THE PETROLOGY AND STRUCTURE
OF THE SOUTHERN PART
of the
LOCH DOON COMPLEX.

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1.

CONTENTS.

I. INTRODUCTION............................................. 1

II. SUMMARY OF PREVIOUS AND PRESENT WORK............... 4

III. TOPOGRAPHY, DRAINAGE and GLACIATION.............. 12

IV. GEOLOGICAL SETTING.................................... 16

V. BLACK SHALES
   (a) General statement................................. 20
       1. Buchan Hill........................................ 21
       2. South-west of Loch Enoch......................... 23
       3. Curleywee.......................................... 24
   (b) Metamorphism........................................ 26
       1. Previous work...................................... 26
       2. Petrographic description........................ 28
           Low grade......................................... 28
           Medium grade...................................... 30
           High grade........................................ 32

VI. GREYWACKE SERIES
   (a) General statement.................................. 39
   (b) Metamorphism........................................ 41
       1. Previous work...................................... 41
       2. Petrographic description........................ 45
           Low grade......................................... 45
           Medium grade...................................... 45
           High grade........................................ 47
           Varieties.......................................... 52
   (c) Summary of facies present in the
       granodiorite aureole............................... 56
   (d) Pods and vein-like patches in the
       metamorphosed greywacke........................... 57

VII. /
VII. CONTACT PHENOMENA IN THE AUREOLE OF THE GRANODIORITE:

A. Mobilization and transformation of the greywacke series.
   (a) Previous work.......................... 59
   (b) General statement........................ 60
      (1) At a height of approximately 800ft. on the south slope of Buchan Hill. 62
      (i) Mobilization........................... 62
      (ii) Transformation.......................... 72
   (2) On the northern summit of Buchan Hill........................................ 79

B. Mobilization and transformation of the Black Shales.
   (a) General statement......................... 81
      1. One third of a mile south-west of Loch Enoch............................. 81

VIII. CONTACT PHENOMENA IN THE HYPERSTHENIC ROCK AUREOLE.

(a) General statement........................... 92
(b) Metamorphic facies.......................... 92
(c) Amphibolite................................ 94
(d) Rheomorphic veins........................... 97
(e) Nature of the contact........................ 99

IX. SUMMARY OF EVIDENCE FROM THE CONTACT AUREOLE.

A. Field evidence
   (a) Relation of the country rocks to the granodiorite.......................... 101
   (b) Relation of the country rocks to the hypersthenic rocks.................. 102
iii.

B. Petrography

(a) Metamorphism of the Black Shales........... 102
(b) Metamorphism of the greywacke series...... 103
(c) Mobilization........................................... 104
(d) Transformation........................................ 105

Basification........................................... 106
Feldspathization................................... 108

X. MARGINAL GRANODIORITE

(a) General.................................................. 113
(b) Relationship of the granodiorite to the country rocks......................... 114
   1. At a height of approximately 800ft., on the south slope of Buchan Hill.... 117
   2. Glenhead Wood area.................................. 121
   3. South-west of Loch Enoch.......................... 127
   4. Elsewhere on the margin of the complex........... 130

XI. GRANODIORITE

(a) General statement.............................. 132
(b) Petrography........................................... 133
   Hornblende-biotite-granodiorite................... 134
   Varieties in the granodiorite................... 140
(c) Transitional to hornblende-biotite-adamellite.................. 142
(d) Inclusions........................................... 144
   1. Basified hornfels inclusions.................... 146
   2. Formation of quartz-diorite.................... 148
   3. Granitization.................................. 152

XII. ADAMELLITES

(a) /
XIII. SUMMARY OF EVIDENCE OF THE ORIGIN OF GRANODIORITE AND ADAMELLITE

A. Granodiorite

(a) Field evidence........................................... 178

(b) Petrographic evidence................................. 179

1. Retention of crystalloblastic characters........... 180

2. Mineralogy................................................. 180

3. Inclusions.................................................. 181

Feldspathization.............................................. 182

B. Adamellites

(a) Field evidence........................................... 186

(b) Petrographic evidence................................. 187

(c) Inclusions.................................................. 188

Late stage enrichment of Potash Feldspar.............. 190

XIV. SOUTHERN MASS OF HYPERSTHENIC ROCK

A. HYPERSTHENIC ROCK

(a) Introduction.............................................. 195

(b) General statement........................................ 195

(c) Petrography............................................... 196
1. The fine-grained marginal hypersthenic rock
2. The medium-grained hypersthenic granodiorite
3. The coarse-grained hypersthenic granodiorite

(d) Inclusions

B. TRANSITION BETWEEN HYPERSTHENIC ROCK AND GRANODIORITE PROPER

(a) General

(b) Field evidence

1. The north-western slope of White Hill

(c) Basic patches in the quartz-diorite

XV. AUGITIC MARGINAL PATCHES

(a) Introduction

(b) Petrography

1. Glenhead Wood
2. Northern summit of Buchan Hill
3. One-third of a mile south-west of the Corse Knowe of White Laggan

(c) Relationship of the augitic marginal patches and the granodiorite

XVI. SUMMARY OF EVIDENCE OF THE ORIGIN OF THE PYROXENIC ROCK

A. Hypersthenic rock

(a) Field evidence

(b) Petrographic evidence

B. Transition Hypersthenic rock-Granodiorite

(a) Field evidence

(b) /
(b) Petrographic evidence.............................. 245

C. Augitic marginal patches.
(a) Field evidence...................................... 247
(b) Petrographic evidence.............................. 248

XVII. DYKES AND VEINS
General statement...................................... 250

A. Dykes.................................................. 250
(a) Petrography.............................................. 253
1. Granophyre and quartz-porphyry............. 254
2. Porphyrites............................................. 255
3. Lamprophyres........................................... 257
Sheared dyke............................................. 259
Two contiguous dykes................................. 260

B. Veins.................................................. 260
(a) General statement.................................... 260
(b) Petrography.............................................. 261
1. Aplites.................................................. 262
2. Pegmatitic aplites................................. 263
3. Granophyres............................................ 263
4. Adamellites............................................ 263
5. Microgranites and microgranodiorites........ 264

Origin of the dykes..................................... 264

XVIII. STRUCTURE
(a) Introduction and Previous Work................. 266
The structural Pattern.................................. 269

(b) Structure of the Sediments....................... 269
1. General............................................... 269
2. In the contact aureole of the granodiorite..... 270
3. The zone of mobilized sediment............... 272
4. In the contact zone of the hypersthenic rock.. 273

(c) Structural Features in the Hypersthenic Rocks 274
XVIII. STRUCTURE (Contd.)

(d) Structural Features in the Granodiorite and Hornblende-biotite-adamellite
1. General
2. Marginal granodiorite
3. Granodiorite
4. Transitional to hornblende-biotite-adamellite

(e) Structural Features in the "Granitic" Rocks
1. Hornblende-biotite-adamellite
2. Biotite-adamellite

(f) Form of the Complex

(g) Summary and conclusion

XIX. GEOCHEMISTRY AND PETROGENESIS

A. Data
1. Analyses and Analysed specimens
2. Explanation of layout of Tables II and III
3. Note on average greywacke

B. Interpretation of data
1. Discussion of von Wolff diagram No. 1
2. Variation diagram No. 1
3. Variation diagram No. 2
4. von Wolff diagram No. 2

C. Mechanism of Migration

XX. CONCLUSIONS

XXI. ACKNOWLEDGMENTS

XXII. BIBLIOGRAPHY

Tables /
Tables I, II and III.
Figs. 2 - 74.
Map in the back pocket.
I. INTRODUCTION

The Loch Doon 'granitic' complex is one of a group of apotectonic Caledonian plutons which occur in the belt of Lower Palaeozoic rocks extending across the Southern Uplands of Scotland and continuing into Ireland. The other major plutons of this belt are Cairnsmore of Carsphairn (Deer, 1935); Cairnsmore of Fleet (Gardiner and Reynolds, 1936); Criffel (MacGregor, 1937 &c.) and Newry (D.L. Reynolds, 1934 &c.) in Ireland. Smaller masses are Broadlaw (Mould, 1947); Cockburn Law (Midgley, 1946); Mull of Galloway (Holgate, 1943); Priestlaw (Subramanyan, 1948); Spango (Sarkar, 1948); and Crossdoney (Harris, 1936). Petrographically each has its own distinctive features, though as a whole the group has sufficient in common to constitute a petrographic province.

The Loch Doon complex outcrops in the south of Ayrshire and the north of Kirkcudbright. It extends for 11½ miles from the end of the Loch Doon road in the north, to a mile or so beyond Loch Dee in the south, the total area being about 47 square miles. It is emplaced in highly folded sediments of Ordovician age which are mainly greywackes with some shales.

The present study is confined to the southern half of the complex. The region covered is more than 20 square miles in area /
area and extends from Loch Enoch in the north to Loch Dee in the south. The whole extent of the complex is shown on Sheet 8 (Carrick) of the one-inch Geological Survey map of Scotland.

The southern part is difficult of access. Glenhead is the only inhabited cottage in the area and it is situated near the south-western margin. There is a road to it from Newton Stewart but from Loch Trool Lodge to Glenhead it is very rough. Loch Dee can be reached from the south by a disused cart track from Auchenstein.

Fourteen weeks were spent on field work and the area has been mapped on a scale of six inches to a mile. 812 specimens were collected from which 543 thin sections have been made for detailed study.

The object of the investigation was to collect evidence with a view to assessing the relative merits and demerits of the magmatic and transformation hypotheses as tentative explanations of the genesis of the various rock types and their mode of emplacement.

The magmatic hypothesis postulates that the 'granitic' rocks represent the consolidated products of magmas which rose in a liquid state from depth. According to this hypothesis the pre-existing sediments have been mechanically displaced or partly assimilated.

The /
The transformation hypothesis on the other hand claims that the pre-existing sediments have been reconstructed by chemical reactions, initiated and maintained by emanations, to form rocks of "igneous" - i.e. igneous-looking - character.

The assemblage of petrological, geochemical and structural evidence consistently supports the transformation hypothesis rather than the magmatic hypothesis. Reasons are given for drawing the following conclusions. The Ordovician sedimentary rocks have been subjected to large scale migration of emanations from the centre of the pluton. The introduction of certain elements and the expulsion of others have converted the sediments into rocks which simulate types commonly regarded as igneous. The emanations (whether fluid or ionic) migrated through rocks which were essentially solid, taking advantage of planes of relative movement (shear planes) and intergranular boundaries. The process was completed by ionic diffusion through crystal lattices.
II. SUMMARY OF PREVIOUS AND PRESENT WORK

The first account of the Loch Doon complex appears to have been made by Dr. Grierson when addressing the Wernerian Society in 1816. In his paper on "Mineralogical Observations in Galloway", he pointed out that a "compact gneiss" there intervened between the transition rock (greywacke) and the 'granite'. He noted the occurrence of inclusions of "gneiss" in the granitic rocks and located several dykes of 'feldspar-porphyry' both in the "gneiss" and in the complex itself. Although his observations were made in a limited area his deductions with regard to the form and size of the complex as a whole were remarkably accurate.

Some fifty years later James Geikie investigated the contact phenomena of the complex and was greatly impressed by the gradual passage from feldspathic greywackes to 'granite'. His paper "On the Metamorphic Origin of Certain Granitoid Rocks and Granites in the Southern Uplands of Scotland" was published in the Geological Magazine (1866). Describing the complex he wrote that "it is bounded by a set of hard fissile slaty shale, which, along the line of junction, are crumpled and puckered, much indurated, and finely crystalline. Across the strike of these beds, the granite does not extend, but it is otherwise where the strata/
strata are highly feldspathic, these last having apparently
offered no hindrance to its out-growth". He further described
the contact of the granite and the feldspathic greywackes as "so
intimate that we have usually no line of demarcation, but, on the
contrary, a gradual passage".

He was struck by the similarity of the inclusions (nests)
in the granite to the galls or "nests" of altered shale in the
aureole. He considered that "the inclusions represented little
detached portions of shale -- or they may be remnants of thin
bands or beds of shale that interleaved the original strata".
Geikie believed (though quite erroneously) that the inclusions
were scattered indiscriminately throughout the granite and used
this supposed fact to disclaim them as stopped blocks.

He concluded that "the crystalline rocks -- have re-
sulted from the alteration in situ of certain bedded deposits".
Geikie was aware that chemical data were required to make the
study complete but he believed that the field evidence told a
"plain enough story". He believed that the transformation was
effected without chemical change, but this was justifiably dis-
puted by David Forbes (1867).

The area was mapped for the Geological Survey of Scot-
land by J. Horne in 1893 and the mapping was revised later by
B.N. Peach and J. Horne. Their work is embodied in the published
one-inch /
one-inch map of the Carrick district (Sheet 8).

The first detailed petrographical description of the rocks of the complex was given by Teall (1899, pp. 607-31). He distinguished five rock types which he classified as quartz-diorites of the tonalite type, hornblende-biotite-granites or granitites, biotite-granites, quartz-augite-diorites, and hyperites. Their distribution was not indicated on the published map (Sheet 8) but he recorded that "these different varieties shade into each other by imperceptible gradations".

He observed and recorded the unusual character of the potash feldspar in the biotite-granites. He termed the crystals "pseudo-porphyritic" for he realised that they belonged to the later phases of consolidation.

Teall was well aware of Michel Lévy's work on the feldspathisation of rocks around granites but he did not consider that the contact zones surrounding the Galloway granites furnished illustrations of such feldspathisation on any large scale. He recorded that "in many cases the feldspar has doubtless been formed out of the constituents of the original rock, and in the few in which it has been introduced the action has occurred only in the immediate neighbourhood of the granite".

As a result of his study he concluded that the magmatic hypothesis was more satisfactory than one involving assimilation.
He thought that "the differences in the average composition of the three great masses (Cairnsmore of Fleet, Criffel and Loch Doon) would be explained by differentiation in a deep-seated reservoir or magma basin, whereas the differences observed in one and the same mass might be explained partly by the intrusion of a heterogeneous magma and partly by differentiation after the magma had reached its present position".

In 1932 C.I. Gardiner and S.H. Reynolds published the results of their re-investigation of the area in a paper on "The Loch Doon 'Granite' Area, Galloway" in the Quarterly Journal of the Geological Society of London. They described the plutonic rocks as ranging from true granites in the central ridge to norites at certain parts of the margins, the major part of the complex being tonalite. They, too, noted the gradations of the rock types, and they added to previous knowledge by a map showing the distribution of the types. This map, largely based on specific gravity determinations, was a valuable contribution which has much assisted later work. From the considerable spread of the metamorphic aureole, which includes the satellitic Burnhead mass to the east of the main mass, they concluded that the intrusion was laccolithic. They differed from Teall in thinking that differentiation took place prior to emplacement. The three main types of plutonic rocks were regarded as the products of three successive intrusions /
intrusions, in order of decreasing basicity, the gradational types (hybrid rocks) being produced by mixing of the magmas at the various "igneous" contacts.

In 1942 the author submitted to Professor Holmes a report on a petrological investigation of the complex carried out as part of the field work required for the B.Sc. Hons. Degree in Geology at Durham University. In the course of his work no important departures from the general disposition of the rock types as mapped by Gardiner and Reynolds were found. Additional information was however obtained on the contact phenomena in which mobilized sediments were recognised for the first time in the Loch Doon aureole (cf. D.L. Reynolds, 1936, p. 355). Owing to war-time control of six-inch maps, detailed mapping was, unfortunately, impossible. The importance of this preliminary study was that some evidence was brought to light which suggested that an alternative explanation of the mode of emplacement of the various rock types was worthy of consideration - namely "pyro-metasomatism" as opposed to the various magmatic differentiation hypotheses.

The pyro-metasomatic or transformist hypothesis was systematically tested by McIntyre at Professor Holmes' suggestion. McIntyre began work in 1945 and carried out an intensive petrographical investigation of the norite of the north-western corner of
of the complex. His results were embodied in a thesis (unpublished) presented for the degree of Doctor of Philosophy at the University of Edinburgh. In 1949 a summary of his work formed the basis of a paper which he read to the Geological Society of London. McIntyre found that the evidence collected from the aureole, the 'norite' and the inclusions, supports the transformist hypothesis. He stated: "the so-called norite -- together with the inclusions of fine-grained norite contained therein, are in no sense igneous rocks. Of a sedimentary origin they have been so altered, both chemically and physically as to assume compositions and textures commonly regarded as igneous". By careful measurements of the amounts of potash feldspar in the 'norite' McIntyre was able to map the distribution of rocks with more than and less than 1% potash feldspar. Stressing the importance of phase petrology he noted "that the most important line in the complex is not the inner margin of the aureole, but the locus of the change from desilication to granitization, and this though mappable cannot be seen in the field". He concluded that the genesis of all the rocks of the complex could be attributed to the results of one process - namely the differential diffusion of chemical elements through a solid medium.

The writer had the opportunity to return to the complex in 1947 and decided to work on the southern half to study in detail /
detail the contact phenomena of the granodiorite, to trace the progressive change towards the centre, and to ascertain whether or not the hypothesis put forward by McIntyre to explain the 'norite' in the north-west corner of the complex is applicable to the southern mass of 'norite'. As in the north, detailed petrographical methods were used and the information so obtained was substantiated by geochemical evidence.

With the completion of this work, the whole complex has now been studied from the petrological and geochemical points of view, but for a thorough investigation of any pluton a structural study is also required. Fortunately the generosity of the British Council enabled Dr. Oertel of Bonn University, to join the staff of the Grant Institute during the session 1948-49. He was anxious to apply the structural technique of the Cloos school to a Scottish granite, and, at the suggestion of McIntyre, undertook the structural investigation of the northern half of the Loch Doon complex. The writer, after acquainting himself in the field with the methods and technique adopted by Oertel, undertook to map the southern half of the complex in the same way in order to complete the structural picture of the whole. The structural pattern so revealed (Fig. 74) indicates by its symmetry that it originated by application of stress from the core of the pluton. The /
The structures are interpreted not as flow planes in a liquid but as shear planes formed in a mass which acted as a solid.

Thus two independent methods of investigation, petrological and geochemical on the one hand, and structural on the other, converge towards a common conclusion as to the origin of the Loch Doon pluton. This is a fact of great significance and importance.
III. TOPOGRAPHY, DRAINAGE and GLACIATION

Although the scenery of the area is amongst the finest in the Southern Uplands of Scotland few people are acquainted with its wild grandeur and unique charm.

The outer part of the complex occupies the relatively low ground lying between the more resistant flanks of the metamorphic aureole, marked by the Merrick Range in the west, and the Kells Range in the east. Extending along the central axis of the pluton is a mountainous ridge which corresponds closely with the outcrop of the granitic core of the complex.

The southern half of the complex is ringed by the highest land in the area. The dominating hill is the Merrick (2764 ft.) - others, all of which lie in the metamorphic aureole, are Buchan Hill (1600 ft.) on the west; Mulldonoch (1826 ft.), Lamachan Hill (2350 ft.), Curleywee (2212 ft.) in the south; Little Millyea (1898 ft.), and Meikle Millyea (2446 ft.) on the east.

The principal summits within the complex lie along the southern half of the central ridge and are namely Craignaw (2115 ft.), Snibe Hill (1650 ft.), and Craiglee (1741 ft.). This ridge forms the main watershed between the area draining to Loch Trool in the S.W. and to Loch Dee in the S.E. The eastern valley between /
between the Kells range and the central ridge is drained by Cooran Lane\(^x\) which rises in the Long Loch of the Dungeon. This stream flows south through a low-lying tract of bog to join the Black Water of the Dee flowing from Loch Dee. The loch is situated in the southernmost part of the eastern valley in a shallow rock basin margined by glacial debris. It receives the drainage of the mountainous land to the south-west, south and south-east by means of Dargall Lane, White and Black Laggan Burns, and Green Burn respectively. (Figs. 13 and 14).

The area between the central ridge and the western margin of the complex has a very irregular surface variegated by Lochs Enoch, Arron, Neldricken, Valley and Narroch, and those of Glenhead, all of which drain into Loch Trool by way of the Gairland or Glenhead Burns. The area immediately to the west of the complex is also drained into Loch Trool - by Buchan Burn.

The Merrick area was an important centre of ice dispersal during the Pleistocene glaciation, with the result that there are good exposures on the high land. In the low-lying areas, however, there are few exposures as bogs are common and the lower slopes of the valleys are often obscured by drift.

The /

\(^x\) Lane is a term applied as a rule to a waterway joining two lochs, but in this area it is used more loosely and is sometimes adopted for a waterway that has no loch in its course, e.g. Cooran Lane.
The whole of the area is bleak and trees are very scarce except in the vicinity of Loch Trool. (Fig. 11).

All types of glacial phenomena are well exhibited. The Trool valley and those of Glenhead and Gairland Burn are typically U-shaped. Numerous hanging valleys are present, e.g. the valley of Buchan Burn hangs on the northern margin of the deeper Trool valley. The lower parts of the valleys of Gairland Burn and Glenhead are profusely covered with drift and morainic mounds. The morainic drift has dammed up the upper part of Gairland Burn valley to form Loch Valley, while Lochs Enoch and Neldricken almost certainly occupy rock basins which were formed by glacial erosion. Glacial overflow channels can be seen on the ridge from Buchan Hill to the Rig of Loch Enoch, and also along the Rig of the Jarkness. Perched erratics of biotite-adamellite can be found resting on high ground of granodioritic composition. However, the most spectacular features are those formed by corries. The formidable Lamachan Hill (2350 ft.) to the south owes its triangular shape to the development of three large corries on the north, north-east and south-east faces. The north corrie is drained by Shiel Burn and it is in this large amphitheatre that the Nick of the Lochans satellitic mass is situated. The north-east corrie is almost a perfect semi-circle with cliffs nearly the whole of the way round /
round the high lip. On the eastern side of this impressive depression, which is nearly a mile across, lies the White Hill satellitic mass. The south-east corrie lies just outside the area with which this thesis is concerned, but it is worth mentioning that its walls have been eaten back towards those of the north corrie so that only a narrow ridge or arrête is left between them. (Fig. 12).

The topography is fairly closely related to geological structure. The mountainous rim surrounding the complex corresponds to the aureole, the central ridge to the 'granite' (adamellite). The granodiorite and the hypersthenic rocks have resisted erosion least and have given rise to the greatest area of low-lying land.
IV. GEOLOGICAL SETTING

The age, lithology and sequence of the rocks of the area can be briefly summarised as follows:

Lower Sandstone

- Porphyrite and lamprophyre dykes
- Plutonic complex replacing Ordovician sediments
- Some minor lamprophyric dykes

Old Red

Period of intense folding in which the Silurian was also involved.

Caradoc

- Greywackes, shales and mudstones
- Conglomerates

Llandeilo

- Greywackes, shales and mudstones
- Black shales with "Hartfell" fossils
- Conglomerates
- Greywackes, shales and mudstones
- Black shales with "Glenkiln" fossils

Arenig

- Red mudstone and radiolarian chert
- Spilitic lavas, ashes and agglomerates
The oldest rocks exposed are spilitic lavas of Arenig age occurring as inliers within the cores of anticlines of radiolarian cherts and mudstones. These latter in turn form inliers in the Llandoilo-Caradoc black shales. The greywackes, shales and mudstones which make up the greater part of the Ordovician sediments in the area have been referred to the Llandoilo-Caradoc.

The country rocks surrounding the Loch Doon complex are highly folded. The fold axes are almost horizontal and trend N.E.-S.W.; this direction was imparted to the rocks in common with all the Lower Palaeozoics of the Southern Uplands during the Caledonian orogeny. The beds dip at very high angles to the N.W. and S.E. and form parts of great anticlinoria and synclinoria.

The black shales containing Glenkiln and Lower Hartfell fossils are repeated by folding and thus possess relatively broad outcrops; they are found to the south-west of Loch Enoch, on Buchan Hill, and on Curleywee - i.e. on the west, south-west and south margins of the complex respectively.

The greywackes, shales, mudstones and conglomerates which overlie the black shales are unfossiliferous. They show pronounced lateral variation, and it is therefore difficult to ascertain /

The only exposure recorded in the area under review lies in the aureole of the complex, about three-quarters of a mile east of Lamachan Hill, and nearly one mile from the margin of the complex.
ascertain their detailed stratigraphy. Greywackes predominate; they are greyish blue or dark in colour, and the chief fragments are angular quartz and feldspar set in an argillaceous matrix.

The plutonic complex is elongated in a north-south direction, oblique to the trend of the Caledonian folds, and is roughly of hour-glass shape. The Lower Palaeozoic sediments are folded but the complex is unaffected. The folded sediments are metamorphosed around the complex and therefore the complex is clearly younger than the post-Silurian movements. The complex is cut by dykes which are believed to be of Lower Old Red Sandstone age.

It consists of the following rock types: biotite-adamellite, hornblende-biotite-adamellite, granodiorite, quartz-diorite, of types formerly regarded as noritic and referred to hereafter as augitic and hypersthenic rocks. The adamellites constitute the central part of the complex and are surrounded by granodiorite into which they grade imperceptibly. The hypersthenic rocks are confined to the north-west and southern corner; patches of dioritic rocks occur at several localities around the south-western margin. Rocks of both these types grade into the granodiorite which forms the major part of the complex. All these rock types are present in the area under consideration.
The metamorphic aureole ranges from half a mile to three miles in width but averages just under one mile. The widest part lies to the east where it stretches from the eastern margin to include the satellitic Burnhead mass.

Numerous dykes (porphyrites and lamprophyres) cut the country rocks and the complex. The majority are definitely younger than the complex, but a few, situated in the metamorphic aureole, show low to medium grade metamorphism and rarely extreme alteration, and are earlier than the pluton.
V. BLACK SHALES

(a) General Statement

The black shales form a conspicuous band in the rather monotonous series of greywackes, flaggy beds and grits. The classical view of the structure of the Ordovician sediments is that it consists of large anticlinorlia and synclinorlia which trend N.E.-S.W. Two of these anticlinorlia run through the area considered. In their cores outcrop the Llandeilo-Caradoc black shales (Moffat Series) and the Arenig radiolarian cherts and mudstones. The northern anticlinorium of the Moffat Series can be traced across the Southern Uplands from south of Portpatrick, north-eastwards by Glen Trool, Carsphairn and Sanquhar to the Moorfoot Hills. The other lies to the south-east and runs from Gabsnout in the valley of the Luce to Curleywee south-west of Loch Dee.

The stratigraphical group referred to as "black shales" consist of carbonaceous shales with thin siliceous ribs or cherty bands from an inch to several inches thick. Towards the north these beds become coarser. This clearly indicates that the source of the material lay to the north-west, in conformity with the classical view of the facies variation between Moffat and Girvan.
The black shales outcrop in the metamorphic aureole at three main localities: these are (i) on Buchan Hill, (ii) to the south-west of Loch Enoch, and (iii) on Curleywee; that is on the south-west, west and south margins of the complex respectively. In all these localities their outcrops are broad because of repetition of the beds by isoclinal folding.

1. Buchan Hill

The black shales have a broad development across the central part of Buchan Hill. The maximum width of approximately 600 yds. is attained immediately to the west of the southern summit. The same band outcrops along the northern side of the Trool Valley where the strike follows the north-east—south-west direction which predominates throughout the Southern Uplands. This direction is maintained as far as Buchan Bridge (1 mile from the southern summit of Buchan Hill). When traced still closer to the complex, the strike swings gradually round until just west of the summit the strike is north—south. The significance of this deflection is dealt with in Section XVIII.

The black shales directly overlie bands of Arenig radiolarian cherts and mudstones in two localities on the western and south-western slopes of Buchan Hill. Fossils belonging to the Glenkiln division and the lower sub-zones of the Hartfell shales /
shales have been obtained from the south-west continuation of the shale outcrop in the Trool valley. From one of the best fossiliferous localities (Pulnabrick Burn, a quarter of a mile west of Glen Trool Lodge), the following assemblage of Glenkiln forms was obtained (Memoir 1899):-

- **Didymograptus superstes** (Lapw.)
- **Lasiograptus bimucronatus** (Nich.)
- **Coenograptus gracilis** (Hall)
- **Diplograptus euglyphus** (Lapw.)
- **Coenograptus surcularis** (Hall.)
- **Diplograptus foliaceus** (Murch.)
- **Coenograptus pertenuis** (Lapw.)
- **Diplograptus mucronatus** (Hall.)
- **Cryptograptus tricornis** (Carr.)
- **Dicellograptus sextans** (Hall.)
- **Climacograptus peltifer** (Lapw.)
- **Dicellograptus moffatensis** (Carr.)
- **Clathrograptus cuneiformis** (Lapw.)
- **Dicellograptus Forchhammeri** (Gein.)

The beds are nearly vertical or dip steeply to the west and north-west (average 80°). They appear to outcrop in anticlines the cores of which are inliers of Arenig radiolarian cherts.
cherts and mudstones. Exposures are fairly good but, considering the complexity of the tectonics and the lateral variation, they are not sufficiently numerous to allow any one bed to be traced with accuracy along the strike for any great distance.

Detailed examination of the shales has been made as nearly as possible along the strike for 800 yds. Specimens were collected from a point 750 yds. north-east of Buchan Farm (height 825 ft.) on the southern slope of Buchan Hill to a height of 1560 ft. on the west side of the southern summit. Here the black shales enter a narrow zone of mobilization which lies adjacent to a tongue of granodiorite.

2. South-west of Loch Enoch

Two smaller outcrops of the black shales occur three-quarters of a mile south-west of Loch Enoch. They measure roughly one and a half miles and one and a quarter miles respectively. The western outcrop lies mainly on the south-east slope of the Merrick, but it crosses the headwaters of Buchan Burn on to a saddle situated midway along the Rig of Loch Enoch. Along the southern margin of its outcrop the black shale is adjacent to the granodiorite. A narrow strip of greywacke (30 to 40 yds. wide) separates the two outcrops. The eastern outcrop is adjacent to the complex along its southern and eastern margins.
The strike varies from north-east—south-west to north-south. Tongues of granodiorite from the main mass run out roughly parallel to the margin making a remarkably intricate contact. The black shales dip steeply (70-80°) to the west or north-west and retain their strike until they are very close (3-5 yds.) to the contact when they swing parallel to it. This is well shown on the Rig of Loch Enoch and, above a tongue of granodiorite, on the south-east spur of the Merrick. (Map Fig. 2).

No fossils have been found in this outcrop and therefore it cannot be definitely correlated with the Buchan Hill shales.

3. Curleywee

The black shales described above lie close to the granodiorite. Those of Curleywee on the other hand are upwards of a quarter of a mile from the hypersthenic rocks. They trend N.E.-S.W. and are repeated by closely packed folds so that they make a broad outcrop which extends from Lamachan Hill over Curleywee to White Hill. At the north-east extremity of this outcrop the general strike swings round to an east-west direction.

Owing to their proximity to the complex most of the fossils originally present have been obliterated. A few graptolites have been obtained (Memoir, 1899, p. 388) in the prolongation /
prolongation of this band south-westwards towards the sources of Cardorkin Burn, south of Larg Hill. The characteristic assemblage of Glenkiln graptolites obtained was as follows:

- Didymograptus superstes (Lapw.)
- Dicellograptus sextans (Hall.)
- Coenograptus gracilis (Hall.)
- Dicellograptus moffatensis (Carr.)
- Lasiograptus bimucronatus (Nich.)
- Dicranograptus ramosus (Hall.)
- Diplograptus euglyphus (Lapw.)
- Dicranograptus minimus (Lapw.)
- Diplograptus foliaceus (Murch.)
- Dicranograptus formosus (Hopk.)
- Diplograptus perexcavatus (Lapw.)
- Climacograptus bicornis (Hall.)
- Cryptograptus tricornis (Carr.)

The black shales overlie the spilites and radiolarian cherts which occupy the cores of the folds. The shales everywhere pass upwards into flags, shales and grits.

The alteration of the black shales was studied along the strike on Buchan Hill and south-west of Loch Enoch. Forty specimens were collected, of which thirty-two were sectioned;
(twenty from Buchan Hill and twelve from south-west of Loch Enoch).

(b) **Metamorphism**

1. Previous work

A general account of the metamorphism of this group is contained in the Memoirs describing Sheets 9 (1877) and 4 (1878). The development of mica in the neighbourhood of the various granitic complexes was emphasized. No further work was done on the shales in the aureole of the Loch Doon complex until 1899 but similar shales (Moffat Series) were studied in the aureoles of the neighbouring complexes.

In 1889 Allport and Bonney described the metamorphism of the sediments bordering the Cairnsmore of Fleet mass in the neighbourhood of Loch Ken. A year later Miss M.I. Gardiner (1890) dealt with the contact alteration of the shales on Knocknairling Hill in the aureole of the Cairnsmore of Fleet complex. Miss Gardiner noted that when the shales are traced towards the complex they grade into a rock composed of quartz, biotite, muscovite, opaque carbonaceous matter and occasional chiastolite. She also noted that the coarser part of the altered shales adjacent to the granite had a "granitic look". Sillimanite, occurring /
occurring as fine needles in quartz, was observed in the flaggy beds and grits.

A general account of the metamorphic rocks of the Galloway district was given by Teall (1899). His description was largely based on specimens collected from the aureole of the Loch Doon mass. He described the more important stages of alteration of the shales on the north-east of the complex as they are traced along their strike towards the granite contact. The principal metamorphic products he noted were garnet-biotite-hornfels and andalusite-mica-schist. Andalusite was observed in a few localities only. It was found in altered black shales near the 'granite' contact on Meikle Craigtarson and chiastolite was recognized in a specimen from Black Gairy, near Buchan Hill. A chemical analysis of a highly altered shale with intercalated lenticles of chert is given.

Gardiner and Reynolds (1932) dealt very briefly with the metamorphism of the black shales. They recognised that cordierite is plentiful in the inner part of the aureole and indeed comes next to biotite in abundance. Corundum, andalusite and sillimanite as hair-like crystals in muscovite or quartz were recorded in a specimen from Buchan Hill. Garnet, they stated, is comparatively rare. Five years later they briefly investigated the metamorphosed sediments in the Cairnsmore of Fleet aureole.
in which they recorded the occurrence of andalusite-mica-schist, and cordierite-mica-schist.

2. Petrographic Description
Microscopically the unaltered black shale is found to consist of very small grains of quartz, minute flakes of chlorite and sericite, and abundant carbonaceous matter. Intercalated with the shales in the field are impersistent black cherty bands. The shales are dark blue or black in colour and are quite fissile. They weather to a characteristic dark reddish brown colour.

In the field induration marks the first sign of metamorphism. With the advance of metamorphism a spotted character is assumed, and this is maintained until quite close to the contact, where the spots are lost and the altered shales become coarsely crystalline.

In the low grade of metamorphism (Nos. 479, 478, 477, 427, 420) the quartz occurs as anhedral microcrystalline crystals (<.01 mm.). Small flakes of biotite have developed from the chloritic and sericitic constituents in the groundmass and are present as small subhedral and anhedral crystals (<0.05 mm.). In certain well defined bands they attain a maximum length of 0.4 mm. (No. 478). Pleochroic haloes are very rare.

Cordierite /
Cordierite occurs as oval-shaped porphyroblasts (average 0.8 - 0.5 mm.) and as microcrystalline plates in the groundmass. Indications of the force of crystallisation are well shown by the bending of the bedding planes around the porphyroblasts (No. 479). Two types of cordierite have been observed (Nos. 477, 427). The smaller crystals are crowded with minute black inclusions (graphite). Microscopically they are conspicuous as rounded black spots. The larger crystals are comparatively free from inclusions and form colourless spots, almost euhedral in form; many exhibit polysynthetic twinning. Sometimes aggregates of crystals form spots measuring up to 2.5 x 2.0 mm. Pleochroic patches from colourless to yellow were observed occasionally (Nos. 427, 420). Rarely the porphyroblasts are slightly altered to pinite and muscovite.

Andalusite was detected in small amount in one specimen (No. 477). It occurs as colourless euhedral prismatic crystals which average 0.3 x 0.2 mm. but reach a maximum size of 0.5 x 0.4 mm. Inclusions of minute scales of graphite are common and generally form an obscure pattern in the centre; sometimes they show the chiastolite cross.

Muscovite is always present but is never abundant. It occurs as minute to small anhedral flakes associated with cordierite.

Graphite /
Graphite occurs commonly as a fine dust or as very small irregular crystalline aggregates (\(<0.01\ mm\)).

Other accessories detected are zircon and rare tourmaline (No. 478).

In the medium grade of metamorphism (Nos. 474, 475, 422, 421, 426, 471) the microcrystalline grains of quartz increase in grain size (range 0.02 - 0.2 mm.; average 0.1 mm. diam.). The biotite flakes increase slightly in size as the contact is approached, e.g. 150 yds. from the contact (No. 471) biotite is abundant as small subhedral flakes which average 0.08 mm. in length. Elongated parallel to the lamination, they are often better developed in certain well defined bands in which they occasionally attain a length of 0.4 mm. The flakes are strongly pleochroic, with $X = $ colourless, $Y = $ reddish brown, $Z = $ deep foxy red brown, and pleochroic haloes are common. Biotite is always present but varies greatly in amount, being abundant in some specimens and very rare in others. When abundant it is easily distinguished in the hand specimen by the glintening of the flakes lying parallel to the bedding planes and it often gives the rock a mottled appearance.

It is noteworthy that there is a definite inverse relationship between the amount of biotite and the amount of carbonaceous material present. If carbonaceous matter is abundant biotite /
biotite is scarce and vice versa. It has been pointed out by Bailey (1922), Vogt (1927) and others, that the presence of carbonaceous matter in quantity tends to inhibit or delay the normal reactions in regional metamorphism, and it seems clear that this is also the case in contact metamorphism.

Cordierite shows little indication of the advance in metamorphic grade. It occurs in a habit similar to that of the low grade. In specimens collected three feet from a porphyry dyke, however, the porphyroblasts are considerably altered. Pinite and muscovite have formed.

Andalusite is much more abundant in this grade and occurs frequently as small anhedral and subhedral prismatic crystals in the groundmass, and as large euhedral porphyroblasts which reach a maximum size of 3.0 x 2.0 mm. (No. 426) (See Fig. 26). Inclusions are often numerous and crowded margins provide evidence of the inability of the mineral to clear itself. There is frequently a rim of graphite with a little iron ore. The inclusions are commonly graphite, biotite, quartz and iron ores. They often sieve the large crystals thus giving them a poikiloblastic texture. The most perfectly developed crystals of andalusite observed lie along one particular bedding plane adjacent to a cherty band.

Muscovite develops as large subhedral and anhedral poikiloblastic
poikiloblastic flakes which average 0.7 x 0.5 mm. and are frequently situated near the centre of cordierite porphyroblasts. Inclusions are mainly quartz, graphite and biotite.

Graphite occurs as larger irregular crystalline aggregates in this grade.

Tourmaline makes a noteworthy appearance as euhedral prismatic crystals which average 0.2 x 0.2 mm. in section. It was detected furthest out in the aureole in a specimen (No. 471) collected approximately 130-140 yds. from the nearest contact and 220 yds. along the strike. Strongly pleochroic X(E) = colourless, Z(O) = golden brown or yellowish brown. From its high birefringence and colour it appears to be schorlite (iron-tourmaline). It is formed from biotite but does not pseudo-morph that mineral.

In the high grade of metamorphism (Nos. 481, 482, 484, 469, 467, 483, 489, 496, 466, 493) the quartz grains constituting the groundmass have increased in size to 0.25 mm. but larger crystals of 1.2 mm. in diameter are common. Frequently minute graphitic inclusions, and rarely small flakes of mica, are concentrated near the centre of the grains giving them black-spotted centres. Some grains have cleared themselves of the graphitic matter which they have, so to speak, pushed to their edges to form black rims.
Cordierite is now much less abundant, but occasionally occurs as large porphyroblasts (2.5 x 2.0 mm.) crowded with minute inclusions. Many of the porphyroblasts are altered to pinite and muscovite.

(?) Anthophyllite is the unexpected mineral in the high grade of shale hornfels. It is found at distances from 5 to 75 yds. from the contact south-west of Loch Enoch (Nos. 481, 484, 496) but was not observed on Buchan Hill. It is present as colourless subhedral and euhedral acicular, and as stout bladed prismatic crystals (see Fig. 27). The acicular crystals reach a length of over 2.2 mm. while the stout prismatic ones average 1.2 x 0.4 mm. Transverse sections are rhombic and show perfect (100) and imperfect (110) cleavages. The mineral is optically biaxial, positive in sign and has a small optic angle. The elongation is positive and the birefringence is moderate.

\[
\begin{align*}
\alpha &= 1.5616; \quad \beta = 1.5650; \quad \gamma = 1.5870; \quad \gamma - \alpha = 0.254 \\
\alpha &= 1.5620; \quad \beta = 1.5689; \quad \gamma = 1.5875; \quad \gamma - \alpha = 0.255 \\
\alpha &= 1.5610; \quad \beta = 1.5621; \quad \gamma = 1.5860; \quad \gamma - \alpha = 0.250
\end{align*}
\]

As the hornfelses are traced towards the contact the mineral becomes increasingly rimmed with muscovite and sericite until eventually it is completely replaced by these minerals.

Muscovite /
Muscovite is more common than biotite up to 10 ft. from the granodiorite. Within this distance biotite becomes very abundant and rapidly increases in size from flakes of less than 0.2 mm. to poikiloblastic flakes greater than 1.0 mm. The flakes are strongly pleochroic, with X = straw yellow, Y = brown, Z = deep foxy red brown. Pleochroic haloes are very common. The largest haloes have diameters greater than 0.6 mm. The great increase in amount of biotite indicates that an enrichment of K, Fe and Mg has taken place.

Tourmaline was observed in seven sections, but is not very abundant except in No. 466 from Buchan Hill (Fig. 25). It is, in all cases, the variety schorlrite, occurring as scattered euhedral to subhedral crystals, which average 0.4 x 0.25 mm. It is strongly pleochroic with X(E) = lemon yellow, Z(O) = rich golden brown. Inclusions are commonly graphite and it is aggregated with muscovite and iron pyrites.

Tourmaline was described by Teall (1899) as a rare contact mineral; it is therefore important to stress its local abundance in the altered black shales. Tourmaline contains 35-40% Al₂O₃ and is thus naturally associated with argillaceous sediments. The crystals are generally confined to certain bands but in some cases are scattered throughout the rock. The concentration along particular bands suggests that replacement /
replacement has been effected by differential diffusion and fixation. Harker (1932, p. 117) states categorically that "tourmalinization may indeed be found at a considerable distance from a granite contact but only in proximity to tourmaline-quartz veins which mark the channels of supply". The hypothesis that tourmaline is a pneumatolitic mineral derived from strongly acid gases has been questioned by F. Gordon Smith (1949). He synthesized tourmaline and from his experiments concludes that -

(1) Tourmaline has a narrow range of stability with regard to alkalinity, but both the limits are on the alkaline side except that, when the water concentration is high, one limit lies on the acid side.

(2) Tourmaline is unstable in strongly acid and strongly alkaline water solutions.

(3) In alkaline solutions, tourmaline is stable with albite, quartz, haematite and pyrite.

The following facts are pertinent in determining the mode of origin of tourmaline in the black shales:-

(a) No quartz veins are seen near many of the tourmaline-rich areas.

(b) Minerals in the vicinity of tourmaline show no signs of alteration which would be expected if the action was hydrothermal and the water concentration high.

(c) The crystals of tourmaline are generally confined to certain bands.

(d) No rounded or obviously detrital grains were observed.

Graphite /
Graphite at a distance of one yard from the contact occurs as long skeletal clusters and clots which reach a maximum size of 3.5 x 3.0 mm. A continuous framework to the quartz mosaic is sometimes formed by graphite, aggregates of which fill the interstitial space between the quartz crystals.

Garnet has been observed in two specimens (No. 468, Buchan Hill; and No. 68, S.W. of Loch Enoch). In both cases chert and shale are intimately folded together (fold-breccias or "riebungs-breccia") and the shale is less carbonaceous than usual (see Fig. 29). The crystals of garnet are subhedral and euhedral in form and range from 0.1 - 0.4 mm. in diameter (No. 468). They occasionally exhibit perfect dodecahedral form. Colourless or faint pink in section, the crystals commonly contain small inclusions of biotite, quartz and iron ores. Some crystals are skeletal and others show marked penetration by biotite flakes (Fig. 31). Generally, however, garnet is scarce in the altered black shales although it was claimed by Teall (1899, p. 638) to be only second in abundance to biotite.

Other minerals which have been observed in the high grade hornfels are as follows:

Iron-pyrites occurs commonly as scattered disseminated granules throughout the groundmass or frequently as yellow scales along /
along the cleavage planes.

Other opaque iron ores - magnetite and ilmenite - are present as subhedral pegs.

Zircon occurs as small anhedral scattered grains - and may possibly be the mineral responsible for the pleochroic haloes developed in some of the biotite.

Apatite is present infrequently as small scattered euhedral crystals; it is characteristically associated with tourmaline in these rocks.

Rutile occurs rarely as small yellow or deep red grains.

Sericite and undetermined clay minerals are abundant throughout the fine grained groundmass in specimens distant from the contact.

Pinite develops as a secondary product of cordierite and is nearly always associated with relics of the latter.

The next stage is the mobilization and the transformation of the highly altered black shales into "igneous-looking" rocks. This change takes place in a remarkably short distance. It is described in detail in Section VII B.

The altered shales thus form predominantly cordierite-hornfels.

Mineral /
Mineral assemblages represented are:-
(i) Cordierite, biotite.
(ii) Andalusite, cordierite, biotite.
(iii) (?) Anthophyllite, cordierite.
(iv) (?) Anthophyllite, cordierite, biotite.
(v) Cordierite, garnet.

Quartz, graphite, iron ores and muscovite are invariably present.

Different assemblages can occur in the same specimen in bands which differ in composition. The advance of metamorphism did not progress at the same rate in all areas. Coarser patches and bands (shown clearly by their lighter colour) occur at varying distances from the contact and all seem to be orientated parallel to the bedding. These coarser patches show a higher grade of metamorphism than the surrounding altered shale. However, the altered shales are only slightly basified outside the zone of mobilization and transformation, which is characterised by conspicuous enrichment in biotite.
VI. GREYWACKE SERIES

(a) General Statement

The greywacke series consists of greywackes of varying grade. They range from mudstones, through shales and siltstones to grits and pebbly grits. Since all these grades have a very similar composition, i.e. that of a greywacke, it is convenient to group them into a single series for the purpose of this study.

The typical greywacke is a grey or greenish-grey rock interbedded with flaggy beds, mudstones and occasional pebbly grits. In the past, the term greywacke has been somewhat loosely applied; the definition adopted in this work is that of Pettijohn (1943, p. 944)\textsuperscript{K} which agrees closely with that given by Milner (1929, p. 281). The greywackes of the area are characterised by their lack of sorting and the extreme angularity of their grains. While quartz is the dominant mineral, feldspar is abundant and rock fragments are present in great variety.

\textsuperscript{K}Greywacke connotes a type of sandstone marked by (1) large detrital quartz and feldspar (phenocrysts") set in a (2) prominent to dominant "clay" matrix (and hence absence of infiltration or mineral cement) which may on low-grade metamorphism (diagenesis) be converted to chlorite and sericite and partially replaced by carbonate, (3) a dark color, (4) generally tough and well indurated, (5) extreme angularity of the detrital component (microbreccia), (6) presence in smaller or larger quantities of rock fragments, mainly chert, quartzite, slate, or phyllite, and (7) certain macroscopic structures (graded bedding, intraformational conglomerates of shale or slate chips, slipbedding, etc.) and (8) certain rock associations.
variety. The latter include chert, mudstone, greywacke, spilitic lava and andesite, whilst trachyte, granophyre and tuff fragments have been recorded from other areas (Eckford and Ritchie, 1936). The matrix is mainly clay. The lack of sorting (0.1-2.0 mm.) leads to the presence of all grades in certain beds and individual beds can vary greatly in thickness from a few inches to several feet. A typical greywacke collected by McIntyre (1947, p. 16-17) from the north-west of the complex has been analysed.

The metamorphic equivalents of the greywacke series form by far the greater part of the rocks in the contact aureole. They everywhere border the complex except in two localities - three-quarters of a mile south-west of Loch Enoch, and on the southern summit of Buchan Hill - where black shales and Arenig cherts outcrop.

The greywackes overlie the black shales and occupy the synclinorium between the anticlinoria of Glen Trool and Curley-wee. The beds directly overlying the black shales are flaggy beds (shales) with intercalated silt and mudstones. The flaggy beds are adjacent to the granodiorite on the south slope of Buchan Hill, in Gairland Burn and one-third of a mile south-west of the Corse Knowe of White Laggan. Pebbly grit bands have /
have been observed south-west of the Rig of Loch Enoch, near Glenhead Wood, along the north-east slope of Muldonoich and near the contact (about 760 ft.) in Shiel Burn. Good exposures of the greywacke series have been found on Buchan Hill, along the Brishies (which form the south wall of Glenhead valley), and in the stream sections of Gairland and Shiel Burns. The dips and strikes of the beds are given on the map (see structure map Fig. 74).

When traced along the strike towards the complex the aureole rocks merge into a narrow zone of mobilization and transformation. The zone extends almost continuously around the south-west and south margins of the complex and will be described in the next section.

(b) Metamorphism

1. Previous work

The first account of the metamorphism of the greywackes was given in the Memoirs in explanation of Sheets 9 (1877) and 4 (1878). The recrystallization of the sediments and the development of mica in the aureoles of the Loch Doon and neighbouring granitic complexes were stressed.

In 1899, Teall pointed out that "a special feature of the Southern Uplands is the development of both coarse and fine grained /
grained grits and greywackes of complex composition. Normal argillaceous sediments make up only a small portion of the area. He also noted that "when the intrusion has taken place in a set of complex sediments of variable character the separation of the metamorphic aureole into subordinate zones, continuous round the central mass, becomes impossible. The alteration of the grits and greywackes was described in the most general terms. The first stage noted was the development of small flakes of mica (biotite). These flakes were observed to increase in size as the rocks were traced into zones of higher metamorphic grade. The most altered rock recorded was a gneissose garnet-sillimanite-hornfels. According to Teall biotite is the most characteristic mineral in the aureole rocks, garnet being next in importance. Of feldspar, he wrote: "This mineral appears to be sometimes destroyed and sometimes regenerated in the process of metamorphism".

Gardiner and Reynolds (1932) confirmed the conclusion of the Geological Survey that quartz-biotite-schist (hornfels ?), varying considerably in coarseness and in amount of biotite, is much the most common metamorphic rock. They pointed out that cordierite is more abundant than had been previously supposed; also that garnet is decidedly rare. Of amphibole they stated that it is a rare constituent of the hornfels, only locally present.
McIntyre (1947) studied in great detail the metamorphism of the medium and coarse grained greywackes in the aureole of the north-west of the Loch Doon complex. He noted that "as the Ordovician sediments are traced into the aureole of thermal metamorphism, granulites take their place". The granulites close to the 'norite' were transformed in the solid to feldspathic rock often in the form of pods. The dominant type of metamorphosed sediment present is biotite-quartz-granulite (with a little feldspar). He gave chemical analyses of unaltered and of metamorphosed greywacke.

The sediments surrounding the other complexes of Lower Old Red Sandstone age in the Southern Uplands have been investigated by many workers. The results of the more relevant works will be briefly mentioned.

In 1889 Allport and Bonney, and a year later Miss Gardiner, carried out their pioneer work on the alteration of the sediments in the aureole of the Cairnsmore of Fleet granite. In 1937 Gardiner and Reynolds investigated the same aureole and recorded that "as in the Loch Doon area quartz-biotite-schist and hornfels are the commonest rocks, andalusite-schist and cordierite-hornfels coming next in abundance".

In 1937, Deer, in an attempt to determine the origin
of the marginal rocks of the Cairnsmore of Carsphairn complex, examined the sediments around this complex. Of these within the metamorphic aureole he stated "they form a somewhat uninteresting series of hornfelses included in Tilley's non-calcareous shale division and defined by the classes 3 to 8 of Goldschmidt's classification".

Malcolm MacGregor (1937) studied the Silurian greywackes and shales in the aureole of the Criffel-Dalbeattie complex. The metamorphism of these sediments, he stated, (p. 469) "evolves biotite and pale green or colourless tremolitic amphibole at medium grade and diopside at high grade. The felsic constituents are gradually reconstituted and recrystallised". Four analyses of the metamorphosed sediments were given.

More recent work has been done on the smaller masses by Holgate, Midgley, Mould, Sarkar and Subramanyan.

D.L. Reynolds in 1934 described the varieties of hornfels surrounding the eastern end of the Newry Igneous Complex. Here they consist predominantly of biotite- and cordierite-hornfels, the metamorphosed equivalents of greywackes and shales, associated with less frequent augite-hornfels, ascribed to the alteration of highly calcareous bands. D.L. Reynolds observed that "as the contact is approached biotite is developed to such an extent as to suggest that there has been an enrichment in potash". Analyses of each type were given. Later, the varieties /
varieties of hornfels present in the Goraghwood Quarry of the Newry Granodiorite were described as diopside-, cordierite-biotite-, and plagioclase-biotite-hornfels (D.L. Reynolds, 1944).

2. Petrographic Description

The purpose of the investigation is not so much to study the grades of metamorphism in the sediments of the aureole as to study the phenomena in the vicinity of the granodiorite. For purpose of description, however, arbitrary grades of metamorphism have been adopted. The effects of advancing metamorphism can easily be seen in the field. The first noticeable change is the induration of the greywackes. They become tougher and slightly darker in colour towards the complex.

In the low grade of metamorphism the first sign of alteration is the development of biotite from the argillaceous matrix. The recrystallization of the muddy chloritic material to form biotite and occasionally amphibole in the matrix is the dominant feature of this grade. The early formed scraps of biotite gradually develop into small subhedral flakes.

In the medium grade of metamorphism (Nos. 473, 472, and 475) the grain size of the groundmass increases. The matrix is composed of recrystallized anhedral quartz grains (0.2 mm. in diameter) and crystals of cordierite. Cordierite is present also /
also as colourless and yellow oval-shaped porphyroblasts which average 0.4 mm. in length. These porphyroblasts reach a maximum size of 1.0 x 0.5 mm. but are usually considerably smaller. They are generally crowded with minute anhedral crystals of biotite, granules of iron ores and small rounded quartz grains (see Fig. 19). Biotite is abundant as small subhedral flakes which range from 0.05 - 0.3 mm. in length, the average being 0.1 mm. The elongated flakes are normally orientated parallel or subparallel to the bedding, except that they commonly curve around the margin of the cordierite porphyroblasts. The biotite is strongly pleochroic, with X = straw yellow, Y = medium brown, Z = dark foxy-red brown. Biotite flakes occurring as inclusions in the cordierite porphyroblasts are usually rounded. Accessories present are tourmaline, muscovite, iron ores, zircon, apatite and amphibole. Of these tourmaline is most abundant; it occurs as subhedral and euhedral prismatic crystals, cross sections of which average 0.2 x 0.2 mm. in specimen No. 472. In this particular example it is most abundant near a quartz-rich vein (cf. p. 35) but in other cases it occurs scattered throughout the rock. It is strongly pleochroic X(E) = colourless, Z(O) = golden brown or yellowish brown. As in the black shales the variety present is schorlite. Muscovite is rare, but in one specimen (No. 472) it occurs along the borders of a quartz-rich /
quartz-rich vein. Iron ores are present as scattered granules and pegs.

The high grade of metamorphism of the greywackes was investigated in detail on Buchan Hill. Serial specimens were collected normal to the contact, (1) approximately at a height of 800 ft. on the southern slope, and (2) across the northern summit.

(1) Southern slope of Buchan Hill

A series of five specimens (Nos. 414-410) from the zone of high grade metamorphism was collected between the contact and a point approximately 50 yds. from it. The rocks are bluey-grey fine-grained hornfelses which weather to a characteristic rusty grey colour and split in a uniform manner parallel to the bedding. The beds dip very steeply to the west but gradually become vertical as the complex is approached.

No. 414, a biotite-hornblende-plagioclase-hornfels, 55 yds. from the contact, is typical of this zone and has been analysed (see Tables I and II). It consists of plagioclase, hornblende, biotite, quartz and cordierite, with accessory zircon, apatite and iron ores.

Plagioclase occurs as small granular crystals in the groundmass mosaic, but is present also as subhedral crystals which average 0.6-0.8 mm. in diameter, and often contain very small granular inclusions.
The plagioclases were determined by measurement of extinction angles in orientated sections. The average composition is andesine (An$_{36}$) and the range is from oligoclase (An$_{25}$) to andesine (An$_{40}$). Examples of the variation are given below.

(i) An$_{35}$  (ii) An$_{35-40}$  (iii) An$_{30}$  (iv) An$_{35}$  (v) An$_{25-30}$  
(vi) An$_{30}$  (vii) An$_{40}$  (viii) An$_{40-45}$  (ix) An$_{35}$  (x) An$_{30-35}$

The crystals are not zoned.

Hornblende occurs mainly as rounded granules less than 0.1 mm. in diameter, partly as subhedral crystals averaging 0.8 mm. across and rarely as porphyroblasts larger than 1.0 mm. All of these forms are moderately pleochroic, with $X = $ colourless or pale green; $Y = $ green; $Z = $ brownish olive green; the absorption being $X < Y < Z$. Some of the subhedral crystals have a flake-like form which suggests that some of the hornblende may have replaced biotite.

Biotite generally occurs as small anhedral flakes ($< 0.1$ mm. long) and occasionally as larger subhedral crystals from 0.7 – 0.8 mm. long. The flakes tend to be aligned parallel to /

The degree of accuracy of the method is not greater than ± 5%. Therefore An percentages are given to the nearest multiple of 5 except when the value lies midway between two multiples.
to the bedding, and certain bands are much richer in biotite than others. The pleochroism is strong; \( X = \) pale yellowish brown, \( Y = \) brown, \( Z = \) dark brown. Pleochroic haloes are common.

Quartz is present as very small granular crystals (0.1 - 0.2 mm. in diameter). With plagioclase it forms a fine-grained mosaic. It occurs also as large porphyroblastic crystals over 1.0 mm. in diameter. Every stage of recrystallization from anhedral grains (<0.1 mm.) to large porphyroblasts can be traced. As a result of growth of the large porphyroblasts biotite has become concentrated around their margins. Undulose extinction is common.

Cordierite appears infrequently as ragged anhedral patches which average 0.5 x 0.3 mm. Numerous inclusions are present and consist predominantly of quartz, biotite and hornblende, and rarely of plagioclase.

As indicated above, the rocks exhibit a variety of crystalloblastic textures. Analysis overleaf.

(2) Northern summit of Buchan Hill

Twenty-one specimens were collected in a traverse from a point 220 yds. within the complex to one approximately 70 yds. outside. Seven of these specimens (Nos. 461-455 inclusive) represent the rocks of high grade metamorphism, 70 - 9 yds. outside the complex.

The /
### ANALYSIS B.

Biotite-hornblende-plagioclase-hornfels (No. 414)
55 yds. from the marginal granodiorite at a height of approximately 300 ft. on the south slope of Buchan Hill. New Analysis.
Analyst: W.H. Herdsman. (Table I).

<table>
<thead>
<tr>
<th>Wt.%</th>
<th>Mol. Prop. x 1000</th>
<th>Mol.%</th>
<th>NORM</th>
</tr>
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<tr>
<td>SiO₂</td>
<td>56.92</td>
<td>947.7</td>
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<tr>
<td>Al₂O₃</td>
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<td>-</td>
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<td>P₂O₅</td>
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<tr>
<td>MnO</td>
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<tr>
<td></td>
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</table>

**VON WOLFF VALUES**

L = 59.2
M = 32.2
Q = + 8.6

Micrometric analyses (vol. per cent) using a Hurlbut Electric Counter

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>Quartz</td>
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<tr>
<td>Plagioclase</td>
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</tr>
<tr>
<td>Hornblende</td>
<td>32%</td>
</tr>
<tr>
<td>Biotite</td>
<td>22%</td>
</tr>
<tr>
<td>Others</td>
<td>1%</td>
</tr>
</tbody>
</table>

100%
The sediments in this locality are mostly coarse-grained greywackes but they are very variable. Argillaceous, cherty and mudstone beds are also present.

The coarse-grained greywackes are grey and brownish grey hornfelses which weather to a light rusty brown colour. They are more massive than the argillaceous or finer-grained type. Large crystals of quartz and feldspar are conspicuous on the weathered surface. The beds are nearly vertical or dip steeply to the west.

No. 461, a muscovite-cordierite-plagioclase-biotite-hornfels, collected 70 yds. from the contact, will be described in detail. It consists essentially of quartz, biotite, plagioclase, cordierite and muscovite, with accessory zircon, apatite, iron ores; minor secondary minerals are sericite, chlorite and pinitite.

Quartz is the most abundant mineral and occurs as subhedral and anhedral grains which average 1.0 x 1.0 mm. but range from 0.2 - 2.0 mm. in size. In the larger grains inclusions of smaller grains of quartz, plagioclase and biotite are common and occasionally strings of minute inclusions and of chloritic material cut across the crystals parallel to the bedding. Undulose extinction is common.
Biotite is next in abundance and is present as subhedral flakes which average 0.7 x 0.3 mm. but which range from minute inclusions in quartz to large idioblastic flakes up to 3.0 x 2.0 mm. The mineral often occurs in ragged aggregates or nests. The flakes are strongly pleochroic with X = pale yellow brown, Y = pale sepia, Z = foxy red brown. Pleochroic haloes are common. The random distribution of the flakes gives an approach to decussate structure.

Plagioclase occurs commonly as subhedral porphyroblasts which average 1.0 x 0.6 mm. and reach a maximum size of 2.5 x 2.2 mm. It is also present in the groundmass as small grains 0.2 x 0.1 mm. in size. Inclusions of quartz and biotite are common in the porphyroblasts. The crystals are remarkably fresh but sometimes show a little alteration to kaolin and sericite. Zoned crystals are present infrequently and range in composition from oligoclase An\textsubscript{25} to andesine An\textsubscript{40}. The average composition is andesine An\textsubscript{30-35}.

The freshness, approximate constancy of composition and porphyroblastic habit all point to growth in situ.

Muscovite also occurs as irregular poikiloblastic flakes but is less common than biotite. The larger flakes reach 1.0 x 0.6 mm. in size and often contain inclusions of biotite and quartz.
Of the accessories iron ores are most abundant. They occur as small granules and pegs scattered throughout the rock.

**Varieties**

(1) *Coarse-grained greywackes*

No. 460 was collected ten yards nearer the contact and is very similar macroscopically to No. 461 (p. 50). Microscopically a marked difference is the presence of abundant potash feldspar. This appears in section both as large anhedral plates 2.0 x 1.5 mm. and more commonly as irregular interstitial crystals enclosing abundant quartz grains. Other inclusions are biotite, apatite and plagioclase. It frequently shows alteration to muscovite and sericite. Muscovite occurs as large subhedral plates which are often skeletal or poikiloblastic. Plagioclase is very subordinate and occurs only as small granular crystals.

No. 458, 40 yds. from the contact, is of the same type as No. 461 except that potash feldspar is again present, but in this case only interstitially. The specimen also contains fine-grained lenticular patches which are crowded with small biotite flakes and specks of pyrite. The lenticular patches are clearly metamorphosed relics of shaly pellicles embedded in the coarse-grained greywacke.

(2)
(2) Fine-grained greywacke

No. 455 is a fine-grained plagioclase-biotite-hornfels, collected 14 yds. from the contact. The groundmass consists of a very fine granular mosaic of quartz with subordinate plagioclase. The anhedral crystals of quartz average less than 0.1 mm. in diameter. Biotite is very abundant and occurs as small elongated subhedral flakes which show marked parallelism to the bedding. These flakes average 0.2 mm. in length but occasionally reach twice that size. They are strongly pleochroic, with X = pale yellow, Y = brown, Z = foxy red brown. Graphite and iron ores are abundant and occur haphazardly throughout the rock. This rock is very similar to the lenticular fine-grained patches embedded in the matrix of No. 458 described above. Both are obviously the metamorphosed equivalents of the flaggy beds in the greywacke series.

(3) Calcareous mudstone

A different type of metamorphosed sediment occurs 24 yds. from the contact. It is a highly metamorphosed calcareous mudstone.

No. 456 was collected and sectioned in order to study this type. Macroscopically it is greenish grey in colour and appears to be highly siliceous; it is much more compact and tough /
tough than the coarse-grained greywacke with which it is intercalated. Microscopically it consists essentially of quartz, cordierite, wollastonite, hornblende, sphene and plagioclase with accessory biotite, iron-ores, zircon and graphite; secondary minerals are sericite and pinite.

Quartz occurs very abundantly as anhedral grains which often form aggregates. The average size of the grains is 0.2 x 0.2 mm. but some range up to 0.8 mm. in diameter. Undulose extinction is common and cryptocrystalline inclusions are usually present. Of the larger inclusions pyrite is the most abundant.

Cordierite is present as interstitial irregular plates which average 0.3 x 0.1 mm. The mineral is extensively altered to pinite. Biotite and pyrite are common inclusions.

Wollastonite occurs as small subhedral prismatic crystals and as granular crystals which average 0.25 x 0.2 mm. Perfect (100) cleavage is often shown in the more equant grains. It is colourless and is strongly associated with sphene, pyrite and hornblende.

Hornblende appears as irregular crystals which are faintly pleochroic with X = very pale green, Y = pale green, Z = medium green. Transverse sections exhibit typical amphibole cleavages. The hornblende crystals, along with wollastonite and sphene, form aggregates which commonly measure 1.5 x 1.0 mm.

Sphene /
Sphene is present as granular and subhedral crystals scattered throughout the rock. Wedge-shaped euohedral crystals are rare. The granular crystals commonly form aggregates up to 0.4 x 0.3 mm. across. The sphene is faintly pleochroic with X = colourless, Y = pale brownish yellow, Z = pinkish brown.

Of the accessory iron-ores, pyrite is most abundant and occurs as granules and subhedral crystals which often form aggregates.

The abundance of the three lime-bearing minerals already described indicates the high calcareous content of the mudstone. Either this was an exceptionally lime-rich sediment or there has been addition of lime by outward diffusion from the complex. Sarkar (1948) studied the metamorphism of the mudstones in the contact aureole of the Spango complex and had analyses made of an unmetamorphosed and metamorphosed mudstone of medium grade (cordierite-biotite-hornfels). By comparing the analyses Sarkar found that "although SiO₂ increases the FeO and MgO decrease in the metamorphosed mudstone (S/41) the rock has nevertheless been desilicated relative to the unmetamorphosed mudstone (S/186) ......... Notwithstanding the fact that FeO and MgO have decreased in S/41, there has been a considerable increment of CaO, Na₂O and K₂O". Altogether "in S/41, SiO₂, Al₂O₃, CaO, Na₂O, K₂O and TiO₂ increase". Sarkar pointed out, however /
however, that the differences between S/136 and S/41 may be due wholly to original differences in composition.

Chemical analyses are not available for similar mudstones in the Loch Doon aureole but as no lime-rich rocks occur nearer to the pluton than 24 yds. in the Buchan Hill area, it is probable that this sediment was a calcareous band originally.

(c) Summary of facies present in the granodiorite aureole.

The rocks of high grade metamorphism were examined in the aureole of the granodiorite around the south-west and west margins of the complex (to a point one-third of a mile south-west of the Corse Knowe of White Laggan).

They consist of six types:

1. Biotite-hornfels.
2. Plagioclase-biotite-hornfels.

They are highly metamorphosed equivalents of fine, medium and coarse-grained greywackes, flaggy greywackes, and grits, members of which have been described above. The biotite-hornblende-plagioclase facies is the most common around the margin of the complex /
complex in the following localities:-

(i) North-west slope of Buchan Hill.

(ii) South slope of Buchan Hill.

(iii) Glenhead Wood area.

(iv) One-third of a mile south-west of the Corse Knowe of White Laggan.

A significant fact is that the mafic minerals of these high grade hornfelses closely resemble those of the contact-quartz-diorite and marginal granodiorite. From an examination of the chemical analyses (Table II) it will be seen that remarkably little addition of SiO$_2$ and K$_2$O with concomitant subtraction of Al$_2$O$_3$, FeO, MgO, and CaO is required to effect the chemical transformation of the hornfels into a marginal granodiorite. The behaviour of beds of different composition indicates that as the complex is approached the process of metamorphism is also one of homogenisation. The greywackes respond more readily than the cherty bands and calcareous mudstones.

(d) Pods and vein-like patches in the metamorphosed greywacke.

Occasionally in the metamorphosed greywackes, irregular lenticular pods occur. These pods stand out from the weathered surface as 'knots' which can measure over 2 cm. in length. The 'knots' are sometimes connected by vein-like patches which are lighter coloured than the host rock.

These /
These pods were observed at 1400 ft. on the south slope of Buchan Hill where they are confined to a particular outcrop.

Microscopically the host rock is seen to be a muscovite-cordierite-biotite-hornfels. The groundmass consists of granular quartz, and plagioclase in which abundant interstitial biotite flakes and highly altered cordierite patches occur. The 'knots' consist of irregular quartz grains, the grain-size of which varies from 0.5 - 1.5 mm., and abundant patches of muscovite and pinite which appear to represent former biotite flakes. The relics of the biotites are riddled with minute needles of (?) rutile. Muscovite forms large poikiloblastic flakes with often decussate arrangement. They average in size 0.6 x 0.2 mm. but reach a maximum size of 1.2 x 0.4 mm.

McIntyre (1947) noted the occurrence of potash feldspar and muscovite-bearing pods and vein-like bodies in the aureole of the north-west hypersthenic rocks, in the vicinity of Craigbrock. From his description it is clear that the 'knots' of the north-west are somewhat similar to those of Buchan Hill; the main difference is the absence of potash feldspar from the Buchan Hill rocks. The presence of potash feldspar in the Craigbrock 'knots' may be due to the fact that they are in the mobilized zone and lie nearer the contact than those located on Buchan Hill.
VII. CONTACT PHENOMENA IN THE AUREOLE OF THE GRANODIORITE

A. Mobilization and transformation of the grey-wacke series.

(a) Previous work

The significance of mobilization of aureole sediments was first recognized by D.L. Reynolds when she discovered and described examples of the phenomenon occurring at the northeastern end of the Newry Complex in 1934. Dr. Reynolds originally termed the part of the rock which had been mobile "fused sediment" and of this part she wrote (1934, p. 595-6) "That this material once existed in a molten condition is evidenced by the occurrence of lenticles of augite-hornfels scattered throughout its mass with irregular orientation, and by the obvious signs of movement shown by the matrix, which curves and twists round the fragments of augite-hornfels so as to suggest that it was stirred whilst in a highly viscous condition." Later Dr. Reynolds realized that there was no justification for the assumption of a molten state and in 1936 (p. 355) the more directive term "mobilized sediment" was substituted for the unsuitable term "fused sediment". Evidence was summarized supporting the interpretation that the mobilization was due to the operation of metasomatism accompanied by either internal pressure or externally applied /
applied stresses. A year later Backlund (1937) introduced the general term *rheomorphism* "for the process whereby a pre-existing rock becomes partially or completely mobilized or fused as a result of the introduction of migrating materials (in great or small amount) with concomitant rise of temperature" (D.L. Reynolds, 1937, p. 260).

(b) General Statement

There exists around the west, south-west and southern margins of the Loch Doon complex a zone in which the metamorphosed sediments have been mobilized. This zone is relatively narrow, the width varying from 3 yds. adjacent to the black shales up to 10-15 yds. adjacent to the greywackes. It separates the high grade metamorphic sediments from the marginal varieties of granodiorite.

The continuity of this zone along the granodiorite aureole contact makes it impossible to trace a bed along the strike into the complex; in the mobilized belt the identity of the bed being followed is lost.

The mobilized rocks show excellent flow structures (Fig. 6). In the field 'knots' or nodular patches can be distinguished around which the flow structures curve. In general these structures are roughly parallel to the margin of the complex, but /
but they are more intricate in certain localities. The rock is a mixed rock consisting of melanocratic host material in which leucocratic material has developed as pods, lenses and stringers, which, on further development, have the appearance of 'veins'. The flow structures in the 'veined' rock are curved in a spectacular manner and are conspicuous in the field. (Fig.16).

Towards the complex the mobilized sediment grades into a coarse-grained rock from which stringers and veins are absent. The whole appearance of this type is more 'igneous-looking'. From this stage there is a gradual transformation into a rock which has an appearance that would formerly have been accepted as 'igneous' by most petrographers — and would still by many. There is no sharp contrast - only a gradual transition; the rock becomes coarser in grain, lighter in colour, and the texture appears more 'igneous-looking'. The resulting rock is either a quartz-diorite, or a marginal variety of granodiorite. There is no actual contact, but for descriptive purposes an arbitrary line has been drawn based on macroscopic characters, dividing the marginal granodiorite from the transitional series of transformed sediments. This will be referred to as the 'contact'.

The contact phenomena were studied in detail at two localities, namely:-
(1) at a height of approximately 800 ft. on the south slope of Buchan Hill, and

(2) on the northern summit of Buchan Hill.

The mobilization and transformation of sediments was also observed at numerous localities around the west, south-west and southern margins of the complex. On the western margin, for example, the phenomena are well displayed in Buchan Burn; half a mile south-west of Loch Enoch; and lower down in the course of the same burn, north-west of Craignine. Along the south-west margin mobilized sediments were observed along the north-east slope of Mulldonoch. (Fig. 17).

(1) **At a height of approximately 800 ft., on the south slope of Buchan Hill.**

Adjacent to granodiorite the contact zone has a width of twelve yards. Its outer part is remarkable for its spectacular flow structures, and its inner portion for its perfect transition from feldspathized metamorphosed sediment into marginal varieties of granodiorite.

(i) **Mobilization**

The rocks in the mobilized part of the contact zone are "mixed" rocks consisting of dark coloured, highly metamorphosed, flaggy greywackes in which pods, lenses and stringers of leucocratic material are developed. The melanocratic host is a plagioclase /
plagioclase-biotite-hornblende-hornfels similar to that described above (p. 47). Occasionally biotite is more abundant than hornblende and the hornfels is then a plagioclase-hornblende-biotite-hornfels. The leucocratic material generally consists of quartz and plagioclase, with subordinate biotite and hornblende; accessory iron-ores and tourmaline; and secondary chlorite and calcite. If this leucocratic assemblage is considered as granitic then the rocks can be described as migmatites, or "mixed" rocks.

Evidence that the rocks in this zone have become mobilized or rheomorphic at a certain stage in their history is supplied by an excellent vertical exposure; the flow structures are well seen on the weathered surface. The contortion of the stringers bears eloquent testimony to the reality of mobilization (Fig. 16).

Quartz veins, an inch or two thick, cut across the dominant plane of flow, which in this case is vertical. They are unaffected by the mobilization and clearly later than it.

Ten specimens (Nos. 410-408, 214-216, 407-404) were collected over a distance of twelve yards and are worthy of detailed description as they show all stages of transformation from the metamorphosed sediment to a rock which, though possessing the same mineralogical composition as a quartz-diorite or granodiorite, still retains metamorphic texture. The classification of such rocks /
rocks is exceedingly difficult. According to the nomenclature proposed by Salomon (1896) the end member of this series is a "contact-quartz-diorite", i.e. quartz-dioritic in composition but metamorphic in origin.

Fig. 10 illustrates a stage in the development of pods of leucocratic material in fine grained hornblende-biotite-hornfels 12 yds. from the complex (No. 410). The leucocratic material consists of quartz with subordinate plagioclase, biotite, (?) cordierite, hornblende and iron-ores.

Description of specimen No. 409: a hornblende-plagioclase-biotite-hornfels collected 11 yds. from the contact, distinctly coarser grained than 410.

Microscopically the host material is seen to consist of quartz, plagioclase, biotite and hornblende with accessory zircon, apatite and iron-ores. The groundmass is generally coarse grained but occasional finer grained lenticular patches occur. Its texture is dominantly granoblastic, with pronounced banding in places (lepidoblastic).

Quartz occurs as granules varying from less than 0.1 mm. to more than 0.8 mm. in diameter. There is a tendency for some of the crystals to be intersertal.

Plagioclase occurs as small granular crystals in the fine /
fine grained lenticular patches, and in the coarser grained groundmass as abundant subhedral medium to large porphyroblasts (greater than 5.0 mm. square). The average composition is that of andesine An$_{35}$ with a range from An$_{30}$ to An$_{50}$. Zoned crystals are not uncommon, and their range in composition is often An$_{45}$ at the core to An$_{30-35}$ at the margin. Alteration to sericite and kaolin is slight. The porphyroblasts have irregular boundaries and lobes around quartz; they include a large number of quartz grains. These facts indicate that the porphyroblasts have grown in situ at the expense of quartz.

**Biotite** is very abundant as ragged sub-parallel flakes. It is strongly pleochroic; X = pale golden brown, Y = sepia brown, Z = very dark foxy red brown; it thus differs slightly from the biotite of No. 414. Pleochroic haloes are common. In certain patches the biotite has been both bleached and altered to epidote and chlorite.

**Hornblende** is scarce and occurs as pale green, medium-sized acicular crystals associated with biotite.

**Accessories.** Of these minerals only apatite is noteworthy. It occurs as small euhedral crystals and also as granules. Minute granules and prismatic crystals occur in small apatite-rich lenses. The lenses measure up to 4.5 mm. long and 0.4 mm. wide.

The /
The finer-grained areas contain abundant iron-ores and in some cases pyrite.

The leucocratic material is confined to pods, or vein-like channels which form only a small proportion of the specimen. The "veins" average 4.00 mm. in width and the adjoining hornfels is biotite-rich where it margins them. They consist of anhedral quartz crystals; medium to large porphyroblasts of plagioclase (andesine An35); small and medium-sized biotite flakes often bleached and greatly altered; and accessory iron-ores and apatite.

Description of No. 214: The best flow structures are exhibited between five and seven yards from the contact in the mobilized sediment. Specimen No. 214 was collected from this locality.

In hand specimen it is a very dark bluey-grey, fine-grained hornfels showing flow structures and "veining". The outstanding feature is the curving and contortion of the leucocratic material which occurs in pods and "veins"). Every stage in the evolution of pods into stringers can be seen. The host or parent rock consists of the dominant type of high grade metamorphic rock in this locality - namely plagioclase-biotite-hornblende-hornfels, similar in most respects to No. 409. The major difference is that some bands are hornblende-rich whilst others are biotite-rich. These mafic-rich bands show marked parallelism.
parallelism of platey crystals, and curve round the margins of the leucocratic areas.

Microscopically the groundmass of the hornfels is coarser than that of No. 409 and consists of granular crystals of quartz and plagioclase (andesine An$_{35}$). The average diameter of the granules is greater than 0.2 mm. Biotite is present as minute ragged flakes, and as small and medium-sized flakes which occasionally form clusters. Pleochroic haloes are common. Hornblende occurs as small granules and as medium sized crystals. It is faintly pleochroic, with $X =$ colourless, $Y =$ pale green, $Z =$ olive-green. Rarely the crystals possess pleochroic haloes. Clusters of granular hornblende along with biotite, and iron-ores are sometimes present. The biotite and hornblende are sometimes bleached and altered in the neighbourhood of the veins.

The leucocratic material consists of quartz, plagioclase, biotite, hornblende and accessory iron-ores and tourmaline, with secondary chloritic minerals and some calcite.

Quartz, by far the most abundant mineral, occurs as large anhedral crystals often greater than 1.0 mm. in diameter. Inclusions are plagioclase, biotite, hornblende, iron-ores and minute opaque matter.

Plagioclase is present as small granular inclusions in quartz, and as medium-sized subhedral crystals up to 1.0 x 0.6 mm. The /
The average composition is andesine $\text{An}_{30-35}$ with a range from oligoclase $\text{An}_{25}$ to andesine $\text{An}_{45}$. The plagioclase is markedly sericitised and this contrasts with the fresher plagioclase in the melanocratic host.

Biotite occurs as small anhedral flakes but is rare. Hornblende is also scarce but occurs as medium-sized subhedral crystals. Analysis overleaf.

Compared with No. 414 (see Table II), this rock is richer in $\text{SiO}_2$. This is due to the predominance of quartz in the leucocratic pods and stringers. Other increases are of $\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}$, with decreases of $\text{Fe}_2\text{O}_3$, $\text{FeO}$, $\text{MgO}$, $\text{CaO}$ and $\text{Na}_2\text{O}$. The significance of these changes will be discussed later (p. 289).

Towards the complex the leucocratic material has a higher feldspar/quartz ratio, and the plagioclase porphyroblasts in the melanocratic hornfels increase in size. This stage is well seen in specimen No. 216 collected two feet distant from No. 214.

**Description of No. 216:** This specimen differs from No. 214 in possessing a much higher proportion of leucocratic material in well developed and wider veins. The veins vary in thickness from 2.0 - 3.0 mm, with an average of about 4.0 mm. (Fig. 57).

The veins and leucocratic areas consist of abundant quartz /
**ANALYSIS C.**

Mobilized sediment (No. 214), from the centre of the mobilized zone and about 18 ft. from the contact-quartz-diorite, at a height of approximately 800 ft., on the south slope of Buchan Hill. Fig. 3. New Analysis.

Analyst: W.H. Herdsman. (Table I)

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100.26 1539.1 100.0

**VON WOLFF VALUES**

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quartz, subordinate plagioclase, infrequent biotite and hornblende and iron-ores.

Quartz occurs as small irregular grains and as anhedral, medium and large porphyroblasts. The large porphyroblasts average 2.0 x 2.0 mm. and have clearly grown by the amalgamation of smaller crystals. The shadowy outlines of these former individual grains can sometimes be seen. Undulose extinction is common.

Plagioclase is much more abundant than in No. 214 but it is still subordinate to quartz. It generally occurs as small, and medium subhedral crystals. The composition is andesine (average An$_{35-40}$), with a range from An$_{35}$ to An$_{45}$. Some porphyroblasts are slightly altered to sericite.

Biotite is scarce and occurs as medium-sized poikiloblastic flakes. Rarely the flakes form clots with iron-ores and hornblende.

Hornblende is present infrequently as medium-sized poikiloblastic crystals similar in habit to those of the biotite.

The host rock is a plagioclase-hornblende-biotite-hornfels. The groundmass is a granular mosaic of quartz and plagioclase. The abundance of biotite and hornblende varies greatly from band to band. Some bands are biotite-rich, others are richer in hornblende, while yet others are equally rich in both constituents.
Hornblende is generally very abundant (more than 50%) as small anhedral grains (<0.05 mm.), medium subhedral crystals and large subhedral porphyroblasts (1.5 x 0.8 mm.). It is strongly pleochroic, with X = colourless, Y = pale green, and Z = brownish olive-green. The crystals have marked linear orientation in bands between the veins. They occasionally form clots with the other ferromagnesiants, biotite and iron-ores.

The widespread commencement of the development of medium-sized porphyroblasts of plagioclase in the groundmass is conspicuous. The crystals are poikiloblastic and enclose numerous small granules of quartz, iron-ores and rounded crystals of hornblende. The composition is andesine An\textsubscript{45}.

The mobilized zone ends approximately 3 yds. from the contact and is marked by the disappearance of the "veins" and stringers. The rock now becomes coarser grained, more "igneous-looking" and homogeneous. Specimen No. 406, collected 9 ft. from the contact, is typical of this stage.

Description of No. 406. Microscopically the rock is seen to consist essentially of quartz, plagioclase, biotite and hornblende, with accessory zircon, apatite and iron-ores.

Quartz is present as small, medium-sized granular crystals and occasionally as large porphyroblasts (>1.0 mm. in diameter). Infrequently two or more crystals form a quartzose patch. Undulose extinction is common. Inclusions are of minute opaque /
opaque matter and very small granules of biotite and hornblende. 

Plagioclase occurs as small granular crystals in the groundmass (0.3 - 0.2 mm. in diam.), and as medium and large porphyroblasts. The increase in size of the large porphyroblasts is one of the most striking and significant changes. They reach a maximum size of 1.5 x 1.0 mm. and are generally crowded with granules of quartz, biotite and hornblende. The average composition is andesine An₄₀.

Hornblende is present abundantly as small granules, commonly as medium-sized porphyroblasts and occasionally as large anhedral poikiloblastic individuals. The amphibole is a moderately pleochroic variety, with X = colourless, Y = pale green, Z = light olive green. It is optically negative, but rarely, in the more leucocratic areas, it is positive (pargasite). The granular inclusions in the large poikiloblasts are quartz and plagioclase. Commonly several individual crystals and porphyroblasts form an aggregate along with biotite and iron-ores.

Biotite is common and occurs as small crystallloblastic flakes (<0.1 mm.) and occasionally as large subhedral flakes (average 0.8 mm. in length). It is strongly pleochroic with X = yellowish brown, Y = brown, Z = reddish brown.

Iron-ores are the most abundant accessory and occur as scattered /
scattered granules or square pegs (0.1 mm. square). Zircon and apatite occur as anhedral grains or prismatic crystals in the groundmass.

(ii) Transformation

Across the remaining nine feet to the "contact" of the complex there is a gradual transition from the plagioclase-biotite-hornblende-hornfels just described, into a rock which has an "igneous" appearance. The transformation has been effected by the feldspathization of the hornfels; the gradual increase in grain-size; and the gradual elimination of metamorphic texture with concomitant increase of granitic texture.

The feldspathization is well shown by specimen No. 405 which was collected six feet from No. 406 described above.

Description of specimen No. 405. In hand specimen this rock has a definite metamorphic textural appearance but it is coarser grained than the hornfels farther out in the aureole. It is strongly banded. Outstanding, however, are large tabular grey porphyroblasts of feldspar which frequently exceed 5.0 x 5.0 mm. (Fig. 58).

Microscopically the rock has the same mineralogical composition as No. 406 but there is a considerable difference in the proportions of the minerals present.

Quartz /
Quartz is less abundant than before and occurs as grains (0.1 mm. in diam.) and anhedral crystals which measure up to 1.0 x 1.0 mm. Many of the crystals are interstitial in character; others occur as inclusions in plagioclase, and most crystals have an irregular border with the feldspar. It is clear that some quartz has been replaced by plagioclase.

Plagioclase is present abundantly as small subhedral crystals in the groundmass (>0.2 mm. in diam.); medium subhedral crystals (average size 1.2 x 0.7 mm.); and large tabular porphyroblasts (maximum size 6.0 x 3.0 mm.). The large and small crystals all have the same range in composition, the average being andesine, An\textsubscript{35-40}. The medium-sized and large porphyroblasts are often zoned and are characterized by patchy extinction and internal irregularities. The range in composition is from An\textsubscript{30} to An\textsubscript{55}. Continuous and oscillatory zoning are present and cores as calcic as An\textsubscript{55} and margins as sodic as An\textsubscript{35} are general. The following are examples to show the variable composition of oscillatory zoned crystals:

(i) An. %  Margin 40-45 \rightarrow 45 \rightarrow 50 \rightarrow 45-50 \rightarrow 50-55 \rightarrow 50 \rightarrow 45 \rightarrow 50 \rightarrow 55 \rightarrow 50 \rightarrow 55: Core.

(ii) An. %  Margin 30-35 \rightarrow 40 \rightarrow 45 \rightarrow 35 \rightarrow 45 \rightarrow 45-50 \rightarrow 35-40 \rightarrow 50: Core.

Inclusions are small rounded crystals of biotite, hornblende, and granules /
granules of quartz, iron-ores and apatite. Some of the larger porphyroblasts have been formed by the union of smaller individual crystals in approximate parallelism.

**Biotite** occurs abundantly as small crystalloblastic flakes, medium-sized subhedral flakes (average 1.0 x 0.5 mm.) and rarely as large flakes (over 2.5 mm. in length). It is the same variety as occurs in No. 406 but the flakes have increased in size and have lost some of their crystalloblastic characters.

**Hornblende** occurs commonly as medium (1.0 x 0.6 mm.), and large poikiloblastic prismatic crystals (average 2.0 x 1.0 mm.) of pale brown and green colours. The brownish coloured variety generally occupies the core of the larger poikiloblastic crystals, the rims of which are green. The prismatic crystals are sieved by granular inclusions of quartz and plagioclase; others are biotite flakes, iron-ores and apatite. The mineral is faintly pleochroic with X = colourless or pale brown, Y = pale brownish green, Z = greenish brown. It is optically negative with Z - c = 20°. It frequently occurs in clots or aggregates with the other mafic minerals.

The rock is obviously of metamorphic origin, yet it has the mineralogical composition of a quartz-diorite—it will therefore be called a **contact-quartz-diorite** (p. 64).

The transformation continues inwards and the last metamorphic-looking /
metamorphic-looking rock (No. 404) was collected 3 ft. from No. 405. Specimen No. 404 is intermediate in the transition series between Nos. 405 and 403, the latter being taken as the first "igneous-looking" rock. The arbitrary line of "contact" has been drawn between Nos. 404 and 403 but it must be emphasized that in the field it is difficult to decide where to draw the line of demarcation between metamorphosed sediment and "igneous" rock as there is a complete gradation between the types.

Description of specimen No. 404: Contact-quartz-diorite. Macroscopically this is a mottled grey and black rock with large conspicuous tabular porphyroblasts of plagioclase which attain a maximum size of 9.0 mm. square (Fig. 60).

Microscopically the rock consists essentially of quartz, plagioclase, biotite and hornblende, with accessory potash feldspar, iron-ores, zircon, apatite, sphene and tourmaline.

Quartz occurs as anhedral interstitial crystals which range from 0.1 x 0.1 mm. to 2.0 x 2.0 mm. It has an irregular boundary with plagioclase and occurs commonly as inclusions in that mineral. It has been partially replaced by the plagioclase. Small micropegmatitic intergrowths with potash feldspar were observed.

Plagioclase is present as subhedral crystals which range from small granules (0.2 x 0.2 mm.), through medium-sized individuals /
individuals (average size 1.2 x 0.8 mm.), to large porphyroblasts reaching a maximum size of 9.0 mm. square. The composition is andesine (average $\text{An}_{40}$ with a range from $\text{An}_{30}$ to $\text{An}_{50}$). Zoned crystals are present with cores of composition $\text{An}_{50}$ and margins of $\text{An}_{35}$. The same types of oscillatory zoning as described for specimen No. 405 (p. 73) are common. Internal irregularities of composition are also characteristic. It is significant that these porphyroblasts have the same composition and character as those developed farther out in the aureole. Inclusions are quartz, biotite, hornblende, iron-ores and apatite.

**Biotite** occurs abundantly as subhedral medium-sized flakes or well developed subhedral laths up to 1.5 mm. in length. It is strongly pleochroic, the pleochroism being the same as in Nos. 405 and 406 described above. Pleochroic haloes are common. The biotite is always closely associated with hornblende and iron-ores in clots or ragged nests, and it frequently rims the hornblende. Alteration to chlorite and sphene is slight.

**Hornblende** is abundant as medium and large anhedral and subhedral crystals which occasionally develop euhedral form and reach a maximum size of 3.0 x 1.2 mm. The larger porphyroblasts are occasionally sieved. The dominant type is common hornblende, which is moderately to strongly pleochroic with $X =$ colourless, $Y =$ green, $Z =$ olive-brown. The other variety, tremolite-actinolite /
tremolite-actinolite, is green and less strongly pleochroic (with
X = colourless, \( Y = \) very pale green, \( Z = \) pale green) and tends
to occur as aggregates of acicular crystals with biotite.
Rarely crystals have cores which may be (?) pyroxene. Inclusions
are biotite, plagioclase, iron-ores, apatite and zircon.

Of the other minerals potash feldspar is the most important. It is present in only small amount and is therefore
included as an accessory mineral. It occurs as very irregular,
intersertal material and very occasionally it is intergrown with
quartz as micropegmatite. Apatite is abundant as euhedral
prismatic crystals; iron-ores are scarce; zircon is plentiful;
sphene is uncommon and tourmaline (schorlite) is rare. Analysis
overleaf.

From Table I it will be seen that transformed sediment
(No. 404), transitional to marginal granodiorite has less SiO\(_2\)
than the mobilized sediment (No. 214). It has also a little
less Al\(_2\)O\(_3\), FeO and CaO, but more Fe\(_2\)O\(_3\), MgO, Na\(_2\)O, K\(_2\)O, TiO\(_2\)
and P\(_2\)O\(_5\). The appreciable differences are that whilst No. 404
is more alkali-rich, it has less alumina and lime. The signi-
ficance of these changes will be discussed in detail later (p.290)

The final phase of transformation to marginal grano-
diorite is effected by:-

(i) /
**ANALYSIS D.**

Transformed feldspathised sediment, or contact-quartz-diorite (No. 404), transitional to marginal granodiorite, at a height of approximately 800 ft., on the south slope of Buchan Hill. Fig. 3. New analysis. Analyst: W.H. Herdsman (Table I).

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(i) an increase in the amount of potash feldspar; 
(ii) a reduction in the mafic content; and 
(iii) a gradual disappearance of the crystalloblastic characters.

This phase is exhibited by specimen No. 408 which was collected 5 yds. from No. 404.

Description of No. 403: Hornblende-biotite-granodiorite

In hand specimen this rock is coarser grained and slightly more leucocratic than No. 404 but it is nevertheless strikingly similar. It possesses pronounced banding parallel to the margin of the complex (Fig. 61).

Microscopically it consists of quartz, plagioclase, potash feldspar, biotite and hornblende with accessory iron-ores, zircon, and apatite. The most significant difference from No. 404 is the increase of potash feldspar which occurs abundantly, both interstitially and as large anhedral plates which occasionally exceed 2.0 mm. in diameter.

Large plagioclase porphyroblasts with the same composition as those occurring farther out in the aureole, and with similar internal irregularities, are still conspicuous.

Biotite is more abundant than hornblende and the amount of ferromagnesiants is reduced although their aggregation into clots is more pronounced.

The /
The grain size is coarser and the texture is more "igneous-looking".

(2) On the northern summit of Buchan Hill.

The mobilized and transformed zone is not so well exposed as on the south slope of Buchan Hill, but its width can be estimated as approximately ten yards. The major part of the mobilized zone is obscured by a patch of bog in a depression lying to the west of the summit.

The hornfelses (Nos. 454, 453, 452, 451 and 450a) collected from the zone are of types similar to those previously described (pp. 50-3) farther out in the aureole. They are the mobilized and highly metamorphosed equivalents of mudstones and members of the greywacke series.

No. 454. Biotite-cordierite-hornfels

Quartz grains < 0.1 mm.; cordierite entirely pinitised.

No. 453. Muscovite-potash feldspar-cordierite-plagioclase-biotite-hornfels

Shows commencement of growth of plagioclase porphyroblasts. Biotite very abundant.

No. 452. Muscovite-potash feldspar-biotite-hornfels

Biotite abundant.

No. /
No. 451. **Muscovite-biotite-cordierite-hornfels**

Quartz mosaic of two grades: 0.1 mm. and 0.2 mm. Cordierite entirely pinitised. Small amount of muscovite developed.

These hornfelses are closely comparable with types farther out in the aureole, except that they are very much richer in biotite; they represent **basified hornfels**.

Specimen No. 450 was collected on the "contact". Within the bounds of a single slice from this specimen, the gradation can be seen from a *pyroxene-biotite-hornblende-hornfels* to a *contact-pyroxene-biotite-hornblende-quartz-diorite*.

This rock differs from the *contact-quartz-diorite* on the south slope of Buchan Hill in containing pyroxene, but nevertheless it has strong similarities in other respects to specimen No. 404 (p. 75). It is characterized by richness in ferromagnesians symptomatic of basification and by the possession of large tabular plagioclase porphyroblasts which indicate its feldspathization; moreover, there is complete gradation in grain size from fine to coarse. The rock is also similar to the *contact-pyroxene-hornblende-biotite-quartz-diorite* (No. 253) from the contact zone of the augitic marginal rock, south-west of the Corse Knowe of White Laggan (p. 228).

During the examination of the contact zone of the granodiorite, specimens were collected from a number of other localities /
localities. All these specimens can be matched with members of the series described above.

B. Mobilization and Transformation of the Black Shales

(a) General Statement

Mobilization and transformation of the black shales were observed one-third of a mile south-west of Loch Enoch and on Buchan Hill. These phenomena are well exposed adjacent to the granodiorite in the former locality and will be described in detail. This area has been mapped on the scale of 36 inches to the mile, for the contact is remarkably intricate (Fig. 2.).

The mobilization phenomena of the black shales are not so striking as those of the greywacke series and the zone is more narrow. The transformation of the black shales into granodiorite is remarkably abrupt; occasionally there is a sharp macroscopic contact, elsewhere the gradation is accomplished within half an inch.

1. One-third of a mile south-west of Loch Enoch

The black shales dip steeply to the west and north-west (70°-80°) and retain their N.-S. strike until they are
Within 3-5 yds. of the contact the hornfels loses its normal slaty character and becomes more massive and coarse-grained.

Specimen Nos. 494, 495a, 495b, 485 and 492b were collected from the mobilization and transformation zone and are worthy of detailed description as they show the changes through which the high grade metamorphosed shale passes as it is traced into the complex.

The first conspicuous change in the hand specimen is the development of large flakes of biotite along the bedding planes. This is well shown by No. 494 collected 7 ft. from the contact, at 1700 ft. on the Rig of Loch Enoch.

**Description of No. 494:** Potash feldspar-biotite-hornfels.

Macroscopically this is a light grey, compact rock. It is coarser grained than the high grade hornfels and possesses conspicuous flakes of biotite.

Microscopically /
Microscopically it consists essentially of quartz, biotite, potash feldspar, and plagioclase with accessory graphite, tourmaline and muscovite.

Quartz occurs as granules which range in diameter from <0.1 mm. up to 0.2 mm. Dust-like particles of (?) graphite, rounded crystals of graphite, and rarely minute granules of biotite form the inclusions present in the middles of the grains. The quartz grains are often rimmed with graphite.

Biotite is present more abundantly than in the rocks further from the contact (p. 34). It occurs as medium-sized flakes (length 0.5 - 0.7 mm.) which are markedly poikiloblastic. The pleochroism is strong with X = light straw brown, Y = pale brown, Z = light foxy-red brown. Pleochroic haloes are common. Inclusions of graphite are present along the cleavage traces and rims of the same mineral occasionally outline the flakes.

Potash feldspar is fairly abundant as interstitial anhedral blebs. In the coarser grained patches it appears in section as small poikiloblastic plates.

Plagioclase is rare and occurs in the coarser grained areas as granular crystals and as small subhedral tabular porphyroblasts (0.2 x 0.2 mm.).

The rock has clearly been basified, as indicated by the abundance /
abundance of biotite. At the same time there is an increase in grain size which does not take place uniformly. Certain lenticular patches and streaks, more or less parallel to the bedding, are coarser grained than the surrounding areas of hornfels. This stage is exhibited by specimen No. 495a collected 3 ft. from the marginal granodiorite.

**Description of No. 495a:** Plagioclase-potash-feldspar-biotite-hornfels. Microscopically the rock consists essentially of quartz, biotite, potash feldspar, and plagioclase with accessory graphite, iron-ores, zircon and apatite.

Quartz occurs as granular crystals which range in size from 0.1 mm. to 0.2 mm. in diameter. The crystals are now cleared of many of the minute inclusions although some of the larger graphitic inclusions are still retained.

Biotite is abundant - much more so than in No. 494 - as poikiloblastic flakes longer than 0.2 mm. The flakes are all approximately parallel to the bedding. In the coarser patches the flakes reach a length of over 1.5 mm. They have the same pleochroism as the biotite of No. 494.

Potash feldspar is more abundant than in No. 494. It occurs as granular crystals and less commonly as larger anhedral plates.

Plagioclase /
Plagioclase has increased in amount and occurs both as anhedral granules and as small and medium-sized porphyroblasts which reach a maximum size of over 0.2 x 0.1 mm. The composition is andesine An$_{30}$.

Graphite occurs as clots or aggregates which occasionally are elongated and skeletal in form.

Iron-ores occur as scattered pegs, sometimes enclosed in biotite.

Zircon and apatite occur most frequently as granular crystals scattered throughout the groundmass and also are present as inclusions in biotite.

No. 495b collected 2 ft. from No. 495a is very similar. The process of basification and the increase in grain size have been carried yet another stage further.

Description of No. 495b: Plagioclase-potash feldspar-biotite-hornfels. Macroscopically this is a dark and light grey mottled rock, with abundant glistening biotite flakes.

It has the same mineralogical composition as 495a. The following are the chief differences:

1. Quartz now ranges from < 0.1 mm. up to medium-sized porphyroblasts > 1.0 mm. in diameter. The crystals are free from all inclusions except the minute dust-like ones.

2. Biotite occurs still more abundantly and as larger flakes. Medium-sized euhedral and subhedral flakes which average 1.0 x 0.4 mm. are common.
3. Potash feldspar crystals have increased in size. Many measure 0.4 x 0.4 mm. Occasionally several small crystals have united to form a composite plate, as seen in section.

4. Plagioclase is more abundant but is subordinate to potash feldspar. The average composition is andesine $\text{An}_{35-40}$ with a range from labradorite $\text{An}_{50-55}$ to andesine $\text{An}_{30}$.

5. Graphite is scarce.

6. Apatite is an abundant accessory occurring as small granules and prismatic crystals scattered throughout the rock.

Within 2-3" of the contact, the grain size of the aureole rock (No. 485) has increased so that it has become comparable with that of the adjacent rocks inside the complex. The rock is extremely rich in biotite, the larger flakes of which give the rock a darker colour.

**Description of No. 485: Feldspar-garnet-biotite-hornfels.**

Microscopically this rock consists essentially of quartz, biotite, garnet, potash feldspar and plagioclase with accessory zircon, apatite, and secondary (?) rutile, chlorite and sericite.

Quartz occurs in the groundmass as irregular interstitial crystals which range in size from 0.1 mm. to over 1.0 mm. in diameter. The crystals have embayed irregular margins against potash feldspar and plagioclase, and since quartz also occurs as a common inclusion in the feldspars it is clearly being replaced by them.

Biotite /
Biotite occurs very abundantly as large, subhedral poikiloblastic flakes. The average size is 1.5 x 0.8 mm. but the larger flakes reach 3.0 x 1.0 mm. They are strongly pleochroic with X = light straw yellow, Y = golden brown, Z = deep foxy-red brown. Pleochroic haloes are very common; e.g. in one particular flake 43 haloes were counted. Rarely biotite is altered to chlorite and minute acicular crystals of (?) rutile. The inclusions present are quartz, potash feldspar, plagioclase, garnet, zircon and apatite. Biotite frequently occurs in clusters with garnet.

Garnet is very abundant and occurs as skeletal, subhedral and euhedral crystals which average 0.6 mm. in diameter. The maximum size is 2.0 x 1.5 mm. It is colourless or faintly pink and commonly contains small inclusions of biotite, quartz, iron-ores and graphite. Some crystals are embayed by biotite flakes which are replacing the garnet whilst others show distinct fractures along which biotite flakes have developed. (Fig. 32).

Potash feldspar is present both as small anhedral crystals and as medium-sized anhedral plates in the groundmass. It appears to be replacing quartz to some extent.

Plagioclase occurs as small subhedral crystals in the groundmass (along with potash feldspar and quartz). It ranges in size from poorly developed granular crystals of 0.1 x 0.05 mm. to /
to larger tabular crystals of 0.4 x 0.2 mm. It is andesine An30-35.

The accessories require no comment.

The change to the final stage in the transformation takes place rapidly; in some cases there is a hair-sharp contact while in others the gradation is effected in a distance of only half an inch.

The changes are:-

(i) Reduction in the amount of biotite.
(ii) Increase in the amount of plagioclase.
(iii) Development of quartzose patches.

These are well shown by specimens Nos. 486 and 492.

Description of No. 486: Biotite-granodiorite. Microscopically this rock consists of quartz, biotite, plagioclase, potash feldspar with accessory iron-ores, zircon and apatite, and secondary chlorite and muscovite.

Quartz occurs interstitially and as large anhedral crystals in the groundmass. Quartzose patches often cover areas greater than 2.0 mm. in diameter. Inclusions present are minute dust-like particles of (?) graphite.

Biotite is common as subhedral poikiloblastic flakes which average 1.5 mm. in length. Many are altered extensively to chlorite and rutile. The mineral is strongly pleochroic with /
with X = pale fawn, Y = pinkish brown, Z = golden brown. Pleochroic haloes are present but not so abundantly as they are in No. 485.

Plagioclase occurs as medium-sized and large subhedral porphyroblasts. The porphyroblasts reach a maximum size of 4.4 x 2.0 mm. They are commonly altered to sericite and kaolin. The composition is andesine An$_{35}$, and the crystals are unzoned.

Potash feldspar is present interstitially and as medium-sized and large anhedral plates. It is subordinate to plagioclase.

Description of No. 492b: Muscovite-biotite-granodiorite. The specimen was collected from the margin of the granodiorite tongue which crosses from the Rig of Loch Enoch to the south-east spur of the Merrick. The locality is at a height of 1700 ft. on the north-west slope of the Rig of Loch Enoch.

In hand specimen the rock is as leucocratic as the normal granodiorite. It is distinguished from the latter by the absence of hornblende and by its quartzose patches. The contact with the basified, biotite-rich hornfels is sharp in some places and gradational in others. The gradation however is rapid and is completed within half an inch. This contrasts with the more extended gradation observed on Buchan Hill (p. 72.).

Microscopically /
Microscopically the specimen consists of quartz, biotite, plagioclase, potash feldspar, and muscovite; with accessory iron-ores, zircon, apatite and sphene; and secondary chlorite and rutile.

Quartz is abundant and occurs partly in small irregular interstitial crystals but more commonly as large anhedral crystals which form patches over 4.0 mm. square. Small amounts of myrmekitic and micropegmatitic intergrowths are present.

Biotite is present as medium-sized and large subhedral flakes. The pleochroism is slightly different from that of the normal granodiorite, a golden tint being present. A characteristic example is $X = $ pale fawn, $Y = $ brown, $Z = $ golden red-brown. Some of the flakes are bleached, with formation of chlorite and rutile. Pleochroic haloes are common.

Plagioclase occurs abundantly as small granular crystals (0.3 x 0.2 mm.), medium-sized subhedral tabular crystals (1.2 x 0.7 mm.), and as large porphyroblasts (over 3.0 x 1.2 mm.). Some of the porphyroblasts are altered to sericite extensively. The composition averages andesine $\text{An}_{35-40}$ with a range from $\text{An}_{30}$ to $\text{An}_{40}$. Zoned crystals are rare. Inclusions are rounded flakes of biotite, and granules of zircon and apatite.

Potash feldspar is present as small subhedral crystals in the groundmass, as medium-sized subhedral crystals, and rarely as /
as large anhedral plates. Inclusions are small biotite flakes, irregular relics of plagioclase and quartz and granules of apatite. Microcline is sometimes present but the potash feldspar is usually orthoclase. The plates have an irregular border against plagioclase.

Muscovite occurs infrequently as anhedral and subhedral flakes, which reach 1.2 x 1.0 mm. in size.

Apatite and iron-ores are the most common accessories. Both occur as inclusions in biotite. The iron-ores, together with biotite flakes, tend to form clots.

This type of biotite-granodiorite is peculiar to this area, and although specially looked for in other areas it has not been found elsewhere. It passes inwards into hornblende-biotite-granodiorite. It is significant that this type of granodiorite occurs only adjacent to the altered shales.
VIII. CONTACT PHENOMENA IN THE HYPERSTHENIC ROCK AUREOLE

(a) **General Statement**

The contact phenomena of the north-west hypersthenic ('norite') mass have been described in great detail by McIntyre (1947, pp. 21-39). The study of the sediments in the aureole of the southern mass of the hypersthenic rock aureole was only incidental to the present investigation; however, whilst mapping the contact of the 'norite', at three localities it was found difficult to distinguish the various types. 25 specimens were therefore collected and sectioned. The three localities are:-

(a) Well Burn, 1100 ft.; (b) White Laggan Burn (Laggan Linn and downstream); (c) Black Laggan Burn, 1026 ft.

(b) **Metamorphic facies**

The rocks of high grade metamorphism near the contact of the hypersthenic rock were found to consist of the following types:-


5. Cordierite-biotite-hornfels (No. 308).

These /
These types correspond to those described above (p. 56) from the aureole of the granodiorite. The hornblende facies is, however, missing. In two particular cases (Nos. 318, 576), iron-ores are remarkably abundant. The hornfelses are the metamorphosed equivalents of the fine, medium and coarse grained greywackes, and grits with shaly pellicles.


7. Amphibolite (Nos. 312, 580) and plagioclase-amphibolite (No. 579).

The sphene-tremolite-hornfels has a finely banded structure and occurs at Laggan Linn, White Laggan Burn. The outstanding feature is the lack of lime feldspar, the Ca being present in the tremolite. The hornfels is a highly metamorphosed lime-silicate rock, comparable with the calc-flintas occurring around the Cornish granites.

The amphibolite outcrops where the contact crosses the White Laggan Burn approximately 200 yds. downstream from the waterfall. It is of interest as it is one of the rare occurrences where the calcareous mudstones lie adjacent to the pluton.

The metamorphism of the Arenig mudstones has not been studied in detail as they make up only a small proportion of the aureole rocks. From a study of the specimens collected for reference it is clear that the metamorphosed equivalents of the argillaceous /
argillaceous mudstones are predominantly cordierite-hornfels. The metamorphism of the calcareous mudstones gives rise to a different assemblage, generally rich in plagioclase and pyroxene in the high grade.

(c) Amphibolite

**Description of No. 312: Amphibolite.** Macroscopically this is a very fine-grained, dark grey, compact rock cut by numerous whitish pink feldspar-rich veins averaging $\frac{1}{4}-\frac{1}{2}$" in thickness.

Microscopically the **host rock** consists essentially of brown and green hornblende, plagioclase, and quartz, with abundant accessory iron-ores. Texturally the rock is granoblastic, the essential minerals occurring as subhedral and anhedral granules in a fine-grained mosaic. There is, however, a great deal of variation; a single slide shows every gradation from a very fine-grained mosaic to medium and coarse-grained textures.

The **veins** consist of abundant plagioclase, brown and green hornblende, pyroxene, and bleached biotite, with abundant accessory iron-ores. The veins are bordered by a basic margin consisting of a concentration of brown hornblende and abundant iron-ores.

**Host Rock**

**Brown Hornblende** occurs abundantly as small dark brown granules /
granules which average 0.1 mm. in diameter and also as larger subhedral to euhedral short prismatic crystals which range up to 1.0 x 0.3 mm. in size. It is strongly pleochroic with X = pale yellow brown, Y = clear brown, Z = dark red brown. Other optical properties: Z ÷ c = 18°; optically negative; dispersion r < u; 2V = 80°. Some crystals have a green tint and it is obvious that the brown and green hornblende varieties grade into one another.

**Green Hornblende** occurs infrequently as part of a brown hornblende crystal and rarely as a single crystal. It is intimately and closely associated with the brown hornblende and the remnants of biotite flakes. It is mostly present in hornblende clots in which it forms anhedral irregular crystals. It appears to be replacing brown hornblende. Z ÷ c = 18°.

**Plagioclase** is present as small granular crystals (average less than 0.1 mm. in diameter) accompanying quartz in the granoblastic mosaic. It also occurs as subhedral porphyroblasts which range from 0.2 x 0.2 mm. to 1.0 x 0.4 mm., in the coarser grade. Carlsbad and albite twinning is characteristic. The average composition is that of andesine An25, the range being from An45 to An25-30. Zoned crystals are common and the average composition of the core is andesine An45 with a more sodic margin averaging oligoclase An25-30. Whilst the granular crystals have suffered /
suffered little alteration those near the veins have been extensively sericitised and kaolinised. Inclusions are rare, but, when present, are minute granules of brown hornblende, iron ores and long acicular gas cavities.

Quartz is present as anhedral and subhedral granular crystals in the mosaic along with plagioclase. It is absent from the coarser parts.

Iron-ores, grey to yellow grey under reflected light, occur as subhedral opaque rectangular or irregular crystals with a tendency to occur in skeletal form and as large clots or aggregates which commonly reach 1.0 x 0.5 mm. in size. The vein material is of much coarser grain. It consists of abundant plagioclase, brown hornblende, bleached biotite, green hornblende, pyroxene, and iron ores.

Plagioclase is of the same composition as that of the main mass of the rock, namely andesine An$_{40}$. However, the crystals are much larger and frequently exceed 2.0 x 1.0 mm. They are greatly altered and many are merely masses of sericite flakes and kaolin. The vein minerals which are absent from the host rock are clino-pyroxene and bleached biotite. Clino-pyroxene occurs as small granules, and as medium-sized and large subhedral prismatic crystals. It is often present as colourless cores /
cores in brownish green hornblende crystals. It is augite; optically negative; $Z^c = 40-42^\circ$. Augite is to be found in clusters with the other mafic minerals where it has presumably undergone replacement by the green hornblende which rims it.

Biotite in crystals averaging 1.5 x 1.0 mm. is common, but almost all of the flakes are bleached entirely, and are now colourless. A few flakes have escaped bleaching and are a peculiar golden red-brown. Chlorite is a common alteration product. Iron ores are exceptionally abundant and large crystals of irregular shape are common.

(d) Rheomorphic veins

At the same locality rheomorphic veins of ultrametamorphosed sediment were observed and Fig. 7 is a sketch of the occurrence as exposed. The veins are more resistant to weathering than the host rock, and stand out as knotted, gnarled, irregular twisting stringers (No. 580).

Macroscopically the host rock (No. 579) is of complex constitution. It is lighter in colour than the amphibolite (No. 312) but denser and more compact.

Microscopically in this rock the following assemblages were observed in different bands and lenses of the slide (No. 579):-

(i) /
(i) Diopside-prehnite
(ii) Biotite-plagioclase-brown hornblende
(iii) Pyroxene-red brown biotite-plagioclase
(iv) Brown hornblende-plagioclase
(v) Green hornblende-biotite-brown hornblende-plagioclase
(vi) Red brown biotite-green biotite-iron ores-prehnite
(vii) Plagioclase lenses or pods.

Pronounced basic rims surround the feldspathic lenses and border the irregular feldspathic bands.

The biotite is strongly pleochroic (Z = deep foxy-red), and is about as abundant as pyroxene, away from the veins and diopside-prehnite lenses. Pyroxene (diopsidic augite) occurs as small granules or aggregates of granules which occasionally form clots. Brown hornblende is present as small anhedral crystals associated with the other mafic minerals. It is remarkably abundant (a) as prismatic subhedral crystals closely associated with abundant iron ores in narrow veins (0.5 mm. wide) and (b) as anhedral and subhedral medium-sized crystals margining the diopside-rich lenses and bands. Fresh granular plagioclase crystals form the groundmass mosaic of the host rock as a whole, their average composition being andesine, $\text{An}_{45}$. The rheomorphic vein-rock was sectioned and Fig. 8 is a macroscopic sketch of the cut.

The /
The following assemblages were distinguished in a single large thin-section:

(i) Pyroxene-plagioclase-hornblende-quartz (granoblastic)
(ii) Biotite-pyroxene-plagioclase-hornblende-quartz.
(iii) Hornblende-biotite-plagioclase-pyroxene (medium grained crystalloblastic).
(iv) Diopside-plagioclase-iron ores.
(v) Biotite-hornblende-iron ores (clots or aggregates).

These assemblages are similar to those of the host rock.

(e) Nature of the contact

The south-western margin of the hypersthenic rock cuts across Well Burn at a height of approximately 1100 ft. At this locality there is a macroscopic gradation from the contact sediments to the fine-grained marginal type of hypersthenic rock. Some evidence of mobilization is present but it is not so clearly defined as on Buchan Hill. The hornfels is predominantly plagioclase-biotite-hornfels which has an abrupt gradation (cf. McIntyre, 1947, p. 34) into biotite-hypersthene-quartz-diorite.

The southernmost outcrop of the pluton occurs in White Laggan Burn. The contact runs along the line of the burn from near Laggan Linn downstream for a distance of 200 yds. There is an excellent exposure of the contact at Laggan Linn. The metamorphosed sediments are vertical and strike E.N.E. - W.S.W. They /
They are undisturbed right up to the contact with the hyperstenic rock, which could equally well be vertical or horizontal or dip outwards at an intermediate angle, at this point. No mobilization has taken place.

At the third locality, approximately a quarter of a mile east of Black Laggan Farm, in Black Laggan Burn, the contact coincides with the site of a waterfall at the head of a gorge. At the top of the fall and on the upper part of the north wall of the gorge the hornfels is well exposed, whilst the marginal type of hypersthenic rock forms the rest of the gorge. The contact is therefore midway up the north wall of the gorge which is inaccessible. This disposition would suggest that the contact is almost horizontal or inclined at a very low angle.

Additional evidence is to be obtained from the manner in which the contact "V" up the valleys of Well Burn and White Laggan Burn; the relations suggest that the contact dips gently to the south and this implies that the hypersthenic rock forms the roof of the pluton.

Against this interpretation is the vertical disposition of the structural planes in the hypersthenic rock, as is shown below (p. 274).

The evidence as to the inclination of the contact is thus conflicting and unfortunately inconclusive.
IX. SUMMARY OF EVIDENCE FROM THE CONTACT AUREOLE

A. Field Evidence

(a) Relation of the country rocks to the granodiorite

(i) The west and south-west margins of the pluton are steeply inclined.

(ii) As the sediments are traced towards the complex they are increasingly metamorphosed.

(iii) The sediments have suffered structural deflection (Section XVIII).

(iv) A zone of mobilized sediment is present in the contact zone. Its width is 10-15 yds. adjacent to the greywackes, and less than 5 yds adjacent to the black shales.

(v) Passing inwards towards the pluton the zone of mobilization is succeeded by the zone of transformation.

(1) There is a gradual transition over 8 ft. across, from the high grade metamorphosed greywacke into an "igneous-looking" rock designated as "contact-quartz-diorite". This in turn grades into the marginal granodiorite over a distance of 6 yds. It must be emphasised that there is no sharp contact, it is difficult to decide where to draw the line of demarcation between metamorphosed sediment and "igneous" rock.

(2) The transformation of the altered black shales into biotite-granodiorite is abrupt; occasionally there is a sharp macroscopic contact, elsewhere the gradation is accomplished within half an inch.

(b) /
(b) Relation of the country rocks to the hypersthenic rocks

(i) The inclination of the contact is uncertain.

(ii) As the sediments are traced towards the pluton they are increasingly metamorphosed.

(iii) The strike of the sediments is deflected but little, and frequently not at all.

(iv) There is little or no mobilization of sediment near the contact.

(v) The transformation of the hornfels into biotite-hypersthene-quartz-diorite is generally abrupt but there are gradations at certain localities.

B. Petrography

(a) Metamorphism of the Black Shales

As the black shales are traced towards the pluton they are altered by thermal metamorphism into cordierite-hornfelses. The sequence of textural and mineralogical changes is described above. That the advance of metamorphism did not progress at the same rate in all areas is shown by the presence of patches and bands which are coarser and at a higher grade of metamorphism than the surrounding altered shale.

Basification of the mobilized and highly metamorphosed black shales near the contact is evidenced by the increase in the amount of biotite as the complex is approached.

That /
That transference of material into the hornfels took place is proved by the following mineralogical evidence:-

(i) The occurrence of plagioclase porphyroblasts identical in both composition and character to those of the neighbouring granodiorite. No visible feeding channels exist.

(ii) The presence of potash feldspar only in the metamorphosed shales of high grade.

(iii) The poikiloblastic character of the potash feldspar and biotite.

The transformation from plagioclase-potash feldspar-biotite-hornfels to biotite-granodiorite is effected by:-

(1) reduction in the amount of biotite;
(2) increase in the amount of plagioclase; and
(3) increase in quartz.

(b) Metamorphism of the greywacke series

The alteration of members of the greywacke series into six types of hornfels of high grade metamorphism is described above. In particular the development of biotite-hornblende-plagioclase-hornfels is described in detail and chemical analyses are given.

From a microscopic investigation of the high grade metamorphosed fine-grained greywacke it is shown that:-

(1) Recrystallization has often taken place in isolated patches.

(ii)
(ii) Hornblende porphyroblasts develop from small granules.

(iii) In some cases hornblende has developed from biotite.

(iv) Biotite flakes have a marked orientation parallel to the bedding.

(v) The amounts of biotite and hornblende increase towards the margin of the complex.

(vi) Quartz recrystallizes from a fine-grained mosaic to large porphyroblasts. This development is demonstrated by the presence of minute inclusions in the crystal aligned parallel to the bedding - akin to helicitic structure (see Goodspeed, 1937, p. 133).

(vii) Isolated plagioclase porphyroblasts have developed without any visible feeders.

(viii) The plagioclase porphyroblasts grew at the expense of quartz.

From the above evidence it is clear that near the complex the metamorphism was accompanied by introduction of material from the pluton.

(c) Mobilization

(i) The host material, plagioclase-biotite-hornblende-hornfels, represents highly altered greywacke.

(ii) Pods or lenses of leucocratic material consisting of quartz, plagioclase, biotite and hornblende with iron-ores have developed in the host rock. The absence of visible feeding channels precludes a magmatic genesis for the leucocratic bodies.

(iii) Coalescence of pods gave rise to stringers or "veins" which have the same composition as the pods but are often hydrothermally altered.

(iv) /
(iv) The veins have been avenues of diffusion, for biotite and hornblende have undergone alteration and bleaching in their neighbourhood.

(v) The pods occasionally have basic rims of biotite.

(vi) Towards the pluton the leucocratic material becomes more feldspathic and coarser grained. At the same time medium-sized plagioclase porphyroblasts become conspicuous in the host rock.

(vii) The "veins" or stringers disappear 3 yds. from the "contact" as the transformation zone is reached.

(d) Transformation

The transformation can be traced as a perfect gradation from a plagioclase-biotite-hornblende-hornfels into contact-quartz-diorite with an "igneous" appearance and finally into a marginal variety of granodiorite.

This transformation is effected by:-

1. feldspathization;
2. increase in grain size; and
3. loss of metamorphic texture.

The following evidence demonstrates that transformation took place in the solid:-

1. All stages in the gradual change of the groundmass of the plagioclase-biotite-hornblende-hornfels by increase of grain size and elimination of metamorphic texture into an "igneous" rock can be traced.

2. The pronounced banding of the hornfels parallel to the bedding is retained in the marginal granodiorite to a lesser degree.
(iii) The occurrence of ferromagnesian clots is common to both these members of the series and their development can be traced through each stage in the transformation.

(iv) The plagioclase present in the groundmass and the large porphyroblasts both have the same range of composition. This would not be so if they had crystallized from a magma.

(v) The patchy extinction, variable composition and the enclosing of small crystals of the groundmass along the margins of and within the large composite porphyroblasts.

(vi) Relics of the poikiloblastic habit of the biotites and plagioclases of the hornfels can be seen in the same minerals in the marginal granodiorite.

(vii) The irregular plates of potash feldspar have a highly poikiloblastic habit.

(viii) The accessories of the end and penultimate members of the transformation series are identical.

From the above evidence it is clear that the results of two processes can be recognized. These processes are basification and feldspathization.

**Basification**

As the contact is approached the hornfelses become enriched in mafic minerals, especially in biotite. The enrichment in mafics takes place frequently in irregular patches, by recrystallization within the still existing sedimentary structure. The mineralogical evidence is clear that these minerals increase in abundance towards the complex and the chemical analyses show
an enrichment in Al Fe Mg and Ca. Whatever the source of the introduced material, the sedimentary rocks have been subjected to metasomatic metamorphism (Holmes and Reynolds, 1947).

It is also evident that the chemical elements migrated outwards from the pluton and of those that became fixed in the hornfelses Fe and Mg were dominant. This is an example of a "basic front" directly comparable with that described by D.L. Reynolds from the Newry Complex (1943, 1944). The material of the basic front may be either concentrated in a narrow zone or disseminated throughout a broad area; the biotite-rich rims to the "veins" in the mobilized sediment, and the contact aureole itself are examples of these two possibilities. The former are directly comparable to the biotite-rich selvedges around the leucocratic veins of the migmatite areas described by Wegmann (1935, p. 328), and interpreted by him as small scale examples of an Fe-Mg front. Basification of hornfels margining granite replacement bodies has been described by Goodspeed (1937) and D.L. Reynolds (1943). Many other workers, notably Backlund (1943) and Brammall (1944), have found that during the process of granitization Fe and Mg have been concentrated in certain areas which have consequently been basified. The chemical evidence for this process has been carefully compiled and analysed by D.L. /
D.L. Reynolds (1944) in her masterly paper on "The sequence of geochemical changes leading to granitization".

**Feldspathization**

Plagioclase porphyroblasts are found in the high grade hornfelses; they increase in size and in abundance through the transformation zone into the contact-quartz-diorite. The textural evidence proves that these porphyroblasts grew in the solid rock and were not intruded or injected by magmatic action. It is significant that the plagioclase porphyroblasts in the hornfelses are identical with those of the granodiorite.

Examples of feldspathization of aureole rocks are too numerous to list. The French School of petrologists, especially Fournet (1837), Delesse, Michel-Lévy and Lacroix, habitually used the term feldspathization to describe the growth of feldspars in country rock near granites. For these workers the terms feldspathization and granitization were sometimes regarded as synonymous. For many years the influence of Rosenbusch prevented the general acceptance of these views in Britain. Today, however, Read (1944, Pt. 2, p. 84) claims that the examples are so numerous and so clear that "Nobody except him who has learnt less and forgotten less than any Bourbon can deny the validity of the conversion of solid rocks to rocks of granitic character without passing through a magmatic stage". The evidence for and the significance /
significance of feldspathization have been recently discussed by numerous writers, notably by Grout (1937, p. 1539), Read (1943, 1944, 1946 and 1948) and Holmes (1945). To Read (1944, p. 81) "feldspathization means the aspect of granitization in which attention is directed to formation of feldspar".

The large porphyroblasts in the altered sediments are identical with the 'phenocrysts' in the granitic rocks. As Holmes (1945) has stated "The crucial nature of the evidence provided by the 'big feldspars' has long been realized, since no one has seriously doubted that they must have shared a common origin. Either they grew in solid rock or they crystallized from magma: identical feldspars could not be assumed to have originated in two entirely different physico-chemical environments". The field evidence at Loch Doon (p. 72) is sufficient to show the large porphyroblasts cannot have been intruded mechanically.

The large porphyroblasts may be zoned or unzoned; oscillatory, and continuously zoned crystals lie side by side with unzoned ones. The explanation of oscillatory zoning of plagioclase has been attempted by the magmatists. Homma (1936, p. 141) stated that each zone "would be due to up and downward circulation of the crystal on a large scale in the magma reservoir". This hypothesis is clearly not applicable to the plagioclase porphyroblasts in the marginal hornfelses of Loch Doon. A case comparable /
comparable to the Loch Doon occurrence is supplied by the hornfels in the Cornucopia area of the Wallowa Mountains of northeastern Oregon (Goodspeed, 1937, pp. 1133-38). There Goodspeed has traced the development of plagioclase porphyroblasts from initial allotrioblastic forms to fully developed idioblastic crystals. As in the Loch Doon marginal hornfelses and transformed sediments, he found that the plagioclase porphyroblasts are characterised by poikiloblastic structures, helizitic inclusions, and complex aggregates. He concluded (1937, p. 1138), "These studies of porphyroblasts show that many features such as zoning or selective "alteration" are not necessarily limited to the crystallization of magmas and lavas".

The oscillatory zoning and the complex character of the Loch Doon plagioclase porphyroblasts can be tentatively explained in principle only by metasomatic metamorphism. In this process the necessary material is introduced, fixed in the hornfels and the unrequired material is driven out. The introduced material is made up of constituents which, when added to the material already present in the hornfels, promote the growth of feldspar. It is unlikely that the introduced material will be of constant composition or that it will be introduced throughout the mass in equal amounts or at uniform rates. More likely the amounts and kinds of migrating elements will vary from time to time according /
according to ruling pressures, temperatures and chemical gradients. Therefore, during their growth, the porphyroblasts will receive varying amounts of the necessary elements. As these elements travel with greatest east along the intergranular boundaries, successive marginal zones of varying composition will be formed. MacGregor and Wilson (1939, pp. 207-8) describe this process as follows: "During metasomatism such rock types as are already saturated for one or more components will not show any reaction to those particular components should they be present in the penetrating medium. Different sediments will not have to order by special delivery from the ascending migmatization front their own exclusive transmuting emanation. Rather they take their pick of a selection brought around on approval, and give in exchange equivalent amounts of those commodities which the new purchases are expected to replace".

Further research on the variations of composition and the oscillatory zoning of plagioclases is required, however, before the problem can be fully solved.

It is clear, nevertheless, that feldspathization is part of the alkali front and an essential part of the granitization process. This particular rôle of feldspathization in the basic front (here including the alkali front) has been elucidated by /
X. MARGINAL GRANODIORITE

(a) General

The granodiorite occupies the major part of the complex, and was described by Gardiner and Reynolds (1932) as tonalite. It is adjacent to the country rocks everywhere except in the northwest and south-east where the hypersthenic rock outcrops, and locally where the augite-bearing rock is developed in patches along the western and south-western margin.

The term tonalite was applied by Vom Rath to a certain rock from Mount Tonale in the Tyrol. The type rock consists of abundant quartz, and andesine, with very small amounts of orthoclase as an accessory, and biotite. Johannsen and others have used the term as a synonym for quartz-diorite. In the Loch Doon rock, however, potash feldspar is an essential constituent, although subordinate to plagioclase. For this reason it is classified here as a granodiorite. More specifically it is a hornblende-biotite-granodiorite, except at a locality south-west of Loch Enoch where biotite-granodiorite and biotite-granodiorite-porphyry are found.

Adjacent to the margin, there is a zone, never more than 20 yds. in width in which the rock is finer grained, more banded and slightly darker than the average rock.
The boundary of the granodiorite has been mapped on a scale of 6" to a mile, but in special localities listed below it was mapped on a scale of 36" to one mile. The marginal variety of granodiorite was studied in detail at the following localities: (1) south slope of Buchan Hill; (2) Glenhead Wood; (3) south-west of Loch Enoch.

(b) Relationship of the granodiorite to the country rocks

Gardiner and Reynolds (1932) stated that "throughout a large part of the tonalite-hornfels margin there occurs a very distinct type of rock, dark, highly biotitic and distinctly denser than the normal tonalite. It is frequently fine-grained, a character which suggests chilling. There are also large parts of the margin where the normal tonalite is found in contact with altered sediments. The dark marginal form of the tonalite with its high density and large proportion of biotite bear considerable resemblance to dark basic patches found here and there in normal tonalite". They also stated that the igneous rock has sometimes thoroughly impregnated the metamorphosed rock in a manner well known in connection with the Scottish Caledonian intrusions.

Within 10-20 yds. of the contact the rocks are generally slightly darker than the average granodiorite of the complex, but otherwise there are no macroscopic differences. Usually the dark, fine-grained, marginal granodiorite is a dense, banded
or foliated\textsuperscript{3}, porphyritic hornblende-biotite-granodiorite with grey feldspar, specks of black amphibole and abundant black flakes of biotite. The relatively fine-grained marginal variety is not generally pyroxene-bearing. There is a complete gradation into the normal granodiorite on the one hand, and into the country rocks on the other. Both macroscopically and microscopically this gradation is from metamorphosed and feldspathised sediments through "igneous-looking" intermediate types to granodiorite. The transition is well exhibited on the south slope of Buchan Hill and has been described in detail above (p. 72). The gradational character of the margin makes it exceedingly difficult to map the boundary of the pluton. Locally, however, the normal granodiorite has a sharp contact with the metamorphosed sediments.

The contact is intricate and, on the western margin of the complex, narrow tongues of granodiorite running out from the main mass are a characteristic feature. A small isolated mass of granodiorite is shown on the one-inch Geological Survey map on the western side of the southern summit of Buchan Hill. Detailed mapping has revealed that it is joined to the complex by a narrow tongue, which, at one point, is only 25 yds. wide. The

\textsuperscript{3}foliated in the sense of parallel arrangement of crystals; not of bands of light and dark constituents.
The question arises whether this body is due to intrusion and veining of the hornfels by a granodiorite magma, or to replacement phenomena. Each possibility must be judged on its merits. The gradational margins of the contact-quartz-diorite and the marginal granodiorite are clearly due to the transformation of the sediments. In the aureole rocks small pods of 'granitic' material have developed, and these coalesce to give stringers and tongues. The different stages of this development are well displayed (a) in Buchan Burn to the north-west of Craignine, and (b) on the south and south-eastern slopes of Buchan Hill at heights of 1400 ft. and 1450 ft.

In rare cases it appears that the normal granodiorite may have become rheomorphic and intrusive to a small degree. The best example of this phenomenon does not lie within the southern area but is exposed in the contact zone on the west side of Loch Doon.

In the marginal granodiorite inclusions are numerous and range from blocks of altered sediment to mere "ghosts". They are described along with those found in the normal granodiorite, in the next section.
1. At a height of approximately 800 ft. on the south slope of Buchan Hill.

Serial specimens across the transformation from plagioclase-biotite-hornblende-hornfels through contact-quartzdiorite to marginal granodiorite have been described above (pp. 72-8). Three further specimens (Nos. 403, 402 and 401), continuing this series into the pluton, were collected at intervals of five yards. As the arbitrary line of "contact" has been drawn between Nos. 404 and 403, these specimens are all taken as varieties of marginal granodiorite. They are members of a perfect gradational series, and differ macroscopically from No. 404 only in their lighter colour, slight increase in grain size, and their more "igneous" texture. Compare Figs. 60, 61, and 62.

Microscopically the final phase of transformation to marginal granodiorite as shown by Nos. 403 and 402 is seen to be effected by:

(i) an increase in the amount of potash feldspar and quartz;
(ii) a reduction in the mafic content; and
(iii) a gradual loss of metamorphic texture.

Specimen No. 401 is typical of the marginal granodiorite and was collected approximately ten yards from the margin of the pluton.

Description /
Description of specimen No. 401: Hornblende-biotite-granodiorite. Microscopically this rock consists of quartz, plagioclase, potash feldspar, biotite, and hornblende, with accessory iron-ores, zircon, sphene, and apatite.

Quartz occurs as small to medium-sized granules in the mosaic of the groundmass and also as interstitial crystals. The crystals range in size from \(< 0.1 \text{ mm}\) in diameter to large composite crystals which reach a maximum size of \(1.5 \times 1.0 \text{ mm}\). The crystals have highly sinuous margins against plagioclase and frequently embay the larger plagioclase porphyroblasts. Occasional small, ragged, optically continuous crystals of plagioclase are found in a quartz host, which along with the other evidence indicates the replacement of plagioclase by quartz. Other inclusions in quartz are minute opaque particles, very small rounded biotite crystals, small hornblends, and apatite crystals. The boundaries of quartz with the mafics may be idioblastic or extremely ragged and frayed. Quartz and potash feldspar have irregular common borders. Rarely there is a micropegmatitic or vermicular intergrowth of the two minerals.

Plagioclase occurs most frequently as medium and large tabular crystals, but all sizes of crystals are present from the smallest (in the groundmass) which measures \(< 0.2 \times 0.1 \text{ mm}\). up to /
to a maximum size of 4.5 x 4.0 mm. Generally the porphyroblasts average 2.0 x 0.8 mm, and are sufficiently numerous to give the rock a porphyritic appearance. Variation in composition is from An$_{15-20}$ to An$_{50}$, and is quite independent of grain size. The porphyroblasts are characterized by patchy extinction, oscillatory zoning, and a composite structure. As an example of variability of composition in a single composite porphyroblast the following data are given:-

An %

Core: 30 → (40-45) → 30 → 40 → (30-25) → 35 → 25; Margin.

Oscillatory zoning with ten or more zones is quite common. These plagioclases are strikingly similar to those developed both in the aureole hornfelses and in the inclusions found in the granodiorites and adamellites. The crystals have highly sinuous borders against orthoclase and have been replaced by it. Many of the porphyroblasts have suffered slight alteration with formation of sericite, kaolin and calcite. Inclusions are usually small rounded crystals of the mafics.

Potash feldspar has increased from a negligible quantity in No. 404 to 3% in No. 403, 5% in No. 402, and 7% in the present specimen. It frequently occurs interstitially in the matrix; anhedral crystals averaging 0.8 x 0.8 mm. are sometimes present. The potash feldspar is mainly orthoclase but perthitic types do occasionally /
occasionally occur. Carlsbad twinning is infrequent. The potash feldspar has conspicuous replacement relationships. It has developed at the expense of the plagioclase and to a smaller extent of the quartz and other minerals in the matrix. All stages of the replacement of plagioclase by potash feldspar can be seen.

**Biotite** is the most abundant ferromagnesian mineral. It occurs as small, ragged crystalloblastic flakes, and medium and large subhedral flakes. The minimum size is $< 0.1 - 0.05$ mm. and the maximum $2.0 \times 1.5$ mm. The pleochroism is $X = \text{straw yellow}$, $Y = \text{golden brown}$, and $Z = \text{deep foxy red brown}$. The flakes are frequently "poikiloblastic" and skeletal. They have highly frayed borders and contain pleochroic haloes around zircon and apatite inclusions. Pale green chlorite along with streaky sphene is formed on alteration. Glomeroporphyroblastic aggregates (often $4.0 \times 2.0$ mm.) of biotite flakes with internal decussate structure are present. Other mafics also contribute to these aggregates and some are particularly rich in iron ores.

**Amphibole** is present as small grains ($< 0.1$ mm.), and as medium to large subhedral porphyroblasts ($1.0 - 2.5$ mm.). The crystals are mostly patchy and composite, and many are poikiloblastic or skeletal. The composite crystals consist of different /
different varieties intimately intergrown with one another. Brownish or greenish amphibole, biotite and iron ores form aggregates with decussate structure. Common hornblende of greenish and brownish green types are predominant, but a colourless or very pale green variety with an acicular habit is also present - it is a member of the tremolite-actinolite series. This pale variety is frequently found in the centre of composite crystals, but is nearly always optically continuous with the surrounding common hornblende. No pyroxene cores were observed in the amphiboles.

**Accessories** are ilmenite, zircon, sphene and apatite. Ilmenite is present in small amount as irregular grains and subhedral pegs associated with the mafics. Zircon occurs as very small infrequent grains and gives rise to pleochroic haloes when enclosed in biotite. Sphene occurs as anhedral crystals often arranged in streaks along the cleavage traces of biotite. Apatite is the most abundant accessory and is present as short euhedral and subhedral prismatic crystals which range in length from 0.4 - 0.05 mm. Analysis overleaf.

2. **Glenhead Wood area**

In this locality there are exposures in Gairland Burn and its immediate vicinity, and in the south-east corner of the wood.
Marginal hornblende-biotite-granodiorite (No. 401), about 15 yds. from the contact-quartz-diorite, at a height of approximately 800 ft., on the south slope of Buchan Hill. Map Fig. 3. New analysis. Analyst: W.H. Herdsman. (Table I).

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VON WOLFF VALUES

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Micrometric analysis, (vol. per cent) using a Hurlbut electric counter:

- Quartz: 17.7%
- Plagioclase: 46.8%
- Potash feldspar: 7.2%
- Biotite: 16.1%
- Hornblende: 11.1%
- Others: 2.1%

Plagioclase/Potash Feldspar ratio approx. 87 : 13
wood. Unfortunately the area between is covered with drift. The marginal granodiorite is seen adjacent to the sediments only in the south-east corner (Map Fig. 4).

In general the rocks within 10 yds. of the contact are darker than the average granodiorite of the complex, but there is no macroscopic difference between the rocks which occur at distances from 10 to 220 yds. from the contact. The marginal rocks are all hornblende-biotite-granodiorites with a medium grained, porphyritic texture. The ferromagnesian minerals frequently occur in aggregates or clots.

Inclusions are numerous and range from mere "ghosts" to large inclusions measuring 12" x 16". Ten inclusions were collected and sectioned. For convenience of description they have been grouped with the inclusions which occur in the main outcrop of granodiorite.

Specimen No. 278 is a marginal variety of granodiorite collected 15 yds. from the contact.

Description of No. 278: Hornblende-biotite-granodiorite. Microscopically this rock consists of quartz, hornblende, biotite, plagioclase, and potash feldspar, with accessory iron-ores, apatite, zircon, sphene, and tourmaline. A small amount of secondary chlorite is present.

Quartz /
Quartz occurs as anhedral granular crystals and is commonly interstitial. The maximum size of the quartzose patches is 1.5 x 1.0 mm. The latter are made up of several individuals which can be discerned by their shadowy outlines. Undulatory extinction is common. The boundaries of the quartz crystals are very irregular adjacent to plagioclase; the latter are frequently embayed and relics are left as inclusions. This is taken as evidence of replacement of plagioclase by quartz. Other inclusions are small biotite flakes and occasional minute prismatic crystals of apatite. Quartz in turn is being replaced by potash feldspar. This is clear from the following observations: quartz has highly irregular boundaries against potash feldspar and is often lobed and penetrated by it; quartz is commonly enveloped and is present as inclusions in the potash feldspar. Very small micropegmatitic and myrmekitic intergrowths were observed. Infrequently the crystals have been fractured.

Hornblende occurs as small anhedral grains (< 0.1 mm.) medium to large subhedral phenocrysts (0.6 - 3.0 mm. in length), and also in aggregates of several individuals associated with other ferromagnesium minerals. Crystals are commonly patchy and composite. The different varieties often exhibit intimate intergrowth among themselves and aggregates and clusters show decussate structure. The predominant variety is common hornblende which /
which is strongly pleochroic with $X =$ colourless, $Y =$ dark olive green, $Z =$ dark green. It is biaxially negative with $2V = 90^\circ$, $Z \wedge c = 20^\circ$. Individual common hornblende crystals often contain irregular patches which differ in colour and pleochroism from the common hornblende. This other variety is faint to moderately pleochroic with $X =$ colourless, $Y =$ very pale bluey-green, $Z =$ pale blue green. It is optically negative, with $Z \wedge c = 17-18^\circ$, and belongs to the tremolite-actinolite series. It often develops around the pyroxene cores, and is in turn converted into common hornblende. The reaction series is:

\[ \text{pyroxene} \rightarrow \text{tremolite-actinolite} \rightarrow \text{common hornblende} \]

Inclusions are clinopyroxene, small pegs of iron-ores, apatite, and small ragged biotite flakes. The sporadic distribution of the ragged biotite flakes in the tremolitic rich clots would appear to indicate that the amphibole sometimes replaces biotite, but this is not at all certain as biotite occasionally rims tremolite.

**Biotite** occurs abundantly as small, ragged and euhedral flakes and also as subhedral large phenocrysts. The maximum size is $4.0 \times 0.8 \text{ mm}$. The large flakes are poikiloblastic but show signs of losing this characteristic in an endeavour to attain perfect form. Occasionally the borders of the crystals are highly crenulated and frayed. The mineral is strongly pleochroic /
pleochroic with $X =$ pale straw yellow, $Y =$ reddish brown, $Z =$ dark reddish brown. Pleochroic haloes are present around inclusions of zircon and apatite. Inclusions are zircon, apatite, xenotime, iron-ores, sphene, quartz and hornblende. Biotite occasionally rims tremolitic-actinolitic aggregates and has a highly irregular border with the amphibole. It forms with the other mafics glomeroporphyritic aggregates or clots with internal decussate structure. Some biotite laths show evidence of stress as the laths are often curved and twisted. A small amount of biotite is altered to pale green chlorite and frequently sphene is formed as a by-product.

Plagioclase in general averages andesine $\text{An}_{40}$ but varies from $\text{An}_{20}$ to $\text{An}_{50}$. It most frequently occurs as large subhedral tabular porphyroblasts which exhibit carlsbad and albite twinning. In section zoned tabular crystals are often larger than 5.0 x 5.0 mm. Simple continuous zoning is common, from $\text{An}_{45-50}$ at the core to $\text{An}_{20}$ at the margin. Oscillatory zoning is very variable, e.g. -

$$\begin{align*}
\text{An.}\% & : \text{Core:} & 25 - 30 - (40-45) - (35-40) - (30-35) - 25 - 35 - 30 - 20; & \text{Margin.}
\end{align*}$$

The /
The large porphyroblasts are not always single crystals, each being often composed of two or three individuals; they are strikingly similar to those developed in the transformation zone and in the inclusions. The plagioclases have been partly replaced by potash feldspar against which they have highly irregular borders. Moreover, optically continuous relics of plagioclase are present as inclusions in the potash feldspar. An interesting feature, found in many zoned tabular crystals, is the occurrence of a roughly circular or elliptical-shaped zone of alteration inside of which are numerous scattered small inclusions of pyroxene, biotite, hornblende, and iron-ores.

Potash feldspar occurs mainly as orthoclase but un-twinned perthitic feldspar is also present, both as anhedral crystals in the matrix together with a few medium-sized phenocrysts. The maximum size of the phenocrysts is 1.0 x 1.0 mm. Generally the potash feldspar is clear and less altered than the plagioclase. It has a replacement border against plagioclase and contains relics of the latter as inclusions. All stages in the replacement of the plagioclases can be seen.

The accessories are iron-ores, apatite, sphene, xenotime, and tourmaline. Of the iron-ores, ilmenite is the most common. It occurs as small grains and pegs associated with the mafics. Apatite is the most abundant of the accessories. It is /
is present as small colourless prismatic crystals which reach a maximum size of 0.5 x 0.3 mm. Zircon is second in abundance and is particularly noteworthy for the size of its crystals. Sphene occurs as streaks of anhedral crystals usually associated with the alteration of biotite, and also as aggregates in the ferromagnesian clots. Xenotime is rare. Tourmaline is present as prismatic and radiating acicular crystals which are strongly pleochroic with:

\[ \begin{align*}
0(Z) &= \text{yellow}, \\
E(X) &= \text{dark brown}; \\
0(Z) &= \text{pale violet}, \\
E(X) &= \text{bluish green}. \\
\end{align*} \]

Analysis overleaf

3. South-west of Loch Enoch

General Statement

The contact between the granodiorite and the country rocks is very irregular and complex in this area (Map fig. 2). It runs approximately west-east along the line of the headwater of Buchan Burn and then turns south and climbs on to the col on the ridge extending south-west of Loch Enoch; it crosses the ridge eastwards in an irregular manner and then turns north on to the summit of the ridge and sends off two tongues in an approximate north-west direction; it finally runs due north across the valley and up the south-east slope of the Merrick. Eight specimens were collected in the vicinity of the contact in this area.

Two /
ANALYSIS F.

Hornblende-biotite-granodiorite (No. 278), from the south-east corner of Glenhead Wood. Map Fig. 4.

New analysis.

Analyst: W.H. Herdsman. (Table I).

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Total 100.10 1541.4 100.00

VON WOLFF VALUES

L = 61.44
M = 21.62
Q = 16.86

Micrometric analysis (vol. %) using a Hurlbut electric counter:

- Quartz 18.1%
- Plagioclase 46.3%
- Potash feldspar 13.5% 59.8%
- Biotite 11.8%
- Hornblende 9.4% 21.2%
- Others 0.9%
Two types are easily distinguished in the field:—

(1) Dark, banded, marginal granodiorite similar to the type described above (p. 118), from the 800 ft. contour on the south slope of Buchan Hill. (No. 401).

(2) Porphyritic, leucocratic rock with large phenocrysts of feldspar embedded in a much finer grained groundmass containing clots and streaks of the ferromagnesian minerals.

The second type was found at two localities only; at the head of a tongue which runs north-west from the complex on to the south spur of the Merrick (Nos. 487, 488); and on the main ridge half a mile south-west of Loch Enoch (No. 274).

Petrography

Microscopically there are three marginal varieties of rock:—

(i) Hornblende-biotite-granodiorite ) dark, banded marginal variety
(ii) Biotite-granodiorite
(iii) Biotite-granodiorite-porphyry - leucocratic type.

(i) It is unnecessary to repeat the microscopic description of the hornblende - biotite-granodiorite (Nos. 270, 276, and 277) as it is strikingly similar to No. 401 described on p. 118 .

(ii) The transformation of the black shales to biotite-granodiorite has been described in detail above (pp. 81-91). This non-hornblendic
non-hornblendic type is confined to the neighbourhood of the
tongue which crosses on to the south-eastern spur of the Merrick.
Inwards it grades into the normal hornblende-biotite-granodiorite.

(iii) Biotite-granodiorite-porphyry. Three specimens
of this rock type were collected (Nos. 274, 488 and 487). No.
274 from the Rig of Loch Enoch and Nos. 488 and 487 from the
tongue on the south spur of the Merrick. The exact relationship
of this rock to the hornblende-biotite-granodiorite could not be
established for lack of exposures.

Microscopically the rocks consist essentially of quartz,
plagioclase, potash feldspar and biotite, with accessory iron ores
apatite, zircon, hornblende, and secondary chlorite, muscovite
and rutile.

Quartz is abundant as small anhedral grains in the
groundmass (average 0.2 mm. in diam) which reach a maximum of 0.5
mm. across. A characteristic feature is the presence of rounded
inclusions near the middles of the grains.

Potash feldspar is the other abundant groundmass mineral;
it also occurs interstitially and as the base of host material of
the quartz grains in large poikiloblastic plates. It is general-
ly orthoclase; microcline being rare.

Plagioclase occurs as medium and large subhedral pheno-
crys ts /
phenocrysts some of which are exceptionally large, reaching over 5.0 x 5.0 mm. They are frequently zoned (continuous and oscillatory) and all are altered to some extent with formation of sericite and kaolin. The phenocrysts possess irregular or ragged boundaries and often contain numerous inclusions. One particular phenocryst was seen to contain a nest of small crystalloblastic biotite flakes in its core. There is a tendency for the phenocrysts to aggregate as clusters of laths which commonly cover areas over 4.4 mm. square. The composition is oligoclase-andesine with a range from An\textsuperscript{25} to An\textsuperscript{40}.

**Biotite** occurs as small anhedral and medium to large subhedral flakes which range in texture from crystalloblastic through poikiloblastic to "igneous-looking". They commonly form nests or aggregates. In No. 487 the majority are poikiloblastic. The biotite is strongly pleochroic with \( \text{X} = \) straw yellow, \( \text{Y} = \) sepia, and \( \text{Z} = \) foxy red brown. Many of the crystals are bleached and greatly altered to chlorite, rutile and muscovite.

The accessories require no comment, except that hornblende was observed in small amount only in No. 487.

4. **Elsewhere on the margin of the complex.**

Specimens were collected at various points along the east, south-east and south slopes of Buchan Hill and on the north-east /
north-east slope of Mulldonoch to see whether the phenomena examined in detail at the previous localities were of general occurrence. In all cases the types observed were found to be contact-quartz-diorites and typical marginal granodiorites which could be closely matched with members of the transformation series described above.
XI. GRANODIORITE

(a) General Statement

The outcrop of granodiorite forms a zone which extends from the central adamellites to the aureole, or the more basic rock types where these occur along the margin. It is narrowest at Loch Enoch (a little over half a mile) but broadens southwards over Craig Neldricken, Rig of Loch Enoch, Ewe Rig, Loch Neldricken, Meaul, to Loch Valley. Near the last of these localities the zone begins to swing round from north-south to south-east. Its maximum width (one and two-thirds miles) is attained where it stretches from Loch Narroch over the Rig of the Jarkness and the Glenhead Lochs, to Glenhead and the south slope of Buchan Hill. Thereafter the zone narrows to a width of approximately one mile, stretching from Craiglee to Loch Dee where it is adjacent to the hypersthene rocks.

At various localities it grades into hornblende-biotite-adamellite or augite-hypersthene-biotite-granodiorite, or into the country rocks. The rock of the gradational zone between granodiorite and hornblende-biotite-adamellite is referred to hereafter as "the transitional type" (p. 142).

From Loch Enoch as far south as Loch Valley the only variation noticeable in the field is in grain size; a slightly coarser
coarser type is found in the middle part of the zone. However, south-west of Loch Valley on the western end of the Rig of the Jarkness and extending south to White Brae Top, there occurs an isolated outcrop of a type which is transitional to hornblende-biotite-adamellite. This field fact cannot easily be explained by the magmatic theory that postulates a mixing of granitic and granodioritic magmas to produce the transitional types. On the other hand, the transformist theory offers a much more satisfactory explanation. In this locality, granitization has progressed further than in the surrounding areas. This interpretation is in keeping with the now well-known sequence of development of porphyroblasts → pods → lenses → isolated areas of a more advanced granitized type surrounded by a type which is less advanced. It is an example of such an isolated area.

(b) Petrography

120 specimens were collected of which 40 were sectioned. Macroscopically the granodiorite is a mottled rock (light grey and black) with a coarse to medium grain size. The leucocratic constituents are porphyritic plagioclase, potash feldspar and quartz. Biotite and hornblende are scattered throughout the rock with frequent clustering in clots.
or reddish and black mottled rock is present at several scattered localities (Glenhead Lochs, south-west of Meaul) but notably on the Knoll to the north-east of Glenhead Wood. The pink colour is due to late stage alteration of the feldspars and in the last of these localities begins with a faint tint in specimen Nos. 508 and 506, respectively 50 and 55 yds. from the contact, and becomes progressively more intense and vein-like in distribution in localized areas (No. 507) until eventually a uniformly pink and black rock is found (No. 509 and 510).

Microscopically the "normal" granodiorite consists essentially of plagioclase (andesine), potash feldspar, quartz, biotite and hornblende with accessory zircon, apatite, iron ores, sphene and xenotime, and occasionally pyroxene and tourmaline. It is a hornblende-biotite-granodiorite.

Quartz occurs interstitially as anhedral crystals. The crystals range from $0.4 \times 0.3$ mm. to aggregates of $3.0 \times 2.0$ mm. The patches are formed usually of several individual crystals which are often in optical continuity. The quartz crystals have frequently highly irregular boundaries against plagioclase, biotite and hornblende. On the other hand margins against $010$ faces of plagioclase are perfectly straight. Inclusions are of plagioclase, hornblende, apatite, biotite and minute dust-like fragments /
fragments. Occasionally the dust-like inclusions occur in trains which may or may not be parallel in the same crystal. Rare micropegmatitic intergrowths with potash feldspar occur. Fracture lines sometimes intersect the quartz crystals, and they appear to be of para-crystallization origin as some are distinct fractures while others are partially healed by recrystallization. Undulose extinction is common.

Plagioclase is present as medium-sized anhedral lath-shaped crystals which average 1.0 x 0.4 mm. in the groundmass, and also as large, subhedral, tabular porphyritic crystals which occasionally attain 4.5 x 2.0 mm. Carlsbad and albite twinning are well developed. Zoned crystals - oscillatory and continuous types - are common. The composition averages andesine An$_{30-35}$. The continuously zoned crystals have commonly a core of andesine An$_{35}$ and are mantled by a zone of calcic oligoclase An$_{25-30}$. Inclusions of rounded granules of hornblende, short prismatic apatite crystals, small anhedral flakes of biotite, and pegs of iron ores, are frequent. The majority of the crystals have suffered alteration in some degree to sericite and kaolin. The borders against quartz and biotite are commonly irregular, and those against potash feldspar are characteristically highly irregular and often lobe-like. Plagioclase occurs as relic inclusions in potash feldspar which further indicates its replacement by that mineral.

Potash
Potash feldspar occurs as orthoclase with carlsbad twinning and occasionally as microcline and perthite. It is present as interstitial crystals and also as subhedral rectangular crystals which reach a maximum size of 4.5 x 4.0 mm. Its boundary against plagioclase is highly irregular; often a vermicular or lobe-like intergrowth is developed in patches along the margin. Generally it margins quartz smoothly. A peculiar ragged and frayed margin is rarely found against biotite; small granules are detached from the main biotite flake and give the mineral a fringe. The most common inclusions are plagioclase relics; others are quartz, biotite, hornblende and apatite. The potash feldspar is much clearer and less altered than plagioclase.

Biotite is present abundantly as small, medium anhedral to subhedral flakes, and also as large subhedral phenocrysts or porphyroblasts which commonly reach a size of 2.2 x 2.0 mm. The crystals are strongly pleochroic, \( X = \) pale straw yellow, \( Y = \) reddish brown, \( Z = \) golden reddish brown. Pleochroic haloes are common around zircon and xenotime crystals. The phenocrysts are often poikilitic but some show signs of their poikiloblastic ancestry. Biotite often surrounds subhedral hornblende crystals and is characteristically associated with hornblende in clots. Inclusions are hornblende, quartz, plagioclase, iron-ores, zircon and apatite. Chlorite and some prehnite are developed in some altered flakes of biotite.
Hornblende, subordinate in amount to biotite, is present as small, medium and large anhedral and subhedral crystals. Occasionally the larger crystals are poikilitic and attain a size of $2.2 \times 0.4 \text{ mm.}$ but are nearly always smaller than the biotite. Strongly pleochroic with $X =$ pale green, $Y =$ green, $Z =$ olive green. Optically biaxially negative. $Z^\circ = 20^\circ$. From the shape of some of the subhedral crystals and the relics of biotite flakes within them it is clear that some of the hornblende formed from the biotite. Hornblende is strongly associated with the other ferromagnesiants and forms clots with biotite and iron ores. Inclusions are iron ores, biotite, zircon, apatite and pyroxene. Some crystals have pyroxene relics as cores.

Of the accessories, apatite is most abundant being commonly an inclusion in biotite or hornblende; zircon is frequent as granules in biotite; sphene occurs as euhedral wedge-shaped crystals associated with hornblende but is rare; iron ores are found as subhedral pegs and granules in biotite and hornblende.

Nine micrometric analyses were carried out and the results are recorded below.
Micrometric analyses of serial specimens from the granodiorite zone

<table>
<thead>
<tr>
<th>Specimen Nos</th>
<th>Series A</th>
<th>Series B</th>
<th>Series C</th>
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<tbody>
<tr>
<td></td>
<td>538</td>
<td>727</td>
<td>705</td>
</tr>
<tr>
<td>Quartz</td>
<td>21.3</td>
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<td>Plagioclase</td>
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<td>39.0</td>
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<td>10.1</td>
<td>15.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Feldspar</td>
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<td>11.7</td>
<td>16.0</td>
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<tr>
<td>Biotite</td>
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<td>9.7</td>
<td>10.0</td>
</tr>
<tr>
<td>Hornblende</td>
<td>0.4</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio</td>
<td>4.0</td>
<td>1.7</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Series A: Rig of Loch Enoch-- Ewe Rig--Black Gairy-- Craignaw.
Series B: Northern end of Buchan ridge--south slope of Meaul--south-west slope of Craignaw--Craignaw.
Series C: Glenhead Wood--Rig of the Jarkness--Craignaw.

The specimens in each series are arranged in order from the margin inwards, reading from left to right (Map Fig. 75).
Remarks

1. Quartz: The content of quartz varies from 17.0 - 25.5%. Except in Series B it can be said to increase slightly towards the middle of the complex.

2. Plagioclase makes up from 39.0 - 51.5% of the rock with an average of approximately 45.0%. It appears to be remarkably constant in amount throughout the zone.

3. Potash feldspar ranges from 9.4 - 16.0%. Taking the average of the contents near the margin of the complex and comparing it with the value obtained from the rocks nearest the hornblende-biotite-adamellite a slight increase inwards can be detected, e.g. 12.3 - 14.0%.

4. The total feldspar content is remarkably constant varying between 51.0 - 59.0% (No. 373 excepted).

5. Biotite ranges from 11.0 - 19.0%.

6. Hornblende ranges from 5.0 - 10.0% and is always subordinate to biotite.

Varieties in the granodiorite

Minor variations in the granodiorite are numerous. Some of the types are quite distinctive and can be matched very closely with (a) marginal granodiorite or (b) inclusions or (c) ghosts of inclusions.
An example of (a) is specimen No. 759 from Long Burn, Glenhead, although it lies half a mile inside the contact; it is almost identical macroscopically and microscopically with No. 403 a marginal type of granodiorite from the south slope of Buchan Hill (previously described on p. 78).

Microscopically No. 759 is a hornblende-biotite-granodiorite and differs from the normal granodiorite as follows:

1. It is richer in ferromagnesian minerals, biotite and hornblende.

2. These minerals commonly form large clots, the maximum size of which was \( \frac{3}{8} \times \frac{1}{4} \)".

3. The texture is more crystalloblastic and poikiloblastic.

4. Clinopyroxene crystals rimmed with hornblende are common.

Apart from the above the rock possesses all the petrographical characteristics of the normal granodiorite.

Specimen No. 739 is an example of (b). Macroscopically it is identical with some "ghosts" of inclusions (which incidentally can also be matched with some marginal granodiorite types). No. 739 has a dark fine-grained matrix in which outstandingly large porphyroblasts of plagioclase are embedded. Microscopically it is a hornblende-biotite-granodiorite with a pronounced crystalloblastic, porphyroblastic texture. Potash feldspar is less abundant than in the "normal" granodiorite and as the amount is /
is small the rock is transitional towards a quartz-diorite. Pyroxene occurs as the cores of several hornblende crystals. Tourmaline is a noteworthy accessory.

(c) **Transitional to hornblende-biotite-adamellite**

A distinction, based on macroscopic textural differences has been drawn between the granodiorite described on p. 133 and the transitional type which passes into hornblende-biotite-adamellite. The chief differences are as follows:

1. The mafics in the transitional type are of smaller grain size than in the "normal" type.

2. The transitional type is more distinctly porphyroblastic in character due to the development of pseudo-porphyritic potash feldspar crystals in addition to the large plagioclase tabular crystals.

3. In the granodiorite (sensu stricto) biotite is outstanding as large subhedral flakes.

Microscopic examination confirmed the observations recorded above.

Seven micrometric analyses were carried out. The results are recorded below:
Micrometric analyses of serial specimens from the transitional to hornblende-biotite-adamellite zone.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Series A</th>
<th>Series B</th>
<th>Series C</th>
<th>Group D</th>
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</thead>
<tbody>
<tr>
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<td>24.0</td>
<td>22.0</td>
<td>25.0</td>
</tr>
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<td>42.0</td>
<td>39.0</td>
<td>44.5</td>
<td>45.0</td>
</tr>
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<td>K Felspar</td>
<td>15.0</td>
<td>18.0</td>
<td>21.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Biotite</td>
<td>15.0</td>
<td>12.0</td>
<td>8.5</td>
<td>11.0</td>
</tr>
<tr>
<td>Hornblende</td>
<td>7.0</td>
<td>6.0</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Others</td>
<td>2.0</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>2.8</td>
<td>2.1</td>
<td>2.1</td>
<td>3.0</td>
<td>2.0</td>
<td>1.9</td>
<td>3.2</td>
</tr>
</tbody>
</table>

The alignment of Series A, B and C is indicated on p. 139. The specimens of Group D are from the south-east slope of Craigle.

The following observations can be made:

1. The quartz content varies from 19.0 - 30.2% and generally increases as the h-b-adamellite is approached, e.g. A and C series.

2. The total feldspar content in each particular series remains remarkably constant with the exception of Group D, the range being 51-66.0%.

   N.B. Flag/Potash feldspar ratio of No. 761 falls just below 66/34 but the rock has been included as the degree of accuracy of measurement is not greater than ± 1%.

3. The potash feldspar content in general increases as the h-b-adamellite is approached, e.g. series A it rises from 15.0 - 18.0% and in series C from 14.5 - 19.5%. Group D is an exception to this generalisation.
4. Biotite ranges from 15.0 - 7.5% and decreases towards the middle of the complex.

5. The hornblende content varies between 7.0 and 3.0% and like biotite generally decreases in amount as the h-b-adamellite is approached.

(d) Inclusions

Inclusions of altered sediment in the granodiorite are numerous; 40 representative specimens were collected. Few inclusions are more than 12 inches in length. The largest inclusions observed is situated 900 yards south-west of Loch Enoch. On the new (1929) edition of Sheet 8, the dimensions of this inclusion as measured from the map are 180 x 110 yds. This, however, is an exaggeration, for the largest inclusion found at that locality measures 10 x 5 yds. It is worth noting that the size of the inclusion drawn on the 1893 edition is more nearly correct. The strike is 6° E. of N., and the beds dip almost vertically. The strike of the aureole hornfelses more than 30 yds. away is 5-8° E. of N. which implies that the inclusion cannot have moved appreciably from its original position.

The inclusions are usually dark coloured and disc-shaped. They are more resistant to weathering than the host rock and stand out as projections. They were observed throughout the zone, but are particularly abundant near the margin and at the following localities:

(1)/
(i) along the south-west shore of Loch Neldricken;
(ii) north-west of Loch Arron; and
(iii) in the vicinity of the Glenhead Lochs.

Gardiner and Reynolds recognized that the "tonalite frequently contains inclusions of altered sediment" and pointed out that inclusions were observed "near the south end of Loch Dee about 200 yds. from the present boundary". Gardiner and Reynolds' report of the distribution of inclusions in the complex was not correct; the inclusions are more numerous than they estimated.

By far the commonest types of inclusions fall in a series from sediment to granodiorite; as at the granodiorite aureole contact the sediments have been converted into igneous-looking rocks. Three successive processes of this transformation can conveniently be recognized:

1. Basification of hornfels.

2. Formation of quartz-diorite, involving feldspathization of the basified hornfels and further recrystallization.

3. Granitization (sensu stricto) - the final process when the quartz-diorite is transformed into granodiorite with increase of potash feldspar and quartz, and concomitant decrease of mafic minerals and plagioclase.

Occasionally all three stages can be observed in a single thin section.

These three stages will now be described in order.

1. /
1. Basified hornfels inclusions

These rocks are generally dark, fine-grained inclusions, with sharp junctions against the surrounding granodiorite. The commonest type is a plagioclase-biotite-hornfels but plagioclase-muscovite-biotite-hornfels and pyroxene-amphibole-plagioclase-biotite-hornfels are also found.

The mafics often constitute over 50% of an inclusion. Accessories are iron-ores (magnetite, ilmenite, pyrite), zircon, apatite, rutile, muscovite and tourmaline.

Biotite. The most common mafic mineral is biotite. There are two varieties: both are strongly pleochroic with:

X = straw yellow; Y = brown; Z = red brown;
X = yellow brown; Y = brown; Z = very dark brown.

Usually only one variety is present in a single specimen but occasionally both are present (No. 527). The red brown variety is similar to that of the normal granodiorite. Rarely pleochroic haloes are very abundant (No. 527). In particular cases the biotite flakes may form continuous layers along the bedding planes and give the inclusion a pronounced banded appearance which is generally accentuated by the presence of abundant iron-ores. On the other hand some specimens exhibit decussate structure. The size of the crystals varies from less than 0.1 mm. to 2.0 x 1.0 mm. (poikiloblastic crystals).

Hornblende /
Hornblende sometimes accompanies biotite (No. 596), but is generally subordinate to that mineral. It occurs as small poikiloblastic crystals which often contain pyroxene relics (No. 277).

Pyroxene (augite) has been observed as individual crystals only in two basified inclusions (Nos. 277 and 530). In one of these (No. 530) it is present only in very small amount, but it is more abundant in the other. It occurs both as minute granules ( < 0.1 mm.) and as the cores of amphibole crystals. It exhibits all stages of replacement by hornblende.

The mafics (biotite commonly) occasionally form conspicuous rims around the inclusions. The most conspicuous rim seen round any inclusion bordered a spinel-muscovite-plagioclase-biotite-hornfels (No. 529). The rim averages 1.5 mm. in width, with a maximum of 2.5 mm.; it consists of biotite considerably altered to chlorite, epidote and sphene, and abundant iron-ores. Basification reaches its acme in the formation of glomero-porphryritic aggregates of mafic minerals. Typical aggregates of iron-ores and biotite occur in No. 529. In others (No. 530) the aggregate may be monomineralic; e.g. at particular points basification is intense and aggregates of biotite, often with a pronounced decussate structure, have developed. All stages in the formation of these basic clots can be traced. The biotite-rich basified inclusions /
inclusions contain on an average 50% of mafic minerals but in the clots this percentage rises to 100.

The groundmass usually consists of a granoblastic mosaic of plagioclase and quartz, the grains being usually < 0.2 mm. in diameter, but some variation in size can occur. With increase in grain-size and the introduction of material to form plagioclase porphyroblasts the next stage is reached.

2. Formation of quartz-diorite

Feldspathization of the basified hornfels sometimes involves the growth of plagioclase porphyroblasts. On the other hand some basified inclusions appear to have changed directly into non-porphyroblastic quartz-diorite. When plagioclase porphyroblasts are present their development appears to have preceded the general recrystallization.

Growth of plagioclase porphyroblasts in the hornfels inclusions. The development of plagioclase porphyroblasts in the basified inclusions is similar to that in the contact aureole hornfels. This progressive feldspathization involves a concomitant decrease in the ferromagnesian content.

Specimen No. 526 illustrates an early stage of this process. It is a plagioclase-biotite-hornfels. The groundmass consists of a granoblastic mosaic of plagioclase and quartz grains which show great variation in size but average > 0.2 mm. in diameter /
diameter. **Biotite** is present abundantly as large platy crystals which average 1.5 x 1.5 mm. but attain a maximum size of 4.0 x 1.0 mm. The pleochroism is very similar to the biotite of the granodiorite: - \( X = \) straw yellow; \( Y = \) brown; \( Z = \) dark red brown. Glomeroporphyritic aggregates (5.0 x 4.0 mm.), with iron-ores and green spinel are common. The texture is decussate. Some crystalloblastic crystals have ragged borders and are skeletal.

The plagioclase occurs in the groundmass as small granoblastic crystals, and also as large subhedral porphyroblasts, (max. size 4.4 x 1.2 mm.). Every stage in the development of these porphyroblasts from the larger crystals of the groundmass can be traced in a single section. The numerous inclusions are small crystals of biotite, apatite, iron-ores and quartz. The composition averages andesine An\(_{35}\)-An\(_{45}\). Continuous and oscillatory zoning is common and examples of each are given below:

**Continuous zoning:**

- Core \( \text{An}_{40-35} \) - \( \text{An}_{30} \) Margin
- Core \( \text{An}_{35} \) - \( \text{An}_{25-30} \) Margin

**Oscillatory zoning:**

- Core \( \% \text{An}:35:30:(30-35):35:30:(25-30) \) Margin
- Core \( \% \text{An}:(40-35):35:30:35:30:(30-35):30:(30-25) \) Margin

These porphyroblastic crystals are very similar to those formed in the aureole of the granodiorite. The variations of composition and the development as porphyroblasts indicates that these crystals could not have crystallized from a magma.

Recrystallization /
Recrystallization of stage 1 types. The transformation from stage 1 takes place chiefly by recrystallization with enrichment in quartz and plagioclase. In this process the hornfels becomes coarser in grain. The mafic minerals undergo considerable recrystallization and rearrangement and the inclusion is transformed into a "ghost" with textures similar to those described in the contact marginal granodiorite. Enrichment in quartz and plagioclase takes place at the expense of the mafic minerals.

Specimen No. 594, a hornblende-pyroxene-biotite-quartz-diorite illustrates an early phase of this transformation. It appears to have developed almost directly from the basified hornfels, for although plagioclase porphyroblasts are present they are not conspicuous.

Pyroxene (common augite) occurs as granules, stumpy prismatic crystals and elongated subhedral crystals. Some of the crystals show the commencement of amphibolization but hornblende is not abundantly developed.

Biotite is present as very large pseudo-hexagonal flakes (max. size 5.0 x 4.0 mm.), subhedral poikiloblastic flakes (average size 2.0 x 2.0 mm.) and small crystalloblastic flakes. It is the red-brown variety.

Plagioclase porphyroblasts average andesine An$_{30-35}$ in composition and show continuous and oscillatory zoning within the limits An$_{25-45}$.

Sphene /
Sphene is a conspicuous accessory.

A further advance in this transformation is demonstrated by specimen No. 376 - a pyroxene-hornblende-biotite-quartz-diorite. Amphibolization has progressed further, since pyroxene is now found only in the cores of the hornblende crystals. Sphene is again abundant.

The end phase of this stage is shown by specimen No. 525, a hornblende-biotite-quartz-diorite - which only requires growth of potash feldspar to convert it into a granodiorite. The groundmass consists of small plagioclase laths ( > 0.2 mm. in length) with interstitial quartz. The mafics are hornblende and biotite. In habit and textural relationships these minerals are strikingly similar to the mafics of the contact-quartz-diorite of the marginal granodiorite zone; the only difference is that they are more abundant and occur more often in glomero-porphyritic aggregates. The mafics have increased in size (average > 1.5 mm.), but are still poikiloblastic in character. Small pyroxene relics are occasionally discernible as cores in common hornblende crystals. Biotite is commonly poikiloblastic and often encloses anhedral hornblende. The predominant variety is the red-brown type but rarely the muddy green type occurs. Andesine porphyroblasts contain minute mafic inclusions and their manner of evolution is similar to the plagioclase porphyroblasts of the feldspathized /
feldspathized aureole hornfelses. Continuous and oscillatory zoning are common and shows the same range of composition as those of (i) the feldspathized aureole hornfelses; (ii) the feldspathized inclusions; and (iii) the 'phenocrysts' of the granodiorite. They average 2.0 x 1.0 mm. but reach a maximum size of 4.0 x 2.0 mm.

It is clear that although some inclusions go through a pyroxenitic phase this is by no means invariably the case. Apparently pyroxene is evolved - given suitable PT conditions - either when the original chemical composition of the inclusion was favourable for its formation or when the stream of chemical elements diffusing through the original sediment was of such composition that pyroxene was the appropriate phase to form.

3. Granitization (Nos. 522, 524, 743, 757)

During this final process the transformation of the hornfels is completed, chiefly by changes leading to enrichment in potash feldspar and quartz. The mafics suffer a concomitant decrease and the biotite/amphibole ratio increases until it approximates to that of the normal granodiorite. Mineralogically the inclusions of this stage are granodiorites which are very similar to the contact marginal granodiorites. The textures, although now /
now more "igneous-looking", still retain relics of their crystalloblastic ancestry.

**Potash feldspar** occurs commonly as orthoclase and less commonly as microcline. It is present as interstitial blebs and as irregular plates in the groundmass. It has highly irregular borders against plagioclase which it is clearly replacing, since relics of plagioclase remain as inclusions in the larger plates (No. 522 illustrates an early phase of this stage). The largest plate observed was 1.0 x 0.5 mm. One part of an irregular crystal may be orthoclase whilst another may exhibit the quadrille structure of microcline (No. 757).

**Quartz** is present as interstitial crystals which, judging from their "replacement borders" seem to have developed at the expense of plagioclase.

**Hornblende and biotite** are more abundant than in the normal granodiorite and occur in clots accompanied by abundant iron-ores and sphene. These clots are identical with those found in the normal granodiorite. In the final stages a large ferromagnesian clot may be the sole record of the former presence of a xenolith.

Inclusions, other than those belonging to the series described are relatively rare. They are characterized by the association of very large plates (up to 3.5 mm. in diam.) of potash /
potash feldspar with mafic minerals. Some inclusions differ from those at stage 1 only by the presence of poikiloblastic potash feldspar. The textures of these inclusions indicate their close relation to the basified inclusions described above. Texturally these potash feldspar-rich basic inclusions are quite distinct from the members of the main transformation series. Also occasional "veinlets", composed almost entirely of potash feldspar, traverse the inclusions, e.g. Nos. 275, 204. The "veinlets" are 1-2.0 mm. in width and their replacement origin is clearly indicated by the non-displacement of earlier biotite laths which project into, and across many of them. In some cases the biotites are unaltered but in other cases they are completely bleached (No. 275).

The transformation of a series of hornfelsic inclusions through various stages into nebulitic or ghostlike relics has been traced in detail. It is deduced therefore that the ghosts represent altered sedimentary rocks.
Sediment

1. Basified inclusions

Basified inclusions enriched in potash feldspar

2. Formation of quartz diorite with growth of plagioclase porphyroblasts

2. Formation of quartz-diorite by recrystallization

3. Granitization

Fig. 1a. Diagrammatic representation of the successive stages of transformation of inclusions from sediment to granodiorite.
XII. ADAMELLITES

(a) General

The adamellites occupy the central part of the complex. Two types have been distinguished: 1. a hornblende-biotite-adamellite, and 2. a biotite-adamellite. There is a nearly perfect gradation between the granodiorite and the central biotite-adamellite, and therefore the boundaries as defined and drawn are purely arbitrary. Whereas Gardiner and Reynolds mapped the types on the basis of specific gravity, the writer has delimited the zones by variations in (i) macroscopic textures and (ii) qualitative and quantitative mineralogical composition.

The boundary drawn between the granodiorite and the transitional zone to hornblende-biotite-adamellite is based on a distinct macroscopic textural difference. There is no change in the qualitative mineralogical composition. The plagioclase/potash feldspar ratio of the rocks of the transitional type measured indicates that they are all granodiorites. This approximately corresponds with a specific gravity boundary of 2.70.

The outer limit of the hornblende-biotite-adamellite is based on micrometric analysis. It corresponds to a plagioclase/potash feldspar ratio of about 65/35 and to a S.G. of about 2.66. The inner boundary of the hornblende-biotite-adamellite is based on the absence of hornblende, proved microscopically. The S.G. is /
is about 2.62.

(b) Hornblende-biotite-adamellite

General

The zone extends from the S.E. shore of Loch Enoch in the north where it is narrowest (approx. 600 yds.) southwards to include the N.E. part of Loch Neldricken and the Black Gairy of Craignaw. It occupies the major part of the southern slopes of Craignaw and crosses the valley connecting Loch Narroch and Cooran Lane to occupy the northern slopes of Craiglee. It attains its greatest width of 1½ miles in the south. This increase in width from the waist of the complex southwards is of great structural significance.

37 specimens were collected, and of these 25 have been sectioned.

Petrography

Macroscopically the rocks have a mottled black and light grey background, in which large and conspicuous rectangular, pink porphyroblastic crystals of potash feldspar are embedded. The latter (average \( \frac{3}{8} '' \times \frac{1}{2} '' \)) have a beautiful pearly lustre and carlsbad twinning can often be easily distinguished (Fig. 66). The rocks differ from the biotite-adamellite in being less leucocratic and having a generally finer groundmass, and from the granodiorite in having a smaller proportion of mafic minerals, the latter (in particular /
particular biotite) being much smaller and more distinctly segregated into clots.

There are two varieties of biotite-hornblende-adamellite:

(1) Normal porphyritic variety with a medium to coarse grained groundmass
(2) Porphyritic type with a much finer groundmass.

The distinction is textural and not mineralogical.

Variety (2) is found only on the southern slopes of Craignaw below a height of 1825 ft., around the Dow Loch and down the main ridge south to Snibe Hill, and the Point of Snibe.

Eight specimens were collected and sectioned.

The hornblende-biotite-adamellite consists essentially of quartz, plagioclase (andesine), potash feldspar, biotite and hornblende, with accessory zircon, apatite and sphene, and iron ores with rare tourmaline, allanite and (?) xenotime.

The following table gives the modal analyses made on seven sections of the normal variety (1):—
Specimen Nos. 657a  380  385  377  671  649  765  Av.

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Modal analyses of 3 sections from specimens of variety (2) are given below:

Specimen Nos.  661b  660  636a  Av.

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A /
A comparison of the two tables shows that there is very little difference in the amounts of quartz and feldspar. The plagioclase/potash feldspar ratio is also the same. The only pronounced difference is that there is less hornblende in variety (2) which indicates its approach to the biotite-adamellite.

Specimen No. 649 from the middle of the zone N.E. of Loch Neldricken is representative of the normal variety (1).

Microscopically it consists essentially of quartz, andesine, potash feldspar, biotite and hornblende, with accessory zircon, apatite, sphene and iron ores.

Quartz makes up 30% of the rock and occurs as large or medium-sized anhedral crystals which are interstitial in character. Very frequently several such crystals form aggregates which commonly measure 3.0 x 2.0 mm. Undulose extinction is common. Fractures are also a notable feature; they cross from one individual crystal to another in the aggregates, and must have a post-crystallization origin. Trains of black dust-like inclusions cross the crystals in definite directions. There is a pronounced contrast between the marginal relationship with plagioclase and that with potash feldspar. The former margins are irregular but those of the latter are nearly always clean and straight or smoothly curved. Inclusions other than the minute "dust" /
"dust" trains are small anhedral plagioclase crystals generally less than 0.1 x 0.2 mm., small hornblende crystals, biotite flakes, and iron ores.

Plagioclase occurs generally as large and medium-sized subhedral laths which make up 35.5% of the average rock. The average size of the larger laths is 3.0 x 2.0 mm. Carlsbad and albite twinning are well developed. A few of the laths contain small granular inclusions which consist of rounded biotite crystals, hornblende, and stumpy prismatic apatite crystals. Some of the crystals show good form but the margins of other individuals against potash feldspar are highly irregular and in patches an intimate lobe-like interpenetration - or intergrowth - has developed. These complex symplectitic intergrowths may be described as dendritic in some cases and wormlike in others, and may extend over an area of 0.5 x 0.3 mm. Plagioclase is more abundant than potash feldspar. From the relationship described above the plagioclase has obviously been replaced. The texture suggests that the replacement took place in an already solid rock. The average composition of the plagioclase is An_{30-35}. Zoned crystals are common, the cores being frequently andesine An_{35} and the margins oligoclase An_{25-30}. Oscillatory zoning also occurs.
Potash feldspar (orthoclase, perthite and microcline-perthite in order of abundance) occurs in every stage from the initial anhedral bleb or irregular patch developing in plagioclase or interstitially, to large and medium-sized anhedral plates which are often highly 'poikilitic'. The large 'poikilitic' plates enclose all the other constituents. As described previously, the potash feldspar has a highly irregular border with plagioclase and all the crystals contain relics of plagioclase laths. Some of the corroded relics of plagioclase form optically continuous groups - clear evidence of replacement. Other inclusions are quartz, biotite, hornblende, apatite and zircon.

Biotite is present as small subhedral flakes which average 0.6 x 0.3 mm. and as larger flakes which rarely attain a greater size than 1.2 x 0.9 mm. It makes up 100% of the rock. Pleochroism is strong and similar to that of the biotite-adamellite biotites: X = straw yellow; Y = sepia; Z = dark brown. Common inclusions are apatite, zircon, surrounded by pleochroic haloes, and hornblende. Rarely some flakes are altered to chlorite with the production of a small amount of sphene. The biotite has a marked tendency to occur in clots with hornblende when the latter is present, and occasionally flakes of biotite poikilitically enclose subhedral crystals of hornblende. The ferromagnesian clots are aggregates of subhedral flakes and laths of biotite, crystals
Hornblende is quite subordinate to biotite and makes up approximately 2% of the rock. It is present as large anhedral and subhedral green crystals which reach a maximum size of 1.0 x 1.2 mm. More rarely euhedral transverse sections are present which illustrate twinning parallel to the orthopinacoid (100). Pleochroism is strong: X = pale green, Y = green, Z = dark olive green. The mineral is commonly associated with biotite in the ferro-magnesian clots and in one particular case it was seen to be associated with a large crystal of sphene. Inclusions are apatite and zircon surrounded by pleochroic haloes, and rarely small pegs of iron ores. Rarely in the cores of some crystals there are relics of pyroxene crystals.

The most abundant accessory in the clots is apatite; sphene is present locally as large subhedral crystals (1.1 x 0.3 mm.); iron ores are very rare; zircon is common as scattered grains.

Specimen No. 660 from the centre of the outcrop of variety (2) differs microscopically from No. 649 as follows:

(i) Quartz occurs in larger aggregates (4.0 x 3.0 mm) but is also commonly present as small granules enclosed in the margin of the potash feldspar porphyroblastic crystals and in the interstitial areas between the larger plagioclase crystals (average 0.2 x 0.2 mm.).
Zoned crystals of plagioclase are very abundant. Composition averages An_{30-35}. Zoned crystals have andesine cores An_{30} with margins that are generally calcic oligoclase An_{20-25} rarely becoming albitic.

Potash feldspar crystals are larger and frequently contain small rounded granules of quartz near the margins. Small subhedral crystals are also present in the fine-grained interstitial areas.

Biotite is more pronouncedly interstitial and hornblende is less abundant.

The major difference is one of texture, the porphyritic character being emphasized by the finer grain of the interstitial groundmass.

(c) Biotite-adamellite

General

J.J.H. Teall published the first description of the Loch Doon occurrence of this type of rock in the "Silurian Rocks of Britain" (Teall, 1899). He divided the acid rocks of the complex into (1) quartz-diorite (tonalite), (2) hornblende-granitites in which plagioclase is generally the dominating feldspar (the granodiorite of this study) and (3) biotite-granites or granitites. No attempt however was made to map the distribution of the types until 1932 when Gardiner and Reynolds re-studied the complex. They discovered that "true granite" was confined to the central ridge and that it showed little variation throughout the seven miles along which it extends. They collected 27 specimens and found /
found that they had specific gravities ranging from 2.60 to 2.65, the average being 2.63.

The writer collected 30 specimens along the southern half of the central ridge from the Nick of the Dungeon on the north, along and over Craignaw (2115 ft.) to the Point of the Snibe in the south. In the field small variations could be detected as one proceeded south, but they did not appear to be mappable. However, in the laboratory it was found that two types could be distinguished:

(1) a coarser grained more leucocratic rock; and

(2) a darker porphyritic type with a finer grained groundmass. This distinction was confirmed by micropetrological study. The coarser grained leucocratic rock is a biotite-adamellite without hornblende, while the darker porphyritic type is one of the varieties of hornblende-biotite-adamellite described on p. 162.

The biotite-adamellite outcrops along the central ridge from the Nick of the Dungeon where it attains its greatest width to just north of the Dow Loch on the southern slope of Craignaw (Map Fig. 75). This type, which is the nearest in the complex to a granite proper, has a much more limited extent than was previously supposed.

Petrography /
Petrography

Macroscopically the rock is generally light whitish grey, some specimens being faintly pink. The outstanding feature is the presence of large porphyroblastic rectangular crystals of potash feldspar which commonly measure $\frac{1}{2}$" x $\frac{1}{2}$". These often show a pearly lustre when cleaved. Quartz, plagioclase, and biotite can be readily distinguished in the groundmass (Fig. 66).

Description of a typical biotite-adamellite (No. 666). The rock consists essentially of potash feldspar, plagioclase, quartz and biotite, with accessory zircon, apatite, sphene and secondary chlorite.

Potash feldspar is present as orthoclase, microcline and perthite and forms just under 50% of the total feldspars. The crystals are often twinned on the carlsbad law. Although the crystals are the largest present, they are not normal phenocrysts. The margins of the crystals are uneven and penetrate intergranular areas but still tend to assume euhedral form - a fact that led Teall to record them as "pseudo-porphyritic". The fact of replacement now recognized implies late potash formation and so suggested to Teall that "the alkali feldspar and quartz always belong to the later stages of consolidation". Clear evidence is furnished by the symplectite intergrowths between the two minerals and the presence of numerous small optically /
optically continuous relic inclusions of plagioclase in the larger potash feldspar hosts. Some inclusions of plagioclase have developed rims distinctly more calcic than the core. As the large crystals of potash feldspar developed mainly at the expense of plagioclase other minerals were enclosed, inclusions of quartz, biotite, apatite and zircon being present. This is exactly the form of replacement assumed by the potash feldspar plates in the inclusions and suggests that in all cases replacement took place in the solid. The "pseudo-porphyritic" crystals have highly irregular borders against every mineral except quartz. The average size of these 'phenocrysts' is 12.0 x 6.0 mm., but the maximum size observed is 1" x ½".

Teall records that the potash feldspar is a typical microcline but according to the writer's observations orthoclase and perthite are the most common types, microcline being quite subordinate.

Plagioclase occurs as medium and large subhedral laths. The medium-sized crystals average 2.0 x 1.0 mm. whilst the larger are commonly over 4.0 x 2.0 mm. Carlsbad and albite twinning are well developed. Zoned crystals are common. The average composition is An_{25}. The zoned crystals average An_{30} in the cores.
cores with rims of $\text{An}_{15}$. As already described there is an obvious replacement relationship between plagioclase and potash feldspar. The borders margining potash feldspar are often of an intergrowth character and lobe-like relics (0.2 x 0.1 mm.) are common as inclusions in orthoclase "phenocrysts".

Inclusions present in plagioclase are small biotite flakes and iron ore granules.

In some cases quartz appears to be replacing plagioclase. Only slight alteration was observed, presumably to sericite.

Quartz is present abundantly (modal analysis 30%) as anhedral and occasionally subhedral crystals which occur interstitially or in aggregates. The crystals average over 1.0 x 1.0 mm. and the aggregates commonly 5.0 x 5.0 mm. Undulose extinction is common and sutured boundaries exist between the quartz crystals of aggregates. Minute biotite flakes and small laths of plagioclase occur as inclusions and very fine dust-like trains are also present.

Biotite occurs as small and medium subhedral laths and flakes, and occasionally as subhedral basal plates. It differs in colour from the biotites of the marginal granodiorites having $X = \text{straw yellow}, Y = \text{sepia}, Z = \text{golden brown};$ lacking the red tint /
tint of the former. Pleochroic haloes are common around zircon, xenotime and apatite. Some flakes are altered to chlorite.

A remarkable feature is the smallness of the flakes - the average size being 1.0 x 0.4 mm.; rarely they reach 2.0 x 1.0 mm.

Of the accessories zircon is noteworthy for its size, subhedral crystals over 0.1 x 0.1 mm. being present. Orthite, allanite and tourmaline, though rare, occur as occasional large euhedral crystals.

**Micrometric analyses of three specimens:**

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*McIntyre's Average from the northern half of the complex.*

*McIntyre's figures include some specimens which are placed by the writer in the hornblende-biotite-adamellite group.*
From the micrometric analyses it will be seen that on average the potash feldspar does not reach 50% of the total feldspar and therefore since in normal granite potash feldspar constitutes more than 50% of the total feldspar the rocks under consideration are not all granites sensu stricto but mostly fall within the adamellite or quartz-monzonite family. No. 667, however, is a true granite.

(d) Relationship between the biotite-adamellite and the hornblende-biotite-adamellite.

There is complete gradation between these two rock types just as there is between the hornblende-biotite-adamellite and the granodiorite. The change from hornblende-biotite-adamellite to biotite-adamellite takes place gradually as follows:

1. Potash feldspar increases in proportion at the expense of plagioclase, which it replaces to form large characteristic pseudo-porphyritic crystals.

2. Quartz also increases.

3. The ferromagnesian minerals decrease until they form only 8-9% of the total mineral content. With this decrease hornblende is eliminated and only biotite remains.
(e) Inclusions in the adamellites

Inclusions are present in the adamellites but they are not so numerous as in the granodiorite or transition zone. Gardiner and Reynolds (1932, p. 11) write: "We have not found any in the central ridge of true granite", but McIntyre (1947, p. 97), "in a brief reconnaissance found inclusions in the transitional zone and in the granite itself, right on the crest of the central ridge". He states "the similarity of such inclusions to the more igneous-looking inclusions of the 'tonalite' is obvious, and makes clear their genetic relationship".

The writer observed over fifty inclusions in the adamellites, whereby it is clear that although inclusions are not clearly so numerous as in the granodiorite they are not rare. The hornblende-biotite-adamellite contains proportionately more inclusions than the central biotite-adamellite. There is thus a definite decrease in the abundance of inclusions towards the interior of the exposed complex. The largest inclusion observed in the hornblende-biotite-adamellite was found on the eastern side of Craig Neldricken. This inclusion measured 2' x 1', but the majority are much smaller and average less than 3" x 2". In the hornblende-biotite-adamellite they are particularly abundant in the following localities: -
(1) a quarter of a mile north of Loch Narroch;
(2) east slope of Snibe Hill; and
(3) south-east of Loch Neldricken.

The dimensions of the largest inclusion found in the biotite-adamellite were only 10" x 6". All sizes were found from this down to inclusions of microscopic dimensions. The localities from which inclusions were obtained are:

(1) one-third of a mile due west of the Long Loch of the Dungeon; and

(2) the north slope of Craignaw overlooking Dungeon Burn.

Fourteen specimens of inclusions were collected; ten from the hornblende-biotite-adamellite and four from the biotite-adamellite.

The inclusions are dark coloured and ellipsoidal in shape. In the hornblende-biotite-adamellite they usually project slightly from the surface of the host rock. In the biotite-adamellite, on the other hand, great difficulty was experienced in collecting the inclusions as they are less resistant to weathering than their host rock and their remains are usually found embedded at the bottom of weathered hollows.

In the field two main types could be distinguished, although there appear to be gradations between these:

(i) a fine-grained, uniform, light-grey rock; and

(ii) a medium to coarse-grained "ghost" with some conspicuous black clots of ferromagnesian minerals.
Microscopically the first type is a biotite-rich hornfels. It is equivalent to the first stage of transformation (i.e. basification), of the sedimentary inclusions in the granodiorite. The "ghosts" correspond to the quartz-dioritic and granodioritic inclusions in the granodiorite, i.e. stages 2 and 3.

1. Basified hornfels inclusions (Nos. 682b, 686, 707, 708, 711 and 716). These generally have sharp junctions with the adamellite. Some have pronounced basic rims; e.g. No. 686 has a basic rim of maximum width 1/10". In most cases, however, there are distinct basic layers parallel to the bedding (Nos. 682 and 708). The majority of the inclusions are plagioclase-biotite-hornfels. Varieties are:


The plagioclase-biotite-hornfels in the adamellite are similar to those previously described from the granodiorite (p. 146): only notable differences need therefore be recorded.

Biotite is the most abundant of the mafic minerals and constitutes approximately 50% of the rock. Only the red brown variety has been observed.

Common green hornblende accompanies biotite (Nos. 716 and 707) but is relatively scarce.

Pyroxene /
Pyroxene was detected in only one section (No. 707).

Cordierite (No. 711) occurs as subhedral crystals (average size 0.4 x 0.3 mm.) in the groundmass along with plagioclase; it contains numerous inclusions of green spinel, iron-ore, apatite and minute biotite flakes. Occasionally large oval-shaped plates of cordierite are seen which stand out in the hand specimen as grey spots (No. 708). The spots measure over 2.2 x 1.2 mm. and are altered extensively to muscovite, prasolite, gigantolite and isotropic substances with high refringence. Iron-ore is a common associate. The cordierite crystals are generally biaxially negative but some crystals have $2V = 90^\circ$ and a few are optically positive.

Accessories are magnetite, ilmenite, pyrite, apatite, zircon, green spinel, muscovite and rutile. Of these the iron-ores are outstandingly abundant.

2. Quartz-diorite xenoliths. An early phase of the second stage of transformation of inclusions in the granodiorite is characterised by the growth of plagioclase porphyroblasts (p. 148). Although no inclusions illustrating this development of plagioclase porphyroblasts in basified hornfels inclusions were found in the adamellites, recrystallized quartz-diorite xenoliths sometimes contain plagioclase porphyroblasts.
The quartz-dioritic inclusions (Nos. 642, 640a and 640b) were all collected from the biotite-adamellite. They are all biotite-plagioclase-quartz-hornblende rock but they have close textural similarities to the obviously metamorphic rocks of the complex. Glomeroporphyritic aggregates of hornblende and biotite are a characteristic feature (No. 642).

Hornblende is the predominant mafic mineral and occurs as small granules > 0.2 mm., medium poikiloblastic crystals (average 1.0 x 0.8 mm.), and large subhedral prismatic crystals over 2.5 mm. in length. The smaller granules and medium-sized crystals form large aggregates which in section sometimes cover an area of 8.0 x 6.0 mm. Rare examples of hornblende crystals have small cores of pyroxene.

Biotite occurs as large subhedral porphyroblasts (2.0 x 1.8 mm.). It is strongly pleochroic with X = pale brown, Y = sepia, and Z = dark brown. It frequently rims hornblende with which it is associated in the clots. Some chlorite has developed as an alteration product of the biotite.

Plagioclase occurs as small anhedral crystals in the groundmass and as large porphyroblasts ( > 2.5 x 1.5 mm.). It averages An$_{30-35}$. Oscillatory and continuous zoning are common. The porphyroblasts contain inclusions of quartz, biotite, hornblende, iron-ores and apatite. When the groundmass is of small grain /
grain size (0.2 - 0.3 mm. diam.), the plagioclase porphyroblasts appear more conspicuous.

Quartz occurs interstitially, as small granules and also as larger crystals measuring 2.0 x 1.4 mm. The latter contain long apatite needles and inclusions of plagioclase, hornblende and biotite. The quartz has intricate, irregular and lobed borders against plagioclase, which it has clearly replaced in part. It is noteworthy that in No. 640a quartz is unusually abundant.

3. Granodiorite inclusions (Nos. 379, 656a, 680, 683 and 714). The transformation of quartz-diorite inclusions into granodiorite is effected by changes which lead to increase of potash feldspar and quartz at the expense of plagioclase and the mafic minerals. The latter decrease in amount and there is a relative increase of biotite to hornblende. Some of the granodiorite inclusions are clearly crystalloblastic but these grade into "igneous-looking" types identical with the normal granodiorite.

No. 680 is a typical granodiorite "ghost" which differs from the quartz-dioritic xenoliths described above only by possessing potash feldspar. The potash feldspar is present interstitially and as large anhedral irregular plates of orthoclase, microcline and perthite with inclusions of quartz, biotite, hornblende /
hornblende, apatite needles and iron-ores; it has replaced
plagioclase extensively during the development of the rock.
The habit and manner of replacement is identical with that of the
potash feldspar 'phenocrysts' of the adamellite.

No. 714 grades imperceptibly into normal granodiorite.
It differs from normal granodiorite in possessing more numerous
mafi clots, and by containing more hornblende than biotite.
Biotite has replaced hornblende in part.

It is clear that the same process of transformation of
altered sedimentary inclusions into granodioritic types obtains
both in the granodiorite and adamellite zones of the complex.
Again all stages of transformation from altered sediments to
"ghosts" can be traced, therefore the origin of the nebulitic or
"ghost-like" patches is clear. From the petrographic description
it is also clear that the "ghosts" differ in composition from the
basified sediments, therefore the inclusions have been metasomati-
cally altered. Stages in the transformation (metasomatic)
can be traced

(a) in a series of inclusions (as above);
(b) in single individual inclusions; and
(c) in the complex as a whole.

From the distribution of the various types of inclusions it is
seen that the proportion of basified inclusions to "ghosts"
decreases /
decreases towards the interior. If it be assumed that the process has progressed farther in the centre, then it can be concluded that the basified inclusions are earlier stages in the transformation process and the "ghosts" are later.

Texturally and mineralogically the inclusions have very close affinities to the metamorphics and therefore the process may be aptly termed metasomatic metamorphism (Holmes and Reynolds, 1947).
XIII. SUMMARY OF EVIDENCE OF THE ORIGIN OF
GRANODIORITE AND ADAMELLITE

There is a perfect gradation from highly metamorphosed greywacke beds through intermediate 'contact' types to a banded marginal granodiorite (p. 72); this gradational margin is due to the transformation of the sediments by a process of metasomatic metamorphism. The evidence for this transformation has been summarized above (p. 101). A continuation of the process is demonstrated by the evidence from the granodiorite given below.

A. Granodiorite
(a) Field Evidence
(1) There is a perfect gradation between marginal and normal granodiorite. The change from marginal to normal granodiorite is effected by (i) increase in leucocratic constituents; (ii) coarsening in grain size; (iii) gradual loss of metamorphic texture; (iv) loss of pronounced banding; and (v) development of two sets of structural planes (see Section XVIII).

(2) In addition to the gradation to marginal granodiorite, at various localities the normal granodiorite grades into hornblende-biotite-adamellite, augite-hypersthene-biotite-granodiorite and biotite-hornblende-quartz-diorite.

(3) /
(3) Rarely the normal granodiorite is adjacent to the aureole hornfelses but more usually the marginal granodiorite intervenes between them.

(4) The 'contact' is intricate and characterized by tongues. These are not generally due to intrusion of magma but are formed from pods of 'granitic' material which form in the aureole and consequently join up into stringers and tongues of the main mass.

(5) The outcrop of rock transitional to hornblende-biotite-adamellite extending from the western end of the Rig of the Jarkness to White Brae Top is interpreted as a "local advance guard"; an example of infiltration ahead of the main front of granitization.

(6) Certain varieties of the granodiorite can be closely matched with either marginal granodiorite or inclusions.

(7) Inclusions are abundant throughout the whole of the normal granodiorite but are more numerous near the margin of the pluton.

(b) Petrographic evidence

The following points considered collectively indicate that the granodiorite was formed essentially in situ and was not intruded in a liquid or otherwise mobile condition into its present /
present position, except perhaps locally near the margin, where mobility became effective.

1. **Retention of crystalloblastic characters** is demonstrated by:

(i) Biotites occurring in ragged crystalloblastic, poikiloblastic and skeletal flakes.

(ii) Hornblende crystals frequently having crystalloblastic and poikiloblastic habits.

(iii) Amphiboles occurring as patchy and composite crystals with ragged borders.

(iv) Decussate texture of ferromagnesian aggregates.

(v) Plagioclase 'phenocrysts' occasionally having porphyroblastic characters.

(vi) Composite plagioclase 'phenocrysts' having decussate structure.

(vii) Plagioclase crystals often having zonally arranged inclusions of mafic minerals.

2. **Mineralogy**

(i) The same internal irregularities are present in the plagioclase 'phenocrysts' of the granodiorite as are shown by those of the aureole feldspathized hornfelses, inclusions and the marginal granodiorite.

(ii) The composition of the plagioclase crystals in the hornfelses, the marginal and the normal granodiorite is very similar and covers the same range.

(iii) The composition of the large and small plagioclase crystals is independent of grain-size.

(iv) Potash feldspar has a striking replacement character. The orthoclase (or perthite) plates enclose relics of plagioclase which have highly sinuous borders.

(v) /
The essential minerals of the granodiorite are the same as those developed by metasomatic metamorphism in the contact zone.

Biotite and hornblende in the granodiorite resemble those minerals in optical properties both in the contact zone and in the basified hornfels.

The accessories of the basified hornfels, the marginal granodiorite and normal granodiorite are essentially the same.

Quartz possesses undulose extinction and has also a replacement character.

3. Inclusions

(1) The following stages in the transformation of the sedimentary inclusions into granodiorite have been traced:

(i) The hornfelses are basified (enrichment in biotite) in a manner similar to those in the aureole.

(ii) They are then feldspathized to form quartz-diorite and/or granodiorite, or pass through an intermediate porphyroblastic stage.

(2) The process is effected by enrichment in feldspar and quartz, reduction of the mafics, and rearrangement by recrystallization. The inclusions can be arranged in an evolutionary sequence from obvious sedimentary hornfelses, through more "igneous-looking" types and "ghosts" with a granitic texture, to granodiorite.

(3) Every stage in the process of transformation of the sedimentary inclusions into granodiorite can be matched with corresponding /
corresponding phases of transformation of the aureole hornfelses into marginal granodiorite. In other words the small scale inclusion evidence supports the large scale marginal evidence.

The determination of the origin of the "igneous-looking" inclusions is recognized by most petrologists to be difficult. The possibility that the inclusions might be xenoliths of pre-existing igneous rocks or cognate inclusions has been fully considered. Evidence against the igneous origin of the "ghosts" is as follows:-

(i) There is no igneous wall rock to the complex.

(ii) The "ghosts" are associated with recognizable sedimentary inclusions.

(iii) No series grading from pre-existing igneous rocks to those of ghost-like character has been found.

(iv) No textures which could be clearly indicative of igneous origin are present. It is pertinent to note that the plagioclase porphyroblasts which develop in the inclusions are identical with the large plagioclase crystals in the host. In this connection Grout (1937, p. 1534) states that in most cases porphyritic texture cannot be distinguished from porphyroblastic.

The growth of feldspars in the inclusions is directly comparable to the feldspathization of the transformed sediment in the aureole contact zone. This growth of feldspar in inclusions has been, and to some extent still is, a subject of controversy. The most famous example is perhaps that of Michel-Lévy's (1893) "dent /
"dent du cheval" from Flamanville, where large well-shaped crystals of orthoclase, identical with those of the adjoining porphyritic granite occur, not only in the sedimentary schists outside the granite, but also in enclaves of similar material within the granite. One of the most important contributions to the study of the potash-soda-feldspars has been made by Spencer (1938). As part of his investigation he studied the alkali feldspar porphyroblasts of xenoliths from the Shap granite, Westmorland, and the Kloof granite, Cape Town. The Shap granite is characterized by large pink orthoclases and in addition to obvious xenoliths possesses darker patches in which occur large feldspar crystals similar to those of the granite proper. Spencer showed that the orthoclase porphyroblasts of the xenoliths are identical with those of the orthoclase phenocrysts of the granite. He concluded (pp. 111-112), "The composition of the xenoliths precludes a simple origin by molecular reconstitution for the feldspar porphyroblasts. ..... It is possible that the silica and alumina may have been more or less in situ, but the potash and soda must have been locally concentrated by migrating solutions or by solid diffusion. ..... These porphyroblasts must have been formed in a relatively short time compared with the total time of magmatic consolidation and magmatic action. It is possible that the same process acting over long periods might produce holocrystalline rocks /
rocks with more or less complete obliteration of the original structure without the mass having reached even a plastic condition."

D.L. Reynolds (1944) has found xenoliths of diabrochite in the biotite-granodiorite of the south-western end of the Newry Igneous complex. In these xenoliths, sporadic large porphyroblasts of oligoclase have grown as a result of introduction of material. She stated "As the plagioclase porphyroblasts increase in number, the matrix of the rock becomes slightly coarser grained and a little lighter in colour, until finally the rock has the appearance of a porphyritic igneous rock".

Other examples of feldspathization of inclusions are numerous although not all have been interpreted in the same manner. Grout (1933) has described feldspathization of the slates around the Duluth gabbro. Goodspeed (1929) has shown that the rocks of Cornucopia, Oregon, have xenoliths which possess plagioclase "phenocrysts". Iwao (1936) described the growth of large porphyroblasts of feldspar in the xenoliths of the Kuga district. As others writers have pointed out, it is difficult to believe that the large feldspars in the basic xenoliths in the Trégastel-Ploumanac'h granite (Thomas and Campbell Smith, 1932), identical with the feldspars of the granite, could have been intruded mechanically./
mechanically. Further examples could be given from the works of Clapp (1921), Daly (1928), Nockolds (1932), A.L. Anderson (1934), G.H. Anderson (1937), Read (1942) and others.

Examples are therefore not lacking to support the growth in solid inclusions of feldspar crystals - whether they be termed porphyroblasts, 'phenocrysts' or metacrysts; these porphyroblasts are usually identical with the 'phenocrysts' of the host rock. There seems to be no doubt that an extension of this process can produce a rock which has the appearance of an "igneous" rock. As pointed out by Read (1944, p. 86) the sedimentary origin of many of the enclaves is more certain than the magmatic origin of the host: "though we can demonstrate the sedimentary origin of the key enclaves, no one can demonstrate the magmatic origin of the porphyritic granite which contains them".

The evidence summarised above has been interpreted by the transformist theory as it is the only theory which gives a satisfactory explanation of the facts.

Gardiner and Reynolds postulated that the complex was formed by three successive intrusions of noritic, tonalitic and granitic magmas respectively which were the crystal differentiates from a once homogeneous magma. With regard to the granodiorite this hypothesis cannot explain the following facts:

(1) Basification of the sedimentary inclusions in which the inclusions become more basic than their host (magma) and the original rock.

(2) /
(2) The types intervening between the altered sediments and granodiorite.
N.B. The tonalitic magma cannot be the source of the basic emanations as such emanations could not be produced as a residuum of a tonalitic magma.

(3) The crystalloblastic textures present in the granodiorite.

(4) The increase in crystalloblasticity towards the margin of the complex and decrease towards the 'granite' which was formed by the last of the assumed intrusions. This fact is explained by Gardiner and Reynolds on the supposition that the granite followed very shortly after the tonalite intrusion; i.e. whilst it was still hot. There is no evidence to support this statement - it is pure conjecture.

B. Adamellites

(a) Field evidence

(1) The biotite-adamellite occupies the central part of the pluton and there is a perfect gradation outwards through hornblende-adamellite to granodiorite. There is no contact between any of the types and the boundaries that have been drawn are purely arbitrary.

(2) The adamellite zone is narrowest at the waist of the complex and its widest extension is in the south.

(3) The 'phenocrysts' of potash feldspar increase in abundance and size as one proceeds from the granodiorite inwards - at /
at the same time the amount and size of the mafics diminish.

(4) Inclusions of undoubted sedimentary origin occur in the adamelllite zone although they are not so abundant as in the granodiorite.

(b) Petrographic evidence

(1) The gradation observed in the field is confirmed under the microscope. The change from hornblende-biotite-adamellite to biotite-adamellite takes place gradually by:

(i) increase in the potash feldspar content;

(ii) increase in quartz; and

(iii) decrease in mafic content with eventual elimination of hornblende.

(2) The essential minerals of the hornblende-biotite-adamellite are the same as those developed in the contact zone and the granodiorite by metasomatic metamorphism.

(3) The accessories of the adamellites are fundamentally also the same; the adamellites however possess a few additional rare minerals such as orthite and allanite.

(4) Quartz possesses undulose extinction and has a replacement character.

(5) Plagioclase becomes more sodic towards the centre of the pluton. This change is very gradual.

(6) /
(6) Internal irregularities are present in the plagioclases similar to those described from the granodiorite zone.

(7) Continuous and oscillatory zoning are also present occasionally.

(8) Plagioclase often contains small granules of mafic minerals and apatite.

(9) Potash feldspar has a highly irregular border with plagioclase and its whole character is that of replacement.

(10) Potash feldspar forms large "pseudo-porphyritic" crystals.

(11) Small granules of quartz are trapped towards and at the margins of the pseudo-porphyritic potash feldspar crystals.

(12) Symplectite intergrowth of potash feldspar and quartz is common.

(13) Occasional biotite flakes are poikiloblastic.

(14) The mafics form aggregates and clots similar to those formed in the granodiorite but on a smaller scale. The reduction in the size of the clots is also a gradual process.

(c) Inclusions

The inclusions in the adamellites show the same evolutionary sequence as that displayed by the inclusions in the granodiorite and clearly indicate an identical genesis.
The following stages in the transformation of the sedimentary inclusions into granodiorite and adammullitic rocks have been traced:-

(i) The hornfelses are basified in a manner similar to those in the aureole and the inclusions in the granodiorite.

(ii) They are then feldspathized and directly formed into quartz-diorite and granodiorite.

The replacement hypothesis is given further weight by the failure of the magmatic theory to explain the lack of blocks of granodiorite which would have been present as numerous xenoliths in the granite if the latter had stopped its way into the granodiorite.

The above evidence indicates that the adammellites were formed by growth in the solid - by granitization of the granodioritic rocks.

The replacement character of the potash feldspar and quartz indicates that the final phase was enrichment of the product of the granodioritic stage, chiefly in potash and silica.

Other workers have clearly seen the difficulties that stand in the way of postulating intrusion of a granitic magma into the heart of a previous intrusion; in an attempt to overcome this obstacle, Deer has invoked the aid of a "partial magma", (Deer, 1935, pp. 68 and 73.

Furthermore /
Furthermore the transitional zone between the granodiorite and the adamellite, with its semi-porphyritic character, is difficult to explain by the magmatic hypothesis. The explanation offered by Gardiner and Reynolds (1932, pp. 16-17) is that it is due to the mixing of the porphyritic 'granite' magma with the granodiorite magma before the latter had cooled after its intrusion. If the 'phenocrysts' of potash feldspar had been the first crystals to form in the granite magma then it would be considered by some petrologists to be feasible to imagine a semi-porphyritic mixture with the granodiorite. But the potash feldspar pseudoporphyritic crystals are the last to form, NOT the first, and therefore the assumption of mechanical mixing is untenable. Also the increase in size of the pseudo-porphyritic potash feldspar crystals towards the centre of the pluton cannot be explained by a magmatic argument.

**Late Stage Enrichment of Potash Feldspar**

Directly comparable occurrences of late stage enrichment of potash feldspar have been described notably by D.L. Reynolds (1943, 1944); A.L. Anderson (1930, 1934); and C.A. Chapman (1939).

D.L. Reynolds (1944, pp. 213-4) has described the enrichment in microcline of hornblende-granodiorite from the southwestern end of the Newry igneous complex. She found that "The general /
general appearances of the textures in thin section suggests that the microcline replaced the earlier minerals, particularly plagioclase, of an already solid rock. Additional evidence that the microcline is a late stage replacement mineral was found in a melanocratic inclusion within the hornblende-granodiorite ...... There can be no doubt, in this example, that the microcline has replaced some of the original constituents, principally plagioclase, of the inclusion. The evidence is clear that perthitic microcline originates as a late-stage replacement of solid rock both in the granodiorite and in its enclosed xenoliths. A year earlier D.L. Reynolds had described similar replacement microcline from the granitized hornfelsed sediments of Goraghwood quarry.

In 1930 A.L. Anderson described the microcline phenocrysts which occur in the porphyritic granodiorites in the Cabinet Mountains in northern Idaho, where they are the latest mineral to form and have done so by replacing the earlier plagioclase and quartz of the normal granodiorite. In 1934, he continued his investigations on "replacement" granite by studying the "Contact phenomena associated with the Cassia Batholith, Idaho". He discovered that the marginal porphyritic granite zone is thoroughly impregnated by late-stage microcline of phenocrysts size similar to the phenocrysts found previously in the porphyritic granodiorite in the Cabinet Mountains. He explained their origin as follows: /
follows (1934, p. 390):- "As the emanations [from a postulated magma] continued to stream through the wide border or contact zone they apparently became increasingly enriched in potash as a result of which large crystals of microcline were deposited by replacement throughout most of the contact zone and produced a granitic rock with marked porphyritic texture". Anderson noted similar work by J.L. Gillson (1927) and suggested that Spurr and Garey (1908) were probably the first to suggest that microcline phenocrysts may form after the solidification of the magma and by recrystallization through solutions. It is interesting to note that Teall (1899, p. 611) at Loch Doon was earlier. He stated "the alkali-feldspar and quartz always belong to the later phases of consolidation, even when the former are developed as large pseudo-porphyritic crystals, which is sometimes the case".

A further example of potash feldspar replacement is furnished by C.A. Chapman (1939, pp. 167-170), from the Mascoma Quadrangle, New Hampshire. To explain the origin of the Oliverian magma series he invokes the processes of assimilation, pure melting, fractional crystallization and replacement. It is to account for the more granitic rocks of the Mascoma dome, which possess large crystals of microcline, that the process of hydrothermal replacement was advanced. By this process the quartz-diorites and /
and the granodiorites of the Oliverian magma series were considered to have been converted into rocks with compositions of quartz-monzonite and granite. Of the microcline Chapman stated (p. 143) "Upon first glance these crystals appear to be phenocrysts but detailed study particularly in thin-section, disclosed lines of evidence which point strongly to the idea that they are metacrysts, introduced subsequent to the consolidation of the original rock."

Other workers, e.g. Terzaghi (1948), have recorded potash enrichment of rocks that have undergone hydrothermal alteration but in such examples the presence of water is always indicated by the associated alteration products. There are no grounds for attributing the "pseudo-porphyritic" character of the Loch Doon potash feldspars to hydrothermal introductions.

The alkali enrichment of the central adamellite is in line with the recent views put forward by Lapadu-Hargues (1945). From a study of the variations of the molecular percentages of the chief oxides in groups of analyses of seven classes of rocks (slates, sericite-muscovite-schists, biotite-muscovite-schists, muscovite-biotite-gneisses, biotite granitized augen-gneisses, granites, muscovite-granites), he concluded that there has been a progressive influx of alkalis from the deeper zones and that soda migrates farther than the potash which remains localized in the /
the deep zones. Although his study is primarily concerned with regional metamorphism it is also relevant to the process of granitization.

The work on "replacement" granites by such leading petrologists as Sederholm (1923), Quirke and Collins (1930), Wegmann (1935) and Backlund (1936), is of course well known and reference has been made to their publications elsewhere. All these petrologists have this in common - that they firmly uphold the hypothesis that granite can be formed out of pre-existing rock by means of emanations, whatever the nature of these may be.
XIV. SOUTHERN MASS OF HYPERSTHENIC ROCK

A. HYPERSTHENIC ROCK

(a) Introduction

The hypersthenic rocks of the north-west part of the pluton have been studied intensively by D.B. McIntyre (1947, 1950). The writer has discussed the genesis of these rocks with Dr. McIntyre both in the field and in the laboratory and is in complete agreement with the interpretation put forward by him. In view of this, the object of the present work has been to determine whether a like interpretation is justifiable for the hypersthenic rocks of the Loch Dee area.

(b) General statement

The southern mass of hypersthenic rocks covers the area lying to the south-east, south and south-west of Loch Dee, and extends from the north-western slopes of White Hill on the west, to the Torrs of Kirerrock on the east. The area is relatively well exposed except in the following localities: the south-west margin of Loch Dee; the valley of White Laggan Burn; and the valley of Green Burn.

An isolated outcrop of hypersthenic rock has been discovered near the summit of the Trostan, nearly half a mile to the west /
west of the main mass. It is surrounded by rocks of quartz-dioritic composition which form a transition to the granodiorite.

Gardiner and Reynolds' statement that "throughout almost the whole of this area the rock is a typical norite" was not substantiated in the field. Fine, medium and coarse-grained types have been observed. The finer and medium-grained types are commonly found near the margin of the complex, but the geographical distribution of variations in grain size is not regular.

The finest grained hyperstheneic rocks, which are characterised by pronounced crystalloblastic texture occur along the margin of the complex, but fine grained patches have been found up to half a mile from the contact. There is a complete gradation from fine to coarse grained types. The coarsest grained rocks are, in general, most distant from the contact. They grade into the medium-grained type towards the aureole and into the granodiorite towards the centre of the pluton.

The observed distribution of the types is in contrast to that of the north-western area, where McIntyre found it impractical to map the variation in texture and grain-size.

(c) Petrography

Seventy specimens were collected over an area of one and a half to two square miles, and fifty of these were sectioned.
The field division of the specimens into fine, medium and coarse-grained types was found microscopically to correspond to quartz-diorite, quartz-diorite to granodiorite, and granodiorite respectively. The qualitative mineralogical composition of these is very similar. All consist of plagioclase, pyroxene (hypersthene and augite), quartz, biotite, potash feldspar, hornblende and accessory opaque iron-ores, apatite and zircon. Potash feldspar, hornblende and biotite are quantitatively the most variable. In the three groups potash feldspar varies from 0 to 20% but it is absent from only three fine-grained specimens. Hornblende varies enormously in abundance; it is absent from six specimens, but its variation cannot be correlated with grain-size. The amphibole has formed by alteration of the other minerals and the distribution of the amphibolization follows no obvious rule. Biotite is most abundant in the finest grained rocks.

1. Specimen No. 311 from White Laggan Burn is a typical fine-grained marginal hypersthene rock.

Macroscopically the rock has a mottled light and dark grey colour and corresponding to its fine grain is compact and tough. Occasional 'phenocrysts' of feldspar and medium-sized flakes of biotite can be distinguished. The small black crystals of pyroxene are evenly distributed throughout the rock and are not outstanding.

Microscopically /
Microscopically the rock consists essentially of plagioclase, biotite, pyroxene, quartz, with accessory potash feldspar, iron ores, apatite and zircon; it is an augite-biotite-hypersthene quartz-diorite (Fig. 42).

Plagioclase occurs as subhedral porphyroblasts averaging 1.8 x 0.4 mm. and also as subhedral to anhedral laths in the groundmass which range from 1.0 x 0.2 mm. to 0.1 x 0.05 mm. in size. The porphyroblasts have irregular margins against quartz, and highly so against potash feldspar. Potash feldspar has replaced the plagioclase in some cases. Carlsbad and albite twinning are very common. Both continuous and oscillatory zoning are frequently present. The crystals have undergone very little alteration, only slight kaolinization and sericitization being seen. Inclusions of pyroxene granules and small biotite flakes are common; others are iron-ores, potash feldspar and quartz. The pyroxene granules are often arranged zonally, and this arrangement is often emphasized by the occurrence of a dusty clouded zone between core and margin both of which are clear. The composition both of porphyroblasts and of groundmass crystals averages andesine An$_{35}$, the range being from An$_{50}$ to An$_{25}$. The continuously zoned crystals generally have a core of An$_{40}$ with a margin of An$_{25}$. Examples of oscillatory zoning are given below:

An % /


The number of zones may be great, e.g. 50; but many of these differ but little in composition and consequently can be grouped into a few major zones.

Potash feldspar. In this rock the amount of potash feldspar is 7.5%, which is probably slightly higher than the average amount in the fine-grained rocks. It occurs as anhedral, interstitial crystals. It has often a lobe-like and occasionally a skeletal character, and has highly irregular margins against plagioclase. The crystals average 0.2 x 0.1 mm. and occasionally reach 0.4 x 0.2 mm. The smallest crystals are blebs in plagioclase; they are elongated parallel to the cleavage of the host mineral. Perthitic and micrographic intergrowths are present on a small scale. Very rarely the potash feldspar is slightly altered, but generally it is clear and fresh even when neighbouring plagioclase is decomposed.

Biotite occurs generally as subhedral to anhedral flakes and laths, with a pronounced crystalloblastic character. The average size of the flakes is 0.3 x 0.2 mm. and the range is from /
from 1.8 x 0.8 mm. to 0.05 x 0.01 mm. The pleochroism varies slightly, but is commonly $X = $ pale yellowish brown or straw yellow; $Y = Z = $ dark reddish brown. Pleochroic haloes are common around inclusions of zircon and apatite. The irregular and often poikiloblastic flakes are closely associated with pyroxene, hornblende and iron ores. They are frequently found rimming pyroxene and hornblende crystals, and small flakes form inclusions in both these minerals. Rarely it alters to a very pale green, almost colourless, chlorite.

**Pyroxene** is the most abundant mafic mineral. Ortho- and clino-pyroxene are both present but hypersthene predominates. Most commonly the pyroxene occurs as subhedral prismatic 'phenocrysts' which average 1.0 x 0.6 mm. The range, however, is from small rounded granules (< 0.1 mm. diam.), to large euhedral prismatic 'poikilitic' crystals which attain a maximum size of 4.0 x 0.7 mm. Some of the latter are poikiloblastic. Clusters of granules sometimes occur. Inclusions are common and these consist of quartz grains, small biotite flakes, minute schiller inclusions, and small plagioclase laths. Twinned crystals are common. Zoning is rare. Hypersthene is usually faintly pleochroic with $X = $ colourless, $Y = $ faint red, and $Z = $ pale red, but the pleochroism varies in intensity from one crystal to another. Augite is colourless or very pale green with $Z \cdot c = 40^\circ$. Rarely /
Rarely a euhedral hypersthene crystal has a narrow rim of clino-
pyroxene. Biotite commonly mantles both pyroxenes, occasionally
enclosing the crystals completely. The pyroxene has been al-
tered to hornblende peripherally and along the cleavage traces.

Quartz occurs generally as anhedral, interstitial
patches and sporadically as rounded granules. Large anhedral
crystals, attaining a maximum size of 0.5 x 0.5 mm., occur but are rare. Undulose or shadowy extinction is common and suggests growth under conditions of stress. Micrographic intergrowth with potash feldspar is frequent. The boundary of quartz with plagioclase is often irregular, and small crystals are to be found enclosed along the margins of the tabular plagioclase or crystals. These facts point to the development of plagioclase at the expense of quartz.

Near the margin of the pluton in Black Laggan Burn the
fine-grained hypersthenic rocks are extensively amphibolized.
The amphibole has developed along the margins and cleavages of the pyroxene. The replacement is rarely complete and all stages in the process can be observed. The colour of the amphibole is variable /
variable; it is generally a light olive-green, but ranges from almost colourless to brownish green. The composite nature of the crystals is brought out by their patchy colouration. \( X < Y = Z. \ Z^1 c 15^\circ - 25^\circ. \)

The complete succession (not always seen in any single crystal) of ferromagnesian minerals, as determined by the observed rims, is as follows:— hypersthene \( \rightarrow \) augite \( \rightarrow \) green or colourless hornblende \( \rightarrow \) brownish green hornblende \( \rightarrow \) biotite \( \rightarrow \) opaque iron ores.

The only quartz-free diorite recorded was found near the contact in Black Laggan Burn. This locality is also remarkable for the extensive veining of the amphibolized pyroxene-biotite quartz-diorite by nearly horizontal quartz-rich veins from 2 - 5 mm. thick and spaced more or less evenly at 10 mm. intervals.

Micrometric analyses were made of two typical fine-grained specimens:

<table>
<thead>
<tr>
<th>Specimen Nos.</th>
<th>311</th>
<th>320</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>12.0%</td>
<td>15.5%</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>51.0%</td>
<td>50.5%</td>
</tr>
<tr>
<td>Potash feldspar</td>
<td>7.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Biotite</td>
<td>12.5%</td>
<td>12.0%</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>14.5%</td>
<td>18.5%</td>
</tr>
<tr>
<td>Amphibole and others</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>
2. The medium-grained hypersthene-granodiorite

In hand specimen the rock is a mottled dark and light grey colour. It weathers to a whitish-grey rough surface. The feldspar possesses a dark grey resinous lustre; occasionally it has a pinkish tint. Biotite as black glistening flakes and pyroxene in the form of black and bronze tinted prismatic crystals are easily distinguished.

Qualitatively the rock has the same mineralogical composition as the fine and coarse grained types. It is a hornblende-augite-biotite-hypersthene-granodiorite (Fig. 46).

Plagioclase occurs as subhedral tabular 'phenocrysts' averaging 2.2 x 0.7 mm. in section. The bulk composition is andesine An$_{35}$. The zoned crystals have a slightly more calcic core (An$_{55}$) than those of the marginal rocks, with a rim of oligoclase, An$_{(30-25)}$.

Potash feldspar is more abundant than in the finer grained type. For this reason the medium-grained rocks are classified as quartz-poor granodiorites. It occurs as anhedral and subhedral plates which occasionally measure as much as 1.0 x 0.5 mm. Micrographic and micropegmatitic intergrowth with quartz is often spectacular and the lobing of the potash feldspar into the plagioclase is well developed. The potash feldspar is always clear and fresh. Its replacement character is again obvious.

Biotite /
Biotite varies in amount greatly. The larger flakes (averaging 1.8 x 0.6 mm.) have lost most of their crystalloblastic character but the smaller flakes are often obviously crystalloblastic.

Pyroxene has the same habit and optical properties as in the marginal rock. Hypersthene is still the dominant pyroxene. Rarely a clot formed of medium-sized crystals and granules covers an area of 4.5 x 2.5 mm. (Fig. 44). Amphibolization has sometimes affected up to 80% of the pyroxene present.

Quartz occurs as interstitial patches.

Micrometric analyses of three medium-grained specimens Nos. 287, 328 and 590 are given below:

<table>
<thead>
<tr>
<th>Specimen Nos.</th>
<th>287</th>
<th>328</th>
<th>590</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>7.0%</td>
<td>12.0%</td>
<td>10.0%</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>54.5%</td>
<td>46.0%</td>
<td>52.0%</td>
</tr>
<tr>
<td>Potash feldspar</td>
<td>13.5%</td>
<td>12.0%</td>
<td>10.0%</td>
</tr>
<tr>
<td>Biotite</td>
<td>6.0%</td>
<td>12.0%</td>
<td>7.5%</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>17.0%</td>
<td>10.0%</td>
<td>19.0%</td>
</tr>
<tr>
<td>Hornblende and others</td>
<td>2.0%</td>
<td>8.0%</td>
<td>1.0%</td>
</tr>
</tbody>
</table>
3. The coarse-grained hypersthenic granodiorite

Mineralogically this rock is closely comparable to the medium-grained type except that the crystalloblastic character has almost entirely disappeared and the texture is now more "igneous-looking". The crystals are more idiomorphic than in the finer types. The rock is an amphibolized augite-biotite-hypersthenegranodiorite (Figs. 48-9).

The results of micrometric analysis of three typical specimens are given below:

<table>
<thead>
<tr>
<th>Specimen Nos.</th>
<th>298</th>
<th>336</th>
<th>353</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>13.5%</td>
<td>12.5%</td>
<td>10.5%</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>43.5%</td>
<td>40.5%</td>
<td>54.0%</td>
</tr>
<tr>
<td>Potash feldspar</td>
<td>8.5%</td>
<td>15.5%</td>
<td>13.0%</td>
</tr>
<tr>
<td>Biotite</td>
<td>9.0</td>
<td>8.5%</td>
<td>7.5%</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>13.5%</td>
<td>21.5%</td>
<td>11.5%</td>
</tr>
<tr>
<td>Hornblende and others</td>
<td>7.0%</td>
<td>2.0%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

According to the classification proposed, the rocks described are predominantly biotite-hypersthene-granodiorites becoming quartz-dioritic near the margin. McIntyre has adopted Goldschmidt's term "opdalite" for the augite-hypersthenebiotite-granodiorites in the north-west corner of the complex: the term is equally applicable to certain rocks in the southern area.
(d) **Inclusions**

The inclusions in the north-western mass of hypersthenic rock were investigated by McIntyre in great detail. The common type of inclusion was found by him to belong to a series ranging from diopside-hornfels to opdalite. He traced every gradation from "inclusions of sedimentary type through progressively more altered varieties resembling fine-grained igneous types (usually opdalite), to the most coarse-grained and thoroughly igneous looking hypersthenene-rock of the complex". The series evolved by the successive development of pyroxene, plagioclase, potash feldspar and biotite.

Gardiner and Reynolds (1932) reported that inclusions in the 'norite' are "very rare", but in McIntyre's opinion "this view is unfounded". The inclusions in the hypersthenic rock of the southern mass are difficult to detect and have to be diligently searched for; nevertheless a large number of inclusions were found. They are not as abundant here as they are in either the north-western mass or the granodiorite. Two localities where they are common are: (1) on the north-east slope of White Hill; (2) one-third of a mile east-north-east of Black Laggan Farm. No large inclusion was found but many small ones of obvious sedimentary origin were located. Patches of fine-grained hypersthenic rock occur in the coarser grained types and are clearly large /
large ghosts or inclusions of pre-existing sedimentary inclusions. The majority of the inclusions measure less than three inches in diameter and inclusions of microscopic dimensions have been found, e.g. in No. 356. Every gradation can be traced from sedimentary inclusions to "ghosts". This confirms McIntyre's conclusion and accordingly further detailed work has not been carried out.

Microscopic examination shows that three types of hornfels occur: namely (1) diopside-hornfels; (2) cordierite-biotite-hornfels, and (3) cordierite-plagioclase-biotite-hornfels.

(1) Diopside-hornfels

This type is characterized by prolific development of granular pyroxene. The pyroxene is dominantly diopsidic augite but rare crystals of hypersthene occur. In addition to the granular crystals, the augite also occurs as subhedral porphyroblasts (average 2.0 x 0.8 mm.). Schiller inclusions are common in the porphyroblasts. Glomero-porphyroblastic aggregates measuring up to 4.0 x 3.0 mm. are present. Plagioclase porphyroblasts, with continuous and oscillatory zoning, reach a maximum size of 1.8 x 0.6 mm. The composition ranges from cores of labradorite An_{55-60} to more sodic margins of andesine An_{35}. The bulk composition is An_{40}. Inclusions of pyroxene granules and pegs of iron-ore are common in the porphyroblasts. A little biotite /
biotite is present. The groundmass consists of anhedral and subhedral crystals of plagioclase (< 0.3 mm.) together with abundant subhedral and euhedral pegs of opaque iron-ores, quartz and potash feldspar being absent.

(2) and (3) Biotite-hornfelses

The varieties of biotite-hornfels are generally finer grained than the diopside-hornfels. They have a sharp junction with the hyperstenhenic rock. These varieties have been described previously (pp. 47-53). In the initial stage of alteration they are characterized by abundant biotite. Pyroxene develops later and the inclusions show all stages of transformation from basified hornfels through intermediate types to inclusions and nebulitic patches of quartz-dioritic and granodioritic composition.

B. TRANSITION BETWEEN HYPERSTHENIC ROCK AND GRANO-DIORITE PROPER.

(a) General

Of the mutual relationship of 'tonalite' (granodiorite) and 'norite' (hypersthenic rock), Gardiner and Reynolds stated (1932 /
(1932, p. 12) that "along the tonalite-norite margin definite tonalite is exposed in the immediate neighbourhood of definite norite, but along much of the boundary it is difficult to differentiate between the two types in the field owing to the occurrence of a rock to which we have referred as one of transitional character". The rock of transitional character was interpreted as a hybrid produced by the marginal mixing of hypothetical norite and tonalite magmas.

D.B. McIntyre studied the gradation between the 'norite' and 'tonalite' of the north-west on the eastern slopes of Shiel Hill and noted that the 'tonalite' is as crystalloblastic against the 'norite' as the latter is against the 'tonalite'.

(b) Field Evidence

A rock transitional in character between hypersthenic rock and granodiorite was found in two main areas:

1. Along the margin of the main mass of hypersthenic rock lying to the S.E., S. and S.W. of Loch Dee.

2. In the neighbourhood of the Trostan and Little Trostan (about a mile south-east of Glenhead Farm).

1. A transition zone was traced from a point half a mile south of the Corse Knowe of White Laggan, along the steep north-western slopes of White Hill as far as a tributary of the Dargall /
Dargall Lane, situated about 300 yds. east of the Corse Knowe of White Laggan. Thereafter drift along the northern slopes of White Hill obscures the margin of the hypersthenic rock. The transitional rock was again seen on the peninsula on the south-eastern shore of Loch Dee. Further east its outcrop is once more hidden by bog and drift.

2. The presence of hypersthenic rock was not known hitherto in the Trostan area. The transitional rock type surrounds the summits of the Trostan and Little Trostan and extends to the south and south-west as far as Glenhead Burn. An isolated patch was found on the south side of the Glenhead Burn valley. Nowhere was definite normal granodiorite found in contact with definite hypersthenic rock. In the field a gradual passage from the light coloured granodiorite to the dark hypersthenic rock was everywhere observed between them. Macroscopically sharp contacts were found between fine-grained hypersthenic rock and a coarser-grained transitional type.

It is noteworthy that the hypersthenic rock is commonly fine-grained along its inner margin, e.g. along the north-west slope of White Hill, on the isthmus of Loch Dee, and on the Trostan. It is probable that an exception to this occurs due east of the Corse Knowe of White Laggan for coarse-grained hypersthenic/
hypersthenic rock (No. 303) outcrops 20 yds. distant from a transitional rock type (No. 305).

(1) The north-western slope of White Hill.

In this area, between the heights of 1050 ft. and 1250 ft., there is a great variety of rock types. They vary in grain size from fine to coarse; in colour from dark to light; in texture; and in the relative abundances of their ferromagnesian minerals. In this respect the area closely resembles the north-west corner of the complex where McIntyre found it impossible to map the numerous varieties present.

Sixteen specimens were collected in this area. All have been sectioned. The gradation from the fine-grained marginal hypersthenic rocks to normal granodiorite involves an increase in grain size; a decrease in the content of ferromagnesian minerals; amphibolization and gradual elimination of the pyroxene and increase of quartz and potash feldspar.

The microscopic investigation also revealed the presence of a zone of quartz-diorites between the hypersthenic rocks and the granodiorite. These quartz-diorites contain either little (Nos. 623, 624) or no (No. 333) potash feldspar. They are fine to medium in grain, and sometimes possess a pronounced crystal orientation. They consist of plagioclase, amphibole, biotite /
biotite, quartz, hypersthene, augite, potash feldspar, apatite, iron-ores, zircon and tourmaline. These transitional rocks are characterised by large composite tabular crystals of plagioclase, which often have turbid or clouded cores; abundant crystalloblastic biotite, frequently curved; pyroxene (hypersthene and augite) partly converted to amphibole and to some extent biotite; relic cores of pyroxene in amphibole; and clots of ferromagnesians with marked decussate structure.

McIntyre subdivided the 'norite' of the north-west part of the complex into two types (1) a marginal type with more than 1% of potash feldspar and (2) an inner type with less than 1% of potash feldspar. The inner type corresponds to the zone of quartz-diorites, between the hypersthenic rocks and the granodiorite, in the south.

The quartz-diorites pass into granodiorites by increase of quartz and potash feldspar and the elimination of the pyroxene cores of the amphiboles. It has been recorded above (p.141) that relics of pyroxene are present sporadically in the granodiorite at a considerable distance from the pyroxene-bearing contact and hypersthenic rock.

The pyroxenic granodiorites are only slightly darker than the normal granodiorite. A peculiar feature is the frequent occurrence of symplectitic intergrowths of plagioclase and potash feldspar.
Micrometric analyses of a related series of specimens of typical quartz-diorites ranging from adjacent to the hypersthenic rocks (No. 624) to a rock transitional to granodiorite (No. 627) are given:

<table>
<thead>
<tr>
<th>Specimen Nos.</th>
<th>Quadratic (X)</th>
<th>Plagioclase</th>
<th>Hornblende</th>
<th>Biotite</th>
<th>Pyroxene</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>624</td>
<td>6.0</td>
<td>53.0</td>
<td>20.0</td>
<td>16.0</td>
<td>4.0</td>
<td>0.5</td>
</tr>
<tr>
<td>787</td>
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<td>46.0</td>
<td>23.5</td>
<td>40.5</td>
<td>4.0</td>
<td>1.5</td>
</tr>
<tr>
<td>623</td>
<td>9.5</td>
<td>56.0</td>
<td>11.5</td>
<td>14.5</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>627</td>
<td>14.0</td>
<td>52.0</td>
<td>12.0</td>
<td>20.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Remarks:

(i) Quartz increases as the elimination of the pyroxene progresses.

(ii) Hornblende is at first more abundant than biotite, but the relationship is reversed as the rock tends towards granodiorite.

(iii) There is a reduction in the total content of ferromagnesians concomitant with the increase in quartz.

(iv) The more basic rocks have an exceptionally high mafic content - approximately twice that of the normal granodiorite and nearly 25% greater than that of the hypersthenic rock.

(c) /
(c) Basic patches in the quartz-diorite

On the northern and eastern slopes of the Trostan at heights of 790 ft. and 830 ft. very dark, coarse-grained patches of a rock approaching hornblendite were located in the quartz-diorite. The patches are distributed sporadically near the summit of the hill and measure between 10" x 3" and 2" x 1". On the weathered surface the contact with the quartz-diorite appears to be sharp (Fig. 9). The patches are characterized by their very dark colour, large black prismatic crystals of hornblende, very large glistening flakes of biotite, and paucity of felsic minerals. Occasionally whitish-pink pods of quartz and feldspar occur in the patches. These pods are up to $1\frac{1}{2}" \times \frac{3}{4}" \times \frac{1}{4}$ in size.

Microscopically the melanocratic patches consist essentially of brown hornblende, green hornblende, tremolite, biotite and plagioclase, with accessory apatite, iron ores, quartz, calcite and zeolites.

**Hornblende.** The brown variety is more abundant than common green hornblende, although every gradation in colour, and presumably also in composition, exists between them. They are intimately associated with one another in single individuals. The varieties are moderately pleochroic with $X =$ pale brown, $Y =$ brown, $Z =$ dark red brown; and $X =$ colourless, $Y =$ pale greenish /
greenish brown, $Z = $ greenish brown. They are biaxially negative with $Z \wedge c = 19^\circ - 21^\circ$.

The hornblende occurs as large subhedral and euhedral prismatic crystals which average $3.0 \times 2.0$ mm. but reach a maximum size of over $5.5 \times 3.0$ mm. They are frequently sieved with anhedral plagioclase and quartz crystals. Other inclusions are biotite flakes, granules of iron ores and prismatic crystals of apatite. The inclusions of biotite are very common and occur in irregular patches. Simple and multiple twinning on 100 is present.

Tremolite is subordinate to the varieties of hornblende. It occurs as acicular and occasionally as fibrous crystals. It is intimately intergrown with the hornblende.

Biotite occurs as large subhedral, euhedral and more rarely as anhedral flakes. The flakes range in size from inclusions $< 0.2$ mm. in length to a maximum size of $5.0 \times 6.0$ mm. They are strongly pleochroic with $X = $ yellow brown, $Y = $ brown, and $Z = $ deep foxy red brown. Inclusions are apatite and iron ores. Rarely the flakes are altered to pale green chlorite. Many small ragged flakes are embedded in the hornblende.

Plagioclase occurs as small, medium and large crystals which reach a maximum size of $5.0 \times 3.0$ mm. Feldspathic areas composed of several plagioclase individuals are common.
Alteration to sericite and kaolin is frequent and rarely the feldspar is replaced by calcite. Inclusions are hornblende, tremolite, apatite, iron ores and quartz. The composition is oligoclase-andesine (An$_{20}$) with a range from An$_{25}$-An$_{35}$. Occasionally the crystals are continuously zoned within these limits.

Quartz is present interstitially but is quite scarce. It contains minute opaque inclusions.

Potash feldspar is present rarely in the feldspathic interstitial patches.

Apatite is an abundant accessory and occurs frequently as stumpy crystals which reach a maximum size of 0.5 x 0.2 mm., and as a common inclusion in all the essential minerals.

Iron Ores are also abundant. They occur as minute granules, and as very small and small anhedral and subhedral crystals. Some crystals are skeletal. The granules are common inclusions in the hornblende. They are often conspicuously clustered together, along with skeletal biotite flakes, near the middles of large brown hornblende crystals. The largest subhedral crystal of iron ore seen measured 2.0 x 0.7 mm. The ores are ilmenite with subordinate magnetite.

Micrometric /
**Micrometric analysis (No. 776d):**

<table>
<thead>
<tr>
<th>Mineral Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hornblende (brown and green)</td>
<td>61.5</td>
</tr>
<tr>
<td>Tremolite</td>
<td>9.0</td>
</tr>
<tr>
<td>Biotite</td>
<td>12.0</td>
</tr>
<tr>
<td>Plagioclase (oligoclase-andesine)</td>
<td>10.5</td>
</tr>
<tr>
<td>Quartz</td>
<td>2.5</td>
</tr>
<tr>
<td>Others (mainly iron ores and apatite)</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>
XV. AUGITIC MARGINAL PATCHES

(a) Introduction

Gardiner and Reynolds stated (1932, pp. 11-12) that: "throughout a large part of the tonalite-hornfels margin there occurs a very distinct type of rock, dark, highly biotitic and distinctly denser than the normal tonalite. It is frequently fine-grained, a characteristic which suggests chilling. In some cases this basic marginal variety of tonalite contains augite as on Buchan Hill, Loch Trool". They also noted that: "The dark marginal form of tonalite, with its high density and large proportions of biotite bears considerable resemblance to the dark basic patches found here and there in the normal tonalite".

As Gardiner and Reynolds noted, the autite-bearing rocks occur in isolated patches between the granodiorite and the hornfels along the western and south-western margin of the complex. During the course of the present work they were studied at Glenhead Wood; the northern summit of Buchan Hill; one-third of a mile south-west of the Corse Knowe of White Laggan; and Craignine.

(b) /
(b) Petrography

1. Glenhead Wood.

Two marginal patches of augite-bearing rock were located on the south-eastern and western corners of the Wood. Six specimens were collected; four (Nos. 202, 281, 282 and 513) from the former and two (Nos. 205 and 206) from the latter locality. Unfortunately exposures are poor and only in Gairland Burn, along the western side of the Wood, was the relationship of the granodiorite to the augitic rock accurately established.

Macroscopically the augitic rock is a dark grey and black mottled rock, distinct from the normal granodiorite, and difficult to distinguish from the more "igneous-looking" hornfelses. Texturally it has closer affinities with the metamorphics. In some specimens the biotite stands out as glistening black flakes and in others the large crystals of augite and hornblende can be distinguished easily in hand specimen.

Microscopically the rock type consists essentially of quartz, plagioclase, biotite and pyroxene, with accessory apatite, zircon and iron ores. Potash feldspar is present in small amounts but is variable. Hornblende is very variable, and in different specimens it may be absent, scarce or abundant. The rock is a biotite-augite-quartz-diorite. The texture varies continuously from /
from predominantly crystalloblastic to "igneous-looking". This transition can be traced from rocks with a fine granular mosaic, through types with a slightly coarser granular groundmass, to coarse-grained rocks in which the quartz occurs either as large crystals or is intersertal. The rocks are characterized throughout by large plagioclase porphyroblasts.

The specimens can be arranged in a series in order of decreasing crystalloblasticity as follows:

\[ 202 \rightarrow 281 \rightarrow 282 \rightarrow 513 \rightarrow 206 \rightarrow 205 \]

Detailed petrographic descriptions of the two end members of the series are given below.

**Specimen No. 202: Porphyroblastic biotite-augite-quartz-diorite.**

Macroscopically the rock is somewhat lighter in colour and finer in grain than No. 205. The essential minerals are quartz, plagioclase, biotite and pyroxene; the accessories are iron-ores, apatite and zircon.

Quartz occurs in the groundmass as small anhedral granular crystals which average 0.1 mm in diameter and rarely exceed 0.2 mm. Along with plagioclase it forms almost the entire groundmass, but a small amount of potash feldspar is also present. Quartz is a common inclusion in plagioclase, biotite, pyroxene and potash feldspar.

**Plagioclase /**
Plagioclase is present abundantly as large subhedral porphyroblastic tabular crystals exhibiting carlsbad, albite and pericline twinning. It also occurs in the groundmass as small anhedral crystals. The porphyroblasts average 2.0 x 0.8 mm. but reach a maximum size of 4.0 x 2.0 mm. The small crystals in the groundmass average 0.2 x 0.2 mm. and are larger than those of quartz, but there is a complete range in size up to the porphyroblasts. Both continuous and oscillatory zoning is common. The plagioclase is andesine with a bulk composition of An₄₀. The continuously zoned crystals have cores as calcic as An₅₀ and margins about An₃₀₋₃₅. Crystals with oscillatory zoning cover the same range in composition. By far the majority of the plagioclase sections available for the measurement of the extinction angles were albite-carlsbad twins $\{10\}$, which implies that there is a preferred orientation in the rock. The large porphyroblasts possess highly irregular boundaries with the groundmass mosaic (Fig. 50). In some zoned porphyroblasts the inclusions are either concentrated internally or lie in a marginal zone. Quartz is a common marginal inclusion; other inclusions are granules and short thick prisms of pyroxene and small flakes of biotite. Many of the crystals are clouded or dusted with minute opaque inclusions.

Biotite
Biotite occurs as sporadic, medium-sized, ragged poikiloblastic laths or flakes, the average size being 0.6 x 0.5 mm. It is strongly pleochroic with X = straw yellow, Y = sepia brown, and Z = dark red-brown. The inclusions are commonly quartz and pyroxene. Biotite is associated in clots with pyroxene and iron-ores; it commonly rims the margins of pyroxene crystals and completely encloses pegs of iron-ore.

Pyroxene is present both as large poikiloblastic crystals which average 1.0 x 0.4 mm. and reach a maximum size of 2.2 x 0.8 mm., and as smaller granular crystals which average 0.2 mm. in diameter. The small granules occasionally occur in aggregates which in one case consist of about a hundred individual grains (in section) concentrated into a clot measuring 4.0 x 2.0 mm (Fig. 51). Both ortho- and clino-pyroxene are present. The orthorhombic varieties are hypersthene with some enstatite; the clinopyroxene, which predominates, is augite. The augite is colourless; optically positive with $\alpha = 50^\circ$. Enstatite and hypersthene are respectively colourless and faintly pleochroic. The poikiloblastic character of all the pyroxenes is very pronounced. Inclusions consist of quartz, plagioclase, biotite and iron-ores. Pyroxene is always closely associated with the other ferromagnesians. Slight alteration has taken place along cleavage traces and at the margins.
Potash feldspar occurs as clear interstitial crystals in the groundmass. It lobes the quartz grains and rarely forms small poikiloblastic plates.

Of the accessories iron-ore is the most abundant. It occurs as very small granules and subhedral pegs which reach a maximum size of 0.2 x 0.2 mm. The ore is grey by reflected light. Apatite is present both as small stumpy and elongated prisms. Zircon occurs rarely as granular inclusions in biotite.

Nos. 281, 282 and 513 are very similar to the above but have a few major differences, notably the development of hornblende. This mineral is not present in No. 202 but increases in abundance through Nos. 282, 281 and 513. In No. 281 the amphibole occurs most commonly as green rims to the pyroxene from which it is obviously derived. It is of the green variety with $X =$ colourless, $Y =$ pale green, $Z =$ olive green. It is always strongly associated with pyroxene, biotite and iron ores in aggregates or clots. Biotite increases in size and loses some of its primitive poikiloblastic character in Nos. 282 and 513.

Specimen No. 206 illustrates an intermediate stage between Nos. 202 and 205. In it the groundmass quartz is coarser; the plagioclase is abundant as small granular crystals in the matrix and as medium-sized tabular crystals; the biotite flakes are /
are less ragged and have a more 'poikilitic' appearance. Hornblende is abundant and shares with biotite a sub-parallel arrangement. It occurs both as small anhedral grains, sometimes in aggregates, and as larger euhedral prismatic crystals. It is a greenish-brown variety. Pleochroism is slight, with \( X = \) colourless, \( Y = \) pale brown, \( Z = \) medium greenish brown. It is always associated with pyroxene and/or biotite and occurs in clots or nests with the other ferromagnesians. The other end member of the series, No. 205, has been chemically analysed. It was collected only 2 ft. from the marginal variety of granodiorite.

Qualitatively it possesses almost the same mineralogical composition as No. 202, but with the addition of hornblende. Texturally it differs from No. 202 in being coarser grained and less crystalloblastic in character (Figs. 53-4).

Quartz occurs in the groundmass as large plates with numerous inclusions of biotite, plagioclase and hornblende, and as smaller anhedral intersertal crystals.

Plagioclase is present as small subhedral granular crystals (0.2 x 0.1 mm.) in the groundmass and as medium-sized crystals which rarely exceed 1.0 x 0.8 mm. It has the same characteristics as the plagioclase of No. 202 but has a smaller range in composition. The range is from labradorite \( \text{An}_{52} \) to andesine \( \text{An}_{42} \).

Biotite /
Biotite occurs less abundantly than in the rocks previously described. Most commonly the flakes are poikiloblastic, averaging 1.2 x 0.9 mm. It is strongly pleochroic with X = fawn; Y = dark sepia; Z = dark foxy red brown. Some flakes are well developed and are almost poikilitic in character. Inclusions are generally plagioclase and hornblende. It is strongly associated with pyroxene, hornblende and iron-ores, which occasionally occur together in clots. Decussate structure is slightly developed in some cases. Pleochroic haloes are present around apatite and zircon inclusions but are not common.

Hornblende commonly occurs as small to medium-sized anhedral and subhedral crystals. The smaller crystals average 0.2 x 0.2 mm, while the larger ones reach a maximum size of 1.2 x 0.8 mm. While the majority lack euheiral form, there are also perfect idiomorphic prismatic crystals. Two varieties are present: pale green and brown. The latter is strongly pleochroic, with X = colourless; Y = yellow brown; Z = brown. It is optically negative with 2V = 86°, ZA = 7°. This variety appears to be akin to basaltic or ferriferous hornblende. The other type usually occurs as a rim to pyroxene, from which it has clearly developed. It is less strongly pleochroic with X = colourless, Y = pale green, Z = green. It is optically negative with ZA = 17°. The two varieties are in places intimately associated /
associated with one another and composite crystals occur.

**Pyroxene** is subordinate to hornblende. It is dominantly colourless augite. Both small anhedral and medium-sized crystals occur. It is optically positive with $Z^c = 52^\circ$.

No potash feldspar has been detected.

The accessories, iron-ores, apatite and zircon, occur with habits similar to those of the corresponding minerals in No. 202. (Analysis overleaf).

2. **Northern summit of Buchan Hill**

The augitic rocks are found in the vicinity of the summit and for some distance east, north and north-west. The rocks from this locality are generally more leucocratic than those from Glenhead Wood. They occur in patches having a distinctive fine grain. Although the patches are generally confined to the margin of the pluton, one large patch was located 110 yds. inside the complex and approximately 35 ft. below the summit. The patches are sporadic and the contact between them and the granodiorite is macroscopically sharp. Sometimes the finer-grained patches appear to be veined by more leucocratic material. Under the microscope, however, it is seen that all contacts are gradational. The complete gradation can be seen either in a series of specimens or occasionally in a single section. In hand specimen the rock is a light grey colour with an /
Augitic marginal rock (No. 205), 2 ft. from the marginal granodiorite in the south-western corner of Glenhead Wood. Map. Fig. 4. New analysis. Analyst: W.H. Herdsman. (Table I).

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| Total FeO | 6.45  |

Von Wolff VALUES

L = 58.96
M = 29.36
Q = 11.10
an even groundmass in which are embedded large tabular crystals of feldspar and aggregates of ferromagnesian minerals.

Twelve specimens (Nos. 230, 448, 435, 449, 229, 228a, 227, 436, 437, 231, 226 and 228b) were collected; six of which were included in a serial traverse into the complex from the contact. Of the twelve specimens sectioned, one possessed a well developed crystalloblastic texture, eight shared characters common to metamorphic and "igneous" textures, while three had strong textural affinities to the granodiorite. None of the groups has a distinguishing mineral assemblage, e.g. hornblende varies greatly in amount but is never absent. Potash feldspar is never totally lacking (though in two cases only an extremely small amount is present). It becomes more abundant in the more "igneous looking" rocks.

If the rocks are arranged in a series on the basis of (a) increase in grain size and decrease in crystalloblastic characters, (b) increase of hornblende relative to pyroxene, and (c) increase of potash feldspar, they fall into six groups as follows:

\[
230 \rightarrow 448 \rightarrow 229 \rightarrow 436 \rightarrow 231 \rightarrow (226, 228b)
\]

This has no geographical significance; the final members of the series are respectively nine and eighty-five yards distant from the /
the outside contact, while No. 435, an early member of the series, is 110 yards inside the complex.

As the members of the series are petrographically very similar to the augitic rocks of Glenhead Wood there is no need to describe them in detail. One process is perhaps shown more clearly in the augitic rocks from this area than in those from Glenhead Wood; namely the gradual elimination of the pyroxene by the development of hornblende. As the amphibolization becomes more strongly developed pyroxene remains only as the cores of hornblende crystals. The process is strikingly similar to that affecting the hypersthenic rocks.

3. One-third of a mile south-west of the Corse Knowe of White Laggan.

The contact zone is well exposed at a height of about 1120 ft. in the former headwaters of Glenhead Burn. The stream has now been diverted into Dalraddy Lane, and so into Loch Dee. In this locality the melanocratic augitic host rock is extensively veined by leucocratic material. The "veining" extends at least 20 yds. and has been wellbrought out by the differential stream erosion. The less resistant melanocratic host rock is removed, leaving the "vein-like" leucocratic streaks standing out rather prominently.

There /
There is a complete gradation from the fine-grained, augitic, metamorphic-looking rock to the "igneous" rock. It is exceedingly difficult in the field to draw a line on the map to represent the line of contact.

Five specimens (Nos. 253, 252, 251, 250 and 254) were collected in this area and four of these are from the veined zone (Fig. 65). It should be pointed out that the veining exhibited in this locality is different from the "veining" present in the mobilized zone on the south slope of Buchan Hill (p. 62). The highly veined rocks are fine-grained, well banded and have a metamorphic texture (Nos. 253 and 252). As the complex is approached (Nos. 251 and 250) the grain size increases, the veined appearance is lost, and the rock becomes homogeneous and more igneous-looking. Macroscopically there are no sharp contacts - there is a complete gradation between the various types in the series:

\[
\frac{253}{252} \rightarrow 251 \rightarrow 250 \rightarrow 254.
\]

The metamorphic end-members of the series (Nos. 253 and 252) are contact-pyroxene-hornblende-biotite-quartz-diorites. The two rocks are practically identical and consist of quartz, biotite, plagioclase, hornblende and pyroxene, with accessory iron-ores, apatite and zircon.

Quartz /
Quartz occurs in the melanocratic areas as granular crystals less than 0.1 mm. in diameter, and as interstitial and irregular plates up to 1.5 x 1.0 mm. in the leucocratic veins. The irregular plates are commonly elongated parallel to the banding and frequently contain small granular crystals of plagioclase and occasionally of biotite. They have developed from aggregates of grains and show undulose extinction.

Biotite is present abundantly as small anhedral crystalloblastic flakes (average 0.2 x 0.2 mm.), medium-sized subhedral poikiloblastic flakes (average 1.0 x 0.6 mm.), and as larger subhedral poikiloblastic flakes which reach a maximum size of over 2.0 x 0.8 mm. The smaller flakes are more abundant in the melanocratic areas. Marked parallelism of the flakes produces the banding discernible in the hand specimen. The biotite is strongly pleochroic with X = straw yellow, Y = sepia brown, Z = dark foxy red brown. Inclusions are generally plagioclase with infrequent quartz, hornblende, pyroxene, zircon and iron ore. Pleochroic haloes are present. Biotite, closely associated with hornblende and less so with pyroxene, frequently occurs as aggregates or nests of flakes.

Plagioclase occurs in the melanocratic portions both as small granular crystals and as small subhedral laths which average 0.3 x 0.2 mm. Larger medium-sized subhedral porphyroblasts are generally
generally present in the leucocratic areas (1.0 x 0.4 mm.). The larger crystals possess irregular boundaries and contain fairly numerous inclusions of quartz and biotite, and more rarely of pyroxene and hornblende. The average composition of the granular crystals is andesine An$_{35-40}$. The porphyroblasts of plagioclase average An$_{40-45}$. Both continuous and oscillatory zoning occurs, but only rarely. The range in composition is slight; from cores of An$_{45}$ to margins of An$_{35}$.

Hornblende is present abundantly as granules, and medium-sized anhedral crystalloblastic and poikiloblastic crystals. The green variety is the most common with faint to moderate pleochroism $X = \text{colourless}, Y = \text{pale green},$ and $Z = \text{light blue green} (Z^c = 17^\circ)$. Another variety is much less common and has a stronger pleochroism with $X = \text{colourless}, Y = \text{pale green},$ $Z = \text{olive green} (Z^c = 19^\circ)$. This latter type is closely associated with pyroxene and biotite. It rims the clinopyroxene and has obviously replaced it; its association with biotite and the presence of pleochroic haloes in some of the crystals suggests that at least some of the hornblende was derived from biotite. Both varieties of hornblende are optically negative with $2V \approx 80^\circ$.

Pyroxene is common both as small granules and as medium-sized anhedral to subhedral prismatic crystals. It is optically positive with $Z^c = 36^\circ - 44^\circ$ and is common augite with probably a /
a little diopсидic augite. It is commonly associated with hornblende which frequently rims both it and biotite. Rarely it is slightly poikiloblastic in character. It is to be noted that no potash feldspar was detected. The accessories, apatite, zircon and iron ores are very scarce.

Specimen No. 252 is almost identical with the above rock with the exception that it has a small vein at right angles to the main plane of banding; this vein is entirely composed of hornblende, some of which is secondary biotite. It often extends across the banding for 16 mm. and averages 0.3 mm. in width. All minerals which lay across the vein are amphibolized.

Specimen No. 251 differs but little from Nos. 252 and 253. It is a contact-hornblende-pyroxene-biotite-quartz-diorite and was collected 28 ft. from the other two specimens. In the hand specimen the main differences are that the banding is less discernible; the grain is slightly coarser and the rock more homogeneous. Microscopically it has the same mineralogical composition but is less crystalloblastic.

Specimen No. 250, collected 2 ft. from No. 251 has an "igneous" textural appearance, but a faint banding is still detectable in the hand specimen. It is coarser in grain size than No. 251 but is finer grained than Nos. 254 and 249. It is a biotite-pyroxene-hornblende-quartz-diorite.

Microscopically /
Microscopically the chief difference from the previously described specimens is that potash feldspar makes its appearance for the first time in the gradational series. It is present only in small quantity as irregular plates or interstitial crystals. Plagioclase is more abundant than in the earlier members of the series, this rock being characterized by large porphyroblasts which reach a maximum size of 6.0 x 1.2 mm. These are very similar to the porphyroblasts in the contact-quartz-diorites of Buchan Hill and are characterized by internal irregularities and patchy extinction.

This biotite-pyroxene-hornblende-quartz-diorite grades eastwards into hypersthenic rock and to the north and north-east into hornblende-biotite-granodiorite. It is situated in the zone intermediate between granodiorite and hypersthenic rock.

(c) Relationship of the augitic marginal patches and the granodiorite.

This relationship has been studied in detail on the northern summit of Buchan Hill and investigated in Glenhead Wood and in the vicinity of Craignine.

1. Northern summit of Buchan Hill

As previously pointed out, the augitic rocks outcrop in this /
this locality up to 120 yds. distance from the margin of the complex. Specimens Nos. 431, 432, 433 and 434, were collected to study the relationship of the augitic rocks to the granodiorite.

In the field it is clear that two kinds of contacts are present. Generally there is a gradation inwards from the fine-grained augitic rock to the coarse-grained granodiorite, but frequently macroscopic sharp contacts exist. However, under the microscope, even the latter are gradational. Patches of the fine-grained augitic rock commonly occur within the granodiorite.

The granodiorite in contact with the augitic rock shows variation in grain size but is generally fine to medium grained. It differs from the normal granodiorite by being finer grained and much darker in colour. It is not so strongly banded as the marginal granodiorite adjacent to the sediments.

A typical specimen (No. 434) of this rock, transitional from augitic marginal rock to granodiorite, was collected 125 yds. from the contact, at a height of 1613 ft. on the east slope of Buchan Hill. The nearest exposed augitic rock (No. 435) was 5 yds. away.

The rock is fine to medium in grain, 'porphyritic' and mottled light grey and black. It consists of quartz, plagioclase, potash feldspar, biotite, hornblende, with accessory augite, iron ores, apatite, zircon and sphene.
Quartz is present interstitially and ranges in size from small anhedral irregular patches (<0.1 mm.) up to large anhedral crystals of 2.1 x 1.5 mm. It often has a sub-ophitic texture with tabular crystals of plagioclase. Inclusions are plagioclase crystals, biotite and minute dust-like matter. Undulose extinction is common.

Plagioclase occurs as small subhedral crystals (0.2 x 0.1 mm.), medium-sized tabular crystals (1.5 x 0.7 mm.) and large subhedral 'phenocrysts' which rarely reach over 4.4 mm. in length. The 'phenocrysts', from the evidence of their form, structure and inclusions, have obviously grown in situ and are really porphyroblasts. Quartz, biotite, hornblende, iron ores, pyroxene and apatite occur as inclusions. Some of the larger 'phenocrysts' are extensively sericitized and kaolinized. Continuous oscillatory zoning may be observed. Twinning is on carlbad, albite, and rarely pericline laws. The bulk composition is andesine An30-35. The range of the zoned crystals is from An45 to An25-30. As many as 15-20 zones are common.

Potash feldspar is present abundantly as blebs, as small interstitial crystals which lobe against quartz and plagioclase, and as large anhedral plates which commonly reach 2.2 x 2.0 mm. It has been occasionally sericitized and kaolinized. The boundaries of the crystals against plagioclase are highly sinuous, irregular /
irregular and lobe-like indicative of replacement of plagioclase. Moreover, the potash feldspar commonly contains large inclusions of plagioclase; the boundaries of these being irregular and sometimes vague. Other inclusions are hornblende, biotite and quartz, and apatite needles.

**Biotite** occurs abundantly as medium subhedral laths and flakes which average 1.5 x 0.7 mm. It is strongly pleochroic with $X =$ straw yellow, $Y =$ sepia, and $Z =$ foxy red brown, like the biotite present in the aureole hornfelses. It is closely associated with hornblende around which it has frequently developed and it commonly occurs in aggregates or nests with the other ferromagnesians. Many of the crystals are altered to chlorite. In one particular zone extensive chloritization has taken place with concomitant development of iron ores and sphene. Occasionally the laths are 'poikiloblastic' with inclusions of quartz, plagioclase, hornblende, iron ores and zircon.

**Amphibole** is subordinate to biotite, and occurs as small anhedral poikiloblastic crystals, medium-sized subhedral crystals, and as large subhedral 'phenocrysts'. Some crystals show strong 'poikiloblastic' texture. Inclusions are usually quartz, plagioclase, biotite and minute radioactive minerals. Two pleochroic varieties are present:

(a) Common hornblende with $X =$ colourless, $Y =$ pale green, $Z =$ olive brown.

(b) /
(b) Tremolite-Actinolite with $X =$ very pale green, $Y =$ pale green, $Z =$ pale green.

Occasionally pleochroic haloes occur and the remnants of biotite in the crystals themselves suggest that some of the hornblende resulted from the replacement of biotite, although the majority of the crystals have clearly developed from pyroxene.

Clinopyroxene occurs in small amount as small subhedral crystals which are colourless, and often as larger prismatic crystals ($0.3 \times 0.2$ mm.). It is commonly strongly associated with hornblende and biotite. A few obscure cores of hornblende crystals suggest the former existence of augite. The augite is biaxially positive with $\alpha e = 42 ^\circ$.

The accessories have the habits previously described (p. 223).

The other specimens (Nos. 433, 432 and 431) were collected at distances between 160 yds. and 220 yds. from the margin of the complex, and between heights of 1490 ft. and 1420 ft. on the east slope of Buchan Hill.

Macroscopically and microscopically Nos. 433 and 432 are identical with No. 434 just described above. No. 431, however, is coarser grained and lighter in colour than the other specimens and is practically a normal granodiorite. A significant fact is that it still possesses fine-grained patches which are /
are more basic than the host. These fine-grained patches contain augite either as small individual prismatic crystals or as numerous cores in common hornblende aggregates. Augitic ferromagnesian clots occur sporadically throughout the normal granodiorite and obviously have a similar genesis to the augitic marginal patches just described.

2. Glenhead Wood

As indicated in the previous section, the augite-bearing marginal rocks occur in two areas (1) Gairland Burn, (2) south-east corner of the wood.

Specimens were collected of the marginal granodiorite adjacent to these basic patches and of these ten have been sectioned (five from each area).

1. Gairland Burn. The transition from augitic marginal rock to marginal granodiorite is well seen in the bed of the burn. Macroscopically the contact is extremely intricate and every stage in the transition can be seen in a single specimen (No. 443). On the other hand, under the microscope the contact is hair-sharp in some cases and gradational in others.

In hand specimen the rock is medium-grained and slightly darker than the 'normal' granodiorite. It possesses a distinct banding and large porphyroblasts of plagioclase (10.0 x 5.0 mm.) are conspicuous. In section the rock is found to be a hornblende-
biotite-granodiorite consisting essentially of quartz, plagioclase, potash feldspar, biotite and hornblende, with accessory zircon, apatite, iron ores and rarely sphene and tourmaline.

The microscopic description of No. 434 from the northern summit of Buchan Hill fits the description of this type accurately. Both rocks have the same texture and mineral composition.

2. South-east corner of the Wood. Macroscopically the rocks are all darker and finer grained than the normal granodiorite, but they show every stage of the gradation from the fine-grained mosaic of the augitic marginal rock to the medium-grained groundmass of the marginal granodiorite. This gradation is well shown by the following specimens, Nos. 500, 501, 512, 506 and 507. Specimens Nos. 506 and 507 are indistinguishable macro- and microscopically from No. 278 (marginal granodiorite previously described from south-east corner of the wood (p. 122) and therefore attention will be confined to Nos. 500, 501 and 512.

Microscopically these consist essentially of quartz, plagioclase, potash feldspar, biotite and hornblende with accessory clinopyroxene, zircon, apatite, sphene and iron ores.

Quartz is present as small anhedral grains (0.2 mm. average diameter) and interstitial crystals in the groundmass of No. 500. Rarely it attains a size of 0.5 x 0.4 mm. in section. In No. 501, however, only a few grains remain as inclusions in plagioclase /
plagioclase - most of the grains have recrystallized and coalesced into small medium-sized interstitial crystals with undulose extinction. In No. 512 the interstitial crystals are also medium-sized, averaging 0.7 x 0.4 mm. Inclusions are plagioclase granules, apatite needles and black dust-like spots. Quartz, in turn, is frequently an inclusion of plagioclase.

Plagioclase occurs in No. 500 as small granular, and medium-sized subhedral crystals in the groundmass, and as large subhedral porphyroblasts. The porphyroblasts are commonly 4.0 x 1.8 mm. In Nos. 501 and 512 the habits are similar, but in No. 512 the porphyroblasts are even larger, e.g. 12.0 x 8.0 mm. Continuous and oscillatory zoning is common. The average composition is andesine An$_{45}$. Continuously zoned crystals commonly have a core of andesine An$_{45-50}$ with a margin of oligoclase An$_{25}$. Granular inclusions are frequent and are mainly hornblende, biotite, apatite, and iron ores. Carlsbad and albite twinning are well exhibited. Slight alteration has been suffered by a few crystals.

Potash feldspar occurs as interstitial anhedral plates of orthoclase which is not so abundant as in the 'normal' granite. That it has replaced plagioclase is shown by lobe-like intergrowths and irregular borders against the latter, and also by /
by the presence of relic inclusions of plagioclase crystals.

Biotite occurs as small, medium and large anhedral and subhedral flakes with, in No. 500, a pronounced poikiloblastic texture. The flakes average 1.2 x 0.8 mm. but in Nos. 501 and 512 the flakes are less poikiloblastic and on the average are larger (1.8 x 1.5 mm.). The flakes are strongly pleochroic with X = pale straw yellow, Y = sepia brown, Z = deep foxy red brown. Inclusions are most commonly zircon, apatite, iron ores, quartz and hornblende. Alteration to chlorite is slight and when the flakes are bleached sphene is formed. Biotite is always associated with the other ferromagnesians and frequently forms clots. It often rims hornblende (e.g. No. 501) iron ore and pyroxene as in some of the medium-grained opdalites of the hypersthenic rocks.

Hornblende is subordinate to biotite and is present as small and medium-sized anhedral and subhedral crystals, some of which attain a size of 2.0 x 0.5 mm. The hornblende is faintly pleochroic with X = pale green or colourless, Y = pale green, and Z = green or olive green. It frequently rims the pyroxene and is always associated with biotite, iron ores and other accessories commonly forming clots. During the amphibolization of the pyroxene, actinolite forms first and is in turn converted into common hornblende.

Iron ore is more abundant than in the normal granodiorit
Craignine

A patch of augitic marginal rock is exposed in the vicinity of some scars, called Craignine, which face west and overlook the valley of Buchan Burn. Here, there is a type transitional from the augitic marginal rock to the 'normal' granodiorite inwards; i.e. towards the interior of the pluton. All the rock types, including the transitional type, can be matched with members of the series from Buchan Hill and Glenhead Wood (pp.232,237).
XVI. SUMMARY OF EVIDENCE OF THE ORIGIN OF THE PYROXENIC ROCKS

A. Hypersthenic Rock

(a) Field Evidence

1. It occurs as a large main mass and also as a much smaller isolated outcrop half a mile to the west of the main mass.

2. There is gradation between hypersthenic rock and granodiorite. The width of the transition zone is 70-150 yds.

3. Three textural varieties of hypersthenic rock are present, viz: fine, medium and coarse grained.

4. The fine and medium-grained types occur near the margin of the pluton, although patches of these are common in the coarse type at some distance from the margin.

5. There is invariably perfect gradation between these types.

(b) Petrographic evidence

1. The rock types are quartz-diorites, and hyperthene-biotite-granodiorites (opdalites). The quartz-diorites are generally confined to the margin.

2. Qualitatively the mineralogical composition of the fine /
fine, medium and coarse grained types are very similar.

3. Potash feldspar, hornblende and biotite vary in amount.

4. The marginal quartz-diorites are highly crystalloblastic.

5. The degree of crystalloblastic development decreases away from the margin.

6. The hypersthenic rock is as crystalloblastic against the granodiorite as the granodiorite is against the hypersthenic rock.

7. The following evidence indicates that the minerals of the hypersthenic rock grew in a solid rather than a liquid medium:

(i) Biotites are poikiloblastic.

(ii) Pyroxene is also crystalloblastic (including poikiloblastic).

(iii) Plagioclase porphyroblasts include small granules of mafic minerals and quartz.

(iv) Large plagioclase porphyroblasts have the same range of composition as the small crystals in the groundmass.

(v) Internal irregularities are present in the plagioclases.

(vi) Plagioclase crystals with continuous and oscillatory zoning occur in close association with unzoned individuals.

(vii) Potash feldspar has developed by replacing plagioclase.

(viii) Hornblende has developed from pyroxene.

(ix) /
Quartz often exhibits undulose extinction.

The accessories of the hornfels and the hypersthenic rock are almost identical.

McIntyre showed that the aureole rocks are changed into granulites by the successive development of plagioclase, potash feldspar, and pyroxene, and that these granulites in turn are transformed into crystalloblastic hypersthenic rock by the same process carried further. He stated that "The changes in the aureole are stages in a process involving diffusion through the solid rocks and culminating in the production of hypersthenic rock". The evidence of the feldspathized and pyroxenized inclusions which he found demonstrated that the whole body of hypersthenic rock represents altered sediments. He concluded that "the hypersthenic rock of the north-west part of the Loch Doon complex, together with the inclusions of fine-grained hypersthenic rock contained within it, are in no sense igneous rocks. Of an initially sedimentary origin, they have been so altered, both chemically and physically, as to assume compositions and textures commonly regarded as igneous".
B. Transition Hypersthenic Rock - Granodiorite.

(a) Field evidence

1. A rock of transitional character exists between the hypersthenic rock and the granodiorite.

2. Macroscopically sharp contacts were found between fine-grained hypersthenic rock and a coarser grained transitional type.

3. Hypersthenic rock often, but not always, becomes finer in grain towards the granodiorite.

4. In the transition zone a great variety of rock types occur. Patches of feldspathic hornblendite occur in the isolated outcrop around the Trostan.

(b) Petrographic evidence

1. Mineralogically the transitional rock is a quartz-diorite.

2. The quartz-diorites are richer in mafic minerals than either the hypersthenic rock or the granodiorite.

3. The gradation from hypersthenic rock to granodiorite is effected by increase of grain size; decrease in mafic content; amphibolization and the gradual elimination of the pyroxene; and increase of quartz and potash feldspar.

4. /
4. The quartz-diorites share many of the crystalloblastic characters of the hypersthenic rock.

The rock transitional between hypersthenic rock and normal granodiorite was interpreted previously as a hybrid produced by the marginal mixing of the 'norite' and 'tonalite' magmas (Gardiner and Reynolds, 1932, pp. 16-17). This interpretation does not explain the following facts:

(i) The presence of fine-grained hypersthenic rock adjacent to coarser grained transitional quartz-diorite.

(ii) The paucity of potash feldspar in the transitional rock. The two supposed magmas would have been of granodioritic composition and therefore on admixture one would expect the resultant rock to be also of granodioritic composition.

(iii) The high mafic content of the quartz-diorite.

(iv) The presence in the transitional rock of patches of feldspathic hornblendite.

Clearly another interpretation must be sought which will explain the above facts. The writer considers that the hypersthenic rocks represent part of the Fe-Mg front which migrated outwards ahead of the alkali front which gave rise to the granodiorites and adamellites. The Fe-Mg front did not advance uniformly; within it the concentration and fixation of certain constituents was preferential. The high mafic contents of the transitional quartz-diorite and of the hornblendite are thus interpreted as culminations /
culminations within the main Fe-Mg front (see D.L. Reynolds, 1944, p. 236).

It might be contended that the hornblendites are modified products of an early intrusion of biotite-pyroxenite magma. This would involve a fourth intrusion of magma which would intensify the difficulties of solving the emplacement problem. The specific gravity of the country rocks varies from 2.70 to 2.85 whilst that of the biotite-pyroxenite magma would be of the order of 3.0. These facts preclude the possibility of emplacement by stoping.

C. Augitic Marginal Patches

(a) Field evidence

1. The patches occur in isolated spots around the margin of the complex.

2. The contacts between them and the granodiorite are often macroscopically sharp but under the microscope they are seen to be gradational.

3. There is great difficulty in distinguishing the fine-grained augitic marginal patches from highly metamorphosed greywackes. Gardiner and Reynolds mapped some of the augitic patches as pyroxene - mica-schist.
(b) Petrographic evidence

The following evidence indicates that the minerals of the augitic rock crystallized (or recrystallized) in a solid medium:

1. Plagioclase is porphyroblastic.

2. The boundaries of the large plagioclase porphyroblasts against the groundmass are highly irregular.

3. The plagioclase porphyroblasts have the same range of composition as the small crystals in the groundmass.

4. The zoning of the plagioclase porphyroblasts is both continuous and oscillatory.

5. The mafic inclusions of the plagioclase porphyroblasts are arranged zonally.

6. Biotite is crystalloblastic and poikiloblastic, and commonly occurs in clots.

7. Pyroxene is also crystalloblastic and poikiloblastic.

8. Potash feldspar has a replacement character.

9. Hornblende has developed from the pyroxene and is associated with the other ferromagnesioms.

10. Quartz often exhibits undulose extinction.

The augitic marginal rock has a pronounced metamorphic texture. This texture indicates that the rock is either a former igneous rock which has been metamorphosed during the emplacement /
emplacement of the granodiorite, or that it is a transitional stage in the transformation of a sediment to granodiorite. The augitic patches are, however, more crystalloblastic near the aureole hornfelses than they are adjacent to the granodiorite. This is contrary to the relationship one would expect if they were pre-existing igneous rocks metamorphosed by a granodiorite magma. For this reason, and because granodiorite has been shown to be formed from sediment by similar evidence, the author favours the view that the augitic marginal patches represent part of the Fe-Mg front and are formed from sediment by introduction and fixation of material. Just as some inclusions go through a pyroxenic phase (p. 207), so do localized patches of the sediment.

The localization of the pyroxenic rocks is a serious problem. Why should the Fe-Mg front become especially intense in some localities and not in others? The material may have come either -

(i) from cafemic sediments (possibly including Arenig lavas), representing the original rocks from which the pyroxenic rocks were eventually evolved, or

(ii) from cafemic sediments now represented by granodiorite - the balance of cafemic material having been driven off to modify the pre-existing rocks immediately ahead.
XVII. DYKES AND VEINS

General statement

A large number of small dykes and veins are found both in the plutonic rocks and in the surrounding Ordovician sediments. The veins (aplates &c.) are most abundant inside the pluton whilst the dykes (porphyrites &c.) predominate outside.

A. Dykes

These dykes belong to the Caledonian swarm which extends from the Ards Peninsula (D.L. Reynolds, 1931) across the Southern Uplands of Scotland. These "minor intrusives" were described by Teall (1899, pp. 625-631), and his work was supplemented by Gardiner and Reynolds in 1932. In 1926 Read described the mica-lamprophyres of Wigtownshire. He concluded that the dykes of pyroxene-olivine-kersantite are characteristic of Wigtownshire and are not found to the north-west of a line stretching from Mull-Port William-Kinkinnen. The Loch Doon area lies well to the north of a prolongation of Read's line. Gardiner and Reynolds found about a dozen lamprophyre dykes and the author, in his restricted area, has observed five lamprophyre dykes, but none of these is equivalent to the pyroxene-olivine-kersantites of Read.

Gardiner and Reynolds described in detail the character and distribution of the minor intrusive rocks and divided them into three /
three groups: (a) acid types; (b) porphyrites; and (c) diorites and lamprophyres. They remarked that "No dykes are shown on the Survey map cutting the plutonic rocks, and, though they do occur, they are certainly far more plentiful in the sediments". On the one-inch Geological Survey map two dykes are shown cutting the pluton and Teall recorded (p. 625) that "dykes occur not only in the sedimentary rocks but also in the granite masses". It is of interest to note that Grierson (1816) recognised dykes in the pluton. Gardiner and Reynolds further stated that "Different parts of the pluton vary much in the extent to which they are penetrated by intrusions, the tonalitic rocks being far more frequently penetrated than either the granite or the norite". The author has mapped 25 dykes inside the pluton. They are not confined to any particular part of the complex; eight have been recorded from the central adamellites; nine from the granodiorites and transition zones; five from the hyperstheneic rock and three from the augitic marginal rock. McIntyre (1947, p. 125) found thirty dykes with measurable thickness within the north-western hyperstheneic rock. Dykes cutting the pluton are clearly not as rare as was at one time supposed. In addition to the works referred to above, comparable dykes have been described by a number of workers, notably D.L. Reynolds (1931), Deer (1935), M. MacGregor (1937), /
(1937), King (1937), and Sarkar (1948). In 1939 Richey reviewed each period of dyke intrusion in Scotland and dealt briefly with the Caledonian dykes (pp. 402-406). He pointed out that the prevalent trend of these dykes is E.N.E., i.e. parallel to the trend of Caledonian folds and to the Southern Uplands Fault. This statement appears to hold good only for dykes not in the immediate neighbourhood of the "granitic" complexes of Loch Doon, Cairnsmore of Fleet and Criffel. Inside the complexes and within their metamorphic aureoles the trend is more northerly. Malcolm MacGregor (1937) has recorded N.W. dykes of hornblende- and biotite-porphyrite around Criffel, whilst McIntyre (1947) noted that in the N.W. of the Loch Doon complex he found only three dykes (out of 30) with bearings east of north, all the others lying within the range 0° to 20° west of north. The author has recorded the following trends:

**Dykes within the complex:**

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<th>N.</th>
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**Dykes within the metamorphic aureole:**

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<th>N.W.</th>
<th>N.N.W.</th>
<th>N.</th>
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These /
These readings bring out the interesting fact that there is a different trend - a more northerly one - within the complex, from that of the dykes in the surrounding Ordovician sediments. The lamprophyres strike dominantly N.N.E. within the complex and between N.N.E. and N.E. in the metamorphic aureole.

The age of the dykes relative to that of the complex is of great importance. From the following evidence it is concluded that, with the exception of a gneissose dyke which shows signs of shearing, the dykes are younger than the complex:—

(i) They frequently possess chilled or fine-grained margins.

(ii) Occasionally a narrow belt of micro-breccia is found along the margins of the dykes.

(iii) The course of the dykes is frequently en échelon and rarely curved.

(iv) Xenoliths of plutonic rock material are uncommon but do occur near the margins of some of the dykes.

(v) Generally the plutonic and metamorphic rocks are altered along the border of the dykes, and appear to be enriched in potash feldspar adjacent to porphyrite dykes. They do not, however, show any change in grain size.

(a) Petrography

The majority of the dykes observed are porphyrites. There is, however, every gradation between the more acid varieties (micro-
micro-granites and quartz-porphyries) and the basic members (hornblende-spessartites).

The varieties of dykes present are listed below in order of increasing basicity:-

1. Granophyre and quartz-porphyry.

2. Porphyrites
   (a) Quartz-biotite-porphyrite.
   (b) Quartz-biotite-hornblende-porphyrite.
   (c) Biotite-porphyrite.
   (d) Biotite-hornblende-porphyrite.
   (e) Hornblende-porphyrite.

3. Lamprophyres.
   (a) Biotite-hornblende-spessartite.
   (b) Hornblende-spessartite.

1. Granophyre and quartz-porphyry.

The only example (No. 643) of a granophyric dyke was found on the slope of Craignaw in the hornblende-biotite-adamellite it strikes N.N.E. However, Gardiner and Reynolds have recorded two others outside the area described here - one near Slidder Ford, and the other at Downies Burn, east of the Long Loch of the Dungeon. Dykes that have abundant small phenocrysts of quartz have been /
been assigned to the quartz-porphyry group, but it must be stressed that they differ but little from the quartz-biotite-porphyrites. Generally they are not markedly porphyritic but they do contain small to medium-sized quartz phenocrysts in a groundmass composed of orthoclase, plagioclase and quartz. Gardiner and Reynolds recorded the following silica percentages and specific gravities of two quartz-porphyries:

\[ \text{SiO}_2: 72.41 \text{ and } 69.44; \quad \text{S.G., } 2.64 \text{ and } 2.64. \]

Two dykes (Nos. 417, 424) of this type occur on the southern slope of Buchan Hill.

2. Porphyrites

This class of dyke is the most abundant in the Caledonian dyke swarm and the Loch Doon area is no exception. The porphyrites are grey or pinkish red rocks which weather to a light pinkish red colour and are characterized by clean rectangular jointing. Rarely they are markedly porphyritic. Five varieties of porphyrites have been recorded and these are listed above. Some of the porphyrites have been albitized and further altered and these can be referred to collectively as albitophyres. The most common variety, however, is hornblende-porphyrite (e.g. Nos. 766 and 222). Some specimens are sufficiently orthophyric to suggest that the term plagiophyre (Tyrrell, 1912, p. 77; and King, 1937) might be appropriately applied to them. The plagioclase is generally /
generally euhedral in form ranging from tabular crystals (5.0 x 3.0 mm.) down to small crystals (0.1 x 0.2 mm.). Aggregates of crystals are characteristic. They average oligoclase-andesine in composition, are strongly zoned, and show fine lamellar twinning. Many of the phenocrysts are rounded and possess indistinct boundaries but others show clean acute angles and are very clear. The larger phenocrysts have commonly a dark altered internal patch composed of kaolin and sericite.

**Hornblende** occurs as small and medium-sized phenocrysts which range in size from prismatic crystals of 1.5 x 0.4 mm. down to < 0.2 mm. in length. When fresh the mineral is strongly pleochroic with X = greenish yellow, Y = olive green, Z = greenish brown. Frequently, however, the phenocrysts are chloritized and only pseudomorphs remain. Other alteration products are epidote and granules of iron ores.

The groundmass is microcrystalline becoming crypto-crystalline at the margins with well defined flow structure. It is composed of plagioclase microlites, quartz and anhedral feldspar with minute dispersed iron ore specks.

The **biotite** of the biotite-hornblende-porphyrites occurs as long ragged and anhedral equidimensional flakes. The long flakes are frequently bent. Pleochroism is strong, with X = deep yellow /
yellow, $Y =$ brown, $Z =$ dark olive brown. Some of the flakes are turbid and others are altered to chlorite (emerald green penninite) or, less commonly, to epidote and calcite.

Quartz is present as small infrequent anhedral phenocrysts, some of which are in optical continuity with interstitial quartz in the groundmass.

3. Lamprophyres

Members of this group of basic dykes are fairly numerous to the south and south-south-west of the complex but the author has observed only six inside the pluton. These six exposures of lamprophyre seem to have been intruded en échelon along a set of fractures; they extend from the Rig of the Jarkness in a staggered line striking N.N.E. as far as Loch Arron. The dykes are well jointed; the close, clear jointing is well illustrated by a hornblende-spessartite dyke north-west of the Murder Hole, Loch Neldricken. The width of the dykes varies greatly; the range is between 1 ft. and 15 ft. with the majority measuring 3 - 6 ft. across.

There are three types of lamprophyres: biotite-lamprophyres; biotite-hornblende-lamprophyres; and hornblende-lamprophyres; of these hornblende-lamprophyre (spessartite) is the most abundant. This conforms with Read's observation that
kersantites predominate amongst the Wigtownshire lamprophyres to the almost complete exclusion of minettes.

Macroscopically the lamprophyres are dark grey compact rocks. Occasionally small black prismatic crystals of hornblende can be detected. The biotite-hornblende-lamprophyres (spessartites) consist of plagioclase, hornblende, biotite, with accessory quartz, orthoclase, apatite and iron ores.

Plagioclase is dominantly lath-shaped in section and in the marginal portions of the dyke exhibits good flow structure. It averages andesine $\text{An}_{40-45}$ but ranges from labradorite $\text{An}_{50-55}$ to oligoclase $\text{An}_{25}$. Continuous zoning is frequently well developed. Some of the larger laths have a narrow rim of clear albite.

Hornblende occurs as subhedral and lath-shaped crystals which range in size from less than 0.05 mm. up to 2.0 mm. in length. The crystals have a preferred linear orientation. The pleochroism is moderate with $X =$ greenish brown, $Y =$ green brown, and $Z =$ red olive brown. $Z \wedge c = 23^\circ$. Optically negative.

Occasional large "phenocrysts" consisting of a mass of acicular actinolite crystals occur; they may be pseudomorphs after augite, though against this is the fact that no augite has been /
been observed. Alternatively they may be related to aggregates of brown hornblende and actinolite which occur sporadically throughout the rock and may represent altered inclusions.

**Biotite** is subordinate to hornblende and occurs as very small ragged and subhedral flakes clustered together with hornblende. Pleochroism is strong with $X =$ pale yellow, $Y =$ red brown, $Z =$ dark foxy red brown. Pleochroic haloes are present.

Of the minor components iron ores, partly euhedral and partly granular, are the most abundant; apatite occurs in abundant needles and quartz is present interstitially. Orthoclase has been detected in the groundmass.

The texture is panidiomorphic with a tendency to porphyritic texture produced by the occasional presence of large phenocrysts of plagioclase and aggregates of amphiboles.

**Sheared dyke**

A remarkable type of gneissose rock was found in the contact zone of the complex, approximately a quarter of a mile south of the Corse Knowe of White Laggan. Though not particularly well exposed, it can be seen that it is adjacent to biotite-hornfels and that the margins are dark, due to concentrations of ferromagnesian minerals. The main part of the dyke is whitish yellow and more leucocratic, but with thin streaks or gneissose bands.
bands of mafic minerals. Large phenocrysts of feldspar reach a maximum size of 10.0 x 5.0 mm. The dyke measures 4 ft. - 8 ft. in width and extends for (?) 50 yds. in a N.E. direction. It lies in a shear zone, the shear plane is vertical and the direction of elongation or orientation in that plane plunges 40° to the south-west.

Two contiguous dykes

On the south-east shore of Loch Dee, just north of the Old Boat House a pair of contiguous dykes was discovered striking 9° E. of N. The whole consists of two parts of almost equal width; one portion, 18" in width, is highly cleaved, much fractured and extensively altered, whilst the other (15" wide) is a fresh compact and evenly jointed portion. The earlier is an albitized and chloritized pyroxene-biotite-granodiorite whilst the later is a granite-aplite.

B. Veins

(a) General statement

Leucocratic veins occur in all zones of the pluton. They are most plentiful in the adamellites and the granodiorites but are also present in the hypersthenic rock. Occasionally they traverse /
traverse the margin of the pluton and extend into the metamorphosed sediments.

The veins have been observed in the biotite-adamellite on the eastern slope of Craignaw in the neighbourhood of Dow Burn; at a height of 1400 ft. south-west of the Long Loch of the Dungeon; and in the vicinity of the summit of Craignaw.

They are particularly abundant in the other zones but the main localities are: south of Loch Enoch; at the Point of the Snibe; above the Clints of the Buss; and on the south slope of Buchan Hill.

They occur in the hypersthenic rock 300 yds. east of the Corse Knowe of White Laggan and along the north and north-eastern slope of White Hill.

The veins vary in thickness from less than an inch to eighteen inches and occasionally more. Some can be traced for distances up to forty yards. The majority strike N. and N.N.E.

Thirty specimens were collected to cover the range of types observed in the field and of these twenty-one have been sectioned.

(b) Petrography

The following types have been distinguished: - aplites
(includes granite aplites and adamellite aplites); granophyres, adamellites, microgranites and microgranodiorites.

1. **Aplites**

The aplitic veins are fine-grained, cream and pinkish white coloured rocks, characterized in hand specimen by a saccharoidal texture. They are the most abundant type of vein and are widely distributed throughout the pluton.

They consist essentially of quartz and potash feldspar (orthoclase and/or microcline) with accessory muscovite, biotite, apatite, zircon and iron ores. Another constituent, which is only rarely present, is tourmaline. The texture is generally xenomorphic-granular but infrequently it tends to become porphyritic as phenocrysts appear in the saccharoidal groundmass (No. 389). Occasionally there is a tendency to develop granophyric structure. Specimen Nos. 315, 339, 480, 636, 644b, 654a, 764b are typical aplites.

Of the accessory constituents biotite is the most common and is followed in abundance by muscovite. Gardiner and Reynolds gave the silica percentage of an aplitic from Snibe Hill as 75.74 with a S.G. of 2.58.
2. **Pegmatitic aplites**

Coarse-grained veins (grain size taken as > 2 mm.) occur frequently. They are the coarse-grained equivalents of the aplites and are of interest as they often contain large crystals of tourmaline (No. 297), schorl with pleochroism X(E) = brown, Z(O) = dark purplish brown - black. This occurrence of tourmaline is significant and can probably be correlated with the intense local tourmalinization of the Fore Burn plutonic complex (MacGregor 1936 and 1948).

3. **Granophyres**

Only two veins were found to have a pronounced granophyric texture. One of these occurs in the aureole on the south slope of Buchan Hill (No. 213) and the other in the hypersthenic rock on the north slope of White Hill (No. 297). An interesting feature is the occurrence in the veins of cavities or druses, partially filled with oligoclase, quartz and potash feldspar. No. 297 exhibits beautiful forms of intergrowth like frost-crystals on the window panes.

4. **Adamellites**

A few veins of hornblende-biotite-adamellite (No. 348) and biotite-adamellite ranging from ½" to 3" in thickness cut the granodiorite /
granodiorite and the transitional granodiorite-hyperstheneic rock on the north-west and the south-east shore of Loch Dee respectively. Some of them have been considerably altered (No. 351) (albitized and chloritized) in a manner similar to the sheared member of the pair of dykes described above (p. 260). Such altered dykes appear to be confined to the Loch Dee area. One vein (No. 597) shows evidence of having been crushed and sheared, as small crush zones of micro-breccia are present. The same vein has also been extensively albitized, the resultant albite being reddened by inclusions of ferriferous dust.

5. Microgranites and microgranodiorites.

The rocks included under this heading consist of potash feldspar, plagioclase and quartz with subordinate biotite. They are characterized by a fine grained texture. They tend towards granite- and granodiorite-porphyry by the development of phenocrysts of potash feldspar and plagioclase respectively. Examples were found in the granodiorite in Glenhead Burn (No. 371) and in the biotite-adamellite on Little Craignaw.

Origin of the dykes

The flow-structures present in most of the dykes indicate that they were emplaced in a magmatic condition. All types of
of dykes present are petrogenetically related to the major rock-types of the pluton. This fact suggests that mobility in depth may have led to the generation of intergranular films of magma which was squeezed out by the pressure of the expanding mass to form the dykes.
XVIII. STRUCTURE

(a) Introduction and Previous Work

As F.F. Grout (1941) has pointed out, to arrive at a balanced hypothesis for the mode of origin of a pluton the problem should be investigated from all aspects, i.e. petrological, geochemical and structural.

In the summer of 1949, Dr. G. Oertel made a structural investigation of the northern half of the Loch Doon complex and of parts of the immediately neighbouring country rocks. A preliminary summary of the results has already been given by him (Abst. Proc. Geol. Soc., No. 1457, Jan. 1950). Although the present study is primarily petrological and geochemical, sufficient structural data have been collected to enable a comparison to be made between the structure of the southern half of the complex and that found by Dr. G. Oertel in the north.

Within the complex the tabular crystals are usually sub-parallel; their preferred orientation gives a mappable structure. This planar orientation is conspicuous in the granodiorite but is difficult to detect in the biotite-adamellite and the hypersthene rocks. The planes are approximately vertical, and in general the orientations of the crystals define two vertical planes which intersect at varying angles. Near the outer contact of /
of the marginal granodiorite distinct orientation is parallel to one plane only. In the normal granodiorite two planes are discernible; they intersect at a very small angle, and only the mean directions are drawn on the map (Map Fig. 74). In the biotite-adamellite and the hypersthenic rocks, however, the angle of intersection of the two planes is nearly 90° and the strike of both planes is shown on the map. As the term "foliation" has a genetic implication it cannot be used for the structure described. For example Balk (1931) defined foliation "as a phenomenon of magma flowage which was caused by the friction between the floating solid mineral grains and the liquid portion of the magma."

The planes of parallel arrangement of crystals in the Loch Doon pluton are not due to magma flowage because TWO planes exist. They further cannot be attributed to deformation from the exterior because of their symmetry. The intersecting planes can be interpreted as planes of movement (i.e. sets of shear planes). Oertel points out that "The intersection of systems of planes of movement (visible as planes of parallel arrangement of crystals) proves the character of the movement to be translation along intersecting systems of shear planes in an essentially solid body. The angle between the shear planes is near 90° in the central granite, low or very low in most of the granodiorite and high again in the hypersthenic rocks". From this it is deduced "that /
"that the degree of pseudoplasticity produced by interreaction of stable and unstable crystal phases in the solid during recrystallization depends on the stage of that process and is highest at the final stage shortly before it becomes stable granite. Then the inter-reaction stops and the granite is rigid again". He further states "The near vertical or vertical position of most planes of parallel arrangements of crystals, which must be considered to be planes of relative movement, shows that there was neither upward nor downward movement on any considerable scale and that most movements took place in the horizontal plane, i.e. that of the map".

Oertel obtained a structural pattern which indicated by its symmetry that it was related to the granitic interior of the pluton and that the structures were formed by movements caused inside the pluton. He postulates that "Only the swelling of the central granite, and to a lesser degree of the granodiorite and hypersthenic rock, can account for the source of energy for the pressure. To produce swelling of the same order of magnitude along a vertical distance of at least eight miles matter and energy transforming the rocks into granite must have reached all points along the central core in equal quantity and intensity. They had to go through the solid. The most probable manner of such transport is ion diffusion".

Oertel /
Oertel pointed out that the rocks of the basic front can be correlated with the less moved parts of the pluton; the hypersthenic rocks have formed in the incompletely moved corners.

The Structural Pattern

The pattern formed by the planes of parallel arrangements of crystals has a definite symmetry. In the granodiorite, the rocks transitional to the hornblende-biotite-adamellite, and the hornblende-biotite-adamellite, the planes are concentric; their centre is in the biotite-adamellite at the centre of the complex. This arrangement of the planes agrees with the results obtained by Oertel in the northern half (see structure map).

(b) Structure of the Sediments

1. General. The prevalent strike of the sediments is N.E. - S.W.; this direction was imparted to the rocks - in common with the rest of the Lower Palaeozoics of the Southern Uplands - during the Caledonian orogeny. According to the Survey geologists the sediments are strongly isoclinally folded into large anticlinoria and synclinoria and the beds dip vertically or are highly inclined, the average dip being between 70° - 80°. As the complex is approached, the strike swings into parallelism with the margin except in certain localities in the aureole of the hypersthenic /
hypersthenic rock. In the contact aureole of the granodiorite a narrow zone of mobilized sediment is present near the contact. Inside this mobilized zone there is a complete gradation from the metamorphosed sediments to the marginal granodiorite. The "line of contact" cannot be defined precisely as generally no sharp junction exists. Instead there is a zone of transformation from hornblende-biotite-hornfels on one hand to marginal granodiorite on the other.

2. In the contact aureole of the granodiorite

The marked deflection of the strike is well exhibited by the black shales. On the north side of the Trool valley their strike is N.E. - S.W., but this is gradually deflected northwards until on Buchan Hill they strike N-S parallel to the contact. Other examples of this type can be seen from a brief inspection of the structural map (Map Fig. 74).

The isoclinal folding of the sediments repeats the same bed or formation several times. For example the black shales, which have been estimated by the Survey geologists to be less than 100 ft. in thickness, measure 600 yds. across their strike on Buchan Hill. In general the fold axes are nearly horizontal but in only two localities were the crests of isoclinal folds observed; namely on the S.E. side of Buchan Hill and due south of the summit of /
of Mulldonoch. The bearing of both axes is 178°, and the pitch of the axes is 15°S and 5°N respectively. The strike has been deflected through an angle of at least 45° and it is clear that the sediments have been displaced. The crucial question is whether the displacement is great enough to solve the space problem of the pluton. This can be answered by studying the deflection of a key bed - the black shales. This formation is the only one which can be traced with certainty along the strike for any distance. If the original structural picture of the sediments is reconstructed by bending the deflected beds back it will be seen that their displacement accounts for only a relatively small part of the space occupied by the pluton.

From Buchan Hill (west) to Little Millyea (east) the pluton has a width of 4 miles. If all the sediments which were originally present were thrust aside by the intrusion of the pluton the displacement should amount to approximately two miles on each side of the complex. However, on the western side the maximum displacement is only about one mile, and on the eastern side the displacement is insignificant. Further, it is highly probable that the black shales of Buchan Hill correspond with those of Meikle Craigtarson and Meaul (eastern side of the northern half of the complex). These beds have suffered some displacement but it is clear that this is not sufficient to solve the space problem of /
of the complex. Unfortunately it is impossible to determine the exact structural position of the black shales which outcrop S.W. of Loch Enoch – they may be a strike continuation of the Buchan Hill shales, or they may have been repeated across the strike.

3. The zone of mobilized sediment

This zone is approximately 12-15 yds. wide and shows excellent flow structures. It is impossible to trace a bed along the strike into the complex as this zone intervenes and in it the identity of the bed being followed is lost. The major flow structures are always aligned vertically in planes roughly parallel to the margin of the complex. That it is true mobilization is clearly demonstrated by the flow structures and the disorientation of fragments. Measurements taken indicate that in the framework of the pronounced preferred orientation parallel to the margin of the complex, random orientation of minor structures exists. The structures of the marginal granodiorite are parallel to the margin of the complex, but as Oertel points out "the parallelism of structures in both country rock and parts of the pluton only shows that under pressure they reacted as a mechanical unit in which the thin lubricating film of mobilization at the 'contact' is insignificant".

The zone is not continuous around the margin of the pluton /
pluton. As far as the exposures allow generalisations to be made, it is probable that it extends everywhere along the margin of the granodiorite but in the aureole of the hypersthenic rocks its occurrence is very local. The discontinuous character of this zone and the fact that the 'contact' plane is much too curved and irregular to serve as a plane of movement under pressure acting from the centre of the pluton, led Oertel to the deduction, quoted above, that in general the country rocks and the pluton acted as a mechanical unit.

4. In the contact zone of the hypersthenic rocks.

The general N.E. - S.W. trend is maintained in the black shales from Lamachan Hill over Curleywee to White Hill, but approximately a quarter of a mile from the contact it swings round E. - W. and almost N.W. - S.E. In other localities, however, there is no disturbance of the general strike whatsoever. At Laggan Linn, a quarter of a mile south of White Laggan Farm the sediments strike E.N.E. - W.S.W. right up to the actual contact, and there is no mobilization. The sediments in the aureole of the hypersthenic rocks have generally been less disturbed than those in the granodiorite aureole; this has an important bearing on the interpretation of the structures of the hypersthenic rocks and will be dealt with later (p. 274).

(c) /
(c) Structural Features in the Hypersthenic Rocks

The majority of the measurements in the area of hypersthenic rocks were made by Oertel in the writer's company. It will be seen from the map that two distinct sets can be distinguished. They intersect at angles between 65° and 90°. The first set, approximately E.N.E. - W.S.W. coincide with the strike of the country rocks. This fact is clearly demonstrated near Well Burn and at Laggan Linn in White Laggan Burn. This set of structures changes to a N.E. - S.W. direction, east of Black Laggan Farm and S.E. of Corse Knowe of White Laggan - but it still parallels the strike of the sediments in the aureole near these localities. The second set of planes intersects the first approximately at right angles but there are a few exceptions to this and the angle of intersection is sometimes as low as 65°. This is comparable with the pattern obtained from the N.W. 'norite' mass where the "planes of parallel arrangement of crystals in most of the hypersthenic rock are nearly parallel to the bedding plane and to the main joint system respectively in the country rock" (Oertel, 1940). Oertel is careful to point out that the planes are "not representation of the bedding planes or joints themselves in the metamorphosed rock" but simply "a sign of the projection of the mechanical anisotropy of the country rock (its planes of weakness) into the nearly rigid rocks of the pluton under common pressure".
It is a significant fact that the shear planes intersect at high angles; the hypersthenic rocks were relatively rigid (compared with the granodiorite) and acted as a unit along with the surrounding country rock. This view is further strengthened by the lack of mobilization of the sediments at the contact.

(d) **Structural Features in the Granodiorite and Hornblende-biotite-adamellite.**

1. **General**

The orientation is present everywhere in the rocks but is most pronounced in the vicinity of the aureole. In the leucocratic granodiorite the parallel arrangement of crystals in a near-vertical plane is emphasized by the ferromagnesian minerals. It is not always easy to arrive at a decision on some exposures but the reliability of the observations can be controlled by measuring directions in numerous neighbouring exposures. The best possible exposure is a large three dimensional one, from which lichen has recently been removed by rain. Sufficiently numerous reliable measurements were made to bring out the general structural features of the granodiorite (Map Fig. 74).

From the map (Fig. 74) it will be seen that the strike of the shear planes in the granodiorite, and in the transitional granodiorite - hornblende-biotite-adamellite, curves around the central/
central biotite-adamellite. The directions of the planes run N.-S. on the western side of the central ridge, and swing round in an arc to run E.-W. across Craiglee. They turn S.W.-N.E. along the N.W. shore of Loch Dee but their course farther to the east is obscured by a large tract of bog. It is highly probable, however, that they continue their swing round to run S.-N. on the eastern side of the central ridge. This structural pattern conforms with the results obtained by Oertel in the northern half where the same concentric arrangement of the planes is found in the corresponding zones.

The concentric arrangement of these shear planes indicates that the source of energy came from the interior of the complex. The angle between the shear planes indicates that relative movement along them was greater in the granodiorite than in any other zone and actually reached a maximum in the marginal granodiorite. This is what one would expect to happen if growth from the interior of the complex took place, accompanied by slight swelling. The deformation of the outer margins of a body growing in the solid from a central nucleus in this manner would be greatest on the periphery and decrease towards the nucleus. Thus recrystallization in the outer zones would be preferential along the shear planes.
2. Marginal granodiorite

The shear planes can be mapped with ease near the margin of the complex; in fact the "banding" becomes more distinct as the marginal granodiorite grades into the contact aureole rocks. Only one plane of arrangement of crystals was observed, and this is parallel or nearly parallel to the margin of the complex. Good examples can be seen at the following localities:

(i) south slope of Buchan Hill, at a height of 800 ft.
(ii) near the northern summit of Buchan Hill.
(iii) south-west of Loch Enoch.

3. Granodiorite

The planar structure is clearly defined in most of the granodiorite and it is in this zone that the concentric arrangement of the shear planes can be best seen.

North and north-west of Loch Neldricken, on Ewe Rig, the strike of the planes is very nearly north-south, and the angle of intersection of the two planes is small. To the south-west of Loch Neldricken, however, the two planes intersect at an angle of approximately 20° and their directions lie west of north. This north-south general trend is maintained as far south as the Rig of the Jarkness. Thereafter the swing round to a general N.W. - S.E. trend takes place in the area of the Glenhead Lochs.
It is also beautifully shown around the spur of the Gairy of Glenhead. The curve round to a general W.-E. direction takes place a quarter of a mile N.N.W. of the Corse Knowe of White Laggan and it maintains this trend to Clashdan Brae which lies to the N.W. of Loch Dee. Along the N.W. shore of Loch Dee the trend swings gradually round until at the exit of the River Dee from the loch it is S.W. - N.E. The area to the north of Loch Dee, through which the Cooran Lane flows, is covered by extensive and dangerous bogs and the area to the immediate east lies outside the area under study. Nevertheless, it is probable that the shear planes continue their swing until, east of Cooran Lane, they run S.-N.

In all cases where the angle of intersection of the shear planes was 20° or greater both directions have been mapped. The angle varies from 20° to a maximum of 60° (the latter locality being just N.W. of the northern part of Loch Valley).

4. Transitional to hornblende-biotite-adamellite.

The planar arrangement of crystals in this zone is definite but not so evident as in the normal granodiorite. The general trend follows a course parallel to that described in the granodiorite zone. In the area of the Glenhead Lochs and Craiglee the zone attains its greatest width and from the map it will be seen that the shear planes roughly follow the petrographic boundaries. Generally only one direction has been mapped but on the average /
average the angle of intersection of the shear planes is greater than in the granodiorite. An interesting feature is the eastward shift of the commencing point of the W.-E. trend.

(e) Structural Features in the "Granitic" Rocks

1. Hornblende-biotite-adamellite

Structural planes are present here but their directions are measurable only in particularly favourable exposures. Two planes are nearly always present and these intersect at angles ranging from 45° to 80°. One set of shear planes lies more or less parallel to the concentric trend in the outer zones.

2. Biotite-adamellite

The mapping of the planes of parallel arrangement of crystals in this zone is very difficult. Very large exposures are required to enable the alignment of the minerals to be detected. Inspection of the structure map (Fig. 74) will show that the planes have a slight tendency to a preferred orientation. Two systems can be recognised (N.W. and N.E. of the Dow Loch of Craignaw), one bearing approximately N.W. - S.E. and the other intersecting at an angle of 80° - 90°. However, in the greater part of the biotite-adamellite the orientation is haphazard.

The absence of shear planes indicates that in the final stage /
stage this zone crystallized without movement, or that there was negligible relative movement within it. The high angle between the planes implies rigidity. The source of energy of the granitizing elements must have originated from this centre.

It is interesting to note that this central zone is widest at the waist of the complex (near Loch Enoch) and the outer zones are narrowest at this point. This would mean that the interior of the pluton acted as a relatively rigid mass and that the greatest pressure, accompanied by swelling, took place where the granodiorite zones attain their maximum width, i.e. in the bulges north and south of the waist of the complex.

(f) Form of the Complex

Judging, apparently, from the presence of outward dipping sediments and the underground extension of the plutonic rocks at no great depth to include the Burnhead mass, Gardiner and Reynolds (1932) suggested that the complex is laccolithic in character. The structural evidence does not warrant such a conclusion.

The term "laccolite" (cistern - stone) was proposed by Gilbert (1877) to describe the form of the intrusions that characterize the Henry Mountains in Utah. Gilbert (1877, p. 19) defined laccolites as intrusions in the development of which magma insinuated /
"insinuated itself between two strata, and opened for itself a chamber by lifting all the superior beds". The three features characteristic of a laccolith are:-

(1) that like a sill, a typical laccolith has followed a bedding plane;
(2) that a laccolith lifted and domed its roof during injection; and
(3) that laccoliths are floored intrusions.

All the available structural evidence for the Loch Doon complex opposes these three points.

1. The pattern of the crystal lineations indicates that the complex was not intruded and did not exist as a magma. Reasons are:-

(i) The planes are vertical or nearly vertical shear planes. The double system of planes cannot be explained by magma flow.

(ii) The structural planes outcrop as concentric lines, in an hour-glass shape, around the interior. To achieve this pattern the "magma" would have to be stirred as if by a large spoon held vertically.

2. There is no evidence of a domed structure. The sediments are isoclinally folded, and it is obvious that the complex is not a concordant intrusion. The structural planes within the complex are vertical.

3. There is no evidence that the complex is floored. To assume that it is floored is pure speculation.

The /
The complex has an hour-glass shape with its longest axis orientated approximately N-S. This direction is oblique to the general strike of the sediments, although it is recognised that some of the aureole sediments have suffered displacement. The complex is therefore better described as a small batholith as it possesses most of the characteristics implied by the use of this term as defined by Daly (1933). (It was suggested by Daly that the term "batholith" be used for masses which at the outcrop cover more than 40 sq. miles.)

(g) Summary and Conclusions

1. The **country rocks** are displaced laterally.

2. The **pyroxenic rocks** are structurally part of the country rocks.

3. The **granodiorite** is characterised by -

   (i) a shear plane system which is concentric on the core of the pluton; and

   (ii) at any locality, two almost parallel shear planes (nearly vertical).

4. The **adamellites** possess shear planes in their outer portion only. Where present the shear planes are at right angles and nearly vertical.
In the plane of the exposure

1. The symmetry of the structure pattern proves that there was a movement affecting all rocks and that the forces producing movement acted from the core of the pluton - i.e. the forces were internal and not external in their origin.

2. The displacement was directed outwards from the core and had no vertical component in the rocks now exposed around the complex.

Attempted extrapolation from the plane of exposure

Oertel has stated (1950, p. 32) that "most movements took place in the horizontal plane, and that the arrangement of forces producing these movements was nearly the same for several miles below and above the recent plane of exposure (at least as much as the mean extension from east to west, i.e. four miles)." He further pointed out that "Any hydrostatic transmission of pressure from below would have resulted in the formation of inclined planes of movement. They do not exist."

Oertel’s conclusions are provisional and the writer understands that they are being tested by experimental methods at Bonn. In view of this the writer feels that the data do not yet warrant further extrapolation.
XIX. GEOCHEMISTRY AND PETROGENESIS

A. Data

1. Analyses and Analysed specimens

Six new analyses have been made. Four of the rocks selected for analysis in this thesis were specifically chosen for the purpose of ascertaining what chemical changes may have taken place in the series of rocks ranging from the high grade aureole hornfelses to the granodiorite. They were selected from the series of specimens collected across the 'contact' at approximately 800 ft. on the south slope of Buchan Hill (pp. 47, 66, 75 and 118).

The analysed specimens are as follows (lettered as in Tables II and III):

- B. Biotite-hornblende-plagioclase-hornfels (No. 414)
- C. Mobilized sediment (No. 214).
- D. Transformed feldspathized sediment or contact-quartz-diorite (No. 404), transitional to marginal granodiorite.
- E. Marginal hornblende-biotite-granodiorite (No. 401).

These analyses are listed in Tables I and II.

Analyses were also made of:

- F. Granodiorite (No. 278), from Glenhead Wood; and
- L. Augitic marginal rock (No. 205), from the south-western corner of Glenhead Wood (see Tables I, II and III).
Also included in Table II are two of the analyses (by E.G. Radley) given by Gardiner and Reynolds (1932). These are:

G. 'Tonalite' (GR.No. 749) from Fore Starr, 2 miles south-south-west of Loch Doon. This almost certainly belongs to the granodiorite zone as defined by the writer.

H. 'Granite' (GR.No. 755) from the central ridge between Hoodens Hill and Mullwharchar. This is a biotite-adamellite.

An analysis of K. 'norite' (GR.No. 532) from the north-western part of the complex was also given by Gardiner and Reynolds (1932). McIntyre has correlated it with the medium-grained hypersthenic rock (see Table III).

In addition to the complete analyses a number of silica percentages were given by Gardiner and Reynolds. The data are as follows:

(i) 'Granite'. Specific gravities range from 2.60 to 2.65 with an average of 2.63 (27 determinations).

(ii) 'Tonalite'. Specific gravities range from 2.67 to 2.74 with an average of 2.73 (94 determinations). Silica percentages are 64.52 and 63.88.

(iii) 'Norite'. Specific gravities range from 2.74 to 3.00 with an average of 2.81 (94 determinations). Silica percentages are 58.92, 54.76, 51.78, 50.4 and 44.56. The lowest silica percentage recorded in this group is of an "olivine-hornblende-norite" collected one mile north-west of White Laggan, whilst the highest is of a transitional 'norite'- 'tonalite' rock collected from the north-west corner of the complex.
McIntyre (1947) had seven new analyses made (by W.H. Herdsman) of rocks from the north-west corner of the complex.

N. Unaltered greywacke.

O. Greywacke granulite - with a little new feldspar.

P. Greywacke granulite - with much new feldspar.

Q. Feldspathized and pyroxenized greywacke granulite.

M. Fine grained opdalite (hypersthenic rock).

I. Coarse grained opdalite ("")

J. Quartz-diorite.

These analyses enabled McIntyre to illustrate the changes that take place in the aureole rocks as they are traced towards the hypersthenic rock and to elucidate the chemical variation of the hypersthenic rocks themselves.

2. Explanation of layout of Tables II and III.

In Table II the chemical analyses are arranged in field order and along a traverse taken from a point 55 yds. outside the granodiorite 'contact' to the centre of the complex as follows:

A. Average greywacke.

B. Biotite-hornblende-plagioclase-hornfels (No. 414).

C. Mobilized sediment (No. 214).

D. Transformed feldspathized sediment or contact-quartz-diorite (No. 404).

E. Marginal granodiorite (No. 401).

F. /
F. Marginal granodiorite (No. 278).

G. 'Tonalite' or granodiorite (GR.No. 749).

H. 'Granite' or biotite-adamellite (GR.No. 755).

In Table III the chemical analyses of the various rocks within the pluton are arranged according to their silica percentages, as follows:—

I. Coarse-grained hyperstheneic rock (opdalite, McIntyre's No. 18).

J. Quartz-diorite (McIntyre's No. 206).

K. Medium-grained hyperstheneic rock ('norite', Gardiner and Reynolds' No. 532).

L. Augitic marginal rock (No. 205).

M. Fine-grained hyperstheneic rock (opdalite, McIntyre's No. 333).

E. Marginal granodiorite (No. 401).

G. Granodiorite ('tonalite', Gardiner and Reynolds' No. 749).

F. Granodiorite (No. 278).

H. Biotite-adamellite ('granite', Gardiner and Reynolds' No. 753).

These analyses are plotted on Variation Diagram No. 3. (Fig. 70).
3. **Note on average greywacke**

The normal procedure in determining the original character of a particular bed of metamorphosed sediment involves the assumption that the change has been isochemical. This assumption is not justified at Loch Doon; it has already been demonstrated that there is a gradation from the hornfels to less altered greywacke on the one hand, and to granodiorite on the other.

When metamorphism is not isochemical the only reliable way of determining the origin of an altered rock is to trace the bed along its strike into its unaltered equivalent. The validity of this method depends on the absence of original lateral variation between the now altered and unaltered rocks. The Loch Doon hornfelses cannot be followed through the aureole as individual beds, and, moreover, the amount of lateral variation in the sediments is great. The analysed hornfels is nevertheless a typical member of the altered greywacke series, and its unaltered equivalent probably approximates more or less closely to "average greywacke". The author considers that the unmetamorphozed equivalent of the biotite-hornblende-plagioclase-hornfels is a poorly calcareous, shaly greywacke.

For these reasons it is believed that the best estimate of the original composition of the hornfels is obtained by taking
an average of all analysed sediments of greywacke type. For this purpose the average given by Pettijohn (1948, p. 250), which covers greywackes of all ages, may be more useful than that given by Tyrrell (1933, p. 26), which is confined to those of Archaen age. Nevertheless the two are remarkably similar.

B. Interpretation of data

1. Discussion of von Wolff diagram No. 1.

The ingenious method of plotting rock analyses devised by von Wolff is most suitable for showing the general nature of the chemical changes.

The analyses of Table II are plotted on the von Wolff diagram No. 1 (Fig. 67) for each rock type. Two stages in the metasomatic alteration of the greywacke group of sediments into 'granitic' rocks can be distinguished:

(i) desilication and basification, involving decrease of $\text{SiO}_2$ and increase of cafemic oxides; and

(ii) granitization, involving increase of $\text{SiO}_2$, $\text{Al}_2\text{O}_3$, and decrease of the cafemic oxides.

The various steps are as follows:

(1) The average greywacke (A) on increasing metamorphism is transformed into biotite-hornblende-plagioclase-hornfels by becoming desilicated with concomitant basification.

(2) /
(2) The biotite-hornblende-plagioclase-hornfels (B), on becoming mobilized is enriched in quartz and consequently is silicated and becomes less basified. By comparison with the hornfels (B), the mobilized sediment (C) is richer in SiO₂, Al₂O₃ and K₂O, and poorer in Fe₂O₃, FeO, MgO, CaO, Na₂O, TiO₂, P₂O₅ and MnO.

(3) The mobilized sediment (C) in turn becomes desilicated on transformation to contact-quartz-diorite (D) with only slight further basification. There is however an enrichment in alkalies as the rock is feldspathized. Relative to the mobilized sediment (C), the contact-quartz-diorite (D) contains more Fe₂O₃, MgO, Na₂O, K₂O, TiO₂, and P₂O₅, and less SiO₂, Al₂O₃, FeO, CaO and MnO.

(4) The transformation of the contact-quartz-diorite (D) into marginal granodiorite (E) is achieved by silication with a concomitant decrease in cafmic constituents. A comparison of the analyses shows that the marginal granodiorite (E) contains more SiO₂, Na₂O, K₂O and MnO than the contact-quartz-diorite (D), but less Al₂O₃, Fe₂O₃, FeO, MgO, CaO, TiO₂ and P₂O₅.

(5) The granodiorite (F) collected from Glenhead Wood within twenty yards of the margin of the complex was considered in hand specimen to be more like the normal granodiorite type rock than the marginal variety, but it will be seen from the von Wolff diagram /
diagram that, chemically, it is more like the marginal granodiorite (E). Although the granodiorite (G) collected by Gardiner and Reynolds contains a higher percentage of SiO₂ than the marginal granodiorite (E), it is nevertheless desilicated relative to the latter (i.e. it is desilicated relative to the bases present).

It would appear that the Gardiner and Reynolds' specimen (G) is not representative of the normal granodiorite. For a granodiorite so far from the margin of the complex (about one and a half miles), it is low in silica and P₂O₅, high in total FeO and MgO, and exceptionally rich in K₂O.

(6) The final stage is the transformation of granodiorite into adamellite (H) by silication and marked reduction in the amount of cafemic constituents. Thus in the final process of granitization, silica and alkalies increase, whilst alumina and the cafemic constituents decrease.

2. Variation diagram No. 1.

In this diagram the series greywacke - biotite-adamellite is plotted on a silica basis. The left hand side of the diagram illustrates basification and the right hand side granitization. (N.B. Analyses G has been omitted.) (Fig. 68).

3. Variation diagram No. 2.

In this diagram the greywacke - biotite-adamellite series /
series is again represented, but in this case the analyses have been placed in their evolutionary sequence. (Again analysis G has been omitted.) (Fig. 69).

The main stages in the evolution of biotite-adamellite from greywacke can be shown schematically as follows:

\[
\begin{align*}
\text{Al Fe Mg Ca} + \text{average greywacke} & \rightarrow \text{biotite-hornblende-plagioclase-hornfels} + K Na Si. \\
\text{Al K Si} + \text{biotite-hornblende-plagioclase-hornfels} & \rightarrow \text{mobilized sediment} + \text{Fe Mg Na Ca}. \\
\text{Mg Na K} + \text{mobilized sediment} & \rightarrow \text{contact-quartz-diorite} + \text{Al Fe Ca Si}. \\
\text{Na K Si} + \text{contact-quartz-diorite} & \rightarrow \text{marginal granodiorite} + \text{Al Fe Mg Ca}. \\
\text{Ca K Si} + \text{marginal granodiorite} & \rightarrow \text{granodiorite} + \text{Al Fe Mg Na}. \\
\text{K Na Si} + \text{granodiorite} & \rightarrow \text{biotite-adamellite} + \text{Al Fe Mg Ca}.
\end{align*}
\]

The same dates are represented diagrammatically in Fig. 73.

A great advance in our knowledge of the geochemistry of granitization was made in 1946 by the publication of D.L. Reynolds' synthesis entitled "The Sequence of Geochemical Changes leading to"
to Granitization. She demonstrated that "when pelitic and semi-pelitic rocks come under the metasomatizing influence of granite 'magma' they undergo changes in two distinct stages. During the first stage of alteration, they become molecularly desilicated relative to the molecular proportions of the bases present. The products of this desilication change, which attain the composition of syenite or of basic or ultrabasic igneous rocks, are characterized by a higher percentage of alkanes and/or cafemic constituents than either the parent sediment or the adjoining granite. For such an increase of any constituent beyond the amounts present in the parent rock and neighbouring granite the term geochemical culmination is proposed. When the desilication change is wholly or largely one of basification (introduction of Fe, Mg, Ca) it is characterized by increase, commonly attaining geochemical culmination, of one or more of the minor constituents TiO₂, P₂O₅ and MnO; when it is essentially one of feldspathization, however, TiO₂, P₂O₅ and MnO may all decrease. During the second stage of alteration the desilicated rock is granitized, i.e. its composition approaches that of the associated granite. Silica and one of the alkanes are added, whilst alumina, cafemic constituents, and the minor constituents TiO₂, P₂O₅ and MnO decrease."
In the case of the transformation of greywacke into 'granitic' rocks at Loch Doon it is clear that the two processes recognized by D.L. Reynolds have also operated. The processes of desilication (and/or basification) and granitization operated successively to produce several intermediate rock types. After the initial desilication and basification the product of the alternately operating processes approaches more closely the chemical composition of the final 'granitic' product. On the other hand if more analyses were available it is possible that the fields of each type might overlap.

The geochemical culminations are illustrated by Fig. 72. Although Al attains its maximum in the mobilized sediment, it is consistently high throughout the contact zone. Si, K and Na clearly culminate in the granitized zone, and Fe, Mg and Ca in the desilicated and basified zone.

The behaviour of the minor constituents conforms to the general principles determined by D.L. Reynolds, e.g. TiO$_2$ culminates in the basified hornfels, and TiO$_2$, MnO and P$_2$O$_5$ show a general decrease towards the adammellite. P$_2$O$_5$ culminates in the granodiorite. Further evidence that analysis G is abnormal is given by the culmination in it of MnO.

The succession of changes leading to granitization may be explained by the hypothesis of "fronts". The term "front" was used /
used by Wegmann (1935) to explain the basification of leptites and sedimentary rocks in the neighbourhood of migmatite complexes. According to Wegmann a front of magnesium and iron has been driven forward from the migmatized rocks.

In 1943 and 1944 D.L. Reynolds described replacement bodies of granodiorite rimmed by biotite-enriched hornfels zones and showed that the minimum introduction necessary for granitization of the original hornfels was Na Ca Si and that the material removed, rich in Al, Fe, Mg and Ca, corresponded to that required to give biotite-rich rims. In 1944 these observations were elaborated and it was demonstrated that both the large- and small-scale zones of biotite enrichment represent Fe-Mg "fronts", and that the granite replacement bodies and the main granodiorite of the complex represent the Na-Ca "fronts". It is especially for the recognition and investigation of the basic front that her work has been acclaimed. In 1947 D.L. Reynolds defined a front as occurring "whenever there is a diffusion limit marked by a change in the mineral assemblage". Two years later she explained that "within basic fronts certain elements, or combinations of elements tend to become concentrated in consequence of the dual control enforced by (a) the particular elements that are displaced from the rocks undergoing granitization, and (b) the mineral composition of the rocks into which the displaced elements migrate. In consequence /
consequence geochemical culminations occur". Geochemical culminations are therefore necessary and characteristic parts of fronts.

4. von Wolff diagram No. 2.

All the available analyses of the various rock types present at Loch Doon have been plotted on a von Wolff diagram, Fig. 71. The fields for the six following rock types are shown: (1) unaltered sediments; (2) aureole sediments; (3) fine-grained crystalloplastic marginal rocks; (4) hypersthenic rocks; (5) granodiorites; (6) adamelites.

The rocks are lettered as follows on the diagram:-

N. Unaltered greywacke
A. Average greywacke
O. Slightly feldspathized greywacke-granulite.
P. Feldspathized greywacke granulite.
B. Biotite-hornblende-plagioclase-hornfels.
C. Mobilized sediment.
Q. Pyroxenized pod.
M. Fine-grained opdalite.
L. Augitic marginal rock
K. Medium-grained opdalite
I. Coarse-grained opdalite
J. /
J. Pyroxene-biotite-quartz-diorite.
D. Contact-quartz-diorite.
E. Marginal granodiorite.
F. Granodiorite.
G. Granodiorite.
H. Adamellite.

It is clear from the diagram (Fig. 71) that, compared with the unaltered sediments, the aureole rocks have been desilicated. Further the biotite-hornblende-plagioclase-hornfels is so strongly desilicated and basified that it falls within the geochemical field of rocks that have been commonly regarded as igneous.

Another important feature is the close chemical relationship between the fine-grained crystalloclastic marginal rocks and the aureole sediments. In general the former are desilicated compared with the latter, but the two fields overlap when pods occur in the aureole.

The position of the granodiorite field shows that the granodioritic rocks occupy a position intermediate between the hypersthenic rocks and the adamellites.

The field representing hypersthenic rocks is naturally the most basic; it lies near the area of chemically undersaturated rocks within which the 'olivine-norite' of Gardiner and Reynolds (1932, p. 8) falls.
A point of great significance which arises out of this study is that while the main basic front is situated in the aureole hornfelses adjacent to the granodiorite, it lies within the pluton in the north-western corner and south where the aureole hornfelses are adjacent to the hypersthenic rock.

C. Mechanism of Migration

It is clear that the processes of transformation described have in all cases invoked the migration of chemical elements. The mechanism of migration of the "emanations" requires elaboration. Because of its non-genetic character the term "emanations" is used for the migrating material.

Solid diffusion is a well established process in metallurgy and the ceramic industry. One of the earliest to suspect its importance in petrology was Greenly (1903). Numerous other workers including Campbell, Reynolds and Holmes have given examples of its possible applications.

As a result of a detailed chemical investigation, Holmes in 1936 demonstrated that transfusion of quartz xenoliths in the potash-rich basic and ultrabasic lavas of south-west Uganda took place by solid diffusion. He further discovered (1945) that granite xenoliths in the potash-rich lavas of Bunyaruguru, south-west
west Uganda, were transformed to leucitite and probably to olivine-leucitite. Holmes showed that $K_2O$, cafemic oxides, $TiO_2$, $H_2O$ and $CO_2$ from the metasomatizing mafurite magma, were introduced and fixed differentially in the granite xenoliths; there was a compensating outward migration of $SiO_2$, $Na_2O$, and some $Al_2O_3$.

Reference to the work of D.L. Reynolds, Wegmann, Backlund and others has previously been made. Perrin and Roubalt (1939) have recently summarized the mechanisms and controls of solid diffusion, a process which they regard as of primary petrogenetic importance.

Two outstanding crystallographers have described the various ways in which ionic migrations take place; namely Jens Bugge (1946), and Kathleen Lonsdale (1947). From their work it appears that solid diffusion can take place in three different ways: (1) along the grain surfaces; (2) through spaces in the crystal lattice; (3) from one unoccupied lattice point to another.

1) Along the grain surfaces.

This is the easiest manner in which ions can migrate. The atoms at the surface of crystals are unsaturated compared with those of the interior and are more easily moved and disordered. This is the manner favoured by Wegmann as a result of his researches in Finland (1931) and Greenland (1935, 1938). In Wegmann's view the migrating material moves as molecules or atoms (Stoffwanderung) /
(Stoffwanderung) through the rock and reacts with the host. The migration proceeds by an "oil-spot" mechanism, no channels being visible. The movement is controlled by chemical, pressure, and temperature gradients. D.L. Reynolds cites an example in which the feldspathization of quartzite commonly proceeded around the margins of the grains (D.L. Reynolds, 1936, p. 383). Cheng also attributes great importance to boundary migration (1944, p. 145). Sarkar (1948, p. 241), writing of the Spango 'Granitic' Complex stated "Material had to migrate through the intergranular film as well as through the crystal lattices, in order to develop metamorphic minerals in the aureole sediments and in the sedimentary relics within the plutonic rocks".

Many of the reactions which give rise to the mantling of one mineral by another in the Loch Doon complex suggest that boundary migration of material has been an important process in the transport of the emanations in this pluton. A consideration which supports this view is the realization that the high shearing stress which must have existed during the growth and development of the pluton would distort the crystal lattices and so promote migration. As Read (1948) has pointed out, most crystals are made up of mosaics with intervening boundaries along which transportation could take place by diffusion through the solid phase without /
without any necessity for the presence of liquid to facilitate reactions. On the other hand, the transportation of matter over long distances would be greatly facilitated by the presence of a gas phase. It is possible that a gaseous or even a liquid phase may have been temporarily generated in the solid framework at Loch Doon.

(2) **Through spaces in the crystal lattice.**

Ions of appropriate size may pass through an open lattice. Eitel (1941, p. 115) for example has passed Li and Na ions through quartz plates parallel to the crystallographic axis. He found, however, that the passage of larger K ions was retarded.

(3) **From one unoccupied lattice point to another.**

Certain lattice points in crystals may not be occupied, and it is then possible for ions to migrate through the crystal by jumping from one lattice position to a neighbouring unoccupied one.

It is believed by some workers that diffusion through the lattices is too slow a process to have been important as a geological mechanism, and experimental evidence has been cited in support of this view. Jagitsch (1949, p. 498), for example, investigated the diffusion velocity of Na₂O in a number of aluminium /
aluminium-silicon compounds, such as metakaolin, sillimanite, albite and nephelite. His results showed that the diffusion is so low that the reaction layer would only attain a thickness of a few dozens of feet in the longest conceivable time of reaction \(10^8 \text{ years}\) and he therefore concluded that "diffusion solely in solid phases cannot play any important part in the transport of matter over long distances". But the work of Glangeaud (1950, p. 62), which is also based on experimental data shows that the speed of diffusion increases when the crystals pass into an oligophasic and dynamomorphous state. Another important point was brought out by D.L. Reynolds in her paper on the "Granite Controversy" in 1947. She stated that "If processes of ionic diffusion are operative in the genesis of granite from pre-existing rocks, it should obviously be possible to find examples of quartz which contain small amounts of Al. Small quantities of impurities can only be detected by spectrographic analysis, and it is of the utmost importance to find that in nineteen spectrographic analyses (Bray, 1942) of quartz from Pre-Cambrian granites and pegmatites, Al was found to be present in every case".

The existence of diffusion in the solid is therefore recognized by all petrologists but the potency of the process as a geological mechanism requires further research and at the present day is a subject of controversy.
The emplacement of the pluton took place in post-Silurian times, after the Caledonian orogenesis. The pluton is therefore apotectonic; a fact brought out by the form of the complex. The longest axis of the pluton is oblique to the Caledonian strike of the sediments.

The emplacement of the pluton is envisaged as follows:

(1) Emanations commence to rise along a north-south line. The course of these emanations is independent of the structure of the Palaeozoic sediments. Therefore the initial supply probably ascended from greater depths than the base of the folded sediment.

(2) The initial emanations consist of Si, K and Na, and on being introduced into the sediments they initiate a chain of reactions. Some of the migrating material is fixed; the remainder continues to advance and is joined by Al, Fe, Mg and Ca driven from the granitized rocks.

(3) The displaced Al, and cafemics eventually form a basic front which is fixed preferentially in the country rocks and in the relatively stable areas of the pluton itself in the north-west and southern corners of the pluton. The advance of the successive fronts is thought to have been partly governed by the then existing physical and chemical gradients. The advance of a front is considered /
considered to be sporadic rather than uniform, taking place in a series of pulses. The material for each front is contributed in part from the front below.

(4) After passing through a series of changes which are illustrated by the contact-zone rock types, the pre-existing sediments are transformed into granodiorite; they suffer a concomitant increase of volume and commence to swell progressively. As a result the country rocks are displaced outwards. By a process of ultrametamorphism, involving an advance front of granitization, a thin film of mobilized sediment is formed ahead of the more maturely transformed sediment. The swelling involves the generation of pressure acting from the interior of the pluton. Under pressure a system of shear planes is formed in the rock undergoing transformation. The shear planes are planes of relative movement along which the migrating emanations can travel with relative ease. At first the shear planes intersect at a high angle but as the pressure and the temperature increase, and the emanations promote chemical interchanges and reactions, mobility increases and the angle between the shear planes is reduced. The shear planes are thus syngenetic and are concentric on the centre of the pluton.

(5) /
(5) To the north-west and south of the source of pressure the rock acts as a rigid body (for some lithological or structural reason not yet elucidated) and develops two shear planes which intersect at a high angle. These two relatively rigid corners of the pluton act as a unit with the country rocks and it is into these two undisturbed areas that much of the cafemical material displaced by granitization of the country rock to form granodiorite is driven.

(6) The granodiorite is transformed into adamellite at a later stage by further addition of Si, K and Na emanations which enrich the rock in potash feldspar and quartz. This late-stage enrichment results in the formation of a rock type transitional between the granodiorite and the central adamellite. The high angle between the two shear planes in the adamellites implies a high rigidity, and their inconspicuous character indicates that in the final stages this zone crystallized without any appreciable movement.

(7) The transformed rocks at the end of the major process of granitization begin to cool and fracture to form a complex joint system. Along the channels provided by many of these joints rheomorphic magma, generated in depth, is squeezed out to form dykes.
dykes. Also along the major lines of weakness residual silica and alkali-rich material continues to migrate, to give rise to late quartz and aplite veins.
XXI. ACKNOWLEDGMENTS

The work embodied in this thesis was commenced at the University of Nottingham under the supervision of Professor C.E. Marshall and I should like to express my thanks to him for his interest and useful criticism.

The major part of the work, however, has been done in the University of Edinburgh under the supervision of Professor Arthur Holmes and Dr. D.B. McIntyre and for their guidance, constructive criticism and correction of the typescript I am deeply appreciative.

I am indebted to Professor Holmes and Dr. Doris L. Reynolds for firing my enthusiasm in the problem of granitization in my student days and since then for supplying a constant inspiration.

I would like to pay special tribute to Dr. D.B. McIntyre for his many hours of instructive discussion both in the field and in the laboratory and for his invaluable assistance throughout the whole of the work.

Grateful acknowledgment is due to my wife for encouragement and generous assistance; to Dr. G. Oertel for his useful criticism and discussion of structural problems; to the University of Bristol for the loan of the late Professor S.H. Reynolds' research material.
This study was undertaken and largely accomplished with the aid of a research grant from the University of Nottingham and a grant from the Royal Society of London to defray the cost of four of the chemical analyses. For this financial assistance I wish to thank the respective bodies.

Finally, to all technicians and friends, too numerous to mention, who have helped me in any way I record my sincere thanks.

Royal Charles


BAILEY, E.B., 1922. The Structure of the South-west Highlands of Scotland. Q.J.G.S., lxxviii, pp. 82-131.


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EXPLANATION of SHEET 9, 1877. Geology of Kirkcudbright (Northeast part) and Dumfriesshire (South-west part). Mem. Geol. Surv. Scotland.


MOULD /


1936 /


1926 /


SPENCER, E., 1938. The potash-soda feldspars. II. Some applications to petrogenesis. Min. Mag., xxv, pp. 87-118.


TABLE I.

Average greywacke (A), obtained by Pettijohn taking the average of greywackes of all ages. (Pettijohn, 1948, p. 250).

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<th>Mol. Prop. x 1000</th>
<th>Mol.%</th>
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Total FeO 5.1

Mol. 1527.1 100.00
TABLE I (2)

B. Biotite-hornblende-plagioclase-hornfels (No. 414)  
55 yds. from the marginal granodiorite at a height of approximately 800 ft., on the south slope of Buchan Hill. Described on p. 47  
See Fig. 3. New analysis.
Analyst: W. H. Herdsman.

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VON WOLFF VALUES

L = 59.2
M = 32.2
Q = +8.6
### TABLE I (Contd.) - (3)

**C. Mobilised sediment (No. 214) from the centre of the mobilised zone and about 18 ft. from contact-quartz-diorite, at a height of approximately 800 ft., on the south slope of Buchan Hill.**

Described on p. 66. See Fig. 3. New analysis. Analyst: W.H. Herdsman.

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<td>Total FeO</td>
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<td></td>
<td>L = 57.1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>M = 26.8</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Q = 16.1</td>
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</tbody>
</table>
TABLE I (Contd.) - (4)

D. Transformed feldspathised sediment or contact-quartz-diorite (No. 404), transitional to marginal granodiorite, at a height of approximately 800 ft., on the south slope of Buchan Hill. Described on p. 75. See Fig. 3. New analysis.

Analyst: W.H. Herdsman.

<table>
<thead>
<tr>
<th></th>
<th>Mol. Prop.</th>
<th>Mol.%</th>
<th>NORM</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Wt.% x 1000</td>
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<td>SiO₂</td>
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<td>Al₂O₃</td>
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<td>10.6</td>
</tr>
<tr>
<td>Fe₂O₃</td>
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<td>3.1</td>
<td>0.2</td>
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<tr>
<td>FeO</td>
<td>5.28</td>
<td>73.5</td>
<td>4.8</td>
</tr>
<tr>
<td>MgO</td>
<td>5.48</td>
<td>135.9</td>
<td>8.85</td>
</tr>
<tr>
<td>CaO</td>
<td>5.14</td>
<td>91.7</td>
<td>6.0</td>
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<td>48.1</td>
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<td>K₂O</td>
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<td>H₂O+</td>
<td>1.36</td>
<td>75.5</td>
<td>-</td>
</tr>
<tr>
<td>H₂O-</td>
<td>0.29</td>
<td>16.1</td>
<td>-</td>
</tr>
<tr>
<td>TiO₂</td>
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<td>0.7</td>
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<tr>
<td>P₂O₅</td>
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<td>1.0</td>
<td>0.05</td>
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<tr>
<td>MnO</td>
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<td>1.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Total FeO</td>
<td>5.72</td>
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</table>

VON WOLFF VALUES

L = 62.0
M = 28.10
Q = 9.15
TABLE I (Contd.) - (5)

E. Marginal hornblende-biotite-granodiorite (No. (401), about 15 yds. from the contact-quartz-
diorite, at a height of approximately 800 ft.
on the south slope of Buchan Hill. Described
on p. 118. See Fig. 3. New analysis.
Analyst: W.H. Herdsman.

<table>
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<th>Mol.%</th>
<th>NORM</th>
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<td>Al₂O₃</td>
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<td>161.3</td>
<td>10.63</td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃</td>
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<td>2.9</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>4.16</td>
<td>57.9</td>
<td>3.32</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>4.23</td>
<td>104.9</td>
<td>6.91</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>4.05</td>
<td>72.4</td>
<td>4.77</td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.18</td>
<td>51.3</td>
<td>3.38</td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>2.72</td>
<td>28.9</td>
<td>1.90</td>
<td></td>
</tr>
<tr>
<td>H₂O+</td>
<td>1.18</td>
<td>65.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>H₂O⁻</td>
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<td>40.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
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<td>9.3</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.13</td>
<td>0.9</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.14</td>
<td>2.0</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>99.79</td>
<td>1623.8</td>
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<tr>
<td>FeO</td>
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<td></td>
<td>4.57</td>
<td>100.00</td>
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</table>

99.79  1623.8  100.00

VON WOLFF
VALUES

L = 61.90
M = 21.72
Q = 16.38
TABLE I (Contd.) - (6)

F. Hornblende-biotite-granodiorite (No. 278), from the South-east corner of Glenhead Wood.
Described on p. 122. See Fig. 4. New analysis.
Analyst: W.H. Herdsman.

<table>
<thead>
<tr>
<th></th>
<th>Wt.%</th>
<th>Mol. prop.</th>
<th>Mol.%</th>
<th>NORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
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<td>1061.6</td>
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<tr>
<td>Al₂O₃</td>
<td>15.18</td>
<td>148.9</td>
<td>9.66</td>
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<td>Fe₂O₃</td>
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</tr>
<tr>
<td>FeO</td>
<td>3.65</td>
<td>50.8</td>
<td>3.30</td>
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</tr>
<tr>
<td>MgO</td>
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<td>97.5</td>
<td>6.33</td>
<td></td>
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<tr>
<td>CaO</td>
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<td>77.0</td>
<td>4.99</td>
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<tr>
<td>Na₂O</td>
<td>3.17</td>
<td>51.1</td>
<td>3.32</td>
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<tr>
<td>K₂O</td>
<td>3.48</td>
<td>36.9</td>
<td>2.39</td>
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<tr>
<td>H₂O⁺</td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O⁻</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.80</td>
<td>10.0</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
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<td>0.08</td>
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</tr>
<tr>
<td>MnO</td>
<td>0.14</td>
<td>2.0</td>
<td>0.13</td>
<td></td>
</tr>
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\[ \text{Total} \quad \text{FeO} \quad 4.26 \]

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100.10</td>
<td>1541.4</td>
<td>100.00</td>
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</table>

VON WOLFF
VALUES

\[ L = 61.44 \]
\[ M = 21.62 \]
\[ Q = 16.86 \]
### TABLE I (Contd.) - (7)

L. Augitic marginal rock (No. 205), 2 ft. from marginal granodiorite in the south-western corner of Glenhead Wood. Described on p. 224
See Fig. 4. New analysis.
Analyst: W.H. Herdsman.

<table>
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<th>Component</th>
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<th>Mol. %</th>
<th>NORM</th>
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<tr>
<td>Al₂O₃</td>
<td>16.30</td>
<td>159.9</td>
<td>10.36</td>
<td>Or</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.26</td>
<td>1.6</td>
<td>0.10</td>
<td>Ab</td>
</tr>
<tr>
<td>FeO</td>
<td>6.22</td>
<td>86.6</td>
<td>5.61</td>
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<td>(CaSiO₃ 1.52</td>
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<tr>
<td>CaO</td>
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<td>108.4</td>
<td>7.03</td>
<td>(MgSiO₃ 0.83</td>
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<tr>
<td>Na₂O</td>
<td>3.14</td>
<td>50.7</td>
<td>3.29</td>
<td>(FeSiO₃ 0.63</td>
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<tr>
<td>K₂O</td>
<td>1.66</td>
<td>17.6</td>
<td>1.14</td>
<td>Hyp</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.09</td>
<td>-</td>
<td>-</td>
<td>Mt</td>
</tr>
<tr>
<td>H₂O⁻</td>
<td>Nil</td>
<td>-</td>
<td>-</td>
<td>Il</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.82</td>
<td>10.3</td>
<td>0.67</td>
<td>Ap</td>
</tr>
<tr>
<td>P₂O₅</td>
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<td>0.07</td>
<td>H₂O</td>
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<tr>
<td>MnO</td>
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<td>0.15</td>
<td></td>
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<tr>
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<tr>
<td>FeO</td>
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VON WOLFF VALUES

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<th>Value</th>
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<td>M</td>
<td>29.86</td>
</tr>
<tr>
<td>Q</td>
<td>11.10</td>
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</table>
LIST of ANALYSES given in TABLE II

A. **Average greywacke**, obtained by Pettijohn by taking the average of greywackes of all ages (Pettijohn, 1948, p. 250).

B. **Biotite-hornblende-plagioclase-hornfels** (No. 414), 55 yds. from the marginal granodiorite at a height of approximately 800 ft., on the south slope of Buchan Hill. Described on p. 47. See Fig. 3. New analysis. Analyst: W.H. Herdsman.

C. **Mobilized sediment** (No. 214) from the centre of the mobilized zone and about 18 ft. from the contact-quartz-diorite, at a height of approximately 800 ft., on the south slope of Buchan Hill. Described on p. 66. See Fig. 3. New analysis. Analyst: W.H. Herdsman.

D. **Transformed feldspathised sediment or contact-quartz-diorite** (No. 404), transitional to marginal granodiorite at a height of approximately 800 ft., on the south slope of Buchan Hill. Described on p. 75. See Fig. 3. New analysis. Analyst: W.H. Herdsman.

E. **Marginal hornblende-biotite-granodiorite** (No. 401), about 15 yds. from the contact-quartz-diorite at a height of approximately 800 ft., on south slope of Buchan Hill. Described on p. 118. See Fig. 3. New analysis. Analyst: W.H. Herdsman.

F. **Hornblende-biotite-granodiorite** (No. 278) from the southeast corner of Glenhead Wood. Described on p. 122. See Fig. 4. New analysis. Analyst: W.H. Herdsman.

G. **'Tonalite' or granodiorite** (GR. No. 749) from Fore Starr, 2 miles south-south-west of Loch Doon (Gardiner and Reynolds, 1932, p. 9). Analyst: E.G. Radley.

H. **'Granite' or biotite-adamellite** (GR. No. 755) from the central ridge between Hoodens Hill and Mullwharchar (Gardiner and Reynolds, 1932, p. 10). Analyst: E.G. Radley.
<table>
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<th>Specimen Nos.</th>
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<th>F</th>
<th>G</th>
<th>H</th>
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</thead>
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<td>63.76</td>
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<td>70.63</td>
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<td>0.46</td>
<td>0.68</td>
<td>1.00</td>
<td>0.54</td>
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<td>3.93</td>
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<td>5.68</td>
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<td>3.55</td>
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<td>2.56</td>
<td>2.72</td>
<td>3.43</td>
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<tr>
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<td>1.20</td>
<td>1.16</td>
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<td>1.18</td>
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<td>0.69</td>
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<tr>
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<td>0.73</td>
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<td>0.22</td>
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<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
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<tr>
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<td>0.80</td>
<td>0.73</td>
<td>0.41</td>
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<tr>
<td>P₂O₅</td>
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<td>0.13</td>
<td>0.19</td>
<td>0.01</td>
<td>0.07</td>
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<tr>
<td>MnO</td>
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<td>0.15</td>
<td>0.14</td>
<td>0.12</td>
<td>0.14</td>
<td>0.14</td>
<td>0.19</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td>99.81</td>
<td>100.26</td>
<td>99.94</td>
<td>99.79</td>
<td>100.10</td>
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<td>100.21</td>
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<td>5.72</td>
<td>4.57</td>
<td>4.26</td>
<td>4.77</td>
<td>2.42</td>
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**TABLE of VON WOLFF VALUES**

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<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
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<td>L</td>
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<td>57.1</td>
<td>62.1</td>
<td>61.90</td>
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<td>M</td>
<td>17.70</td>
<td>32.2</td>
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<td>28.1</td>
<td>21.72</td>
<td>21.52</td>
<td>23.43</td>
<td>8.20</td>
</tr>
</tbody>
</table>
LIST of ANALYSES given in TABLE III


K. Medium-grained hypersthenic rock (Gardiner and Reynolds 'norite' No. 532) from just south-west of Loch Girvan Eye, north-west corner of the complex (Gardiner and Reynolds, 1932, p. 9). Analyst: E.G. Radley.

L. Augitic marginal rock (No. 205), 2 ft. from marginal granodiorite in the south-western corner of Glenhead Wood. Described on p. 224. See Fig. 4. New analysis. Analyst: W.H. Herdsman.


E. Marginal granodiorite (No. 401) about 15 yds. from the contact-quartz-diorite on the south slope of Buchan Hill at a height of 800 ft. Described on p. 118. See Fig. 3. New analysis. Analyst: W.H. Herdsman.

G. Granodiorite (Gardiner and Reynolds 'tonalite' No. 749), from Fore Starr, 2 miles south-south-west of Loch Doon. (Gardiner and Reynolds, 1932, p. 9). Analyst: E.G. Radley.

F. Granodiorite (No. 278) from the south-east corner of Glenhead Wood. Described on p. 122. See Fig. 4. New analysis. Analyst: W.H. Herdsman.

H. Biotite-adamellite (Gardiner and Reynolds 'granite' No. 755) from between Hoodens Hill and Mullwharchar (Gardiner and Reynolds, 1932, p. 9). Analyst: E.G. Radley.
<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>E</th>
<th>G</th>
<th>F</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>55.34</td>
<td>65.78</td>
<td>56.90</td>
<td>58.82</td>
<td>60.06</td>
<td>61.62</td>
<td>62.95</td>
<td>63.76</td>
<td>70.63</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.97</td>
<td>0.53</td>
<td>0.98</td>
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SOUTH SLOPE of BUCHAN HILL

LEGEND

- Highly metamorphosed shaly greywacke
- Mobilized sediment
- Feldspathized hornfels
- Contact-quartz-diorite
- Marginal granodiorite
- Normal granodiorite

Contours: 900

Scale: 72 inches = 1 mile

Map Fig. 3.
LEGEND

Rock Types

Granodiorite

Augitic Marginal Rock

Country Rock

Contours

Walls

Boundary of Wood

Margin of Complex.

Scale: 36" = 1 mile.
Fig. 5. Sketch of mobilized sediment on the Rig of Loch Enoch.

Fig. 6. Sketch of flow-structures in the mobilized sediment, south slope of Buchan Hill.
Fig. 7. Sketch of rheomorphic vein in White Laggan Burn.

Fig. 8. Sketch of sectioned rheomorphic vein (No. 580).
Fig. 9. To show the relationship of Hornblendite to amphibolized-pyroxene-biotite-quartz-diorite. Although all contacts are shown here as sharp some are diffuse. Locality: The Trostan. Scale: 1" = 1'.

Fig. 10. To illustrate a stage in the development of pods of leucocratic material in fine-grained hornblendebiotite-hornfels. (Natural size).
Fig. 11.

View of Loch Trool from the south slope of Buchan Hill. The glaciated Trool valley cuts the aureole in the middle distance and opens out into the unaltered country rocks which form the plain in the background.

Fig. 12.

View looking south-south-east from Craig Neldricken. In the middle distance part of Loch Valley can be seen, its southern shore margined by the Rig of the Jarkness. The southern part of the metamorphic aureole forms the high ground in the distance. The hills are Lamachan Hill and Curleywee. Note the two fine corries facing north.
**Fig. 13.**

View of Loch Dee from White Hill. Hypers-thenic rock forms the crags in the right fore ground whilst the high hills (Little and Meikle Millyea) in the back ground lie in the eastern part of the metamorphic aureole.

**Fig. 14.**

Another view of Loch Dee showing the shoulder of Craiglee (granodiorite) on the left and the large tract of bog through which Cooran Lane flows between Craiglee and the higher ground of the Kells Range in the back ground.
Fig. 15.

View of Loch Enach from Craig Meldricken. The numerous exposures of granodiorite and transitional rock are typical of the higher ground.

Fig. 16.

A vertical exposure of mobilized sediment at approximately 800ft. on the south slope of Buchan Hill. Note the "veining" of the hornfels by leucocratic material. (p. 62).
Fig. 17.
Mobilized sediment. A loose block on the northern slope of Mulldonoch.

Fig. 18.
Mobilized sediment from the south slope of Buchan Hill. (p. 62).
Fig. 19.
Metamorphosed greywacke of medium grade (No. 473). The oval-shaped cordierite porphyroblasts are crowded with very small anhedral inclusions. (p. 46). (x 18).

Fig. 20.
Metamorphosed calcareous greywacke (No. 412). Abundant hornblende has developed with little or no biotite. The groundmass consists of granular crystals of quartz and plagioclase. (x 18).
Fig. 21.

Highly metamorphosed coarse-grained greywacke (No. 461), 70yds. from the margin of the complex on the northern summit of Buchan Hill. (p. 50). (x 18).

Fig. 22.

The same field as Fig. 21 under crossed nicols. The plagioclase porphyroblasts show continuous and oscillatory zoning. (x 18).
Fig. 23.

Highly metamorphosed calcareous shaly-greywacke (No. 414), 55yds. from the margin of the complex on the south slope of Buchan Hill. The biotite and hornblende crystals have a sub-parallel arrangement. (p.47). (x 18).

Fig. 24.

The same field as Fig. 23 under crossed nicols. Note the plagioclase and quartz granoblastic groundmass. (p.47). (x 18).
Fig. 23.

Fig. 24.
Metamorphosed black shale from Buchan Hill. Abundant small subhedral crystals of tourmaline (schorlite) are conspicuous by their high relief: they are most abundant towards the lower part of the field. (p. 34). (x 18).

Andalusite-cordierite-hornfels (No. 426). Large euhedral porphyroblasts of andalusite margined by graphite and a little iron ore. (p. 31). (x 18).
Fig. 27.

(?)Anthophyllite-cordierite-hornfels (No. 484). The acicular porphyroblasts are (?)anthophyllite and the opaque matter is mainly graphite with some iron-ores. (p. 33). (x 18).

Fig. 28.

(?)Anthophyllite-cordierite-hornfels (No. 484). Transverse sections of (?)anthophyllite crystals rimmed with muscovite and sericite are seen in the lower right hand quadrant. (p. 33).
Fig. 29.

Chert and black shale folded together (riebungsbreccia) from Buchan Hill. (p. 36). (x 18).

Fig. 30

The same field as Fig. 29 under crossed nicols. (p. 36). (x 18).
Fig. 31.

Garnet-biotite-hornfels (No. 468). Two large subhedral crystals of garnet with inclusions of biotite, quartz and iron ores. Note that the biotite flakes penetrate the garnet crystals. (p. 36). (x 18).
Fig. 32.

Feldspar-garnet-biotite-hornfels (No. 485) within 2-3 inches of the contact southwest of Loch Enoch. Biotite is very abundant and is shown embaying and penetrating numerous euhedral crystals of garnet. (p. 87). (x 18).
Fig. 33.

Contact-quartz-diorite (No. 404), from the gradational series on the south slope of Buchan Hill. A general view showing the abundance of the ferromagnesians. A large twinned crystal of hornblende with a pyroxenic core occupies the lower centre of the field. (p. 75). (x 18).

Fig. 34.

The same field as Fig. 33 under crossed nicols.
Fig. 33.

Fig. 34.
Fig. 35.

Large composite plagioclase porphyroblast in marginal granodiorite (No. 203), from the south slope of Buchan Hill. Note the internal irregularities and the large number of granular and flaky inclusions. (x 18, crossed nicols).
Fig. 35.
Fig. 36.

Biotite–granodiorite (No. 490), from the Rig of Loch Enoch. A biotite flake (dark) with inclusions and pleochroic haloes: quartz and feldspar appear white and grey respectively. (x 18).

Fig. 37.

The same field as Fig. 36 under crossed nicols. A large twinned plagioclase crystal is seen in the top left hand quadrant. Anhedral quartz appears white. (x 18).
Fig. 38.

Basified hornfels inclusion (No. 204), from Glenhead Wood. Note the abundance of biotite and the decussate structure. (x 25).

Fig. 39.

The same field as Fig. 38 under crossed nicols. The groundmass consists of quartz and plagioclase. (x 25).
Fig. 40.

Porphyroblast of orthoclase in biotite-adamellite (No. 649). (x 18).

Fig. 41.

The same field as Fig. 40 under crossed nicols. Note the inclusions of plagioclase in the large twinned (carlsbad) orthoclase porphyroblast. (x 18).
**Fig. 42.**

Fine-grained marginal hypersthenic rock (No. 311), from White Laggan Burn. A general view of crystalloblastic biotite flakes (black); prismatic hypershene crystals (dark grey) and plagioclase (light grey). (x 18).

**Fig. 43.**

The same field as Fig. 42 under crossed nicols. (x 18).
Fig. 44.

Medium-grained hypersthene rock (No. 328), from White Hill, Loch Dee. An aggregate of pyroxene (mostly hypersthene) crystals in an augite-hypersthene-biotite-granodiorite. (x 18).

Fig. 45.

The same field as Fig. 44 under crossed nicols. (x 18).
Fig. 46.

Medium-grained hypersthene rock (No. 328) from White Hill, Loch Dee. A general view to illustrate the textural relationships of the minerals. Biotite(almost black) is shown mantling pyroxene.(x18).
(p. 203).

Fig. 47.

The same field as Fig. 46 under crossed nicols. Feldspar and quartz form the groundmass (x18).
Coarse-grained hypersthene rock (No. 298), from White Hill, Loch Dee. Pyroxene is shown mantled by hornblende in the top of the field and in the lower part biotite is enclosing iron ores, pyroxene and hornblende. (x 18).

The same field as Fig. 48 under crossed nicols. (x 18).
Augitic marginal rock (No. 202), from Glenhead Wood. Note the large zoned plagioclase porphyroblast set in a fine-grained mosaic of quartz, biotite, plagioclase and a little potash feldspar. The porphyroblast has a highly irregular boundary with the groundmass mosaic. (p. 220) (x 25).
Fig. 51.

Augitic marginal rock (No. 282), from Glenhead Wood. Note the aggregate or clot of small pyroxene granules and crystals. (p. 222). (x 25).

Fig. 52

The same field as Fig. 51 under crossed nicols. Part of a large plagioclase porphyroblast is shown in the top left hand corner. (x 25).
Fig. 53.

Augitic marginal rock (No. 205), from Glenhead Wood. The dark grey crystals are pyroxene and brown hornblende. (p. 224). (x 25).

Fig. 54.

The same field as Fig. 53 under crossed nicols. Note that the groundmass of quartz and plagioclase is coarser than that of No. 202. (x 25).
Fig. 55.
Ferromagnesian aggregate in rock transitional from augitic marginal rock to normal granodiorite (No. 431), from the northern summit of Buchan Hill. The clot consists of amphibilized pyroxene, biotite and iron ores. (p. 236). (x 18).

Fig. 56.
The same field as Fig. 55 under crossed nicols. (x 18).
Fig. 55.

Fig. 56.
Fig. 57.
Mobilized sediment (No. 216), from the mobilized zone on the south slope of Buchan Hill. (p. 68). (natural size).

Fig. 58.
Mobilized sediment (No. 215), from the south slope of Buchan Hill. (natural size).
Fig. 59.
Feldspathized sediment or contact-quartz-diorite (No. 405), from the south slope of Buchan Hill. Large grey plagioclase porphyroblasts are outstanding. Note the metamorphic textural appearance. (p. 72). (natural size).

Fig. 60.
Contact-quartz-diorite (No. 404), from the south slope of Buchan Hill. The rock is more "igneous-looking" than No. 405 and has abundant plagioclase porphyroblasts (p. 75). (natural size).
Fig. 59.

Fig. 60.
Fig. 61.
Marginal hornblende-biotite-granodiorite (No. 403), collected byds. from No. 404. The rock is more igneous in textural appearance than No. 404. (p. 78). (natural size).

Fig. 62.
Marginal hornblende-biotite-granodiorite (No. 402), collected byds. from No. 403. The mafics show a strong tendency to occur in clots. (natural size).
Fig. 63.
Marginal granodiorite (No. 401), collected byds. from No. 402 on the south slope of Buchan Hill. Note the parallelism of the mafics and the inclusion elongated parallel to the banding. (p. 118). (natural size).

Fig. 64.
Normal granodiorite (No. 528), from the south-western shore of Loch Neldricken. (natural size).
Fig. 65.

'Veined' augitic marginal rock (No. 253), from the contact zone one third of a mile south-west of the Corse Knowe of White Laggan. (p. 228). (natural size).

Fig. 66.

Biotite-adamellite (No. 666), from near the summit of Craignaw. Note the large porphyroblasts of potash feldspar (which appear as white) and the small amount of biotite (black). (natural size).
VON WOLFF

DIAGRAM NO. 1.
Fig. 68.

VARIATION DIAGRAM NO. 1.

Variation diagram showing the variation of various components such as CaO, Na2O, K2O, MgO, and Al2O3 over different intervals of rock types such as biotite-hornblende-plagioclase-hornfels, South-east quartz-diorite, marginal granodiorite, and granodiorite. The diagram illustrates the relative abundance and distribution of these components across different rock types.
Fig. 69.

VARIATION DIAGRAM NO. 2.

Average Greywacke A.

Biotite-hornblende-plagioclase-hornfels B.

Mobilized sediment C.

Contact-quartz-diorite D.

Marginal granodiorite E.

Granodiorite F.

Biotite-adamellite H.

Composition: Al₂O₃ - 5

SiO₂ - 58

CaO

Na₂O

K₂O

CaO

Na₂O

K₂O

H.R.
Fig. 71.

VON WOLFF

DIAGRAM NO. 2

UNALTERED SEDIMENTS

ADAMELLITES

AUREOLE SEDIMENTS

GRANODIORITES

FINE GRAINED CRYSTALLOBLASTIC MARGINAL ROCKS

HYPERSTHENIC ROCKS AND QUARTZ DIORITE
FIG. 72. TO SHOW CHEMICAL CHANGES IN THE SERIES GREYWACKE—ADAMELLITE. GEOCHEMICAL CULMINATIONS ARE INDICATED BY RED LINES.
Fig. 73. Schematic representation of the geochemical exchanges and migrations in the Loch Doon complex.

Hornfels.  
\[ \text{Al Fe Mg Ca} \quad (\text{K Na Si}) \]
Basification

Mobilized sediment.  
\[ \text{Al K Si} \quad \text{(Fe Mg Na Ca)} \]

Contact-quartz-diorite.  
\[ \text{Mg K Na} \quad (\text{Al Fe Ca Si}) \]
Feldspathization with minor basification.

Marginal granodiorite.  
\[ \text{Si K Na} \quad (\text{Al Fe Mg Ca}) \]

Granodiorite.  
\[ \text{Si K Ca} \quad (\text{Al Fe Mg Na}) \] Granitization.

Adamellite.  
\[ \text{Si K Na} \quad (\text{Al Fe Mg Ca}) \]

\[ \text{Si K Na} \quad \text{Source of emanations} \]

Legend.

\[ \text{Material introduced and fixed.} \]

\( () \)

\[ \text{Material expelled.} \]

\[ \text{Material not expelled but migrating forward.} \]
STRUCTURE MAP
OF THE SOUTHERN HALF
OF THE
LOCH DOON COMPLEX

EXPLANATION OF SIGNS:
- BLACK SHALES GROUP
- GREYWACKE ORT SERIES
- PLUTONIC ROCKS
- STRIKE OF SHEAR PLANES IN THE COMPLEX
  - SHEAR PLANES ABSENT
  - STRIKE OF VERTICAL BEDS IN SEDIMENTS
  - GENERALISED STRIKE OF SEDIMENTS
  - PETROGRAPHIC BOUNDARIES

SCALE
0 1/4 1/2 1ML

Fig. 74.