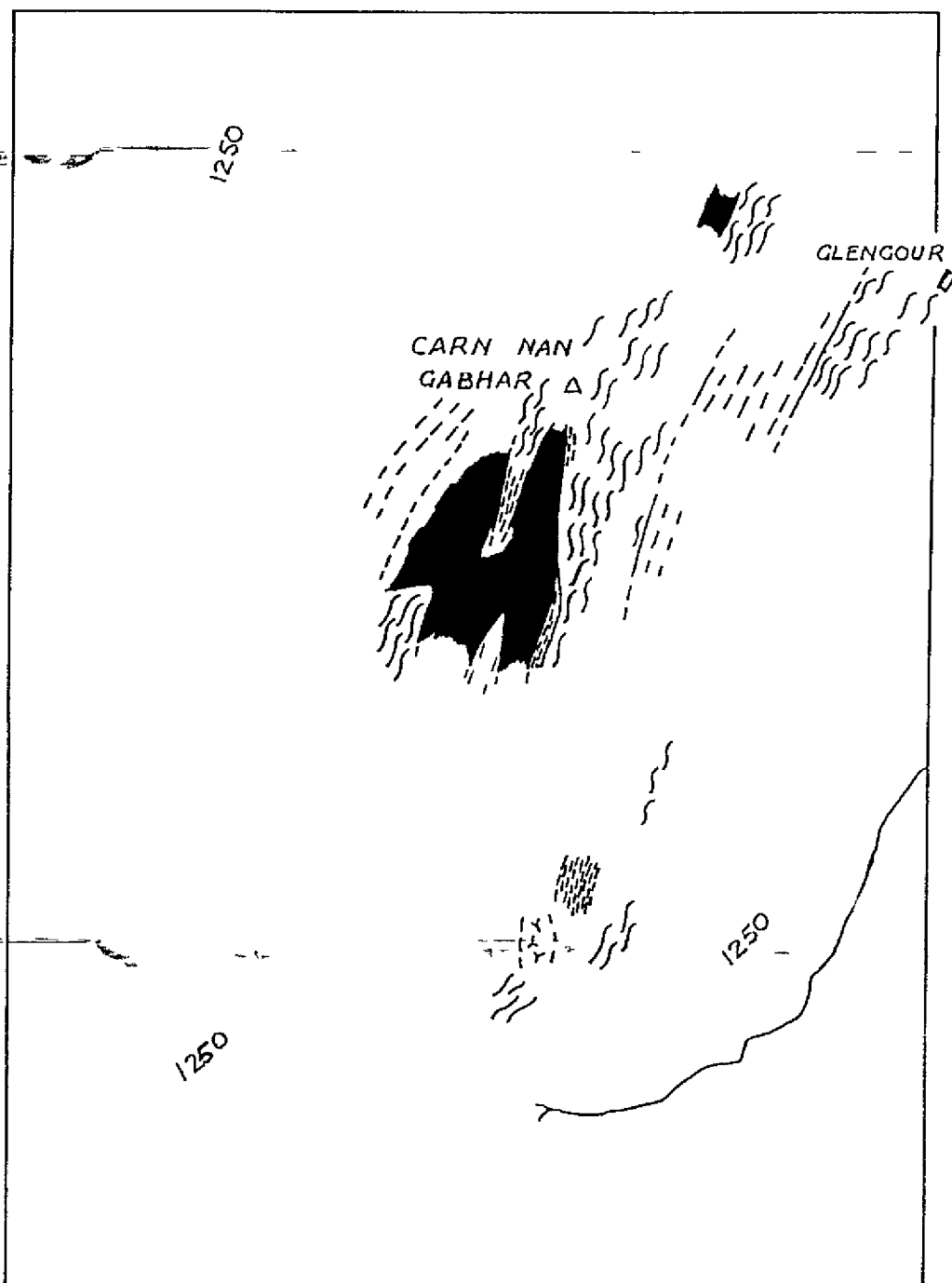
The regional fold axis plunges at 30° towards the south-east. Form lines on the rock groups show the strike of the foliation.





GENERAL LOCALITY MAP WITH AREAS OF
MAPS A AND B IN OUTLINE

METAMORPHOSED BASIC ROCKS NEAR LOCHINDORB



A

LEGEND

QUARTZO-FELDSPATHIC GNEISS

PELITIC AND SEMIPELITIC GNEISS

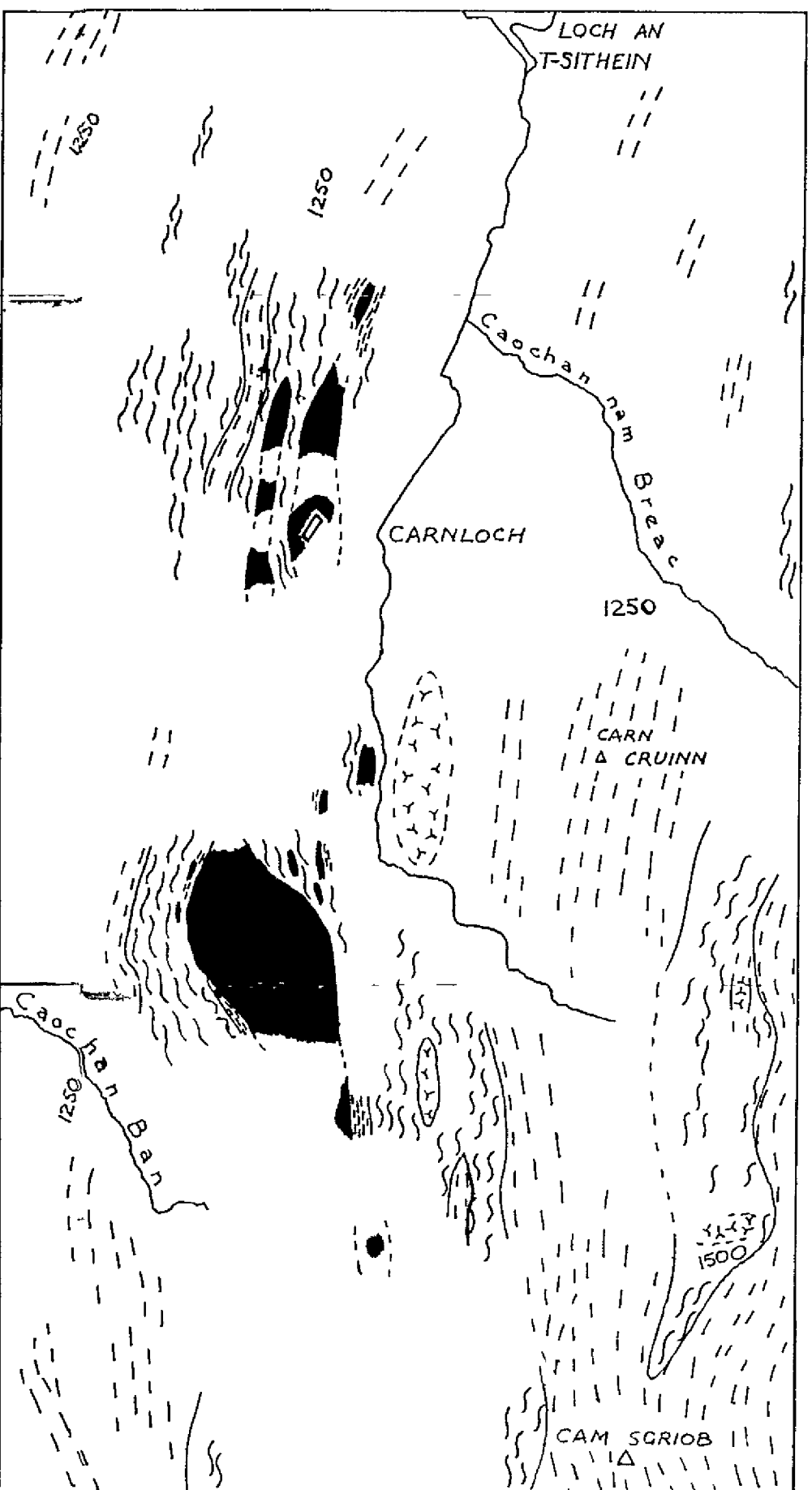
HORNBLENDE-GNEISS

AMPHIBOLITE

GRANITE

DRIFT

FORM-LINES ON ROCK GROUPS INDICATE
GENERAL STRIKE OF FOLIATION REGIONAL
DIP TO EAST AND SOUTH-EAST



B

