THE NORTH-WEST PART OF THE LOCH DOON PLUTONIC COMPLEX: a Study in Petrogenesis.

By

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"What mean these stones?"
Scripture.

"I have seen a medecine
That's able to breathe life into a stone,
Quicken a rock".
All's Well that Ends Well.

"Here's a change indeed!"
Othello.

"The blest infusions
That dwell in vegetives, in metals, stones".
Pericles.

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I. INTRODUCTION

The Loch Doon complex is one of the larger of the Galloway "Granites". It is situated in the northern belt of the Southern Uplands of Scotland, in the counties of Ayr and Kirkcudbright. Here the country rocks consist of highly folded strata of Ordovician age, which in the Loch Doon area are mainly greywackes with some shales. Over an area of nearly fifty square miles between Loch Doon and Loch Dee the place of the sediments is taken by granitic and allied rocks including types that have been described as granite, tonalite, and norite.

The main object of the present investigation was to determine whether the granitic rocks represent (a) consolidation products of a magma which rose in a liquid state from depth with the simultaneous mechanical displacement of the original sediment or (b) transformation products of pre-existing sediments reconstructed in situ by chemical interchange with migrating materials The first is the Magmatic Hypothesis; the second is the Solid Diffusion* Hypothesis.

The problem may be put thus: Is the boundary between the altered aureole sediments and the granitic rocks at any particular locality an igneous, transgressive junction, or a diffusion limit? Are the inclusions within the complex stoped-blocks /

blocks from the aureole, or do they represent relics of the transformed material at a stage of alteration different from that of their surroundings?

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As used in this thesis, the term solid diffusion is not restricted to such simple two-way diffusion as takes place at a lead-gold interface, but includes the complex sequence of chemical interchanges, and chain-reactions, which are initiated by (one-way) migration through the solid rocks, of small quantitie of material (presumably ionic), whether through the crystal lattices, or by way of the intergranular surfaces. If the reactions were exothermic, such a process might well generate magma.

II /

II. PREVIOUS WORK

(i) In 1866 James Geikie contributed a paper "On the Metamorphic Origin of Certain Granitoid Rocks and Granites in the Southern Uplands of Scotland" to the Geological Magazine (1866, p. 529). Referring to the Loch Doon mass as "a very characteristic granite of the district under review", he observed, "Where the hard slaty shales impinge upon the granite we have no difficulty in laying our finger upon the line that separates the one rock from the other; but at the point where the granite and the felspathic greywackes come together, the union of the two rocks is so intimate that we have usually no line of demarcation, but, on the contrary, a gradual passage". He stressed that "We must beware of assuming an igneous character merely from the appearance of veins ramifying from crystalline into granular non-igneous beds. This may in general be an excellent test of eruptive origin, but it certainly cannot always prove that the main mass, from which the veins appear to have come, has been forcibly thrust into its present position".

Geikie considered that the inclusions characteristic of the Ayrshire granites "either represent such little detached portions of shales as are of common occurrence in the Lower Silurian greywackes, or they may be the remnants of thin bands or beds /

beds of shale that interleaved the original strata". They are thus interpreted as relics of undigested material, the greywacke in which they were contained having been altered to granite. He dismissed the hypothesis that the inclusions represent stoped-blocks from the aureole because, as he believed, though erroneously, they are scattered indiscriminately throughout the mass, and are not more abundant near the margin.

Although giving his opinion that the dioritic rocks "perhaps evince a less intensity of metamorphic action" than do the true granites, Geikie repeatedly asserts that differences in metamorphic rocks reflect differences in the composition of the original sediments; "the ultimate character of a metamorphic rock must always depend upon the composition of the stratum acted upon". The possibility of change of composition during metamorphism was not considered.

"It is obvious", wrote Geikie, "that many of the so-called eruptive granites must be re-examined, their igneous character having been assumed at a time when as yet the study of metamorphism had made little progress." Having considered the available evidence bearing on the genesis of the granites of the Southern Uplands, he sums up thus: "I am therefore forced to conclude that the crystalline rocks described above have resulted from the alteration in situ of certain bedded deposits".

This /

This paper by Geikie stimulated David Forbes to initiate a vigorous correspondence in the Magazine. The only point of importance in Forbes' criticism is the chemical difficulty: "How, may it fairly be asked, can any educated man, whether geologist or not, be expected to believe that greywacke may be converted into granite; unless, first of all, he is shown by chemical analysis that you have present in the first, the chemical elements requisite for the formation of the latter, or if not, that you have a rational mode of explaining how any deficiency in component parts has been supplied, or any surplus removed". (1867, p. 54).

Forbes engaged in similar controversy with A.H. Green in 1871 over the granitic rocks of Donegal (1871 (1), p. 428; 1871 (2), p. 450).

The chemical difficulty was first faced boldly by J. Clifton Ward when he dealt with the granites of the Lake District (1876, p. 30). He wrote: "Although a simple melting down of clay-slate might never produce granite, yet a moist fusion, accompanied by elementary substances, brought upwards from still greater depths, might effect a great transformation. .... Hence a rock of the composition of slate may be converted into granite by undergoing a change in the arrangement of the elements pre-existing in it, together with the addition from below of some /

some of those elements which were lacking in the original slate".

At this time Ward was alone in realising that some sort of diffusion accompanied by chemical interchange was necessary to reconcile theory with observation. His suggestion - only recently proved to have a real foundation - was still-born. It is a remarkable fact that for two generations no petrologist or chemist considered it worth while to put the matter to the test.

(ii) The first detailed description of the area and its rocks was by J.J.H. Teall (Teall, 1899, p. 610). Teall distinguished and described the following rock-types from the Loch Doon complex: Biotite-granite, hornblende-biotite-granite, quartz-diorite of the Tonale type, quartz-augite-diorite and hyperite. He noted the gradations between these types; their distribution, however, is not indicated on the Survey map (Sheet 8).

The presence of feldspar in the rocks of the aureole was observed by Teall. Describing an altered chert with orthoclase "moulded on the larger quartz grains which represent the chert", he stated that "there can be no doubt that the felspar of the altered rock has been derived from the granite magma". He /

He also recorded that "in a few abnormal rocks from the immediate neighbourhood of granite masses plagioclase has . . been observed. .... The individuals are often zoned and idiomorphic, and closely resemble the plagioclase of the granite rocks. ..... In many cases the felspar 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." (1899, p. 637) No chemical evidence is given to support this contention.

Teall significantly described the microcline crystals in the granite as "pseudo-porphyritic" (1899, p. 611), but he did not attempt to develop the implications of this observation.

According to Teall, the local differences observed in the mass cannot be correlated with the nature of the country rocks; moreover, he says, "the junctions of the granite with the surrounding rocks are in general perfectly sharp, and furnish no support to the view that the granite either represents the sediment crystallised in place or has even had its composition appreciably modified by the assimilation of portions of the surrounding rock" (1899, p. 623). In 1885 C. Callaway (1885, p. 229) drew attention to the sharply defined margins of schist inclusions in the Donegal granites. These sharp junctions would, he said, "surely be an impossibility if these fragments were merely the unmelted /

unmelted remnants of a series which had undergone partial fusion. Recent work, including the present investigation (p. 46), has shown that with diffusion this assurance is unfounded. Basing his views on an inadequate study of the relationships in the field, Teall ignored Geikie's evidence and Ward's suggestion.

Teall concluded that the evidence supports the magmatic hypothesis, maintaining that the differences observed within the complex are in part due to the intrusion of heterogeneous magma but mainly to "differentiation after the magma had reached its present position" (1899, p. 623).

(iii) In 1932 C.I. Gardiner and S.H. Reynolds published a paper on "The Loch Doon 'Granite' Area, Galloway" in the Quarterly Journal of the Geological Society of London. These authors made a valuable contribution to the solution of the problem by publishing a map showing the distribution of the three main types present in the complex. These types they designate as, norite, at the north-west and south-east margins; tonalite, forming the main body of the complex; and granite, at the centre. After presenting much fresh data, for example on the occurrence of inclusions within the complex, Gardiner and Reynolds failed to recognise the significance of their findings, and postulated three successive intrusions, in order of decreasing basicity.

Gardiner /

Gardiner and Reynolds thus agree with Teall that the evidence supports the magmatic hypothesis.

The mechanism of differentiation, whether in depth or in <u>situ</u>; the space problem involved by the intrusion of a large body of magma; and the possibility of solid diffusion, were not discussed by Teall or by Gardiner and Reynolds.

(iv) In 1942 H. Rutledge submitted to Professor Arthur Holmes a report (unpublished) on the Complex which he had investigated as the independent field work required for the B.Sc. Honours Degree in Geology at the University of Durham. For us, the main importance of the report lies in its demonstration that the diffusion hypothesis was worthy of consideration. Rutledge questioned the traditional magmatic hypothesis and was the first investigator to give serious consideration to the merits of "pyro-metasomatism" as a possible mode of genesis of the rocks of the Loch Doon complex. He concluded his report thus, "If stopin could be ruled out as the major process (of emplacement), and a general tightening up of the evidence would quite likely lead to such a result, then the complex would become an important one for the study of emplacement by pyro-metasomatism and rheomorphis processes of which at present very little is known".

III. TOPOGRAPHY

The area is one of the most desolate in the south of Scotland. To the east it is bounded by the Rhinns of Kells, which, for a distance of six miles, maintain an altitude of over 2,000 feet, culminating in Corserine (2,668 feet). To the west it is bounded by a similar lofty range, culminating in the highes hill in the south of Scotland, the Merrick (2,764 feet). The elongated basin lying between these two ranges is blocked at the northern and southern ends by lesser hills.

Four gaps lead into the basin through the enclosing mountain-girdle: Balloch in the north-west, Loch Doon in the north-east, the River Dee in the south-east, and Loch Trool in the south-west. These gaps all drain out of the basin, with the exception of that at Balloch which forms a low wind-gap between the drainage basins of the Doon and the Girvan. Thus the Doon drains the northern half, and the Dee and the Trool the southern half of the basin.

Bog, peat, and broad lochs cover much of the surface of the basin, the monotony of which is broken by a long north-south central ridge. This ridge, the highest point of which is Mullwharchar (2,270 feet), has gentle slopes on the west, but on the east is flanked by a fine line of cliffs. The Eglin Lane* on /

on the west of the ridge, and the Gala Lane on the east, drain into Loch Doon.

The two largest lochs in the northern half are Loch Macaterick and Loch Riecawr. The former drains into the Eglin Lane by the Black Garpel, the latter by the Whitespout Lane, the united waters being called the Carrick Lane. Although Loch Enoch, which is the highest loch in the area, lies between the Merrick and Mullwharchar, it all but drains into the Gala Lane by the Pulskaig Burn through a gap in the Mullwharchar ridge.

This basin was an important centre of ice dispersal during the Pleistocene Glaciation. In consequence, clean, ice-moulded exposures abound - even amongst the bogs of the lowlying areas and the outcropping rock is generally very fresh. The absence of trees, inhabited dwellings, paths and roads (except for a rough track from Loch Doon to Loch Riecawr), and the presence of abundant ice-moulded, rocky exposures, combine with the lochs and the outlines of the hills to give a topography that is neither Highland nor Lowland. It is unique. It is Galloway.

Topography is fairly closely related to geological structure. The mountain-girdle surrounding the basin correspond to the aureole, the central ridge to the granite. Tonalite forms the weak element in the structure and topography, and outcrops but sparsely over the loch and peat covered basin. Norite outcropping /

outcropping in the north-west and south-east, is characterised by an intermediate type of relief, with the rocky hill of Craigmasheenie (1,769 feet) in the north-west as the most striking feature.

*
Lane: 1. A brook, of which the motion is so slow as to be scarcely perceptible. Galloway, Lanarkshire.

2. Those parts of a river or rivulet which are so smooth as to answer this description. Galloway.

Icelandic: Lona, to stagnate. Jamieson.

IV. FORM and AGE of the COMPLEX

The Loch Doon complex is elongated in a north-south direction, oblique to the fold axes of the country rocks. The relation of the inner margin of the aureole to the contours shows that both roof and wall are present. It appears that tonalite is directly adjacent to the aureole along the walls, while norite intervenes at the roof of the complex. The roof position of the north-western occurrence of norite is particularl clear.

The contact is everywhere discordant, and the term laccolith used by Gardiner and Reynolds is in no sense appropriat If a "batholith" is defined as a discordant plutonic mass with sides generally steeply inclined and with no visible or determinable floor, then the Loch Doon complex is a small batholith.

The complex is younger than the post-Silurian movements which folded the Lower Palaeozoic rocks of the Southern Uplands. It is shown in a later section (pp.69,124) that while the complex is older than the majority of the associated dykes, some of these dykes are older than the complex. These facts are in accord with a Lower Old Red Sandstone age.

V. PRINCIPLES and PROCEDURE

Problems of space and of magmatic differentiation are often ignored by those workers on plutonic rocks who defend the magmatic hypothesis. In this Loch Doon has been no exception. Nevertheless at Loch Doon those problems are so weighty, and to the present writer appear so impossible of solution, that the solid diffusion hypothesis has been given serious consideration throughout the present investigation. In testing the two rival hypotheses, the principles and technique of phase petrology, as enunciated by S.J. Shand and as opposed to the older conception of species petrology, have constantly been employed.

Referring to the Cortlandt Complex, New York, Shand states, "If we wish to make progress in understanding the Cortlandt complex we shall have to abandon the traditional practice of mapping 'rock-types', which characterise the observer rather than the rocks, and proceed instead to map the distribution of critical phases which afford clues to the cooling history of the system. In short, we must abandon 'species petrology' and put 'phase petrology' in its place" (1942, p. 414; see also 1944, p. 45).

Accordingly, a very detailed investigation of the most crucial region was undertaken. The part thus examined was an area of the north-western norite, about one mile square, includi[ng]

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the areas of tonalite and transitional norite-tonalite mapped by Gardiner and Reynolds between this norite and the rocks of the aureole. Particular attention was directed to the inclusions within the norite and to the specially critical zone on either side of the norite-aureole contact. To supplement that study, serial specimens were collected across the relevant part of the aureole, traverses were made through the tonalite to the granite, and part of the tonalite-aureole contact was examined in detail.

The data available on those parts of the complex not included in the present investigation have, of course, been considered, but it is nevertheless recognised that continuation of detailed work over a wider area may entail minor modifications or extensions of some of the conclusions presented here.

VI. COUNTRY ROCKS

(i) Lithology

The country rocks round the north-west part of the complex consist of greywackes, flaggy beds, and black shales, amongst which the greywackes predominate. The term "greywacke" has given rise to considerable controversy; here it is used for rocks which are greywackes according to the definitions given by Milner (1929, p. 281), Bailey (1930, p. 87) and Pettijohn (1943, p. 944). After detailed analysis of the term, Pettijohn sums up thus: "Greywacke connotes a type of sandstone marked by (1) large detrital quartz and feldspar set in a (2) prominent to dominant 'clay' matrix which may on low grade metamorphism be converted to chlorite and sericite and partially replaced by carbonate, (3) a dark colour, (4) generally tough and well indurated, (5) extreme angularity of the detrital components, (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 shale chips, slip bedding, &c.), and (8) certain rock associations".

A specimen of greywacke (485), collected on the south side of Craiglure Hill, has been analysed (Table 2). The analysed /

analysed specimen is a greyish-blue, medium-grained rock in which quartz and muscovite can be recognised macroscopically. Thin sections show that it is composed of about 50% of ill-sorted and angular quartz grains, most of which show shadowy extinction. While grains may reach maximum diameters of 1 mm., they are usually less than 0.5 mm. Flakes and splinters of muddy and silty material occasionally reach a length of 2 mm. Other composite grains commonly present include spilites and fine-grained quartz aggregates, which may be chert. Fragments of plagioclase are rather common. Muscovite is present. Well-rounded grains of zircon are frequent. The matrix of the rock is a mixture of green chloritic and dark muddy material. Signs of metamorphism are shown in the rock by the formation of a little new biotite from the muddy fragments and matrix.

Although other specimens show variations in coarseness and in amount of muddy material, this rock may be taken as representing the dominant type in a rather monotonous series of beds.

(ii) Age and Structure

The country rocks at the north-west part of the Loch Doon complex are highly folded Ordovician sediments, the fold axes /

axes of which trend E.N.E.-W.S.W. The stratigraphical sequence of the Ordovician of the Southern Uplands of Scotland is:

Upper Hartfell Shales

Lower Hartfell Shales

Glenkiln Shales

In 1899 the Survey geologists referred the Glenkiln Shales to the Upper Llandeilo, and the Hartfell Shales to the Caradoc. In 1935 J. Pringle regrouped the stratigraphical divisions and placed the Glenkiln Shales and the Lower Hartfell Shales in the Caradoc, and the Upper Hartfell Shales in the Ashgill.

Less than three quarters of a mile from the norite-aureole contact at Ballochbeatties there occurs a bed of black graptolitic shale, well seen in a roadside quarry near Craiglure Old Lodge. Isoclinal folding repeats the bed two or three times but it does not outcrop in the aureole. The zonal ranges given by Dr. Gertrude Elles for the graptolites collected by the Survey geologists are shown in Table 1 . The graptolitic evidence is that the bed belongs to subzones 9 and 10, Nemagraptus gracilis and Climacograptus peltifer, and may include part of subzone 11, Climacograptus Wilsoni, above, and part of subzone 8, Glyptograptus teretiusculus, below. The black shale is thus the equivalent of the Glenkiln Shales of the central belt of the Southern Uplands and possibly also of the lowest beds of the Lower Hartfell Shales.

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The stratigraphical evidence collected by the Survey geologists shows that mudstone and chert, and not greywacke, underlie the equivalents of the Glenkiln Shales in the northern belt. The outcrops of the shale are therefore at the crowns of successive anticlines, and the greywackes of the aureole are younger.

To the south-south-west and south-east of the area under review, the same shales again outcrop in the cores of the anticlines. At these localities, however, they are immediately overlain by shales with a Hartfell fauna. By lateral variation greywackes therefore replace the Hartfell shales towards the north and west, in agreement with the well-known fact that Ordovician sediments become coarser in grain and increased in thickness as they are traced from Moffat to Girvan. The region now under consideration fell within the zone of shale deposition during the Glenkiln stage; at the Hartfell stage, however, the margin of this zone lay immediately to the south-east.

The greywackes of the north-west part of the aureole are thus above the subzone of Climacograptus peltifer, and possibly above that of Climacograptus Wilsoni. They are equivalent to the Lower Hartfell Shales of the central belt, and probably the Balclatchie and Ardwell Groups at the base of the Ardmillan Series of the Girvan district. They fall within the Caradoc of both /

both the Geological Survey, 1899 and J. Pringle, 1935.

As already pointed out, the underlying black shales outcrop just outside the aureole and again about three or four miles to the south, across the strike. This implies that the general structure from noth-west to south-east approximates to that of a synclinorium, the axial planes, however, nearly all dipping at high angles to the south. As a consequence of the structure, amply confirmed by field investigation, the same greywackes are constantly repeated along a north-west to south-east traverse of the aureole taken across the strike.

VII /

VII. THE AUREOLE

(i) General

The most detailed part of the present investigation has been the study of the norite of the north-west part of the complex, but an investigation of the surrounding aureole was essential if decision was to be made between the rival Magmatic and Solid Diffusion hypotheses. The purpose of the investigation of the aureole was not so much to study grades of metamorphism around the supposed intrusion, as to determine whether or not changes in the aureole could be interpreted as stages in a process resulting in norite. It was important, therefore, to study the dominant rock-type, greywacke, even though, being quartzose, it is not such a sensitive index to changing conditions as the more flaggy beds.

Accordingly serial specimens were collected along the strike from Cairnadloch to the Shepherds' Cairn on Shiel Hill. Some sixty specimens were collected on this traverse and twenty thin sections have been cut. Owing to the form of the complex a considerable length of the strike-traverse is parallel to the norite-aureole contact and to that extent is unsatisfactory. Nevertheless significant changes were observed as the contact was approached at the Shepherds' Cairn. The phenomena observed are not confined to this locality, but were found wherever the norite-aureole /

norite-aureole contact was examined in detail.

Serial specimens were also collected on a traverse from the south slope of Craiglure Hill to the Cow Craig near Ballochbeatties. It has been demonstrated above that, although this traverse is across the strike, isoclinal folding repeats the same beds throughout. The forty specimens collected are all derivatives of the same type so that successive comparisons are possible. Fifteen thin sections have been prepared. The analysed greywacke (485), described above, is the first member of this series.

The contact zone was examined at other localities also, in particular on Craigbrock where twenty specimens were collected; of these, fifteen thin sections have been prepared.

(ii) Petrography

(a) Biotite and Quartz. The first step in the alteration of the greywackes is the development of biotite from the muddy and chloritic material. Even half a mile from the contact, and twice as far out as the Survey geologists' mapping of the outer limit of the aureole, the analysed greywacke (485) contains a little new biotite. Its content of nearly 3% of H_2O (+ 105°) is probably in the muddy and chloritic material, and much of this water /

water is driven off during further metamorphism. The biotite is rather pale and shapeless at first, but soon develops strong pleochroism and regular habit. The dimensions are not great, the diameter of the plates being seldom more than 0.5 mm., even in proximity to the contact. A decussate arrangement is characteristic, the rock being largely massive, but this pattern is occasionally interrupted by the intervention of bedding-planes. X = almost colourless; Y = Z = dark red-brown. Pleochroic haloes are common. With the formation of biotite many of the composite fragments, e.g. spilites, soon lose their identity, but some of the fine-grained muddy pellicles can be recognised as inclusions throughout the altered greywacke and even in the norit

Soon after the formation of the first biotites a physic change can be observed in the detrital quartz grains; the larger of these break down into smaller individuals closely bound together by interlocking sutures, but with varying optical orientations. At a later stage the small quartzs and fine-grained chert fragments become coarser. The product resulting from these changes is a homogeneous granulite with a background of decussate biotites set in a matrix of a more or less even-grained quartz-mosaic. The term "granulite" has been used in a number of senses; it is used here to designate a rock with granulitic texture, i.e. with even-sized and closely-fitting grains (Brit. Petrograph. /

Petrograph. Nomen. Com. 1921, Min. Mag., Vol. 19).

These changes are well seen under the microscope, and are reflected to some extent in the hand-specimens. With the driving off of combined water, and the alteration of chloritic and muddy material to biotite, the greywackes lose their greyish-blue colour and become grey or black. The original greywackes are well-consolidated, massive rocks, and further induration is therefore not conspicuous. As the contact is approached the rocks become so homogeneous that stratification may disappear completely within sixty or seventy yards from the contact.

(b) Feldspar. Migration of diffusing materials into the rocks of the aureole is shown by the rather common occurrence of tourmaline in the contact granulite. It is in small grains usually with a dark-blue and often zoned colouration, and is identical with the tourmaline occurring in the leucocratic veins which traverse the granite (p. 111).

When the greywackes are traced to within some fifty or sixty yards from the contact, patches are observed in which grains of plagioclase are abundant. Mineralogical and chemical work (p. 39) shows that these crystals do not all represent detrital fragments, as Teall (1899, p. 637) believed, but that there has been definite introduction first of Na and Al, and later of Al, K, Na, and Ca from an extraneous source.

Specimen /

Specimen 506, from the Cow Craig, and some forty-five yards from the contact, illustrates an altered greywacke in which feldspathisation has commenced but has not gone so far as to destroy the essentially sedimentary structure of the rock. This specimen has been analysed (Table 2).

Description of Specimen 506 -

The body of the rock is a quartz-mosaic (the individuals of which are usually less than 0.25 mm. in diameter but occasionally up to 1 mm.) with a superimposed pattern of decussate biotites averaging about 0.1 mm. in length. The pleochroism of the biotite is X = almost colourless; Y = Z = reddish brown. Intensely developed pleochroic haloes round zircon inclusions are rather common.

A small amount of pale-green isotropic material is present; this is probably prasiolite after cordierite. Zircon is a common accessory; it is usually in rounded grains, but rare examples of a skeletal habit occur, due either to extensive recrystallisation or to introduction of zirconium. Tourmaline is present, having a maximum diameter of nearly 1 mm. It is strongly zoned and has a patchy dark-blue colour. There is a small amount of black ore.

The plagioclase is slightly turbid and is thus easily distinguished from the quartz. There is a tendency for the development /

development of lath-shapes. Many of the individuals are over 0.5 mm. in length, one crystal being 2 mm. long and 0.6 mm. broad. This big crystal encloses quartz grains and, indeed, is divided in two by a continuous belt of these. Its relation to other minerals as seen in thin section shows clearly that this crystal grew in the solid granulite, either by local diffusion from neighbouring detrital grains or by introduction of material to the granulite. Chemical evidence (p. 41) shows that there has been addition of Na and Al to this rock.

Feldspathisation in isolated "pods" or "kernels" a foot or two in diameter, is well seen in the greywacke-granulite of the Cow Craig. Mineralogical, textural, and chemical gradation to the granulite, the occurrence of detrital zircons, and of biotite with the same decussate arrangement as in the granulite, and the field-fact of their isolation from the norite, show that the pods have indeed been formed by the feldspathisation of the greywacke-granulite.

A thin section cut from specimen 727 from the Cow Craig shows in the bounds of a single slice 1½ inches long, the gradual transition from a slightly feldspathised granulite rather coarser than 506, to a highly feldspathised granulite containing euhedral plates of plagioclase up to 3-4 mm. in diameter and 0.5-1 mm. thick /

thick, and poikilitic plates of potash feldspar upwards of 1 mm. in diameter.

Specimen 507, from the Cow Craig, is of a highly feldspathised granulite and has been analysed (Table 2). Plates of plagioclase are conspicuous in hand-specimen, and are sometimes over 1 cm. in diameter. In thin section the occurrence of decussate biotites links it to the normal granulite, but the biotite is rather coarser and darker than that in 506.

Description of Specimen 507 -

Plagioclase is zoned from andesine (An_{45}) at the centre to oligoclase at the margin. Large and small crystals have the same range of composition. The core often has oscillatory zoning but the zones differ but little from each other. The oligoclase zone has a sharp boundary against the rest of the crystal. Inclusions of biotite abound in the larger crystals, and "schiller" inclusions are sometimes present. Internal irregularities and patchiness of composition are common in the plagioclase crystals. This is no doubt due to growth in the solid, some of the porphyroblasts being formed by the union of several smaller crystals - exact parallel orientation of the individuals not always being achieved.

The plates of potash feldspar sometimes reach 2 mm. in diameter, but, being anhedral and highly poikilitic, are easily overlooked /

overlooked. Quartz now appears as irregular, interstitial grains, and is much less abundant, showing that the process of feldspathisation has been one of desilication.

Plagioclase may appear without potash feldspar but not vice versa, thus showing that in feldspathisation plagioclase forms first and is followed by potash feldspar.

(c) Cordierite. Specimen 685/1 from the contact zone on Craigbrock, illustrates a type which, though not common, is of considerable significance. Though closely allied to 506, it differs from that rock in containing cordierite and no new feldspar. The biotite tends to be rather more coarsely crystalline, and its colour rather redder (Y and Z) than in 506. Cordierite is in part fresh, colourless, and subhedral, and in part represented by pale-green prasiolite. Yellow haloes occur but are rare. In hand specimen the rock is remarkable for its even-grained homogeneous character.

This biotite-cordierite-granulite has many points of resemblance to the mobilised sediment from the Newry complex, described and figured by D.L. Reynolds (1934, p. 602), who has shown (1944, pp. 234-238) it to represent the "secondary Fe-Mg front" in which the Fe-Mg expelled from the zone of feldspathisation has been fixed. In the Loch Doon granulites cordierite is /

is found immediately adjacent to the feldspathised pods.

When the flaggy beds are traced into the aureole they become "spotted" with crystals of cordierite 0.5-1 mm. long and about 0.25 mm. in diameter, easily recognised by sector twinning, and usually crowded with inclusions. Even at a distance of three hundred yards from the contact, cordierite forms such a large proportion of the rock that Fe-Mg enrichment is suggested. These elements were perhaps able to pass through the more quartzose beds with greater ease, becoming fixed as cordierite in the more flaggy beds.

(d) Pyroxene. Where feldspathisation has locally been intense, potash feldspar becomes less conspicuous, and the dominant feature of the rock is the presence of laths and plates of plagioclase with decussate arrangement. At this stage pyroxene appears and the resulting rock could easily be mistaken for one of igneous origin had the stages in its formation not been traced, and had its mode of occurence as pods within the aureole not been known.

Specimen 685/5 from Craigbrock, a typical example of such a feldspathised and pyroxenised pod, has been analysed (Table 2). In hand-specimen it is a grey, rather fine-grained rock in which the pyroxene and plagioclase porphyroblasts can

easily /

easily be recognised.

Description of Specimen 685/5 -

Almost colourless, non-pleochroic, orthorhombic pyroxene, and almost colourless, pale-green, non-pleochroic monoclinic pyroxene, with $Z \wedge c = 42^{\circ}$, and probably best described as diopsidic augite, are both present. The pyroxenes occur as sieved porphyroblasts 2-3 mm. long, and also as small granules. The larger individuals are often rimmed with biotite and are sometimes altered to almost colourless, fibrous amphibole which is commonly flecked with biotite.

Biotite is poikilitic or skeletal and preserves its decussate arrangement, although this is less conspicuous than the decussate arrangement of the plagioclase. It is pleochroic from X = almost colourless, to Y = Z = reddish-brown, and pleochroic haloes are common. The developing biotite - and less frequently the pyroxene - is sometimes highly skeletal, being composed of numerous isolated individuals which, although enclosed by several adjoining quartz grains, are at least approximately parallel. Occasionally two such crystals, one of pyroxene the other of biotite, are mutually parallel and intergrown; each is formed of numerous individual units, none of which comes into contact with its neighbours. In such cases the biotite tends /

tends to occur around and outside of the area occupied by pyroxene. Good examples of this are seen in a similar rock, specimen 401, from the Shepherds' Cairn.

Plagioclase occurs as plates usually less than 0.6 mm. in diameter but sometimes up to 2 mm. There is a strong tendency for this mineral to be euhedral. Pyroxene granules are often enclosed in the larger crystals and may have a rough zonal arrangement within the host. The larger crystals are often dusted or clouded with minute inclusions. Internal irregularities are characteristically seen between crossed nicols. The plagioclase shows highly complex oscillatory zoning and large and small crystals alike have the same sequence of composition. Seventy zones were counted in one of the smaller crystals, but these, as in other cases, can be grouped into a few major zones, each of which consists of numerous minor oscillations of composition, differing but slightly from one another. For example, in one particular crystal (cut parallel to 010) about forty subsidiary zones can be grouped to form six major zones, thus:

Core: 45 → 35-40 → 45-50 → 35 → 45-50 → 20-25 An% : margin.

Potash feldspar is interstitial or poikilitic, but is not so abundant as in the feldspathised types without pyroxene.

Apatite is abundant, generally as very fine needles but occasionally as more stumpy crystals. Ore is rather more common than in the types already described.

The /

The mineralogical and textural changes described above relate to the dominant rock of the aureole, medium to coarse-grained greywacke, and are in the main gradational. When finer grained beds are traced within the critical contact-zone rather different changes take place. These changes involve coarsening of grain-size and tend to the homogenisation, or convergence in type, of the varied rocks of the aureole as these approach the contact.

Structural relation?

(iii) Vein-like Bodies in the Aureole Rocks of the Cow Craig

Specimen 728 shows the contact of a three-inch wide "vein" against rather fine-grained biotite-granulite from the Cow Craig. This "vein" cuts abruptly across the direction of bedding, and in hand-specimens appears to have a hair-sharp junction with the granulite. The granulite traversed by the "vein" consists of a quartz mosaic, the individuals of which are usually less than 0.15 mm. in diameter, and decussate biotites about 0.1 mm. in diameter. A little feldspar, some blue tourmaline, and possibly some cordierite are present.

The "vein" also consists of a quartz mosaic and decussate biotites, and the biotites of both "vein" and granulite are rather reddish and contain intense pleochroic haloes. The "vein" /

"vein" is, however, coarser than the granulite, the grain-size of the quartz mosaic being 0.5 mm. and of the biotites 0.4 mm. More or less euhedral, platey plagioclases are present and reach 2 mm. in diameter. They are zoned from a calcic core to a sodic margin, and sometimes have oscillations of composition. A little interstitial potash feldspar, a little muscovite, and also a certain amount of greenish and yellowish material, probably secondary after cordierite, are present. Some of the biotite is highly skeletal.

In thin section, while some parts of the contact are sharp, other parts - even in the same slice = are gradational, showing that the "vein" formed by coarsening and feldspathisation of the granulite.

Relics of fine-grained granulite occur in the "vein" and must be distinguished from picked-up xenoliths in an intrusive vein. Many of the feldspathised pods in the aureole have similar relic-inclusions, the margins of which are sometimes (e.g. 729) enriched in ore. While many of the inclusions are essentially relics of the same parental material of the host, but less altered, some (e.g. 510) represent detrital fragments in the original grit which proved more resistant than the dominant type.

(iv) /

(iv) Contacts on the Shepherds' Cairn

Near the Shepherds' Cairn inclusions of fine-grained biotite-granulite, up to three or four inches across, are enclosed in a coarser and feldspathised biotite-granulite. Petrographically these granulites are similar to those of the "country rock" and of the "vein" occurring on the Cow Craig and described above.

The biotites of the feldspathised rock, i.e. of the host, are coarser than those of the inclusions, but show the same pleochroism and decussate arrangement; some are highly skeletal. Euhedral plagioclase and large poikilitic potash feldspar (possibly microcline) are both present. In thin-section the contact is seen to be the same "abruptly gradational" type as that of the "vein" from the Cow Craig described above; by this it is meant that the contact is gradational, but that the gradation takes place in a small compass.

The coarsened and feldspathised biotite-granulite, i.e. the rock containing the inclusions, is in contact with an igneous looking rock with large platey plagioclase and conspicuous pyroxene. Macroscopically the junction is sharp, but in thin section there is no sharp line of contact.

The plagioclase of the igneous-looking rock may be up to 1 cm. in diameter, has pronounced internal irregularities, and contains /

contains inclusions of biotite and of pyroxene granules as well as being dusted with minute and "schiller" inclusions. The biotite and pyroxene inclusions are often zonal in distribution and are sometimes in contact in a manner suggesting the development of one from the other. Oscillatory zoning is common and the following are examples:

Core: 45-50 → 40-45 → 45-50 → 40 → 25 An% : margi

Core: 45-50 → 40-45 → 45-50 → 25-30 → 40-45 → 20-25 An% : margi

Another crystal in the same slice varies uniformly from An_{50} at the core to An_{40} towards the margin, and has a narrow marginal zone of An_{25}. Some specimens (e.g. 400a) illustrate in a remarkable manner the formation of large porphyroblasts of plagioclase with internal irregularities by the union of several smalle crystals in approximate parallelism.

In the igneous-looking rock pyroxene occurs in crystals 2-3 mm. long and also in granules. Both orthorhombic and monoclinic forms are present. Biotite is reddish on both sides of the contact, but is noticeably darker near and at the contact itself. On the "igneous-looking" side it is coarser and usually skeletal, and frequently fringes the pyroxene and fingers into the cleavages of that mineral.

The matrix consists of small plagioclase laths in a poikilitic quartz background, and is very rich in "pegs" of ore which /

which are sometimes twenty times as long as broad. The ore gradually decreases in amount towards the contact with the feldspathised granulite, there being an almost linear "front" beyond which very large plagioclases and pegs of ore are not found. Ore is not enclosed in the large plagioclases except in their marginal zones, and, accompanied by quartz and biotite, along the junction of two or more plagioclases which have united in approximate parallelism to form a porphyroblast. Minute apatite needles are abundant.

Similar "igneous" types with peg-like ore occur at the Craigbrock contact, and it is inferred that these have the same genesis as the Shepherds' Cairn rocks.

(v) The Potash Feldspar and Muscovite Bearing Pods and Vein-like Bodies in the Aureole Rocks of Craigbrock

Remarkable miniature pods are found in a rock near the Craigbrock contact. The rock is a biotite-cordierite-granulite. The quartz grains are up to 1 mm. in diameter and enclose the other constituents poikilitically. Biotite is rather reddish and about 0.25 mm. in diameter. Cordierite is fairly abundant. Muscovite may be 1-2 mm. long, encloses biotite flakes, and some examples are skeletal.

Standing out from the weathered surface are little "knots" /

"knots", silvery with muscovite, and from 0.25-1 cm. in diameter. The incidence of these "knots" is very variable; at one point there are none, but less than a foot away a square inch yields half a dozen.

The "knots" are miniature pods of bleached biotite and of new plagioclase and potash feldspar. The rock containing these "knots" sometimes crosses the strike like an intrusive vein. The breaking-up of bedding (fig. 4), a very rare occurrence, shows that locally the "knotted" rock became mobile. Though on a much smaller scale, this is comparable with the wholesale mobilisation of sediment along some of the Newry contacts (D.L. Reynolds, 1934, 1936).

Along the Craigbrock contact "veins" and fine stringers intersect the aureole rocks. The material of the "veins" is similar to that of the knots, and is silvery with muscovite. In hand-specimen the contacts usually appear very sharp, and the colour difference between the silvery "veins" and the black granulite is most striking.

In thin section the "vein"-rock is seen to consist of a quartz mosaic, the grain-size of which is from 0.25-1 mm. As in the granulite, the rock contains decussate biotites but these are mostly bleached and are criss-crossed with rutile needles, only a few unbleached, reddish-brown biotites remaining. Muscovites are /

are large and often skeletal. The rock is very rich in anhedral potash feldspar (at least some of which is microcline), the plagioclase being inconspicuous in comparison.

(vi) The Nodules of the Aureole

One feature of the aureole remains to be described; the occurrence in the greywacke-granulites of nodules, seldom more than a foot in diameter, which stand out on the weathered surface. They are usually fine-grained, siliceous rocks showing no effervescence with dilute HCl. It is not known whether these nodules represent sediment deposited in situ, pebbles due to contemporaneous erosion, concretions within the sedimentary series, or the products of metamorphic diffusion.

Thin sections show that the nodules contain clastic quartz grains, on occasion reaching 2 mm. in diameter, set in a very fine-grained matrix. Some of the nodules are rich in brassy or bronze-coloured sulphides. Highly poikilitic tourmalines are sometimes present, e.g. in 454. Pale-green or almost colourless hornblendes are often abundant and in such types sphene is usually present. In some specimens colourless pyroxene and idocrase appear to be present to the exclusion of amphibole, but these have not been diagnosed with certainty.

A /

A thin section (753) of the contact of a nodule with the surrounding greywacke-granulite shows that the only difference between the nodule and the granulite is the occurrence of pale-green amphibole in the nodule instead of biotite in the granulite. Brassy sulphides occur in both.

(vii) Summary of Evidence Bearing on the Petrogenesis of the Aureole Rocks

1. Metamorphism of Greywacke to Granulite. As the Ordovician greywackes are traced into the aureole of thermal metamorphism, granulites are seen to take their place. The sequence of mineralogical and textural changes linking representative greywacke to the corresponding biotite-quartz-granulite (with a little feldspar) is described, and is interpreted as a sequence in time as well as in space; that is, in the formation of the granulites inside the aureole, the same sequence of changes was passed through in time as is passed through in space when the greywacke-granulites are traced across the aureole.

2. Feldspathisation of Granulite. Pods or kernels, without link by visible feeding-channels to the rocks previously supposed to be igneous, but containing abundant feldspar, occur in /

in the granulites close to the norite contact, and are described. The following evidence demonstrates that greywacke, metamorphosed first to granulite, was, with change of chemical composition, transformed in the solid to the feldspathic but still more or less granulitic rock of the pods:

(a) The absence of possible feeding-channels precludes a magmatic genesis.

(b) There is a petrographic gradation (field and microscopic) to the granulite.

(c) The same pleochroic biotites occur as in the granulite.

(d) Rounded zircons occur as in the granulite.

(e) The quartz is similar in habit and other characters to that of the granulite, but its quantity is inversely proportional to the quantity of feldspar; the process of feldspathisation has been one of desilication.
see p.120

(f) Relics of the detrital fragments in the original gritty sediment are sometimes present.

The following mineralogical evidence demonstrates that the minerals of the pods grew in the solid:

(a) Internal irregularities and the manner of "trapping" inclusions along the boundaries of the component individuals, show that the large plagioclase crystals are porphyroblasts which developed by the union, with increasing parallelism, of smaller crystals.

(b) The plagioclase crystals are frequently sieved with biotites, identical with those of the granulite, in the manner common in the cordierites of a hornfels.

(c) Where plagioclase is present in two orders of size, both have the same composition. Had crystallisation been from magma, the smaller crystals would have been more sodic than the larger.

(d) /

(d) Continuous and oscillatory zoning are often present in adjoining plagioclase crystals. It is most unlikely that this phenomenon could have occurred had crystallisation taken place in a medium where equilibrium is attained fairly readily, as it is even in viscuous liquids.

(e) Both plagioclase and biotite have decussate arrangements; a pattern common in metamorphic rocks.

(f) The highly poikilitic habit of the potash feldspar suggests growth in a solid rather than in a liquid medium.

Chemical analyses (Table 2) demonstrate that:

(a) There is a chemical gradation between the feldspathic pods and the biotite-quartz-granulite.

(b) The formation of feldspar reflects a change of chemical composition and is not merely a thermal change. Teall's assertion that "In many cases the felspar has doubtless been formed out of the constituents of the original rock", is thus without foundation.

(c) The elements introduced were first Na and Al, and later Al, K, Na, and Ca; which implies that the components of the new feldspar were added severally, not as "molecules" or crystals of feldspar, but as atoms (or ions) in the proportions required, so to say, from time to time and from point to point. Teall's assertion that "in the few (cases) in which it has been introduced" the feldspar "has been derived from the granite magma" is disproved chemically; it is already disproved by the mineralogical evidence demonstrating growth in the solid, and by the obvious mechanical impossibility of such bodily introduction.

(d) The presence in the contact granulites of tourmaline, identical with that associated with the central granite, shows that certain chemical elements did diffuse through the solid granulite. In order to effect the chemical change from greywacke to fully feldspathised granulite about 1.8%, K, 1.6% Al, 1.2% Na, and 0.7% Ca must have diffused into and been fixed in the granulite, and appropriate amounts of Si, combined water, and a little /

little Fe, Mg, and Mn must have been expelled.* The migrating elements must have formed a highly dispersed system, and it is probable that the diffusion was ionic.

That an igneous-looking rock was produced by the process discussed is obvious from the petrographic description; that the product approached an igneous rock from a chemical standpoint is well seen by comparison of the proportions of corundum in the norms:

Greywacke (485)	Slightly feldspathised granulite (506)	Fully feldspathise granulite (50
5.91%	4.48%	2.23%

3. Pyroxenisation of Feldspathised Granulites. Associated with the feldspathised granulite which has been described and discussed above, and occurring together with this in the same pods, is a pyroxene-bearing rock. The following evidence shows that, after feldspathisation of the granulites had taken place, further change of chemical composition transformed the already altered rocks, which were still in the solid state, into the pyroxenised rocks of the pods:

(a) As with the feldspathised rocks, the absence of possible feeding-channels precludes the introduction of magma.

(b) There is a petrographic and field gradation to the feldspathised granulite.

(c) /

*Percentages refer to bulk composition, assuming no change in density or porosity.

(c) The same plagioclase, with its many individual characters, occurs as in the feldspathised granulite.

(d) The same pleochroic biotite occurs as in the feldspathised granulite.

(e) Both potash feldspar and quartz have the same habit and other characters as the in the feldspathised granulite.

(f) As in the feldspathised granulite the individual minerals show evidence of growth in a solid and not in a liquid medium.

The following is the mineralogical evidence which demonstrates that the minerals of the pyroxene-bearing rocks grew in the solid.

(a) The presence of internal irregularities in the plagioclase.

(b) The only difference in the plagioclase inclusions in the rocks being compared is that, in the pyroxenised rock, pyroxene granules take the place of some of the biotite inclusions.

(c) The small plagioclase crystals are not more sodic than the big crystals.

(d) Plagioclase crystals with continuous and oscillatory zoning are present side by side.

(e) Both plagioclase and biotite have decussate arrangements.

(f) Both pyroxene and biotite are often sieved, and both are sometimes highly skeletal.

(g) The highly poikilitic habit of the potash feldspar suggests growth in a solid medium.

Chemical analyses (Table 2) demonstrate that:

(a) The formation of pyroxene has reflected change of chemical composition and is not merely a thermal change.

(b) /

(b) In order to effect the chemical change from feldspathised granulite to the pyroxene-bearing rock about 1.9% Ca, 1.0% Mg, 0.9% Al, and a little Fe must have diffused into and been fixed in the feldspathised granulite, and about 2.5% Si, 1.3% K, and 1.0% Na must have been expelled.

(c) As with feldspathisation, the new pyroxene was not introduced as "molecules" or crystals; the necessary elements migrated individually.

(d) Pyroxenisation made the altered rock even more igneous-like in composition than feldspathisation did. This is shown by the reduction of corundum in the norm to 2.00%

4. Feldspathisation and Coarsening of Fine-grained Granulite. That this process, which usually gives rise to pseudo-veins, does operate is shown by the following evidence:

(a) The rock of the "vein" is a granulite with decussate biotite with the same pleochroism as in the fine-grained granulite traversed.

(b) The contact is of the type described above as "abruptly gradational".

(c) Cordierite is present in the "vein".

(d) Some of the biotite is highly skeletal, the components being distributed between several adjoining quartz crystals.

(e) The plagioclase shows internal irregularities.

(f) Plagioclase crystals with continuous and oscillatory zoning are present side by side.

(g) The potash feldspar is highly poikilitic.

(h) /

(h) Relics of fine-grained granulite occur within the "vein" and the margins of some of these relics are enriched in ore. This shows that diffusion was taking place. (cf. F.F. Grout, 1926, p. 29; 1937, p. 1559).

5. Pyroxenisation of Coarsened and Feldspathised Granulite in the Form of Pseudo-veins. In the field the feldspathised granulite, characteristically found as pseudo-veins, is sometimes associated with a pyroxene-bearing rock of igneous appearance. The following evidence demonstrates that the latter is not igneous, but was formed from the feldspathised granulite in a manner more or less analogous to the pyroxenisation described under heading 3, above:

(a) There is no sharp line of contact between the two rocks when the junction is examined in thin-section.

(b) The plagioclase of the "igneous" rock is merely larger than that in the granulite; in both rocks the plagioclase has the same composition and characteristics, and shows all the signs of growth in the solid detailed above under the appropriate headings.

(c) Both large and small plagioclases have the same composition.

(d) In the igneous-looking rock, pyroxene granules take the place of some of the biotite inclusions in the plagioclase.

(e) The biotite is characteristically skeletal.

(f) There is a "front" of ore-pegs beyond which very large plagioclase, crystals of pyroxene, and pegs of ore are not found. This is a typical diffusion limit.

6. /

6. Evidence of Solid Diffusion from the Aureole Rocks of Craigbrock:

(a) Miniature pods occur and the absence of feeding-channels is demonstrable on any hand-specimen. As the mineral composition of these pods shows, the formation of the pods involved change in chemical composition. Passage for the incoming and outgoing materials was possible only through the solid rock.

(b) "Vein"-like bodies are found in the field in the vicinity of these pods, and the material of the "veins" is similar to that of the pods.

(c) The background of the rock both of the "vein" and of the granulite, is a quartz mosaic, the "vein" being rather coarser than the granulite.

(d) Decussate brown biotites are characteristic of the granulite. In the "vein" similar biotites occur but these are almost entirely bleached. Where unbleached biotite occurs in the "vein" it has the same pleochroism as the biotite of the granulite.

(e) Muscovite is present in both rocks but is larger and more strikingly skeletal in the "vein".

(f) The "vein" is very rich in anhedral potash feldspar, the irregular habit of which suggests growth in the solid.

(g) In hand-specimen, the margin of the "vein" against the granulite is very sharp.

(h) There is a narrow zone of cordierite enrichment of the granulite against the "vein".

This evidence shows that both pods and "veins" have a similar origin; both have been produced from the granulite by solid diffusion in which potassium has clearly played an important part. These rocks offer an excellent demonstration that sharp boundary lines can be produced by solid diffusion.

VIII. THE NOMENCLATURE OF THE ROCKS OF THE COMPLEX.

As is shown in detail in the conclusion, the aureole rocks and the rocks called norite, tonalite, and granite, are successive stages in a process leading eventually to homogenisation. Discussion of the position of these stages in the general sequence, and of the relative significance of the various boundary lines on Gardiner and Reynolds' map of the complex, must await the presentation of the field, microscopic, and chemical evidence.

Phase petrology, and not species petrology, is the philosophy of approach required for the study of the effects of an evolving process. Nevertheless, for ease of reference and simplicity of explanation, the use of rock names is useful, and is justified if the background of development of mineral assemblages and of changing phases is kept in mind.

The sub-divisions of the complex to which the terms norite, tonalite, and granite were given by Gardiner and Reynolds are all, though not all equally, of petrogenetic significance, and must be severally distinguished. Which labels are attached is not believed to be a matter of great importance so long as the series is pictured as a whole and in its interrelations. Nevertheless continued use of the unqualified terms <u>norite</u> and <u>tonalite</u> is likely to lead to misunderstanding should the rocks of Loch Doon be compared with those of other complexes.

Distinction /

Distinction between diorites and gabbros is a matter on which petrologists have expressed a variety of opinions. At different times these two groups have been distinguished on the basis of silica percentage, occurrence of amphibole or pyroxene, composition of the plagioclase, colour index, &c. The Committee on British Petrographic Nomenclature, 1921, adopted the following definitions and recommendations:

Gabbro: a plutonic rock of basic, i.e. subsilic, composition, consisting essentially of a calcic plagioclase with one or more ferromagnesian constituents, usually pyroxene but sometimes hornblende, and with or without olivine.

Diorite: a plutonic rock of intermediate, i.e. mediosilicic, composition, the dominant feldspar being sodic plagioclase.

Granodiorite: a plutonic rock intermediate between quartz-diorite and granite, in which orthoclase, while present as a notable constituent, is always subordinate in amount to the plagioclase.

The Committee recommended that the term tonalite be replaced by quartz-diorite, Tonale type; i.e. a hornblende-biotite-quartz-diorite with very little potash feldspar.

The so-called norite of Loch Doon is very variable and according to these definitions and recommendations is partly quartz-diorite, partly granodiorite.

The /

The so-called tonalite has been found always to contain an appreciable proportion of potash feldspar, and is therefore properly speaking, a granodiorite.

The core of the complex contains more potash feldspar than plagioclase and is therefore a true granite.

Although it is demonstrated below that the so-called norite must be subdivided, it is impossible to distinguish between the two types in hand-specimen. As the three types of Gardiner and Reynolds are easily recognised in hand-specimen, it is useful to retain the terms "norite" and "tonalite" as convenient "sack-names".

IX. THE PETROLOGY OF THE SO-CALLED NORITE

(i) The Variations; their Petrography and Serial Relationships

A field investigation was made of the "norite" of the north-west part of the complex, especially that of Shiel Hill and the masses of "tonalite" and "transitional Norite-tonalite" mapped by Gardiner and Reynolds between the "norite" and the aureole in the vicinity of Loch Cornish.

In the field the macroscopic variations within the "norite" were found tobe so considerable that it was impossible to map the innumerable varieties. In hand-specimen most varietie are dark in colour, generally grey, but the grain-size varies enormously - from fine to coarse. Furthermore, the variations in rock-types throughout the Loch Cornish area were found to be the same as occur in the main body of the "norite"; the existence of a tonalitic border facies along part of the contact, as sugges-ted by Gardiner and Reynolds, was not confirmed.

From an area of approximately one square mile, 325 specimens of the "norite" and the supposed "tonalitic" border facies were collected and the localities of these plotted on the scale of six inches to a mile. Other specimens were collected outside the square mile and studied in detail to make sure that the main varieties had in fact been collected. To systematise the large number of varieties, the specimens were arranged in some thirty /

thirty groups, those included in any particular group being macroscopically similar. From each group 1-5 specimens were selected for sectioning, the number depending on the size of the group and the minor variations within it. Over one hundred thin-sections were prepared, so providing a systematic sampling of the rocks of the north-west part of the complex.

An examination of these sections showed that the rocks consist of the following minerals: plagioclase (averaging andesine), potash feldspar, quartz, biotite, pyroxene (both orthorhombic and monoclinic), amphibole (which can generally be demonstrated to have developed from the pyroxene), and the accessories black ore, apatite, and zircon. These minerals will now be described in turn.

(a) Plagioclase. The plagioclase occurs as lath or plate-shaped crystals of varied dimensions. Although the elongation may be upwards of 1 cm., the commonest length is about 0.5 to 0.75 mm., with subsidiary frequency maxima at about 2mm. and 5-7 mm. There is sometimes a definite tendency towards development of plagioclase in two orders of size. The ratio of the larger to the smaller is variable, sometimes reaching 14 (0.5 and 7 mm. respectively) but most commonly about 2-3 (e.g. 0.75 and 2 mm. respectively.

The /

The crystals are approximately euhedral, but adjacent crystals may mutually interfere and potash feldspar may "corrode" the plagioclase.

Zoning is common and may be either continuous or oscillatory. Both may be shown in the same slice, and individual oscillations may themselves show continuous zoning. In 130 determinations of anorthite percentage only eleven are more calcic than An_{50}; none is more calcic than An_{60} or more sodic than An_{20}. The bulk average is probably near sodic andesine (about An_{35-40}). Crystals showing continuous zoning usually have cores of andesine-labradorite (about An_{50}) and margins of calcic oligoclase (about An_{25}). Crystals showing oscillatory zoning tend to become more sodic towards the margin; examples are:-

$40 \rightarrow 50 \rightarrow 40 \rightarrow 45 \rightarrow 35 \rightarrow 45 \rightarrow 50 \rightarrow 35 \rightarrow 45 \rightarrow 25$

$40 \rightarrow 35 \rightarrow 25 \rightarrow 35 \rightarrow 25 \rightarrow 40 \rightarrow 35 \rightarrow 25 \rightarrow 20$

When oscillatory zoning is present the number of zones may be very great, e.g. 70; these may, however, be grouped into broader zones consisting of oscillations of only slightly varying composition. Patchiness of composition is often present in addition to concentric zoning. When two orders of size of plagioclase are present the smaller are not more sodic than the larger; the bulk composition of each is, as far as can be estimated, the same.

Inclusions are common and are of three types: (a) blebs

of /

of pyroxene (or sometimes of biotite), often arranged zonally, (b) minute dusty inclusions giving a "clouded" appearance, often absent from the outer zone of the plagioclase, (c) minute "schiller" plates with crystallographic orientation within the plagioclase. Occasionally a clear outer zone is separated from a clouded core by a zone of pyroxene granules, the junction being abrupt and sometimes "unconformable".

The optic sign is often anomalous with respect to the composition as determined by extinction angles. Crystals of the same composition as judged by extinction angles, and of the same dimensions, occurring in the same slice, may differ in sign. This implies that the published data linking composition with optic sign and with extinction angles does not fit the feldspars present in the Loch Doon rocks. It is suggested that the reason for this may be the presence of potassium or other "foreign" atoms in the lattice.

Twinning is common on ?albite, ?carlsbad, and ?pericline laws, in that order of frequency. The width of the twin lamellae varies from very fine to moderately coarse without obvious relation to the zones of composition.

Curvature of many of the crystals and shadowy extinction of others indicate either growth under conditions of stress, or subsequent deformation. As mechanical deformation would be likely to leave V-shaped gaps, which are not in fact present, it is /

is probable that the crystals did grow under conditions of stress. What may be termed "internal irregularities" are common within the plagioclase; between crossed nicols many of the crystals are seen to be mosaics, the individual components of which are sometimes only in approximate parallelism. Inclusions of biotite or quartz have occasionally been trapped along the junctions of these individuals and may remain even after sensible parallelism has been achieved, the mosaic structure then being apparent only by interruption of twin lamellae.

Alteration to materials akin to kaolin and sericite is sometimes observed. Such altered plagioclase crystals have an opaque porcellanous appearance in hand-specimen, and are rather more common in specimens with little potash feldspar, and usually with little quartz and with more amphibole than pyroxene.

(b) Potash Feldspar. This varies from 0-20% but is rarely more than 15%. Microcline cross-hatching is sometimes observed; perthitic intergrowths, and micrographic intergrowths with quartz are also to be seen. The potash feldspar is interstitial, often poikiloblastic, sometimes skeletal, and, in specimens with but little of the mineral, is found as minute blebs within the plagioclase and frequently slightly elongated along the plagioclase cleavage. Where it mantles the plagioclase the /

the junction is often highly irregular, fingers of potash feldspar penetrating the plagioclase. The relation between the two minerals is clearly a replacement one. The potash feldspar often remains fresh and clear when the plagioclase has been partially decomposed.

(c) Quartz. Quartz is interstitial, normally as anhedral crystals which are optically continuous over an area often of 2 mm. but sometimes as much as 5 mm. in diameter. Quartz occurs as inclusions in crystals of plagioclase, biotite, and pyroxene. It is sometimes in micrographic intergrowth with potash feldspar. Rather shadowy extinctions suggest growth under conditions of stress. In some cases the relations of quartz to surrounding minerals are suggestive of development at the expense of its neighbours (e.g. plagioclase). The similarity in habit to that of potash feldspar suggests a similar type of origin.

(d) Biotite. Biotite is variable in amount, in dimensions, and to some extent in pleochroism. It is, however, a characteristic mineral in all the varieties. It is usually strongly pleochroic; X = pale-yellowish brown, or almost colourless, Y = Z = dark reddish-brown, foxy red, or almost black. Pleochroic haloes are common around inclusions of zircon and apatite.

The /

The crystals are usually poikiloblastic and frequently skeletal. Biotite is often moulded on pyroxene, amphibole, and ore, and may occur within pyroxene, amphibole, or plagioclase. Curved crystals are sometimes seen.

Alteration to pale-green pleochroic chlorite, in part as an aggregate and in part as single crystals, is sometimes observed. The single crystals show straight extinction, distinct pleochroism, and pleochroic haloes. Rutile needles, in three-fold clusters on the cleavage planes of the biotite, may develop with or without chlorite.

(e) Pyroxene. Pyroxene is generally rather abundant and, although the relative proportions are variable, orthorhombic pyroxene usually predominates over monoclinic. The crystals occur both as small rounded blebs and as larger crystals with rectangular development. The latter may reach elongations of 1.5 cm. but are usually not more than 2 mm. The small blebs are usually enclosed within the plagioclase and often have a zonal arrangement; the larger crystals are usually sieved. Crystals are occasionally seen with a massive centre and a crystalloblastic margin. Biotites enclosed in the pyroxene sometimes have a more foxy brown-red colour than the normal biotites of the rock. Clusters, about 2 mm. in diameter, of pyroxene granules are sometimes /

sometimes observed, usually in association with abundant minute, dark granules, often brown and almost opaque, which may be picotite. "Schiller" inclusions are common and herring-bone structure is often seen.

The orthorhombic pyroxene is variable in the intensity of its pleochroism. Commonly it is faint but definite from pale green-grey to pale red-grey. The optic sign is negative. Striations resembling twinning are frequently seen parallel to the elongation, and probably to (100).

The monoclinic pyroxene is very pale grey-green, almost colourless. $Z \wedge c = 40^\circ$. This diopsidic augite is sometimes seen to mantle the hypersthene.

(f) Amphibole. The pyroxene is frequently more or less thoroughly amphibolitised, and all stages between 100% pyroxene and 100% amphibole can be observed. Of the pyroxene-bearing specimens 25 contain hornblende, 13 being without it; of the specimens without pyroxene 25 contain hornblende, only 4 being without it.

The colour is very variable and patchy variation may be observed in single crystals. Green, brown, and colourless varieties predominate, but others of grey, yellow, and blue tones are also seen. $X < Y = Z$; $Z \wedge c = 20\text{-}28^\circ$. Haloes are sometimes seen round apatite inclusions.

In /

In the sense that one mineral mantles another, the following "reaction series" can be recognised:
hypersthene → diopsidic augite → colourless amphibole → brown amphibole → green amphibole → biotite.
This however is never complete in any one assemblage and hypersthene can be mantled directly by biotite. Amphibole may develop from pyroxene either marginally or along the cleavages.

(g) Accessories. Opaque Ore: this occurs in irregular grains or sometimes as peg-like rods. It is often rimmed with ferromagnesian minerals, especially biotite. Sometimes the ore and the enclosing biotite have ragged edges of a peculiar "cockscomb" type. In reflected light some of the ore shows a brass or bronze colour.

Apatite: this is variable in amount but is sometimes very abundant either as slender needles or more stumpy crystals. Pleochroic haloes are sometimes seen round apatite crystals, particularly when these are enclosed in biotite. This shows that the apatite is in part radioactive. Hollow crystals occur.

Zircon: this is a common accessory in small rounded grains. When enclosed in biotite it usually gives rise to pleochroic haloes.

Sphene: although sphene has been observed in these rocks it is of rare occurrence.

,In /

In addition to the minerals noted above, the rather doubtful, and certainly very rare occurrence of garnet, spinel, and orthite is tentatively recorded.

Part of the area was reconstructed by laying out specimens on the scale of eight feet to a mile. This reconstruction confirmed the impression gained in the field that the distribution of the numerous macroscopic varieties is in complete disorder.

Approximate modal analyses of 70 thin-sections were made, and various mineralogical classifications were devised. The only one of these giving a mappable geographic distribution of the different types was on the basis of the presence or absence of potash feldspar.

The percentage of potash feldspar in 20 selected thin-sections was determined by measurement on a Shand Stage. Standard powders were then prepared containing respectively 1% and 10% of potash feldspar. Powders of each of the 325 specimens were then compared with the standards and the results plotted on the six inch maps.

It is possible to draw a line (Fig. 2) separating rocks with less than 1% of potash feldspar from those with more than 1%. A marginal zone with 1-15%, and probably averaging about 10% of potash feldspar is separated from the (potash-feldspar /

feldspar-rich) "tonalite" of Gardiner and Reynolds by a zone with less than 1% of potash feldspar.

Conspicuous pyroxene and biotite tend to be restricted respectively to the marginal and inner zones. At one point, in the Balloch Lane, the potash-feldspar-rich marginal zone passes directly into the "tonalite".

To check the accuracy of the technique adopted, serial specimens were collected near the summit of Shiel Hill where the potash feldspar 1% line doubles back on itself in an S-shaped bend. As is shown in Fig. 3 the reality of this bend is confirmed in a remarkable manner.

It is clear that the so-called norite of the north-west part of the complex, and including the "tonalite" border facies mapped by Gardiner and Reynolds, may be subdivided into two types, (i) a marginal type with more than 1% of potash feldspar, and (ii) an inner type with less than 1% of potash feldspar.

It has already been stressed that emphasis should be laid on phases rather than on supposed rock species, but it is convenient to have two separate names for the two rock types just distinguished. To avoid controversy the recommendations of the 1921 Committee on British Petrographic Nomenclature are followed. This gives the following subdivision of the quartz-bearing plutonics:

Potash /

Potash feldspar dominant	Plagioclase dominant		
	Potash feldspar present	Potash feldspar absent	
		Less than An_{50}	More than An_{50}
Granite	Granodiorite	Quartz-diorite	Quartz-gabbr

According to this classification the "noritic" rocks under consideration are granodiorites and quartz-diorites. Teall termed the rocks "hyperite", but the 1921 Committee, of which Teall was a member, recommended that the name should be abandoned.

Quartz-diorite

Almost without exception the specimens of this type are biotite-quartz-diorites. Out of 21 specimens only 5 contain appreciable amounts of pyroxene. The remaining 16 are almost completely amphibolitised, 5 having more hornblende than biotite, 5 more biotite than hornblende, and 6 approximately equal amounts of these minerals.

Such /

Such rocks may be described as amphibolitised pyroxene-biotite-quartz-diorite.

<u>Granodiorite</u>

All but two of the specimens of this type are biotite-granodiorites.

Out of 44 specimens, 20 have both pyroxene and hornblende, 11 pyroxene only, 10 hornblende only, while 3 have neithe pyroxene nor hornblende.

Such rocks may be described as more or less amphibolitised augite-hypersthene-biotite-granodiorite.

(Note: Following convention, the more important mineral names are closest to the primary rock-name. In the case of "quartz-diorite", however, it is not meant to imply that quartz (of the rock name) is necessarily more abundant than, say, biotite.)

After reading a description of the augite-hypersthene-biotite-granodiorite of Loch Doon, Professor V.M. Goldschmidt (personal communication) writes:

"If the modal amount of biotite is comparable with about half the total amount of orthorhombic and monoclinic pyroxene, I think you are quite correct in naming the rocks opdalites ....I would not have the least objection to the use of the name "opdalite" for a rock considered to be of metasomatic origin if only the chemical and modal composition is near the original description. At the present time, when the truly magmatic or metasomatic /

metasomatic status of so many crystalline rocks is under discussion, we cannot afford to create two different sets of names."

(ii) Inclusions: their Origin and Evolution

Gardiner and Reynolds reported that while "tonalite" "frequently contains inclusions of altered sediments", inclusions in the "norite" are "very rare". This view is unfounded. Although to estimate the proportion of inclusions is a matter of great difficulty, it is believed that inclusions are as numerous in the "norite" as they were recognised to be in the "tonalite". That inclusions in the "tonalite" should attract attention during the preliminary surveys, while those in the "norite" passed unnoticed, is easy to understand. The inclusion being dark, are conspicuous only where they occur in light-coloured "tonalite"; where enclosed in dark "norite" they must be specially searched for. Moreover, inclusions in "tonalite" are usually upstanding from the weathered surface, while those in "norite" have more often weathered at the same rate as the enclosing rock. This difference of response to weathering reflects on a small scale the relative strengths of the three rock-types in the topographic relief.

Obvious inclusions in the "norite" may measure as much

as /

as twenty yards in maximum diameter, but examples more than three yards in diameter are uncommon. More frequently the diameter of the inclusions is under two feet, and many thin-sections of "norite" show inclusions of microscopic dimensions. Rocks which were referred to during the first field-season as "patches of fine-grained ?norite" (measuring 10 to 250 yards in diameter), have since been found to differ in no respect other than magnitude from some of the inclusions measuring five or six inches. They are, in fact, very large inclusions.

On occasion, proof that some of the inclusions are altered sediments is shown by preservation, either of angular quartz grains, identical with those in the greywackes, or of sedimentary bedding, which, where it has been observed, is always parallel to that of the adjacent aureole-rocks. (v. rare)

The few inclusions found to contain detrital quartz grains occur on the north side of Shiel Hill. Petrographically these closely resemble the "nodules" occurring in the aureole, but whereas the inclusions are up to ten feet in diameter, the "nodules" are seldom more than one foot. The quartz grains are about 0.5 mm. in diameter and, with round granules of diopside averaging 0.05 mm. are set in a fine-grained matrix. Such rocks are similar to those described as diopside-hornfels by M. MacGregor (1937, p. 470; 1938, p. 484) and by D.L. Reynolds (1943, p. 235).

Every /

Every gradation can be traced from these 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 "norite" of the complex. While the inclusions represent a variety of petrographic types, the majority belong to the diopside-hornfels - opdalite series, as do also the innumerable large and small "patches of fine-grained ?norite".

The series evolves by the more or less successive development of four minerals:

(a) Pyroxene:

Early development of granular pyroxene is characteristic. In the early stages diopsidic augite normally predominates but as evolution advances, and in particular when porphyroblasts of pyroxene appear, hypersthene usually becomes the dominant form. In some specimens pyroxene is almost absent, whereas in others it may form more than 50% of the rock. The extraordinarily varied character of the pyroxene extends even to the colour which varies from colourless, to distinctly green in monoclinic varieties, and from almost colourless, to strongly pleochroic in red and green in orthorhombic varieties. Diopside sometimes mantles the hypersthene, but this is not commonly seen. "Schiller" inclusions are common and are occasionally so densely concentrated /

concentrated that some of the crystals are almost completely opaque. Aggregates up to 8 mm. across occur; in these the pyroxene is usually associated with ore and with a little biotite.

(b) Plagioclase

Contrary to the sequence in the aureole, plagioclase here develops after the pyroxene. At first it is highly crystalloblastic, and even in later stages the crystals are often curved, and the bigger ones characterised by typical internal irregularities. Inclusions of pyroxene granules are common, being arranged zonally in some of the plagioclase crystals. The crystals are occasionally heavily dusted with minute inclusions, but others remain quite clear. In the more advanced stages of the series, the crystals have characters identical with those of the "norite" plagioclase (P. 51); "norite" is, indeed, a member of the series.

(c) Potash Feldspar

As in the aureole, potash feldspar appears after the plagioclase, and at the expense of the latter. It often "fingers" along the cleavages and sends "veins" into the plagioclase, as well as mantling it. Its development and habit are the same as in the opdalite of the complex (p. 54).

(d) /

(d) Biotite

This rarely becomes conspicuous until a late stage in the evolution of the series. When it does develop it is always skeletal and typically crystalloblastic. Very rarely biotites as large as 1-2 cm. in diameter have formed; these have a marked foxy-red pleochroism and are associated with colourless amphibole.

Other minerals occurring in the rocks of this series are:

Opaque ore: Normally this is rather abundant, but its distribution is patchy and it may be almost absent from some parts of the same inclusion. Some of the ore has a brass or bronze colour in reflected light. When plagioclase begins to develop the ore is occasionally segregated into patches.

Rounded zircons are common and apatite needles are locally abundant. Green and colourless hornblende are sometimes present, and green spinel occurs sporadically.

Among inclusions other than those of the diopside-hornfels - opdalite series, the commonest are characterised by abundance of biotite and poverty of pyroxene. The biotite is foxy-red or grey-brown in colour, and sometimes has curious "frayed" /

"frayed" edges which are believed to be crystalloblastic in origin. Plagioclase is often untwinned and poikilitic, while potash feldspar with its typical replacement habit is sometimes present, sometimes absent. In some of the biotite-rich inclusions large euhedral plagioclase crystals, identical with those of the "norite", occur as porphyroblasts. Green spinel is often abundant.

The inclusions of microscopic dimensions sometimes seen in thin-sections of "norite" are always more fine-grained than the enclosing rock. They are characterised by an abundance of granules either of opaque ore or of red spinel. Small biotites are usually abundant and these may locally be in approximate parallelism, as if representing an early stage in the formation of skeletal crystals. Plagioclase is common, and where determinable has the same composition as that in the enclosing "norite". Quartz and orthoclase are absent. A little pyroxene or amphibole is sometimes present.

Although macroscopically the junction between inclusion and "norite" is normally sharp, in thin-section it is seldom so well defined. Frequently the mineral assemblages of both inclusion and host are the same and the distinction between the two rocks may then depend on degree of granularity, slightly less well developed crystalloblastic textures in the host, or relatively greater abundance of ore in the inclusion.

Of /

Of the numerous inclusions which have been observed and studied all but two individuals are considered to be derivatives from sedimentary rocks. This view is based on (a) the fact that many of the inclusions are linked in petrographic series to inclusions which retain sedimentary structures, and (b) that the remainder are rich in biotite, contain abundant spinel, and sometimes show relics of bedding.

The two exceptions are considered to represent members of the Caledonian lamprophyric (and related types) dyke-swarm (p. 124) intruded immediately prior to the formation of the rocks of the complex. The first, measuring 12 feet in diameter, occurs on the south-west side of Shiel Hill. In thin-section it is seen to consist of small semi-parallel laths of plagioclase about 0.25 mm. in elongation, with interstitial blades of pale green hornblende. The second, measuring five or six inches in diameter, was found on the east side of Cornish Hill. It consists of numerous and conspicuous prisms of brown hornblende, sometimes 5 mm. or more in length and often with zoned colouration, with a few small and rather stumpy crystals of plagioclase, set in a grey cryptocrystalline base. Brass coloured ore is rather common. (cf. Teall 1899, pp. 628, 630-1 ; Gardiner and Reynolds 1932, pp. 25-6)

The interest of these two camptonitic inclusions lies in the evidence they provide with regard to the age of the complex /

complex. As some members of the Caledonian "lamprophyric" suite cut the rocks of the complex and others, even though rarely, are enclosed within it, it is clear that while the complex is earlier than the period of maximum injection of dykes, the dykes and complex do overlap in time.

(iii) Summary of Evidence Bearing on the Petrogenesis of the So-called Norite.

The following phenomena demonstrate that the minerals of the "norite" crystallized (or re-crystallized) in a solid and not in a liquid medium:

(a) Internal irregularities are present in the plagioclase (cf. p. 40)

(b) The manner in which inclusions are "trapped" along the boundaries of the individuals composing the plagioclase porphyroblasts.

(c) The inclusions of pyroxene granules in the plagioclase of the "norite", and the fact that they are genetically related to the biotite inclusions in the plagioclase of the feldspathised granulite.

(d) Large and small plagioclase crystals have the same range of composition.

(e) Continuous and oscillatory zoning can co-exist in neighbouring plagioclase crystals, or even in the same individual.

(f) Plagioclase crystals are often curved.

(g) /

(g) In all their individual characters, the plagioclases both of the "norite" and of the feldspathised granulite (the non-magmatic genesis of which has been demonstrated above) are identical.

(h) The potash feldspar has a replacement habit, in particular in relation to the plagioclase.

(i) The biotite, and to some extent the quartz also, has a poikiloblastic and skeletal character.

(j) The biotite is sometimes curved.

(k) The pyroxene is often crystalloblastic.

(l) The pyroxenes of the "norite" and of the pyroxenised granulite (the non-magmatic genesis of which has been demonstrated above) are identical.

(m) The amphibole seems everywhere to have developed from the pyroxene.

(n) Small rounded grains of zircon are present as in the granulite.

It is important to recall that in the preliminary survey of the complex Gardiner and Reynolds (1932, p. 14) recognised that at least part of the "norite" has textures which are not explicable in terms of simple crystallization from magma. They based that view on the following evidence:

(a) "The development of small pyroxenes in some of the felspars leading to a kind of granulitization" (italics mine).

(b) "The replacement of some of the pyroxenes by actinolite".

(c) "The frequent development of brown hornblende and biotite at the margins of the pyroxenes".

(d) The "curious turbidity sometimes to be seen in the felspars".

(e) Occasional "signs of shattering" to be seen in thin section

(f) /

(f) In one specimen "the earlier felspars are bent".

These phenomena were attributed to the intrusion of "tonalite" after the "norite" had undergone normal magmatic crystallization; to "contact alteration" and to "hybridization". Gardiner and Reynolds concluded that "It is probable that a large part of the Loch Doon norite is to some extent affected (by contact alteration), but we have no evidence to lead us to believe that this is the case with the whole". It is, of course, certain that simple heating could not cause the development of small pyroxene granules within plagioclase crystals. Although Gardiner and Reynolds never considered the possibility that the pyroxene-granulite led to the "norite" and not vice versa, they did realise that something more than simple crystallization was required to explain the textures of the "norite".

The order of crystallization of the minerals in the Loch Doon "norite" has not been determined in the course of the present investigation, for the evidence given above demonstrates that crystallization of the component minerals has been more or less simultaneous, as in metamorphic rocks. In 1946 S.R. Nockolds published a paper (1946, p. 206) on "The Order of Crystallization of the Minerals in some Caledonian Plutonic and Hypabyssal Rocks". As the criteria adopted in the determination of the order of crystallization are not given, the sequence stated is open to question. The supposed order of crystallization /

crystallization determined by Nockolds has been shown by the present writer (1946, p. 291; 1947, p. 119) to be inconsistent with the principles of phase-rule chemistry. It must therefore be supposed that the rocks dealt with by Nockolds do not owe their textures to crystallization from magma. As his paper included the Galloway Granites (Loch Doon was not, however, mentioned specifically), we have here another line of evidence - assuming Nockolds' order to be correct - showing that the minerals of the "norite" crystallized (or re-crystallized) in a solid and not in a liquid medium.

Two possibilities are now evident: does the "norite" represent (i) igneous rocks which, after normal magmatic crystallization, have lost to some extent their primary igneous texture by the action of subsequent metamorphism; or (ii) rocks of sedimentary origin which, by reactions in the solid state, have been feldspathised and pyroxenised, basified and desilicated, and in this way have acquired a pseudo-igneous texture? Is the crystalloblastic texture (i) igneous texture "going", that is, being lost by later metamorphism, or (ii) igneous, or pseudo-igneous, texture "coming", that is, being produced in non-igneous rocks as a consequence of solid diffusion?

The solution of this problem may be reached by three independent lines of evidence:

1. /

1. <u>The distribution of crystalloblastic texture in relation to geological structure.</u> If the crystalloblastic "norite" is an igneous rock which, by metamorphic action, has partly lost its igneous texture, one would expect to find, (i) a sharp break between the aureole and thoroughly igneous-looking "norite", (ii) the "norite" becoming increasingly crystalloblasti away from the aureole, and (iii) an intrusive contact between highly crystalloblastic "norite" and thoroughly igneous, and perhaps chilled "tonalite".

If the crystalloblastic "norite" is a non-igneous rock which, by changes attendant on solid diffusion, has acquired a pseudo-igneous texture, one would expect to find (i) gradational types between the "norite" and the rocks of the aureole, (ii) the "norite" becoming decreasingly crystalloblastic away from the aureole, and (iii) the absence of an intrusive contact between "norite" and "tonalite", and perhaps (iv) signs of crystallo-blastic texture in the latter also.

What, in fact, is found is (i) highly crystalloblastic "norite" against the aureole, and the occurrence of intermediate types between these, (ii) that the less crystalloblastic types are distributed patchily throughout the mass, (iii) that the "tonalite" is as crystalloblastic against the "norite" as the latter is against the former, and (iv) detailed phenomena, such as the development of pyroxene granules within the plagioclase, inexplicable /

inexplicable by simple contact alteration.

This evidence shows that the crystalloblastic "norite" represents a more advanced stage of alteration of the greywackes than do the granulites of the aureole. The distribution of crystalloblastic textures demonstrates a non-magmatic genesis of the Loch Doon "norite".

2. The changes in the aureole rocks as they are traced towards the contact. These changes have been detailed above, where it is shown that plagioclase, potash feldspar, and pyroxene (both orthorhombic and monoclinic) are successively developed in the granulite at isolated loci in the neighbourhood of the contact. Mineralogical and chemical evidence indicates that these crystals grew in the solid by the addition to the rocks of the appropriate elements, and not by the insoaking of "feldspathic" or other liquids. Mechanical consideration had already precluded forcible introduction of the crystals as such. Through the chemical and mineralogical changes thus undergone by the granulite that rock is indistinguishable from some of the fine-grained varieties of "norite". When the granulites of finer grain were affected, these changes coincided with an abrupt coarsening of grain size. The process was therefore one of homogenisation.

The /

The individual porphyroblasts in the aureole "pods" are identical in habit and other characters to the same minerals occurring in the "norite". This is so striking in the case of plagioclase, with its numerous oscillations of composition, its internal irregularities, its inclusions, and its form, that there is no room for doubt that the porphyroblasts, both of the aureole and of the "norite", have the same origin.

The evidence furnished by the changes in the rocks of the aureole demonstrates that the crystalloblastic texture of the "norite" is a pseudo-igneous texture developed by the same process which metamorphosed the greywackes in the aureole, but which, in the production of "norite", was carried further and with greater intensity. The changes in the aureole are stages in a process involving solid diffusion and resulting in "norite".

3. <u>The relation of the inclusions to the sedimentary rocks of the aureole and to the "norite".</u> As is described above, amongst the inclusions are some of diopside hornfels, of undoubted sedimentary origin. All gradations are found between such inclusions and others of fine-grained "norite". It is therefore beyond doubt that those inclusions of fine-grained "norite" are sedimentary rocks which have changed mineralogically /

mineralogically and texturally in response to change of physico-chemical environment, and this conclusion is as valid for the inclusions measuring 250 yards in diameter as it is for those only a few inches across. But such mineralogical changes cannot take place without change of composition, and, indeed, chemical analyses show that the fine-grained "norite" lying within the mass is actually a little more altered than the pyroxenised and feldspathised granulite of the aureole. There is now no corundum in the norm, and the rock is chemically and mineralogically an opdalite. The biotite-rich inclusions are probably to be interpreted as relics of the more flaggy beds in the original greywacke series.

This demonstration that the numerous large and small patches of fine-grained "norite" are altered sedimentary rocks is of the utmost significance, for the fine-grained "norite" is as much an integral part of the complex as is the coarser rock. Both are intimately intermixed in their field-association, and there is every gradation, mineralogical, textural, and chemical, from the one to the other. The junctions of actual inclusions with their hosts, though sometimes gradational, are, however, usually sharp.

The relations of the inclusions to the sedimentary rocks of the aureole on the one hand, and to the "norite" on the other, demonstrate that the whole body of "norite" represents altered /

altered sediments. Feldspathisation and pyroxenisation, basification and desilication, have caused these metamorphosed sedimentary rocks to acquire a pseudo-igneous texture, and the inclusions are to be interpreted as masses of the original rocks which have been altered to a different degree from their surroundings and nearly always to a less degree. Most of the inclusions represent relics of early stages in the evolution of their hosts.

These three independent lines of evidence thus lead to the same conclusion, namely, that the so-called norite of the north-west part of the Loch Doon complex, 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.

X /

X. THE PETROLOGY OF THE SO-CALLED TONALITE

(i) Petrography and Mineralogy

As determined by study of 60 - 70 serial specimens from the "norite" of Craigbrock to the granite south of the Black Garpel, the so-called "tonalite" of the Loch Doon complex consists of plagioclase, potash feldspar, quartz, biotite, and hornblende. Plagioclase is in excess of potash feldspar, but as the latter is an essential component, the term tonalite is inappropriate. Biotite is normally in excess of hornblende, and the rock is thus properly described as hornblende-biotite-granodiorite.

(a) Plagioclase. Plagioclase is in excess of potash feldspar and has the same characters as the plagioclase of the "norite". Zoning from about An_{50} to An_{25} is rather common, and oscillatory zoning with 15 or more zones is occasionally met with. Internal irregularities are frequent and curved crystals occur. Inclusions, usually of hornblende granules but sometimes of biotite or pyroxene, are locally abundant.

(b) Potash Feldspar. Microcline and untwinned potash feldspar are much more abundant than in the "norite", but have the same habit as in that rock. Small blebs are common through-out /

throughout the plagioclase and are often elongated along the plagioclase cleavages. Innumerable examples of "veining" and "corrosion" show that potash feldspar develops at the expense of the plagioclase.

(c) Biotite. The most abundant ferromagnesian mineral is biotite. It is often poikiloblastic and sometimes skeletal. Pleochroism is in rather redder tones than is common in the "norite". Pleochroic haloes, often intensely developed, are abundant.

(d) Hornblende. Hornblende is usually, but not always present. The colour is patchy, usually green, but sometimes brown or almost colourless. On occasion, hornblende is more abundant than biotite. Clots, about 2 mm. in diameter, of ferromagnesian minerals, especially hornblende, are fairly common. Pyroxene relics are sometimes found within the hornblende, and have been observed as far from the outcrop of pyroxene rocks as the south-east of Loch Macaterick.

Accessories. The accessories apatite, zircon, ore, sphene, and epidote occur, and sphene is more common than earlier descriptions suggest. Epidote is probably an alteration product of /

of the ferromagnesian minerals.

(ii) <u>Relation of the "Tonalite" to the "norite" of the North-West Corner of the Complex.</u>

The light colour of the "tonalite" contrasts with the dark colour of the "norite", and the gradual passage between the two rocks is easily seen in the field. On the eastern slopes of Shiel Hill, above the Balloch Lane, 25 serial specimens were collected, along a line 100 yards long, to demonstrate the gradation. All the specimens have been sectioned.

The gradation apparent macroscopically is confirmed under the microscope. It essentially involves a decreased content of ferromagnesian minerals; increase of quartz and potash feldspar; and conversion of pyroxene to amphibole, and to a lesser extent to biotite. It is therefore not surprising that relics of pyroxene are common in the "tonalite" where it approaches the "norite", and may occur even at a great distance from it.

Highly crystalloblastic "norite" is found against the aureole, at a maximum distance from the "tonalite". It is likewise significant that the "tonalite" is as crystalloblastic (e.g. with skeletal biotite) against the "norite" as the latter is against the "tonalite".

(iii) /

(iii) Relation of the "tonalite" to the rocks of the Aureole.

Gardiner and Reynolds state (p. 11): "Throughout a large part of the tonalite-hornfels margin 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. In some cases this basic marginal variety of the tonalite contains augite ...... There are also large parts of the margin where the normal tonalite is found in contact with the altered sediments. The dark marginal form of the tonalite, with its high density and large proportion of biotite, bears considerable resemblance to the dark basic patches found here and there in the normal tonalite". The relation of "tonalite" to the rocks of the aureole was not examined thoroughly during the present investigation and the augite-bearing "tonalite" described by Gardiner and Reynolds has not been studied.

On page 11 of their paper, Gardiner and Reynolds state "on the south-east and south-west of Craigmulloch Hill, which lies about 2 miles north-west of Craigmulloch Farm, the contact zone is particularly impressive, innumerable masses of hornfels, large and small, being enclosed in the tonalite, while tongues of tonalite penetrate the hornfels. Sometimes the igneous rock has thoroughly impregnated the metamorphosed rock in a manner well /

well-known in connexion with the Caledonian intrusions elsewhere in Scotland". Those exposures have been examined and many thin sections prepared. The interpenetration has actually been of a more subtle type than is suggested by the description quoted. In many of the sections it is not possible to separate the minerals into those belonging to the granulites of the aureole and those belonging to the "tonalite". A rather reddish biotite is common to both but, when occurring in undoubted "tonalite", is usually developed as larger crystals. Porphyroblasts of plagioclase occur in the rocks of the aureole and have the same composition and characters as the plagioclase of the "tonalite". Examples of oscillatory zoning from core to margin are given below, but the figures refer only to the major zones; crystals with more than 30 oscillations of zoning have been observed:

30-35 → 45-50 → 30-35 → 40 → 30 → 20-25

50-55 → 75 → 45-50 → 55 → 40-45 → 30 → 40 → 30-35 → 40 → 35 → 30 → 40-45 → 45-50 → 40-45 → 35 → 30 → 15-20

One rock (707) from the aureole exposures of Craigmulloch Hill consists of decussate biotites set in a background of elongated laths of plagioclase, with only a little quartz as interstitial grains. Zircon and apatite are also present.

On /

On Craigmulloch Hill the colour contrast between the aureole and the "tonalite" makes the intricacy of the contact conspicuous in the field. Isolated pods have formed in the aureole and these are essentially examples, on a larger scale, of the same phenomenon as plagioclase porphyroblasts. Where bedding is preserved the inclusions retain their parallelism. Some of the inclusions have margins very rich in biotite. "Veins" of "tonalite" are sometimes seen cutting sharply across the granulites, but in thin-section the rock of such veins is petrographically the same as that of the normal "tonalite" of this locality and has, one must suppose, the same genesis.

(iv) Inclusions: their Origin and Evolution

The number and variety of the inclusions in the "tonalite" is indeed very great, and, as the main object of the present investigation is the study of the petrogenesis of the "norite", it is not to be supposed that the sampling of the inclusions has necessarily been complete. Nevertheless several new observations have been made, and, as these are of considerable petrogenetic significance, it is considered worth while to record them. Future work will, doubtless, lead to some modifications and extensions of the conclusions here drawn from the evidence now available.

Gardiner /

Gardiner and Reynolds recognised that the "tonalite" "frequently contains inclusions of altered sediments", and recor:ded that these have been found "not only near the boundary but at considerable distances from it, as, for instance, 1200 yards distant at a spot west of Ballochling Loch, and, again, near the southern end of Loch Dee about 2000 yards from the present boundary". (1932, p. 11). In the present investigation, inclusions in the "tonalite" were observed <u>throughout</u> the traverse from the "norite" of Craigbrock to the granite south-east of the Black Garpel, and a considerable number have been collected and sectioned. The point on that traverse most distant from the aureole is east of Loch Macaterick, and about 4,400 yards from the present boundary.

Many of the inclusions are relatively fine-grained and with sharp junctions against the surrounding "tonalite". Most commonly the matrix of these consists of grains and stumpy laths of plagioclase, with or without quartz. Some of the inclusions are biotite-granulite with a little muscovite and plagioclase, and often with a little green spinel. Biotite is characteristic - some specimens are highly biotitic - usually highly sieved and often redder than the dominant biotite of the "tonalite". Small grains, or, more rarely, highly sieved porphyroblasts, of green hornblende are common, and sphene is often /

often developed in association. Monoclinic pyroxene is nearly always present either as individual grains or as relics enclosed by the hornblende. Potash feldspar is usually absent, but when present, as locally happens, it is poikiloblastic. Strings of bronze-coloured ore, often associated with biotite, traverse many of the inclusions. These strings often intersect each other and do not represent heavy mineral bands of sedimentary origin.

A rather coarse-grained and somewhat more igneous-looking type of inclusion, characterised by poikiloblastic plates of potash feldspar, is also rather common. Biotite is usually skeletal and has the same pleochroism as the biotite of the "tonalite". Sieved porphyroblasts of green hornblende are characteristic, and these very often contain relics of pyroxene. Hornblende-biotite-sphene clusters occur as in the "tonalite" itself. Zoned plagioclase porphyroblasts with internal irregularities and numerous inclusions of biotite and hornblende, and sometimes of pyroxene granules as in the plagioclase of the "norite", are usually conspicuous. Quartz is interstitial. Numerous rather fine needles of apatite are present. Such inclusions are never so sharply defined from their "tonalite" host as the finer-grained inclusions are, and, indeed the contacts are often quite gradational. Some of the coarse-grained /

grained inclusions are ill-defined against the "tonalite"; others are mere "ghosts" now hardly distinguishable from the "tonalite" itself. It is significant that the hornblende of the "tonalite" in the vicinity of these coarse-grained inclusions more often contains pyroxene relics than in the normal rock.

The finer-grained inclusions occasionally contain patches which are transitional to the coarser-grained and more igneous types. There is little doubt, therefore, that there is an evolutionary sequence from relatively well-defined inclusions through ghost-like remnants to "tonalite".

(v) Summary of Evidence Bearing on the Petrogenesis of the So-called Tonalite

It has been demonstrated above that the "norite" of the north-west part of the complex represents the Ordovician sediments in a highly altered condition, the alteration being caused by the diffusion, fixation, and expulsion of chemical elements (probably in ionic condition) within the solid rocks. Previous investigators assumed that the three main rock-types of the complex, "norite, "tonalite", and granite, were the crystallized differentiates from a once homogeneous magma. Having shown that one of these rocks is metamorphic rather than /

than igneous, it is at once evident that the other two can no longer be assumed to be magmatic. The work carried out during the present investigation has not been exhaustive whether on "tonalite" or on granite. Further research is desirable to provide a wealth of detail. Nevertheless, the writer is satisfied that sufficient data are now available in the light of which the rivalry between the Magmatic and Solid Diffusion hypotheses can be decided.

Four independent lines of evidence throw light on the genesis of the "tonalite":

1. Mineralogy and texture

(a) Internal irregularities are present in the plagioclase.

(b) The manner in which inclusions are "trapped" along the boundaries of the individuals composing the plagioclase porphyroblasts.

(c) The inclusions of hornblende granules in the plagioclase of the "tonalite", and their genetic relation to the pyroxene inclusions in the plagioclase of the "norite", and to the biotite inclusions in the plagioclase of the feldspathised granulite.

(d) Continuous and oscillatory zoning co-exist in neighbouring plagioclase crystals, and even in the same individual.

(e) Plagioclase crystals are sometimes curved.

(f) In many of their individual characters the plagioclases of "tonalite", of "norite", and of feldspathised granulite, are identical.

(g) The potash feldspar has a replacement habit, in particular in relation to the plagioclase.

(h) /

(h) The biotite has a poikiloblastic and sometimes skeletal character.

(i) Pyroxene relics are often found within the hornblende, forming a link with the amphibolitised pyroxene of the "norite" and of the inclusions.

(j) As described above (p. 72), the order of crystallization in similar rocks as determined by Nockolds, has been shown by the present writer to preclude a magmatic genesis

(a-i) implies that the "tonalite" preserves definite traces of the crystalloblastic textures so well developed in much of the "norite".

2. Relation to the aureole. The growth in the sedimentary rocks of the aureole of complex plagioclases identical to those of the "tonalite", the development of obviously "mixed rocks" or migmatites, and the occurrence of augite-bearing "tonalite" along a large part of the "tonalite"-aureole contact, are of obvious significance. To write that "the tendency ..... shown by the tonalite to become more basic at various points along the line of junction with the sediments may be attributed to differentiation and marginal segregation of the more basic constituents" is not an explanation of the phenomena as they have been observed in detail and analysed above.

3. The Relation to the "norite" of the north-west part of the complex. Gardiner and Reynolds write (1932, p. 16) "On the whole, it seems probable that the relation of the norite to the /

the tonalite is best explained on the supposition that the tonalitic followed very shortly after the noritic intrusion. The temperature of the country rock at the time of the noritic intrusion seems to have been so high that no definite chilled margin was formed. Similarly, at the time of the tonalitic intrusion, the norite, though practically completely consolidated, appears to have been still so hot that there was little or no chilling of the tonalite against it, or inclusions of blocks of norite in the tonalite. On the other hand, much of the sedimentary rock was sufficiently cold to chill the tonalite margin ....There is, occasionally, definite evidence that the norite was completely consolidated prior to its invasion by the tonalite. ....On the other hand, the extreme scarcity of xenoliths of norite in the tonalite is remarkable if the norite was completely solidified prior to the tonalitic intrusion. The acceptance of the conclusion that the norite was completely solidified prior to the advent of the tonalite implies that in places where a rock of transitional type is found the host of the tonalite was sufficient to partly liquefy the norite and allow diffusion to take place".

If the rocks of the complex are to be accounted for by crystal differentiation, then it must be emphasised that "norite" is a higher temperature differentiate than "tonalite". If /

If the temperature in the magma chamber was low enough to allow "tonalite" magma to be differentiated, the intruded body of "norite" (whether liquid or crystal accumulate) must have become essentially solid. There can be no evasion of the conclusion "that the norite was completely solidified prior to the advent of the tonalite".

Now, on the intrusion of "tonalite", the "norite" must have disappeared as if by magic, for "the extreme scarcity of xenoliths of norite in the tonalite" shows that stoping did not take place, just as the presence of unfractured roof-rocks shows that there was no upward displacement. But further, despite the fact that the country rocks must have been at so high a temperature that the intruded "norite" (itself a high temperature differentiate) did not chill; and despite the fact that the temperature of the country rocks must have been raised by the intrusion of the hot "norite", and the still further fact that intrusion of the "tonalite" came so swiftly after the "norite" that the latter was not cool enough to chill it; despite all these circumstances, the "tonalite", a low temperature differentiate, not only chilled against the country rocks, but actually fused the "norite" with which it came into contact, baked most intensely that furthest from it, and was itself baked against it - presumably by a supposed flow-back of heat from the baked /

baked "norite", i.e. by autometamorphism. Such an array of inconsistencies and contradictions shows that crystal differentiation is incompetent to explain the phenomena observed, even without considering the evidence that the "norite" is not an igneous rock.

The "tonalite" magma cannot be appealed to as the source of the basic emanations which converted the sediments into "norite", for (i) their composition is not that of a possible residuum from "tonalite" magma, (ii) alkaline emanations acted on the sediments actually in contact with "tonalite", (iii) no explanation would be forthcoming for the gradation from "norite" to "tonalite", for the crystalloblastic texture of the "tonalite" near the "norite", or for the existence of pyroxene relics within the hornblende of the "tonalite".

4. The Inclusions. The inclusions in the "tonalite" show an evolutionary sequence from undisputed sedimentary types, through more or less igneous-looking types and ghost-like relics, to "tonalite". Just as the sequence from "norite" to "tonalite" involves the conversion of pyroxene to amphibole, so also does this evolutionary sequence. From both points of view the occurrence of pyroxene relics within hornblende is of great significance.

The /

The inclusions show that it is possible - at any rate on a small scale - to convert sediments into "tonalite", with, of course, change of composition. The gradation from the sediments through the "norite" to "tonalite" shows on a big scale that it is possible to convert sediments into "tonalite", again, of course, with change of composition. In both cases the change is accomplished through pyroxene-bearing types, i.e. with basification of the original rocks before the granitization of the basified products. The pyroxene-bearing types are interpreted as the basic front in which the constituents driven from the zones of granitization were fixed. The tendency "shown by the tonalite to become basic at various points along the junction with the sediments" finds here a more rational explanation than attributing it "to differentiation and marginal segregation of the more basic constituents", as supporters of the magmatic hypothesis are compelled to do. It is believed that the degree of basicity achieved in the basic front at any particular point depends in large measure on how far the front is concentrated and how far it is dispersed through a large volume of rock.

All four lines of evidence (1-4 above) point in the same direction, namely that continuation of the same process which /

which produced "norite" was responsible for the genesis of the "tonalite"; that the "tonalite" is not an igneous rock, but represents the Ordovician sediments in an advanced stage of alteration - first basified, then granitised.

XI. THE PETROLOGY OF THE GRANITE

(i) Petrology and Mineralogy

The granite of the central ridge is a true granite, being rich in quartz and having potash feldspar in excess of plagioclase. The potash feldspar consists of microcline and untwinned crystals, both types up to 2 cm. in length. These large crystals of potash feldspar are not normal phenocrysts, a fact fully realised by Teall when he wrote (1899, p. 611) "the alkali-felspar 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." (Italics mine). They are, in fact poikiloblastic, and contain inclusions of many of the other minerals, especially of rounded grains of quartz.

Plagioclase is less abundant than the potash feldspar, but is still an essential constituent. Internal irregularities are present and inclusions are sometimes common; these consist mainly of biotite and hornblende. One individual showing oscillatory zoning was determined to have the following composition:

$$15\text{-}20 \rightarrow 30 \rightarrow 15\text{-}20 \rightarrow 30 \rightarrow 15\text{-}20$$

The ferromagnesian minerals are less abundant than

in /

in the "tonalite", but both biotite and hornblende are present in all the sections which have been prepared. Biotite is generally the more common; it shows intense pleochroism, but lacks redder tones, and has pleochroic haloes. Biotite sometimes shows a slight tendency towards the development of skeletal form. Hornblende is usually green, but is sometimes brown, and sometimes colourless. A pyroxene relic was observed in the interior of one of the hornblende crystals. Zircon is an accessory, but is not conspicuous. Clots of hornblende-biotite-sphene occur sporadically.

(ii) Relation of the Granite to the "Tonalite".

Gardiner and Reynolds record that "So far as our observations go, the white, coarse-grained granite of the central ridge is everywhere separated from the normal tonalite by a rock of transitional character". During the present investigation this transitional zone was examined immediately to the south of the Black Garpel, where serial specimens were collected from which sections have been prepared. The transition recorded by earlier workers is confirmed. As the "tonalite" is traced towards the "granite" the number and size of the potash-feldspar porphyroblasts gradually increases and the proportion of the dark constituents decreases.

(iii) Inclusions: their Origin and Evolution.

No detailed examination of the granite or of its inclusions has been carried out in the course of the present investigation. Previous workers did not find inclusions in the granite of the central ridge, but the present writer, in a brief reconnaissance, found inclusions both in the transitional zone and in the true granite itself, right on the crest of the central ridge. The reconnaissance, though not sufficient to enable the abundance or variety of inclusions to be estimated, made it evident that inclusions in the granite are not rare.

The inclusions collected were of uniform type; granules of monoclinic pyroxene, often mantled by green-brown hornblende, biotite, and laths of plagioclase with typical internal irregularities, are embedded in poikiloblastic plates of microcline with a little quartz. Fine apatite needles are rather abundant, and clots of the ferromagnesian minerals were found. The similarity of such inclusions to the more igneous-looking inclusions of the "tonalite" is obvious, and makes clear their genetic relationship.

(iv) Summary of Evidence Bearing on the Petrogenesis of the Granite. The problem of the petrogenesis of the granite closely resembles /

resembles that of the "tonalite" dealt with above. The mineralogical evidence indicates, as in the "tonalite", growth in the solid, and this hardly requires detailed re-tabulation; it is, however, rather less clear than in "tonalite", with the notable exception of the potash feldspar, the "pseudo-porphyritic nature of which was recognised by Teall.

The significance of the gradation from "norite" to "tonalite" has been analysed above and is paralleled in almost every respect by the gradation from "tonalite" to granite; the points stressed above do not need repetition now. It should nevertheless be pointed out that while, by assuming the transitional semi-porphyritic zone to have originated in or through the mixing of porphyritic and non-porphyritic magmas, it may be possible to explain the decreasing number of phenocrysts towards the "tonalite", it is not possible thus to explain their decrease in size. In view of Teall's observation that the potash feldspar is "pseudo-porphyritic", i.e. porphyroblastic, even the distribution of the "phenocrysts" cannot be explained by mixing of magmas.

Sufficiently detailed work has not been carried out on the inclusions in the granite to determine an evolutionary sequence in these. If, however, the inclusions are inclusions of "tonalite" - as must be assumed if granite magma broke its way /

way into earlier "tonalite" - it is most remarkable that those inclusions which have been examined are without exception pyroxene-bearing. The "tonalite" hornblende contains relics of pyroxene, thus showing that pyroxene was not a stable phase in the supposed "tonalite" magma. The granite also shows this phenomenon, though much more rarely, thus suggesting that the pyroxene was even more unstable in the supposed granite magma than it was in the "tonalite". What incentive would a block of "tonalite" immersed in the "granite" magma have for the conversion of its hornblendes into pyroxene? Even if some reason could be given, the inclusions themselves patently show that the pyroxene was being converted to hornblende and not vice versa. Where, one may ask, are the stoped blocks of "tonalite"?

The similarity of the inclusions in the granite to the more igneous-looking inclusions in the "tonalite" is so marked as to put beyond question their identical genesis. The inclusions must therefore be regarded as (i) relics of earlier stages in the evolution of their host, and (ii) as concentrations of the basic materials driven from the materials being granitised. In this connection the clots of hornblende-biotite-sphene which are widespread in these rocks are significant, and it is hardly necessary to emphasise that a single crystal of hornblende is, though on a small scale, as basic as an amphibolite.

These /

These considerations make the conclusion inevitable that the granite of the central ridge represents the country rocks in an extreme state of alteration, and that, before granitization produced the rocks now called granite, these rocks were pyroxene-bearing, i.e. they were the depositories of the basic materials driven from zones of granitization which was then proceeding beneath the present level of erosion.

XII. SUMMARY OF CONCLUSIONS REACHED AS TO THE PETROGENESIS OF THE THREE MAIN ROCK-TYPES OF THE COMPLEX.

The genesis of all the rocks of the complex is ascribed to a single process, namely diffusion through solid rocks. The geochemistry involved is discussed in detail below (p. 113), but the findings may be so far anticipated as to permit the statement that the essential process is conceived as the advance of three "fronts" of what may be described as "chemical metamorphism". A basic front moves in advance of the main granitization, while a secondary alkali front, or front of feldspathisation, moves in advance of the basic front. Each front represents the depository of the materials displaced by the advance of the front which it precedes. At any time, the sequence is a sequence in space; at any point, the sequence is a sequence in time. Inclusions are considered to be loci where alteration has not kept pace with the changes in the surrounding rock, but not all the inclusions are merely less altered than their host, for patches of basic material tend to become still more basic, especially in the more leucocratic rocks, and the distinction between inclusion and host then becomes augmented rather than diminished.

In the field one can pass from country rocks to granite either by way of "norite" and "tonalite", or by way of "tonalite" /

"tonalite" alone. This is interpreted to mean that the basic materials expelled from the zone of granitization are driven upwards and not simply outwards. The reasons for this view, i.e. for the view that both "tonalite" and "granite" have passed through a pyroxenic ancestry, are (i) that the "norite" mass which has been studied intensively, namely the "norite" of the north-west part of the complex, lies below the bedded roof-rocks, (ii) that "tonalite" is found against the bedded wall-rocks, (iii) that gradations from aureole to complex are more definite where the rock of the complex is "norite" than where it is "tonalite", (iv) that the pyroxene of the "norite" is partly converted to hornblende, while the hornblende of the "tonalite", and to a lesser degree of the granite, contains relics of pyroxene, and (v) that although neither "tonalite" nor granite contain pyroxene as a stable phase, inclusions in both rocks are pyroxene-bearing.

It must be assumed, therefore, that a large mass of basic rocks originally roofed the complex. The thickness and basicity of this mass were no doubt at a maximum near the centre, while both these variables decreased as the gradient of the roof increased. The most basic front would, in fact, thin out like a wedge where the roof became wall. The masses of so-called norite represent just these wedging-out margins of a once extensive /

extensive basic front, the central and thickest parts of which may have been considerably more basic than the present "norite". As erosion continues, so the "norite" roof-rocks remaining will diminish, until, finally, when the basic front is completely eroded away, the most spectacular part of the evidence of a non-magmatic genesis will have disappeared also.

Some of the phenomena of granitization per se might conceivably be explicable in terms of granitic ichors, juices, watery magmas, and the like, for the source of the incoming material causing granitization is unknown. But the origin of the basic front is known. The source of the "basic emanations" can be traced to the zone of underlying granitized rocks. They represent the chemical elements driven from the country rocks when these were granitized. The hypothesis of solid diffusion is alone competent to explain the basic front, and there is no reason to suppose that the front of granitization has a different mechanism.

The space problem can hardly be said to exist for the diffusion hypothesis, but it becomes serious for adherents of the magmatic hypothesis who must, therefore, attempt to solve it. The problem may be stated thus: If the so-called igneous rocks are the result of intrusion of the country rocks by magma, where are /

are the rocks which once occupied the site now occupied by the rocks of the complex? There are three possibilities -

1. The country rocks have been displaced sideways.

The one inch geological map shows that there has been a certain amount of lateral thrusting away of the country rocks, but this has not taken place on a scale sufficiently great to account for the volume required. At the north-west part of the complex there has been no lateral thrusting at all.

2. The country rocks may have been displaced upwards.

Undoubted roof-rocks are exposed at the north-west part of the complex. This relic of roof is neither cracked open nor is the strike of the beds altered. There are no faults in the surrounding rocks which could be interpreted as evidence of doming of the roof. In fact, where the roof can be studied, it puts upward displacement of the country rocks out of the question.

3. The country rocks may have been displaced downwards.

Two types of mechanism have been suggested for downward displacement of country rocks through magma:

(a) Stoping. This involves the sinking of blocks prised off the roof and walls by the moving magma. We have described above /

above how the inclusions both in "norite" and in "tonalite" (and probably in granite also) fall into what are apparently evolutionary sequences from sedimentary types to types not distinguishable from the enclosing rock. It has also been shown that, while inclusions are to be found within the granite, they are much less common, and much more altered to igneous-looking types, than are the inclusions in the "tonalite" and "norite". On the magmatic interpretation it must be assumed that the inclusions are "made over" to the corresponding igneous rock-type. The relative scarcity of inclusions in the granite must imply dissolution of the entire mass of inclusions at a certain depth. This implication involves the magmation of a volume of country rock equal to that of the intrusion, and the "making over" of such a mass implies chemical changes for which some explanation is required.

(b) Subsidence of a central block into an underlying magma basin. If this took place uniformly the space originally occupied by the block could perhaps be filled by magma, originally homogeneous, which could differentiate in situ. If subsidence was spasmodic and the underlying magma was differentiating in depth, successive intrusions of varying types could take place. The inclusions would then be explained as pieces which broke off from the sinking block. The absence of evidence of faulting round /

round the complex, the hour-glass shaped outline of the complex, the gradations between the three rock-types, and the enormous depth to which such a block would have to sink because of its steep sides, preclude this from serious consideration. Moreover, the ultimate space problem is not solved, it is merely transferred to a hypothetical magma basin in depth.

To explain the structure of the complex as being due to three successive intrusions from a magma differentiating in depth, each intrusion breaking its way into the preceding one (Gardiner and Reynolds write (p. 14) "the central and, presumably less consolidated part of an earlier plutonic mass would offer less resistance than any other part to a subsequent intrusion"), not only cannot explain the gradation between the three rock types and the apparent metamorphism of the "norite", but multiplies the space problem three times. Moreover, if differentiation was in depth, it is necessary to assume that large masses of basic and ultrabasic rocks lie below.

It is necessary to state once more that the hypothesis of solid diffusion meets with no such problem.

For convenience a summary is given of the main points which require explanation by upholders of the hypothesis of crystal differentiation:

1. /

1. The origin of feldspathised and pyroxenised pods in the granulite of the aureole.

2. The presence of crystalloblastic textures throughout, being most intense in the norite and decreasing until almost imperceptible in the granite.

3. The occurrence of types grading from greywacke through "norite" to granite.

4. Internal irregularities in the plagioclase.

5. Inclusions in the plagioclase giving the sequence, biotite $\longrightarrow$ pyroxene $\rightarrow$ hornblende on passing from granulite to "norite", and to "tonalite" respectively.

6. Large and small plagioclase crystals have the same composition.

7. Continuous zoning, oscillatory zoning, and absence of zoning may co-exist in neighbouring plagioclase crystals, or even in the same individual.

8. Plagioclase crystals are often curved.

9. The plagioclase of the "norite" and "tonalite" is the same as that growing in the granulites of the aureole.

10. Potash feldspar has a demonstrable replacement relation to other minerals, particularly to plagioclase.

11. Biotite is poikiloblastic and skeletal.

12. Biotite is sometimes curved.

13. Pyroxene is sometimes crystalloblastic, and usually in two orders of size.

14. The pyroxene of the "norite " is amphibolitised, while the hornblende of the "tonalite" not infrequently contains relics of pyroxene.

15. The order of crystallization as given by Nockolds for similar rocks.

16. /

16. The varieties within the "norite", and in particular the potash feldspar marginal zone.

17. In the "norite" the sedimentary inclusions show every transition to "norite".

18. In the "tonalite" the sedimentary inclusions show every gradation through pyroxene varieties to "tonalite".

19. The inclusions in both "tonalite" and granite are pyroxene-bearing, yet neither of these rocks contains pyroxene as a stable phase.

20. "Norite" is found against the roof, and "tonalite" against the walls.

21. The augite-bearing margin to much of the "tonalite".

22. The assumption of a great mass of basic and ultrabasic rocks in depth.

23. The gradation from "norite" to "tonalite".

24. The gradation from "tonalite" to granite, with special reference to the distribution and size of the potash-feldspar crystals.

25. The space problem, and the mechanics of intrusion.

XIII. "VEINS" IN THE ROCKS OF THE COMPLEX

Leucocratic "veins" traverse the rocks of the Complex, and quartz-veins are common in the rocks of the aureole. The width of those cutting the "norite" is generally about an inch but is locally as much as a foot. In different exposures there is considerable variation in the abundance and directions of the "veins"; they are often branching and may locally have a parallel disposition, e.g. at places on the south-east slopes of Shiel Hill they trend 50° west of north. The "veins" are conspicuous in the field because of their relative resistance to weathering.

The "veins" in the "norite" are composed essentially of microcline, untwinned potash feldspar, and quartz, together with a little sodic plagioclase and biotite. Quartz is present as more or less rounded grains, plagioclase is lath-shaped and often slightly curved, and potash feldspar is either rather shapeless or "pseudo-porphyritic", enclosing rounded quartz as it does in the granite of the central ridge, and some of the plagioclase contains similar inclusions.

The plagioclases of the surrounding "norite" are often heavily dusted with minute inclusions, but when projecting into the "veins" - as they often do - the clouding stops abruptly at marked /

marked "fronts" within the crystals. The "norite" often contains abundant, easily recognisable apatite needles; locally the quartz of the "veins" contains many minute needles - possibly of apatite. Monoclinic pyroxene similar to that of the "norite" has been found in the "veins", and there is no evidence that the pyroxene was other than a stable phase. It is therefore unlikely that the pyroxene is xenocrystic. Such crystals cannot be explained on the hypothesis that the "veins" are "squeeze-outs" of residual mother liquor from granite crystallising in depth. The clearing of the clouded feldspars shows, too, that something more was involved than mere injection of liquid. Webb (1946) has described a good example of a replacement "vein"; it seems probable that the Loch Doon "veins" are also replacement phenomena. (See also G.E. Goodspeed, 1939, p. 418; E.S. Bastin, 1935, p. 715.)

Both aplitic and micrographic "veins" are found in the granite and there is probably a gradation between these two types. The quartz and plagioclase feldspar of the granite are often surrounded by micropegmatite, and the quartz is sometimes "corroded". Xenocrysts of "corroded" quartz rimmed with micropegmatite have been seen in the "veins", and the rock of such "veins" is very similar to the rheomorphic, xenoporphyritic granophyre of N. Ulfön (J.M. Sobral, 1913, p. 121). Some of the coarser "veins" contain /

contain very dark, macroscopic tourmaline with intense absorption.

Small quartzose patches, often no more than an inch across, are commonly found in the "norite", and it is not known definitely whether these are "veins" or isolated patches. One of the leucocratic "veinlets" has been seen to pass into a three inch broad, quartzose patch for six inches of its length. Although quartzose, these patches are rich in hornblende (rare examples containing relics of pyroxene), often biotite also, and some have abundant apatite and sphene. Feldspar is usually absent.

The theory that aplites and associated veins represent the squeezed-out residual magma, leaves many facts unexplained. After an investigation involving field, petrological, and chemical studies, N. Sundius concluded (1926) that the differentiation of the aplites of the Loftahammar massive cannot be explained by crystal differentiation, and that "the most acceptable explanation of the differentiation of the aplites is that it occurred in the fluid state of the magma". S.R. Nockolds (1947) is forced to call on "potash metasomatism" and "albitization" to account for certain of the ~~Scottish~~ aplites with which he treats. Adding to the complexity of the subject, N. Sundius (1935) maintains that the residual solutions of "wet" granite magmas are rich in Mg and Fe.

Phase /

Phase diagrams do not distinguish between the last residual liquids of a cooling system and the first-born liquids of a rheomorphic system, yet Nockolds has asked "Is it an accident that the last residual liquids of natural magmas should lie on the ternary cotectic curve?" To assume in this way that aplites were formed with falling rather than with rising temperature is a hypothesis which requires evidence for its support. Phase diagrams cannot provide that evidence.

XIV /

XIV. GEOCHEMISTRY

(i) Relation of Chemical and Geological Evidence

Interpretation of chemical analyses involves more than mere arithmetic, for the material which the chemist analyses in the laboratory is first collected in the field by the geologist. James Geikie realised the implications of this fact so long ago as 1867 when he rebuked Forbes (Geikie, 1867, p. 178) for the assertion that chemical analyses "may not improbably entirely annihilate" evidence purely geological (see p. 5); yet, so easily is this simple truth forgotten, that, three-quarters of a century later, S.R. Nockolds has written (1940, pp. 494, 497), "Any theory of origin (of the rocks of the Garabal Hill - Glen Fyne complex) must <u>first</u> be capable of explaining the form of the variation diagram", and further, "Can this <u>assumed</u> parental magma be regarded as a suitable <u>choice</u> apart from its position in the variation diagram?" (my italics). Quantitative chemical work may appear weighty, but it should ever be borne in mind that no superstructure is more stable than the foundation on which it rests. Sederholm was attempting to restore the correct perspective in such matters when he wrote, "Purely theoretical deductions whether they may be based on geophysical or chemical considerations cannot lead to any definite solution of these problems, nor can laboratory experience do so. The safest way in geology is the old /

old way of inductive science, by studying nature's methods in her own great workshops, where they are available to our observation . . . . . conjoined with microscopical research, and of course giving due consideration to the important results of modern physico-chemical science".

In earlier sections of this thesis, the genesis of the three main rock-types of the Complex was traced to diffusion, with chemical interchange, through the solid country rocks. In the present section an attempt is made to unravel that sequence of geochemical exchanges, but it must be emphasised again that the evidence used to demonstrate such an origin for the complex is petrological (field and microscopic) and not chemical.

(ii) The Analyses and the Analysed Specimens

Three analyses by E.G. Radley were given by Gardiner and Reynolds (1932, pp. 9, 10), and are repeated on Table 2 . The specimens analysed by Radley were

1. A fine-grained variety of biotite-"norite", from just south-west of Loch Girvan Eye,
2. "Tonalite", from Fore Starr, 2 miles south-south-west of Loch Doon; and
3. Granite, from a locality between Hoodens Hill and Mullwharchar.

In /

In addition to the complete analyses a number of silica percentages and specific gravities were given by Gardiner and Reynolds:

1. "Norite": S.G. 2.74 - 3.00, average 2.81 (94 determinations

SiO_2% 58.92; 54.76; 51.78; 50.40; 44.56.

The SiO_2% of 58.92 refers to a specimen of so-called transitional norite-tonalite mapped by Gardiner and Reynolds between the "norite" and the aureole, in the vicinity of Cornish Loch. The SiO_2% of 50.40 refers to a "hornblende-gabbro" from the south shore of Loch Girvan Eye.

The SiO_2% of 44.56 refers to an "olivine-hornblende-norite", about a mile north-west of White Laggan, in the southern "norite" mass. It is "exceptionally coarse, and consists of biotite and hornblende with abundant pyroxene, both rhombic and monoclinic, and but little felspar. Magnetite is plentiful, and small grains of serpentinised olivine are present". This is the only specimen from the Loch Doon complex in which olivine has been found. The S.G. is 3.00.

2. "Tonalite": S.G. 2.67 - 2.74, average 2.72 (94 determinations

SiO_2% 64.52; 63.88.

3. Granite: S.G. 2.60 - 2.65, average 2.63 (27 determinations).

From the detailed description of the so-called norite, it is obvious that the geochemistry of the Complex could be elucidated /

elucidated only if analyses were provided of carefully selected specimens of "norite", the petrogenetic relations of these being known, and if analyses of certain aureole-rocks of great petrogenetic import could be obtained.

Seven new analyses by W.H. Herdsman are given on Table 2. The analysed specimens are as follows:

1. Unaltered greywacke (485) from the south side of Craiglure Hill (see p. 17).

2. Greywacke-granulite (506), with a little new feldspar, from Cow Craig (see p. 25).

3. Greywacke-granulite (507), with much new feldspar, from Cow Craig (see p. 27).

4. Feldspathised and pyroxenised greywacke-granulite (685/5), occurring as a pod in the altered greywackes close to the contact, south of the summit of Craigbrock (see p. 30).

5. Fine-grained opdalite (333), from the west shore of Cornish Loch.

6. Coarse-grained opdalite (18), 100 yards south of Balloch Lodge.

7. Quartz-diorite (206), with little potash feldspar and pyroxene, but with abundant biotite, quartz and hornblende. From the south side of Shiel Hill.

Nos. 1 - 4 were selected to illustrate the changes that take place in the aureole rocks as these are traced towards the contact.

Nos. 5 and 6 were selected to illustrate the two extreme varieties in the opdalitic margin of the "norite".

No. 7 illustrates the potash-feldspar-poor inner zone.

Fortunately /

Fortunately the relation of Gardiner and Reynolds' analysed "norite" to the specimens which have been analysed during the course of the present investigation, is determinable.

(a) The description and camera lucida drawing of the analysed rock links it to the fine-grained opdalite (333), but, as the latter has been selected by a system of exhaustive sampling, it is probably finer-grained than is Gardiner and Reynolds' rock.

(b) Chemically the analysed rock is intermediate between the fine (333) and coarse (18) opdalites analysed by Herdsman; this fact is seen by comparison of the actual analyses, the norms, von Wolff values, and Larsen "positions", as given below.

For these reasons, the analysed "norite" of Gardiner and Reynolds is referred to below as "medium opdalite". There are, therefore, ten relevant chemical analyses from which to determine the geochemical exchanges operative in the Loch Doon complex.

(iii) <u>The Choice of Suitable Variation Diagrams</u>

1. <u>Silica Percentage</u>

It was this diagram to which Nockolds referred in the statement quoted above "Any theory of origin must first be capable of explaining the form of the variation diagram". The individual constituents are plotted against the silica percentage directly. The Loch Doon rocks fall into the following order when /

when plotted:

Greywacke
Biotite-granite
Slightly feldspathised greywacke-granulite
Feldspathised greywacke-granulite
Hornblende-biotite-granodiorite
Pyroxenised pod
Fine opdalite
Medium opdalite
Pyroxene-biotite-quartz-diorite
Coarse opdalite

Such a sequence is quite without meaning. Mere omission of the feldspathised and the pyroxenised greywacke-granulites, so as to obtain smoother curves, is so flagrantly to ignore the petrological (field and microscopic) evidence as to be unworthy of further consideration.

2. <u>The Larsen Variation Diagram</u>

E.S. Larsen has recommended (1938, p. 505) the use of a variation diagram in which one or more constituents (in particular CaO + MgO + FeO) is plotted against $^1/_3 SiO_2 + K_2O - MgO - CaO - FeO$ (the "position"), the main oxides first being summed to 100, and all iron expressed as FeO.

The Larsen "positions" for the Loch Doon rocks are given on Table 5. They fall into the following order:

Biotite-granite
Greywacke, and feldspathised greywacke-granulite
Slightly feldspathised greywacke-granulite
Hornblende-biotite-granodiorite
Pyroxenised pod
Fine opdalite
Medium opdalite
Coarse opdalite
Pyroxene-biotite-quartz-diorite.

The /

The remarks made regarding the sequence in the silica percentage diagram are quite as relevant when applied to the Larsen sequence.

3. Variation Diagram on a Silica Basis in Petrological (Field and Microscopic) Order

When the analyses are arranged in petrological order (as they are in Table 2), it is observed that SiO_2% decreases from greywacke to coarse opdalite, and increases from the latter to biotite-granite. Indeed, there are actually two series, SiO_2 decreasing in the one and increasing in the other, and these are not distinguished in the ordinary silica percentage diagram. Si suffers a geochemical depression between greywacke and biotite-granite; the sequence is not chemically continuous. This difficulty is avoided by combining silica percentage with petrological order, for the two series, basification and granitization, are then separated. The resulting diagram is shown in Fig. 5 . Total iron is calculated as FeO, and SiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O and K_2O are summed to 100.

4. The von Wolff Diagram

So successful in the attack of the "granite problem" has Doris L. Reynolds proved the von Wolff diagram to be (see especially 1946, p. 389), that no investigation of a granitic complex /

complex can be regarded as complete unless such a diagram is provided and interpreted. Discussing the Newry complex, D.L. Reynolds has written (1944, p. 237) "The chemical relationships between the various members of the complex are most easily expressed on a von Wolff diagram, for not only is it possible to plot both chemically undersaturated and chemically oversaturated rocks on this diagram, but the diagram also has the additional advantage of separating the felspathic and the ferromagnesian constituents, and thus emphasizes the contrast between the rocks of the alkali and Mg-Fe 'fronts'". This is equally true for the Loch Doon complex, and the diagram is given in Fig. 7 .

(iv) Interpretation of Chemical Analyses

To facilitate interpretation, the norms are given in Table 3 , the variation diagram on a silica basis in petrological order in fig. 5 , and the von Wolff diagram in fig. 7 ; these three modes of presentation of the chemical evidence are the only ones which have proved to be of service.

Both diagrams show clearly the division of the geochemic changes into

1. A preliminary desilication, ie.decrease of silica relative to the bases, due in an outer zone to increase in the total alkalis, i.e. feldspathisation, and in an inner zone to the increase in the cafemic constituents, i.e. basification.

2. /

2. A subsequent granitisation, whereby the rocks were changed in composition so as to approach that of granite.

The geochemical culminations and depressions of the major constituents are summarised diagramatically in fig. 6 . Points of interest are:

(a) The refuge of the Si driven from the zones of desilication is the quartz veins in the aureole and in the country rocks.

(b) Small quantities of Fe, and to a lesser extent of Mg, are driven ahead of the main feldspathisation.

(c) Na-Al, K, Ca appear in that order.

(d) Al culminates immediately after the alkalis.

(e) There is a minor culmination of Na along with the Fe-Mg, but taking the zone of cafemic enrichment as a whole, there is probably an expulsion of Na.

(f) K is driven from the zone of cafemic enrichment.

(g) Ca introduction is over a wide range, but it culminates after the Fe-Mg and in the zone of silication; this fact is more evident from the norms and the von Wolff diagram than from the SiO_2% per se.

(h) The main granitisation involves introduction of Si, K, Na and expulsion of Ca, Mg, Fe, Al.

The minor constituents, P, Ti, and Mn, are somewhat irregular in their distribution, but all culminate in the coarse opdalite with the culmination of the main Fe-Mg front.

The predominance of lozenge-shapes on the culmination and depression diagram (fig. 6) is of considerable significance; zones of appropriate elemental expulsion lie below zones of introduction /

introduction, or, put in a different form, what one front loses by expulsion, other fronts, further forward, gain by fixation. These geochemical exchanges are given in generalised form in fig. 12. Five main fronts can be recognised:

1. Si enrichment, mainly as quartz veins.
2. Secondary Fe-Mg front, weak, and overlapped by 3.
3. Al-alkali front.
4. Ca-Mg-Fe front.
5. Si-alkali front.

The material required for each front is contributed (at least qualitatively) by the fronts below. One would therefore deduce, that the minimum necessary introduction required to effect the changes observed, is the difference between the first and last members of the rock series, i.e. greywacke and granite. Calculating total iron as FeO, and summing the main oxides to 100 in each case, the introduced material consists of approximately K 2.5%, Na 1%, Al 0.5%, the material expelled being approximately Fe 3%, Mg 1%. That this is not the complete picture is seen by glancing at the von Wolff diagram; the greywacke field does not lie between the fields of granite and "norite". As far as the rocks which are exposed are concerned, the complex is poorer in Si and probably in Fe, and richer in Al, Ca, Na, and K, than are the country rocks. Such a change of composition of the system as /

as a whole corresponds to that undergone by the greywacke-granulites on feldspathisation. Owing to denudation of the main mass of the basic front, and to the probable presence of a zone of granitisation below the present level of erosion, there are too many unknowns to warrant further speculation relating to the geochemical system as a whole.

In conclusion, it is interesting to note 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 granitisation, and this, though mappable (see p. 59) cannot be seen in the field.

XV. THE DYKES AND DYKE-LIKE BODIES

The "minor intrusives" were described by Teall (1899 pp. 625-631), his work being supplemented in 1932 by Gardiner and Reynolds (1932, pp. 19-26) who remarked that "No dykes are shown in the Survey map cutting the plutonic rocks, and, though they do occur, they are certainly far more plentiful in the sediments". Teall, however, did record that "The dykes occur not only in the sedimentary rocks but also in the granite masses" and, even in the limited area covered by the present investigation, a dyke cutting the granitic rocks is marked on the Survey map. This dyke is conspicuous on the path from Balloch Lodge to the monument erected by the Fishing Club. Gardiner and Reynolds state that tonalite is "far more frequently penetrated than either granite or norite", and that a few of the dykes in the sediments "show metamorphism" and must be older than the plutonic rocks. In addition to the descriptions given by Teall and by Gardiner and Reynolds, the petrology of comparable dykes has been dealt with by a number of workers, notably by H.H. Read (1926, p. 422) A.G. MacGregor (1930, p. 31), D.L. Reynolds (1931, pp. 97 & 155), W.A. Deer (1935, p. 63), M. Macgregor (1937, p. 465), and B.C. King (1937, p. 282).

The object of the present investigation was to determine the genesis of the plutonic rocks, and the "minor intrusives were /

were examined only in so far as their study appeared relevant to this major issue. The age of the dykes relative to that of the Complex was clearly the determining factor; if any or all of the dyke-like bodies cutting the plutonic rocks were actually older than the Complex then they would be, for us, of the utmost importance; on the other hand, if no pre-plutonic "dykes" could be found enclosed in the plutonic rocks their present value would be greatly diminished. In brief, our interest in the dykes is structural rather than petrographical (cf. J.J. Sederholm, 1926, p. 31, G.E. Goodspeed, 1939, p. 411; T.C. Phemister, 1945p. 74; H.H. Read, 1945, p. 83).

Although previous workers have suggested that dykes in the "norite" are rare, during the course of the present investigation thirty dykes with measurable thickness or direction were found in the small area studied intensively. One dyke with a thickness as much as twenty feet was observed, but nearly all the others are five to ten feet in width. Only three dykes with bearings east of north were found; all the others lie within the range from 0° to 20° west of north, and some have a slight wobble. This is notable in view of the fact that the dyke-trend in this part of the Southern Uplands is given as E.N.E.-W.S.W. by J.E. Richey (1939, p. 404), and as N.E.-S.W. by Gardiner and Reynolds.

The /

The dykes found are all of the type generally referred to as "porphyrite". Phenocrysts of plagioclase, hornblende, and biotite, and occasionally of rounded and corroded quartz crystals, occur in a fine-grained groundmass. Plagioclase is optically positive; oscillations of zoning are characteristic, and as many as fifty oscillations have been counted. Potash feldspar - quartz intergrowths are occasionally found, and may perhaps be xenocrysts.

The following facts are significant for us:

1. The dykes run for only short distances, are often found en echelon, and are sometimes slightly curved.

2. The junctions of the dykes against the "norite" are usually very irregular, with embayments which are sometimes angular. The junction of a dyke with greywacke near the inner edge of the aureole is curved but flowing, and without irregularities. The regularity of this dyke cannot be ascribed to its conformity with the bedding of vertical rocks, for it crosses the strike of the greywackes.

3. Their direction approximately corresponds to certain minor shatter-belts younger than the "norite", and at least one of the dykes is itself shattered.

4. In some cases a micro-breccia of "norite" up to 0.5 cm. wide has been found parallel to the dyke margins.

5. The two igneous inclusions described above (p. 69) are interpreted as members of the same suite as the dykes under discussion.

6. The dykes are fine-grained and flinty-looking towards the margin, and while the dyke-centres are sericitised, the plagioclase in the dyke margins is usually much less altered. This, however, has been observed also in a dyke in the aureole.

7. /

7. The "norite" is not altered against the dykes.

8. An inclusion in a dyke just on the sedimentary side of the aureole-"norite" boundary, is rather schistose and appears to be slightly less altered than are the adjoining greywackes. If this is actually the case, the phenomenon could be interpreted as the protection of an inclusion in a pre-plutonic dyke.

The balance of this evidence is believed to indicate that the dykes are younger than the "norite".

XVI. THE PETROGENESIS OF THE LOCH DOON COMPLEX IN RELATION TO THE ORIGIN OF GRANITES IN GENERAL

It is customary to conclude the petrological description of a plutonic complex with some remarks on related areas. The conclusions presented in the course of this thesis differ so fundamentally from the petrogenetic views previously held, that it is certainly necessary to consider the relation of the Loch Doon findings to the general problem of the petrogenesis of granite.

Three aspects will be discussed: 1. The other Galloway "Granites" and the "granites" of the Southern Uplands in general; 2. Other complexes which, though similar, have been interpreted differently; and 3. Complexes in which a comparable mechanism has been recognised. Neither an historical or an exhaustive treatment is attempted.

1. During the last twenty years the "granites" of the Southern Uplands received considerable attention. The chief workers have been, F. Walker, (1925,28), Spango, Polshill, Cockburn Law, Priestlaw, and the small masses of Lamberton Beach, Broad Law, Kernielaw, and Lyne Water (the last being outwith the Southern Uplands); H.H. Thomas and W. Anderson (1932), Cheviot; W.A. Deer (1935,37), Cairnsmore of Carsphairn; C.I. Gardiner and /

and S.H. Reynolds (1936,37), Cairnsmore of Fleet; Malcolm MacGregor (1937,38), Criffell-Dalbeattie; A.G. Jhingran (1942) Cheviot; N. Holgate (1943), Portencorkrie; and H.G. Midgley (1946), Cockburn Law. The work of A.G. MacGregor (1930), Distinkhorn, Ayrshire, and of F. Walker (1939), Glenduckie, Fife, may be included here on petrographical rather than on geographical grounds.

Before discussing the findings of these workers, it must be emphasised that, with partial exception in the case of M. MacGregor, the field evidence and suggestions of James Geikie and other early workers have been completely ignored. For example, A.G. MacGregor (1930, pp 51-2) wrote: "There is no evidence against the assumption that the various members of the plutonic complex are differentiation products of one magma-basin. In fact the close association of similar rock types elsewhere in the south of Scotland makes the truth of such an assumption quite certain" This is significantly reminiscent of Gardiner and Reynolds' statement (1932) now proved to be entirely without foundation: "It may be safely assumed that the plutonic rocks originated by differentiation of the contents of the same magma reservoir" (my italics). The writer of this thesis has recently (1947) drawn attention to the frequency of the fallacy of Petitio Principii in discussions on the plutonic rocks: "We can study plutonic /

plutonic rocks, but we cannot study plutonic magmas. To maintain that a given plutonic rock originated from a magma is no more than a hypothesis, and as such requires evidence for its support". Magma has been accepted uncritically as a necessary antecedent of any of the plutonic rocks commonly regarded as "igneous". The problem discussed has seldom been: what is the evidence for the postulated magma? More often it has been: differentiation, in depth or in situ?

The following review of what is considered to be significant evidence, is based on the published work already referred to. It must be understood, therefore, that absence of recorded evidence must not be given too much weight; for example at Loch Doon early workers reported that inclusions in the "norite" are very rare, but this is now known to be incorrect.

(i) General

The most acid varieties occur centrally and the basic types are present, generally discontinuously, along the margins, as at Loch Doon. The proportion of acid to basic is very variable, being high at Cairnsmore of Fleet and low at Cairnsmore of Carsphairn. The tendency for diopsidic augite and hypersthene to be found marginally is marked, and diopside usually extends further into the centre than hypersthene does. Examples are, Criffell (no hypersthene), Carsphairn, Distinkhorn, Portencorkrie /

Portencorkrie, Cheviot, and Cockburn Law. Where the more basic types are absent (as at Fleet), or do not completely encircle the complex (as at Criffell), the tendency for the granite or granodiorite to become slightly more basic towards the country rocks has usually be observed (cf. p. 82).

In all cases where contacts between the members of a complex have been described, these are gradational and there is no evidence of chilling. Supporters of the magmatic hypothesis meet with a dilemma: the theory that differentiation was in depth, and emplacement was by successive intrusion "implies that in places where a rock of transitional type is found the heat of the tonalite (or other intruding rock) was sufficient to partly liquefy the norite (or other intruded rock) and allow diffusion to take place " (Gardiner and Reynolds, 1932, p. 16; cf. p. 90 of this thesis); but, "all the evidence is against differentiation in situ. The contacts between the various type although not chilled, are of a rapidly merging character " (Deer 1935, p. 65). Some of the contacts at Criffell appear sharp in the field but all are gradational under the microscope.

The variable or patchy nature of some of the rocks, in particular of the basic marginal types, has been observed at Criffell, Carsphairn, Cheviot, and Cockburn Law. (cf. p.150)

(ii) /

(ii) Mineralogy

(a) Large and small plagioclase crystals have the same composition; Criffell, and Cockburn Law (cf. p. 40).

(b) Plagioclase, especially that of the basic marginal types, is often dusted. This is discussed on page 138.

(c) Pyroxene at Carsphairn, and biotite, pyroxene, and sillimanite at Cockburn Law, are enclosed in plagioclase (cf. p. 70).

(d) "Pseudoporphyritic" potash feldspar is present at Fleet (Teall, 1899, p. 618), Carsphairn, and in some of the smaller masses (cf. p. 95).

(e) Plagioclase is corroded by orthoclase at Carsphairn and Portencorkrie (cf. p. 54).

(f) Skeletal and sieved biotite is described at Criffell, Portencorkrie, and Cockburn Law (cf. p. 56).

(g) The reaction series, hypersthene → diopsidic - augite → colourless amphibole → brown amphibole → green amphibole → biotite, is represented. The amphibole series was observed at Carsphairn as a field sequence; it is the same as that determined at Loch Doon by study of the mineral relations in thin sections (cf. p. 58).

(h) Pyroxene relics are found in hornblende in granodiorite at Criffell, tonalite at Carsphairn, and "granite" at Portencorkrie (cf. p. 89).

(i) Clotting of ferromagnesians has been noted at Criffell, Carsphairn, Portencorkrie, Cheviot, and Cockburn Law. At Carsphairn the presence of sphene indicates Ti culmination, and the field association of clots and basic inclusions is significant (cf. p. 99).

(j) Mineralogically and chemically the Glenduckie quartz-diorite is equivalent to the medium-grained opdalite of Loch Doon and it is probable that its genesis is similar. No details are known regarding the relationships of this rock.

(k) At Criffell, the fine-grained basic rocks are less basic than the coarse.

(iii) /

(iii) <u>The Country Rocks</u>

Chemical investigation of the country rocks has been carried out only at Criffell, but the results correspond to the Loch Doon findings. MacGregor notes: "the hornfelses, unlike normal shales or sandstones, occupy a (chemical) field not far removed from that of intermediate or basic igneous rocks". Traced towards the contact, the sediments become enriched in alkalies (dominantly Na) and Al; poikiloblastic plates of potash feldspar are found in the diopside-hornfels (cf. p. 27).

At Cockburn Law, Midgley has recorded that, as the sediments are traced inwards through the aureole, (a) biotite is produced, (b) biotite and cordierite develop at the expense of the quartz, and (c) a biotite-cordierite rock is formed with conspicuous absence of quartz. These mineralogical changes indicate chemical introduction, probably of K-Fe-Mg, with concomitant expulsion of Si.

At Portencorkrie, Holgate has observed porphyroblastic plagioclase, with characters similar to the plagioclase of the diorite, in the aureole rocks close to the contact (cf. p. 39).

Gradations from the so-called igneous rocks to the rocks of the aureole have been observed at Criffell and at Cockburn Law. The Criffell gradation is described by Malcolm MacGregor: "On the inner side of the zone of mobilization fine-grained /

grained quartz-diorite types occur. Under the microscope these types still betray their hornfels parentage by their textures and mineralogy; relict hornfels inclusions are common, and some varieties contain diopside derived from calcareous shale or greywacke hornfels. The rocks as traced away from the margin lose their relict features, attain a coarser grain, and become, sometimes within a few yards, sometimes over a distance of quarter of a mile, the typical quartz-diorite of the area". MacGregor records that, at one point at least, "the granodiorite passes rapidly into the hornfelses".

Of Cockburn Law, Walker writes, "A feature of the mass, which impressed both Stevenson (1849) and Sir Archibald Geikie (1864), is the gradual transition of the rock from a fine-grained grey 'syenite' at the margin to a coarser pink 'granite' at the centre. They also observed that the marginal 'syenite' was practically indistinguishable from the surrounding hornfelsed greywackes." More recently, Midgley has described the gradation from the biotite-cordierite rock of the aureole to patchy "hybrid-hypersthene-diorite" with numerous inclusions of hornfels, large and small.

(iv) Inclusions

At Criffell inclusions are often abundant. Describing the inclusions in the marginal quartz-diorite, MacGregor writes, a /

a few "retain features which suggest an origin in disrupted country-rocks, and probably all have been derived from this source but have suffered granitization . . . . Their minerals are those of the plutonic rocks but in different proportions". Even without chemical analyses, the mineral assemblage indicates that this is more likely to be basification than granitization (cf. pp. 93, 101).

Describing supposed igneous inclusions in the tonalite of Carsphairn, Deer writes of, "the possession of a large number of small pyroxene and biotite inclusions in the plagioclase, which serve roughly to distinguish it from the plagioclase of the tonalite". (my italics, cf. p. 107, No. 5). Deer was probably describing geochemical culmination when he reported the "lack of a simple variation in which the composition of the xenolith would be intermediate or would show linear variation between the two end points"; see D.L. Reynolds 1946.

According to Holgate inclusions are rare in Portencorkrie. He reports that they are almost confined to altered sediments, with a few "igneous types". Holgate did not find any intermediate stages between these.

At Cheviot, Jhingran reports that "It is no exaggeration to say that there is hardly an area in the granite which can be singled out as being perfectly free from inclusions".

D. /

D.L. Reynolds has recently (1946) reviewed the evidence as to the origin and evolution of the Cheviot inclusions; the basic inclusions probably represent desilicated andesite from the country rocks, and the roof and marginal types of the granite may well be stages in the granitization of the desilicated andesite.

Midgley describes the inclusions in the "hybrid-hypersthene-diorite" of Cockburn Law as consisting of biotite, cordierite, and green spinel, the spinel being absent from the margin of the inclusions. In the inner, or "hybrid-diopside-diorite" zone, the inclusions consist of augite, with a little olivine, biotite, and plagioclase. Lack of data make certain interpretation impossible, but further research may well show that these inclusions form a good desilication series.

The Petrogenetic Theories Advanced

(i) Teall, A.G. MacGregor, and Gardiner and Reynolds postulated differentiation of a once homogeneous magma. The overwhelming objections to this view are given on pp. 70, 87. The criteria used in recognition of "baked" rocks, and for supposed demonstration of a sequence of intrusions, is now briefly reviewed. That the matter is of exceeding complexity has been shown /

shown in a recent contribution to the Geological Magazine entitled "On Chilled and 'Baked' Edges as Criteria of Relative Age" (McIntyre and Reynolds, 1947).

Supposed baking of the basic marginal rocks has been recorded at Criffell, Fleet (the Talnotry diorite), Distinkhorn, Portencorkrie, and with less assurance, at Cheviot. What is the evidence for this ubiquitous phenomenon? At Criffell: the "textural features and mineralogy" suggest metamorphism. See p. 132.

At Fleet: the Talnotry diorite shows "clear signs of metamorphism".

At Distinkhorn: feldspars are clouded like those in the contact-altered dykes of the aureole.

At Portencorkrie: granulitic patches of pyroxene, clouded plagioclase, corrosion of plagioclase by orthoclase, and sieved biotites are present.

At Cheviot: clouded plagioclase is found.

No attempt has yet been made to decide whether these textures and mineralogical phenomena represent igneous texture "going", or igneous texture "coming" (see p. 73). The evidence shows that the basic marginal rocks are not explicable in terms of straightforward crystallization from magma; the assumption that /

that they are altered igneous rocks is only speculation, unsupported by evidence.

That clouded feldspars cannot always be accepted as proof of thermal metamorphism was recognised by Jhingran: "The plagioclase crystals are sometimes clouded in a manner which has been attributed to thermal metamorphism. This type of alteration should be a feature of the country rock rather than of the rock which supplied the heat, causing metamorphism. In the present rocks, however, clouding is shown by felspars in the invading rock as well as by those in the invaded rock". Belyankin (1932) is mentioned as having described clouded feldspars in an intrusive rock from Cape Medvezhy, White Sea, Russia. Reference may be made to the discussion by G.H. Anderson (1937, p. 65).

At Distinkhorn, A.G. MacGregor ascribes the metamorphism to the granodiorite, but records that similar inclusions are developed in the plagioclase of several granodiorite specimens. MacGregor concluded that "The hyperites described by Teall from the Loch Dee 'granite' mass (i.e. the Loch Doon complex) have so many points in common with the contact altered 'hyperites' of the Distinkhorn complex, notably the clouded felspars, that it seems probable that the former are also contact-metamorphosed". The present investigation indicates that the conclusion should now read "The 'hyperites' described by MacGreg

from /

from the Distinkhorn 'granite' mass have so many points in common with the basic-front 'hyperites' of Loch Doon, including the clouded feldspars, that it seems probable that the former also represent the basic front".

(ii) Hybridisation of magma has been adopted by Deer, Holgate, and Midgley. The presence of geochemical culminations (p. 135) made Deer realise that simple mixing of magma and inclusions did not explain the observed facts. He concluded that "the basic xenoliths in the tonalite have not been contaminated or altered by tonalite magma but by a partial magma, 'a quartz, potash felspar magma'". What a "partial magma" is; in what respects it differs from "complete magma"; how it separates from tonalite magma; and what the mechanism of its reaction with the "basic xenoliths" may be; none of these questions is even mentioned, much less discussed or answered.

Holgate and Midgley merely assert that their rocks are "hybrids" without attempting either to analyse the mechanism or to present any evidence.

(iii) In 1935 Malcolm MacGregor "considered that the marginal quartz-diorites of Criffell originated by an acid ichor permeating the country rocks (shales), and as the evidence of this process showed only the stages before permeation ceased as a /

a result of waning energy, that the whole mass originated in the same way. The gravitational differentiation in situ of the syntettic magma so formed, had brought about the variation of the rocks in the complex". This view was somewhat modified in 1938 when he wrote: "Metasomatism brought the composition of the country rocks nearly to the composition of quartz-diorite before mechanical mixing with parent-magma started. The amount of introduced magma was small . . . . The quartz-diorite was formed almost in place". His view then as to the granodiorites was, that "the intruded material, already of granodiorite composition, was apparently emplaced mechanically at the level now exposed".

It is hardly necessary to point out that gravitational differentiation cannot explain an upward increase in density, or that gradational contacts cannot be explained by "mechanical mixing" of country rocks with "parent magma".

The propriety of pronouncing on the origin of complexes not personally examined may, of course, be questioned. The writer of this thesis feels justified in doing so in this particular case because,

(i) All agree that the Caledonian complexes of the South of Scotland are of like origin. For example, Teall considered that they were all intrusives from a common parent magma; Deer stated /

stated that "the fundamental similarity of these extensive and widely separated complexes points to a common process operating with remarkable consistency"; and M. MacGregor expressed his view that "the various outcrops of 'granite' in the Southern Uplands of Scotland were no doubt all parts of one large batholith and it was to be expected that the same theory of petrogenesis would apply to them all".

(ii) The Loch Doon complex presents what is considered indisputable evidence of its non-magmatic genesis.

(iii) Workers on other complexes have passed lightly over evidence inconsistent with the hypotheses which they have submitted. This may not be conspicuous in any one instance, but taken altogether, as has been done in the present analysis, the cumulative weight of such evidence is great. This evidence, however, is perfectly in harmony with the petrogenetic hypothesis adopted to account for the observations made at Loch Doon*.

Reactions between solids, and probably ionic reactions within solids, are usually exothermic, and therefore a liquid phase may have been generated in some of the complexes, but as far /

* The results of work in progress by S.N. Sarkar at Spango, and by M.R. Subramanyam at Priestlaw and Cockburn Law, are in agreement with the conclusions presented here.

far as the exposed plutonics are concerned, no evidence demonstrating this has yet been brought forward. Until further research reveals such evidence, we may reasonably conclude with James Geikie, that "the crystalline rocks described above have resulted from the alteration in situ of certain bedded deposits".

2. Complexes which, though similar, have been interpreted differently. The Loch Doon complex was once considered to be a very typical, small igneous batholith, emplaced by three successive, and progressively acidic intrusions. As workers on certain other plutonic complexes have stated that their areas are closely comparable with Loch Doon, a brief review of a few typical "igneous" granites is now given. It is, however, beyond the scope of this thesis to give a detailed and exhaustive analysis of the whole literature of granite.

(i) Complexes which have been compared directly with Loch Doon.

The Arrochar complex was described by J.G.C. Anderson (1935), who stated that "the Loch Doon mass bears a considerable resemblance to the main Arrochar intrusion, differing chiefly in its much greater proportion of intermediate rocks. In fact it is the large proportion of basic rock which gives a fairly distinctive character to the present area (i.e. Arrochar)." Anderson postulated a sequence of five or six successive intrusions, the last being granite, but did not discuss the multifold space problem involved. Medium-grained diorite is the most abundant type and it is said to be identical with the "hyperites" of the Southern Uplands. Anderson gives no evidence to show that, at Arrochar, the magmatic hypothesis is to be preferred to that of solid /

solid diffusion. Gradational contacts are recorded, and of one of these Anderson suggested that, "the apparent merge is really the cooled edge of the coarse diorite passing into the <u>remelted</u> edge of the medium". (My italics, cf. p. 91).

In their description of the Oatland (Isle of Man) complex, J.H. Taylor and E.A. Gamba (1933) emphasise the similarity to Cheviot, and also remark that "in many ways the Loch Doon complex resembles that at Oatland". At Oatland the granite has a gabbro roof, contains pyroxene cores to the hornblende, and becomes more basic and pyroxene-bearing towards the gabbro. The granite-gabbro contact is stated to be "intrusive". Numerous basic inclusions are found in the granite, and the authors believe that these have been brought upwards from depth by the magma. Taylor and Gamba also conclude that "the gabbro itself must have retained a considerable amount of heat at the time of the granite intrusion, otherwise the magma could hardly have failed to have been cooled at an early stage by contact". Oatland is indeed comparable to Loch Doon.

Taylor and Gamba recognised the existence of a space problem but left it unsolved: "The authors are convinced that the granite at Oatland has stoped its way into its present position which was formerly occupied by the gabbro; and, unless the volume displaced was assimilated during the process, it is difficult /

difficult to imagine by what means the emplacement was effected. The only alternative appears to be the subsidence of a central block of gabbro with consequent uprise of acid magma to take its place - a process similar to that which gave rise to the ring bosses of Mull. Although the evidence at Oatland does not entirely prohibit the possibility of cauldron subsidence, the intrusive nature of the gabbro-granite junction and the absence of anything resembling a ring-fault do not favour it".

The available data suggest that the relationship of these complexes to Loch Doon is petrogenetic as well as petrographic.

(ii) <u>The concept of a basic front</u>

Doris L. Reynolds has recently analysed the chemistry of rocks associated with granite (1946), and drawn attention to the importance of the concept of a basic front (1947). The first of these most important publications incorporated all complexes which had received adequate chemical study; of these the following are directly comparable, in one or more respects, with Loch Doon: Flamanville, Normandy; Dartmoor, Devonshire; Falmouth, Cornwall; Boulder Peak, Inyo; Giants Range, Minnesota; Victor Harbour, South Australia; Boulder, Montana; Stavanger, Norway; Orijärvi, Finland; Riddarhyttan, Sweden; and Blue Hill, Maine. Detailed /

Detailed discussion and full bibliography are given in the paper. An important conclusion is reached, namely: "In none of the areas has granitization of pelitic or allied rocks taken place without an initial or complementary stage of desilication. . . . . Moreover, the minor constituents TiO_2, P_2O_5 and MnO characteristically reach geochemical culminations during the desilication stage of change, unless it be essentially one of feldspathization, in which case they may decrease. They decrease in each example, during granitization".

(iii) Feldspathisation

Numerous examples of feldspathisation of rocks surrounding granite masses have been recorded since the publication of the classic work of Barrois (Rostrenon, 1884), Michel Lévy (Flamanville, 1893), and Lacroix (Pyrenees, 1898-1900). The first conclusive chemical demonstration that silicate-forming materials could be introduced to aureole rocks was provided by V.M. Goldschmidt's investigation of the metamorphism of the pelitic rocks in contact with the Stavanger trondhjemite (1920, pp. 108-21), where, as A. Harker pointed out (1939, p. 251), there has been introduction, not of feldspar, but of Na and Si (cf. p.41

The evidence for and significance of feldspathisation has recently been discussed by F.F. Grout (1937, p. 1539), H.H. Read (1943-44; 1946, p. 667), and A. Holmes (1945, p. 412). Holmes /

Holmes wrote: "The crucial nature of the evidence provided by the 'big felspars' has long been realized, since no one has seriously doubted that they must all have shared a common origin. Either they grew in solid rock or they crystallized from a magma: identical felspars could not be assumed to have originated in two entirely different physico-chemical environments". Read is no less emphatic: "If identical complex felspars can be formed in two such different environments, then the application of physical chemistry to rock formation becomes meaningless. It is clear that there can be only one environment, the one that can be proved, that of the solid country-rock". At Loch Doon the evidence is particularly clear: (a) the plagioclase crystals are exceedingly complex, (b) the distance separating the feldspathised pods from the "igneous" rock is measurable in yards, (c) there is no evidence to suggest that the crystals were forcibly introduced as such, and the poikilitic potash feldspar plates have patently not been so introduced, and (d) the evidence of the inclusions in the plagioclase of both the aureole and the "igneous" rock demonstrates beyond all doubt a community of origi

The role of feldspathisation in the basic front has been analysed by Doris L. Reynolds, and with that analysis the Loch Doon evidence is completely in accord.

Since Goldschmidt's classic work at Stavanger, chemical work /

work has been carried out on the aureoles of several complexes. We may mention A. Brammall and H.F. Harwood (Dartmoor, 1932), G.H. Anderson (Northern Inyo, 1937), and G. Wilson (Kopaonik, 1938). The dominant role played by Na is striking. Brammall and Harwood wrote "at an early stage in the intrusion history alkaline diffusions from the magma enriched the shales in both soda and potash, and, on balance, this initial impregnation was of the nature of albitization"; the soda/potash ratio increases from 0.12 to 0.40 as the contact is approached. Anderson found that potash is in excess of soda at a distance from the batholith but that the reverse is true in the vicinity of the contact. Wilson considered that "in the hornfels bordering on the granite soda seems to have replaced potash as magmatic impregnation proceeded. The evicted potash from the sediments has tended to enrich the granodiorite locally in that constituent". Such a mechanism cannot account for the marginal potash-feldspar-rocks at Loch Doon, for, (a) although Na has penetrated further into the aureole than K, both were introduced, (b) in the feldspathise pods at Loch Doon the Na_2O/K_2O ratio actually <u>falls</u> to unity, (c) of Kopaonik Wilson wrote: "The enrichment, however is not at the actual margin of the granodiorite . . . but further back in the intrusion . . . . This potash enrichment has caused the local development of late orthoclase in the form of large poikilitic crystals, sometimes at the expense of the plagioclase".

Had /

Had the final stages of feldspathisation of the aureole passed unnoticed expulsion of potash from the Loch Doon contact rocks might well have been (wrongly) deduced. An alternative source of the "late orthoclase" is considered below (p. 157).

(iv) Basic margins

Referring to complexes such as are being considered here Nockolds wrote (1934) "basic margins are a common phenomenon, sometimes gabbroic or noritic, sometimes dioritic, and have often been supposed to represent the original magma, chilled before differentiation in situ could commence. The alternative suggestion is here made that such material represents an earlier basic intrusion in all cases". (My italics). Nockolds' generalisation can no longer be maintained for Doris L. Reynolds has demonstrated (1946) that desilication precedes granitisation in all areas which have received adequate chemical study; a demonstration which is in accord with the Loch Doon evidence.

In their investigations at Trégastel-Ploumanac'h, H.H. Thomas and W. Campbell Smith (1932) considered that basic inclusions in the granite were derived from an earlier norite mass, which now in part roofs the complex. Doris L. Reynolds has pointed out (1946) that no desilication corresponding to the granitisation of the norite has been described, justly remarking that "the norite itself may represent the basification of pre-existing /

pre-existing rock". Indeed, in all cases, the possibility that the basic margins are basic fronts must be considered. This is especially the case where there is great variation in the basic rocks (e.g. H.H. Thomas and W. Campbell Smith, 1932; S.R. Nockold 1932). The significance of variation in so-called igneous rocks was clearly perceived by G.H. Anderson who wrote (1937): "The writer believes that the Pellisier granite was formed in situ, partly by recrystallization and partly by replacement of older rocks of both sedimentary and igneous character. . . . The Pellisier granite is variable, both in texture and composition. This is obviously to be expected in 'igneous' rocks formed by granitization".

(v) Contacts

The contacts between the various plutonic rocks of an individual complex may be sharp, as at Bibette Head (S.R. Nockold 1932), or gradational, as at Dhoon (S.R. Nockolds, 1931). Where sharp contacts occur, it should be remembered (a) that contacts which appear hair-sharp macroscopically may be gradational microscopically; numerous examples from Loch Doon have been cited abo and (b) that, as G.E. Goodspeed has pointed out (1939, p. 404), although sharp contacts are not usually considered to be indicative of metasomatic replacement, they are common in replacement o ore-deposits; for example, L.C. Graton, a geologist well acquain ted /

acquainted with ore-deposits, has written (1924, p. 520), "as for the transitional boundary as a criterion of replacement, . . . very frequently replacement is complete as far as it goes and will yield as sharp contacts as can be produced by simple filling of open spaces". H.H. Read has remarked (1943-44) that "circumstances of temperature, pressure, or concentration may give rise to knife-edge boundaries to the products of granitization reaction. An example of the production of sharp contacts by solid diffusion is given on page 46.

The problems raised by gradational boundaries, whether differentiation is assumed to have been in depth or in situ, are referred to on page 131. In several complexes, gradations are found not only between the various plutonic rocks, but between the latter and the aureole (e.g. G.H. Anderson, 1937; G. Wilson, 1938). That this is of considerable significance is obvious.

(vi) Inclusions

"Granitic plutons are commonly characterized by so-called cognate inclusions of more basic composition than the enclosing granite. At one time these inclusions were regarded as segregations of the early crystallized basic constituents of the granite magma. During the last fifteen years, however, this conception has largely been abandoned, and basic cognate inclusions in granitic /

granitic rocks are now more commonly interpreted as hybridized relics of an early basic intrusion which occupied the site of, or roofed, the present granite". (D. L. Reynolds, 1946, p. 427). In some cases the inclusions are known to be of sedimentary origin a complete series linking obvious sediments with the more altered types (e.g. P.K. Ghosh, 1934); in others the source is unknown or hypothetical (e.g. S.R. Nockolds, 1932). Where the source of the inclusions is supposed to be an early basic intrusion, granitisation sequences are found without corresponding desilication series, but, in such cases the "least altered" inclusions are often characterised by high contents of P and/or Ti (e.g. D.R. Grantham, 1928; S.R. Nockolds, 1932). As Doris L. Reynolds has shown (1946, p. 427) "this precludes the possibility that such inclusions have arisen directly by the granitization of a basic igneous parent".

Daphne D.C. Pochin Mould recorded (1946) abundant "basic dioritic inclusions" in the Foyers "granite", and stated that "they are obviously being made over into varieties resembling the enclosing tonalite and granodiorite". Comparing these basic inclusions with the diabrochites of J.A. Dunn (1942) and with the basic fronts of D.L. Reynolds (1944), she writes: "It should be pointed out that in the Foyers plutonic complex, no transitions from the basic inclusions to ordinary Moine schists have been found /

found, and that if the basic enclaves do represent relics of basified schist, the process must have taken place at depth, prior to the intrusion of the complex into its present position". It is probable that the "xenoliths of feldspathised schist" found in the tonalite represent just such transitions; it is certainly significant that these inclusions of feldspathised schist "often have a selvage of large, lustrous biotite plates".

It is probable that in every case the sequence in the production of inclusions is, country rock ⟶ basic "igneous" rock ⟶ granite.

As Nockolds has pointed out (1933), preservation of shape by the altered inclusions "shows that the xenoliths remain essentially solid throughout the whole course of their alteration". Change of composition must therefore take place, and must be effected by diffusion through the solid rock. F.F. Grout has written (1937, p. 1543) "there can be little doubt that a magma may so change an inclusion, while it still remains an inclusion, that the chemical criteria of origin are lost. This is a perfectly logical conclusion from Bowen's careful study of the physical chemistry of the inclusion in magmas . . . All inclusions in granitoid igneous rocks should be expected to have igneous compositions except those included at so late a magmatic stage that they had no time to react". This is a common misconception:

(a) /

(a) Bowen qualified the assertion that a magma will tend to make inclusions over into the phase or phases with which it is saturated, by the seldom quoted phrase "in so far as the composition of the sediments permits" (1928, p. 216); (b) either the last residual liquids are aplitic or they are cafemic; the magmatic hypothesis cannot explain both desilication and granitisation.

(vii) "Clotting" and magmatic strew

"Clotting" of ferromagnesian minerals, usually accompanied by sphene, is a widespread phenomenon at Loch Doon and in the plutonics of the South of Scotland in general; the significance of this has been discussed above (pp. 99, 132). Examples of the same phenomenon are Dhoon (S.R. Nockolds, 1931), Shap (D.R. Grantham, 1928), and Bibette Head (S.R. Nockolds, 1932), at all of which the abundance of apatite and sphene, and the genetic relation of the clots and the basic inclusions, have been recorded. Describing hornfelsed inclusions in the metasomatic granodiorites of Cornucopia, Oregon, G.E. Goodspeed has remarked (1939, p. 409), "Some of the smaller hornfels xenoliths are decidedly more basic than the average hornfels. They may consist almost entirely of hornblende or biotite, and in some occurrences the transition from a xenolith to an aggregate of biotite and finally to a single large crystal of biotite seems clear. . . . Although it is possible to explain the biotite as a segregation from a magma, it would /

would not be possible to give the same interpretation to an angular hornblendic inclusion. Since the original hornfels is higher in iron, calcium, and magnesium than the granodioritic material by which it is replaced, the feldspathization requires the assumption of the removal of these constituents as well as the addition of silica and alkalies. The large biotite- and hornblende-rich xenoliths may represent a local concentration of these constituents". Such a possibility must be considered for all basic inclusions, ferromagnesian clots, and indeed for all ferromagnesian minerals.

F.F. Grout (1937) has considered that "glomeroporphyritic clusters" are probably magmatic segregations, but most workers are agreed that the clots are derived from the basic inclusions with which they are associated, a popular mechanism being that of "magmatic strew". At Dhoon, Nockolds (1931) has shown that the biotite of the granite has the same pleochroism as that of the clots, and that its abundance is proportional to that of the clots; at Bibette Head (Nockolds, 1932) similar biotite and hornblende inclusions occur in the plagioclase of both the granite and the inclusions, and the whole mass is stated to be uniformly contaminated; at Kopaonik, G. Wilson (1938) described poikilitic green hornblende as occurring throughout the inclusions and the granodiorites, and demonstrated that "the euhedral hornblendes are the products /

products of progressive recrystallization of the earlier anhedral crystals."

There are two possibilities: "The ubiquity of these crystals, which have a dominantly sedimentary parentage, throughout the granodiorites, suggests that either the batholith now represents the final product of granitization in place, or that an original magma, arising from an unknown depth, worked its way upwards by reaction with and assimilation of the sediments in its path". Against the latter possibility there is (a) the necessity of postulating an aplite parent, and the incorporation of some 30-40% of hornfels for the production of granodiorites. Aplite is generally considered to occur in relatively small amounts and to be the last residual liquid from the crystallization of granite magma. Whether or not that view is correct, it seems most unlikely that aplite is the parent of the granitic rocks; (b) the necessity of involing the hypothesis of "magmatic strew", against which there is, first, the occurrence of skeletal and highly skeletal crystals (see plate 30); second, as G.E. Goodspeed has recorded (1939, p. 407), "some (xenoliths) appear as extremely angular irregular fragments consisting of two larger portions joined by a relatively thin connecting link which would be unable to withstand magmatic mobility"; and third, C.S. Ross (1935, p. 12) has pointed out that in certain rocks associated with ore-deposits /

ore-deposits "single needlelike crystals may penetrate several crystals, as where actinolite needles extend through several quartz and plagioclase grains. The formation of such groups in a melt seems improbable, and the development of such forms directly from a hydrothermal solution seems even more improbable. Therefore the replacement of quartz and feldspar after its formation is the only reasonable explanation of the radial groups described in this paper". The tourmaline of luxullianite "radiating tapering needles of bluish tints spreading outwards through the quartz" (J.S. Flett, 1907, p. 56; A. Harker, 1935, fig. 10A), is generally accepted as due to replacement, and even in 1877 T.G. Bonney (p. 220) thought it "rather strange" and "very perplexing" that "the acicular schorl passes from grain to grain of the quartz". Although the apatite needles of the granitic rocks being discussed are not so remarkable as the luxullianite tourmaline, the marked basal cleavage increases the probability that the mineral is not of magmatic origin, and makes it certain that there was no magmatic turbulence.

(viii) Late potash feldspar

The late development of replacement potash feldspar at Kopaonik has been referred to above (p. 148). Deuteric microcline has been described by J.E. Spurr and G.H. Garrey (1908), J.L. Gillson /

Gillson (1927), A.L. Anderson (1934), and R. Gibson, I. Campbell, and W.F. Jenks (1938). For reasons which apply equally to Loch Doon, Doris L. Reynolds (1943) is doubtful whether the term deuteric should be applied to the microcline of the replacement bodies of Goraghwood Quarry, Co. Armagh. "Deuteric" as defined by Sederholm (1916, p. 142) refers to changes "which have taken place in direct continuation of the consolidation of the magma of the rock itself". Reynolds has shown that the Goraghwood bodies "are not the products of the crystallization of magma, as generally understood", but remarks that "if on the other hand it be permissible to apply the term 'magma' to the mobile antecedents of an igneous-looking rock, even though they were of the nature of a succession of emanations, then the microcline may be properly described as deuteric".

(ix) Garabal Hill

The Garabal Hill-Glen Fyne complex has been interpreted by S.R. Nockolds (1940) as an example of crystal differentiation. The implications of this interpretation have recently been pointed out (McIntyre, 1947; cf. p. 113 of this thesis), and it is not necessary to repeat these here. It is believed that they make the hypothesis of crystal differentiation at Garabal Hill untenab

(x) The Aberdeenshire Norites

The norites of Aberdeenshire are more calcic than the

so-called /

so-called norites of Loch Doon (cf. pp. 48, 61). H.H. Read, however, has recorded (1935) quartz-biotite-norite, sometimes containing a little orthoclase, from Haddo House. If the Aberdeenshire norites are actually of magmatic origin (Read considered that they represent contaminated magma), they must not be confused with the basic front "norites" of Loch Doon. Further research may show that in their genesis the rocks of the two areas are indeed comparable, for H.H. Read has demonstrated (1923, p. 473) that at Arnage "the strike and dip of the bedding of the larger xenoliths agree with those of the adjacent country rock", and G. Whittle at Insch has recorded (1939) not only skeletal biotite in the contaminated rocks, but basification of the inclusions, the abundance of apatite in which suggests P culmination. The hypothesis that the Aberdeenshire norites represent basic fronts is undoubtedly one that deserves consideration.

(xi) Opdal-Inset

Reference has already been made (p. 62) to the petrographic similarity of the Loch Doon "norite" and the opdalite of V.M. Goldschmidt (1916). In a personal communication Goldschmidt writes (1946): "There is no indication of any metasomatic origin of the original opdalite; it contains angular fragments of hornfels. But the geographical distribution of the rock prefers the regions near the contact aureole". A.M. Bateman, however, has demonstrated /

demonstrated (1924) that angularity of inclusions does not preclude a replacement origin for the deposit that contains them. Moreover, although in 1946 Goldschmidt evidently had no doubt that the inclusions were of hornfels, in 1916 he stated that the fine-grained dark greenish-grey inclusions found abundantly in the opdalite south of Austberg consist of plagioclase and hypersthene, and suggested that they might be fragments either of a fine-grained marginal facies, or of a hypersthene-hornfels. It is obvious that the inclusions of hornfels must be "igneous looking".

Goldschmidt has emphasised that the series biotite norite —— opdalite —— trondhjemite is characterised by a rather high proportion of biotite: "Der wesentlichste Unterschied dieser Art von Stämmen gegenüber dem im Normaldiagramm dargestellten Fall besteht in dem schon frühzeitigen und sehr reichlichen Auftreten von Biotit". (1922, p. 6). It is not surprising, therefore, that Goldschmidt never seriously discussed the possibility of a genetic relation between the biotite-poor inclusions, and the opdalite. It is important to recall that in the diopside hornfels —— opdalite series of inclusions at Loch Doon, biotite is usually not conspicuous until a fairly late evolutionary stage (p. 67).

Further work is undoubtedly required at Opdal-Inset, and it is obvious that the solid diffusion hypothesis deserves serious consideration.

F. /

F.F. Grout has written (1941): "There are many evidences that granite magmas exist as normal magmas, that they inject the crust as normal magmas, and are capable of forming such rocks as the 'orthodox' magma should". The review given here shows that such statements must be accepted with caution.

3. <u>Complexes in which a comparable mechanism has been recognised</u>
The production in situ of igneous-looking rocks of granitic and allied character is well established in post- as well as in syn-tectonic belts. There is, for example, the work of A. Keith (1913), W.H. Emmons and F.B. Laney (1926), T.T. Quirke and W.H. Collins (1930), A.L. Anderson (1934), G.E. Goodspeed (1937), G.H. Anderson (1937), H.G. Backlund (1938), B.C. King (1942), D.L. Reynolds (1943, 1944), and J.A.W. Bugge (1945).

For us the investigations of Doris L. Reynolds at Newry and of B.C. King at Cnoc nan Cuilean, have especial significance, but G.E. Goodspeed's early recognition of basic fronts and of the stages in the development of plagioclase porphyroblasts, must be mentioned. Of the former he wrote: "It is noticeable that adjacent to some of the more leucocratic granodioritic masses there is an increase of mafic constituents in the hornfels. . . .
Under /

Under a metasomatic explanation of additive metamorphism, it would be expected that the introduction of activating siliceous solutions or emanations would promote felspathisation and remove iron, lime, and magnesia from the loci of intense replacement. In other words, accompanying the additive chemical action contemporaneous with the granitization of an area, there would be a complementary outward movement of such elements as iron, calcium, and magnesium" (1939, p. 405). Of plagioclase porphyroblasts he wrote: "They can be seen in various arrested stages of growth. Some appear to have been formed by the coalescing of many small crystals which are in alignment so as to produce the necessary optical continuity in the larger crystal" (1937, p. 16; see also 1937, p. 1133).

Comparing Newry and Cnoc nan Cuilean, Doris L. Reynolds pointed out (1944, p. 238) that these areas "differ in the energy levels of the comparable 'fronts'. This is evidenced by the fact that in the Newry area the main Mg-Fe 'front', the secondary alkali 'front', and that part of the secondary Fe-Mg 'front' which is represented by the mobilized sediments, lie within the igneous boundary, whereas in the Cnoc nan Cuilean area the boundary of the igneous mass falls within the main Fe-Mg 'front', so that part of this 'front', together with the secondary alkali 'front', lie outside the igneous contact".

To these two complexes may be added Boundary Peak (see D.L. Reynolds, 1946, p. 404) and Loch Doon. The position, in relation to the inner margin of the aureoles in each of the four complexes, of the basic front, and, where known, of the secondary alkali front, are shown diagrammatically in fig. 10. It is evident that a basic front associated with granitisation may lie (a) entirely within the plutonic rocks (e.g. Newry), (b) mainly within the plutonic rocks (e.g. Loch Doon), (c) mainly within the aureole (e.g. Cnoc nan Cuilean), or (d) entirely within the aureole (e.g. Boundary Peak).

It is a fact of the utmost significance that lines easily observed in the field may be of little petrogenetic import. That the so-called margins of these complexes are of much less importance than has hitherto been believed is a fact which places their non-magmatic genesis beyond question. It is clear, moreover, that the so-called norite of Loch Doon is actually much more closely related to the iron-schists of Boundary Peak, to the aegerine-augite- and hornblende-schists and the basic syenites of Cnoc nan Cuilean, and to the biotite-pyroxenite and the ultrabasics of Newry, than to any igneous or contaminated rock, however alike petrographically.

Conclusion

During recent years there has been published a large number of general papers on the subject of granite; notable are those by Malcolm MacGregor and G. Wilson (1939), H.H. Read (1939; 1943-44; 1946), A. Holmes (1945), R.H. Rastall (1945; 1947) J.A.W. Bugge (1945), H.G. Backlund (1946), G.W. Tyrrell (1947), and Doris L. Reynolds (1947). In the first of these an important principle was stated: "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 <u>will not have</u> 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".

The term emanation was originally "a neutral term . . . free from genetic implication", but it has now come to imply "a migration of ions within solids by way of structural faults, deformations, and crystal discontinuities, and by means of potential differences of lattice energies" (H.G. Backlund, 1946). E.J. Bowen (1946) and Kathleen Lonsdale (1947) have recently pointed out that discontinuities are present even in "ideal" crystals; one /

one cannot doubt, therefore, that in such obviously imperfect crystals as the plagioclase of the Loch Doon rocks, crystal deformities are of major importance. A replacement mechanism not requiring crystal discontinuities has been described by G.V. Douglas, N.R. Goodman, and C.C. Milligan (1946). The state of aggregation of the diffusing material has recently been discussed by A. Holmes and Doris L. Reynolds (1947), and the evidence for regarding "emanations" as an ionic disperse system has been summarised.

J.A.W. Bugge has emphasised the importance of diffusion in the solid state, and pointed out that, from a formal point of view, transport in the intergranular film may be classified with diffusion in the solid state. High pressure, moreover, tends to diminish the interstices between the crystals, and therefore decreases the potential barrier passed by a particle transferred from a surface position on one crystal to a surface position on another. As lateral pushing aside of the country rocks has taken place locally, the Loch Doon complex must have suffered compression during its formation, which would facilitate migration by a process of solid diffusion.

To the factors recognised by Wegmann (1935) as influencing large scale diffusion, namely differences in concentration, temperature /

temperature (the Soret effect), and electric potential, Bugge added specific gravity, external pressure, vapour tension, and chemical potential. Of the last he writes: "In the same way as electric conductivity depends on differences in the electric potential we may say that diffusion depends on differences in chemical potentials. The chemical potential is a thermodynamic intension quantity, and is a function of the free energy F and of the thermodynamic potential G". Indeed he goes so far as to state that "the only exact method to study the currents of molecules or ions between two phases is by means of the chemical potentials" Naturally diffusion always tends to eliminate differences in chemical potentials.

"A long-distance migration of matter through the crystal is still a hypothesis; but when most of the reactions between the individual minerals in a heterogeneous rock complex of great extension are found to take place in the solid state, it may be justified to conclude that also the migration of material to and from the reaction places has passed in the solid state". (J.A.W. Bugge, 1945, p. 38)

Discussing the origin of the ferromagnesian minerals associated with the Ducktown ores, C.S. Ross wrote: "Only two probable sources of ferromagnesian minerals seem to present themselves /

themselves. First, there may have been two distinct magmas, or two distinct phases of what was originally a single magma, which, on differentiation, formed ferromagnesian-free and ferromagnesian-rich fractions, both high in mineralizers, which acted as transporting agents. Second, there may have been a single magma high in mineralizers in which the ferromagnesian materials had been eliminated by their early crystallization, followed by their partial restoration to the residual magma by re-solution, replacement or base exchange". (1935, p. 52). He himself inclines to the second possibility, but admits that the difficulty is to account for the reassociation of two fractions once separated - "that is, to restore a relationship that has been lost". Ross, of course, accepted the magmatic hypothesis a priori: "The veins were no doubt derived from some differentiating magma, but no parent igneous rock has been identified in the region".

The possibility that ore deposits are a particular form of the basic front must be considered in every case. This is especially so in view of A. Holmes' finding (1946), based on Nier's isotopic analyses, that it is probable that "ore-lead was a concentration from lead that was dispersed through crustal rocks before their granitization", and that "naturally, if this were true for lead, it was likely to be equally true for many of the other elements geochemically associated with lead ores".

R. /

R. H. Rastall has recently (1947) directed attention to the association, and lack of association, of certain ores with certain granites, and concluded that "It can hardly be denied that most of the phenomena here briefly discussed are most easily explicable by some theory of magmatic differentiation". Further work is undoubtedly required, but that the magmatic theory offers the correct explanation of the genesis of ore-deposits, most certainly can be questioned.

That there is a close connection between metamorphism and "igneous action" is now certain. Since H.H. Read's suggestion in 1939, the work of R. Perrin and M. Roubault (1941), of Doris L. Reynolds (1942; 1947), and of P. Lapadu-Hargues (1945) has clearly shown that during regional metamorphism there is migration of an ionic disperse system, " a succession of overlapping emanations", similar to the diffusions which have produced the plutonic rocks discussed above.

As we more clearly perceive the genetic relation between such apparently diverse phenomena as plutonic complexes, ore-deposits, regional metamorphism, and the cementation of sediments, so we may more fully understand that "according to the hypothesis postulated /

postulated, one continuous process alone is invoked, which is closely supported by the continuity in the phenomena observed". (B.C. King, 1942). To understand the genesis of a plutonic complex we must study a physico-chemical system larger than that enclosed by the inner margin of the aureole; but, in order to solve the broader petrogenetic problems, the unit studied must be increased in proportion. Great earth movements disturb the balance of chemical potentials, and the geological consequences of the resulting migrations can hardly be overestimated.

"Here on their knees men swore: the
    stones were black,
Black in the people's minds and words,
    yet they
Were at that time, as now, in colour
    grey."

Wordsworth.

XVII /

XVII. ACKNOWLEDGMENTS

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APPENDIX.

The process found to have been operative in the Loch Doon complex has been termed "solid diffusion" throughout the course of this thesis (see pp. 1-2).

The following is a list of other terms which were considered:

Diadromic	running across; wandering through or about.
Diameipsic	to exchange, e.g. one thing with another (Plato), one thing for another (Plato and Solon), Asia for Europe (i.e. passing into - - from - -: Euripides); making a journey (Aeschylus); passing over or through (Aeschylus); changing or altering (Herodotus); to requite (lex talionis: Dio Cassius).
Diamudainic	filter through.
Dianaic	percolate.
Diaperasimic	penetrating.
Diaplanetic	wandering (going astray).
Diapneutic	dispersion in vapour (evaporate).
Diaporeutic	going through and out.
Diaprassic	making one's way through.
Diascorpic	dispersion.
Diastrephic	turning or twisting about (as in a dance); distorted.
Diatoric	piercing.
Dieimic	roaming about.
Dierchomatic	going through and out.

Metaphrase /

Metaphrase	a word-for-word translation as distinct from a paraphrase.
Pycnogenetic	originating in the solid.
Transform	to change in form, shape, or appearance: to metamorphose.
Transfuse	to cause to 'flow' from one thing to another; to diffuse into or through something; to cause to permeate.
Translate	to change in form, appearance, or substance; to transmute; to transform.
Transmute	to alter or change in nature, properties, appearance, or form.

The author is indebted to the Rev. R.E. McIntyre and to the Rev. Professor Wm. Manson for advice and suggestions.

NOTES on the TABLES

The analyses are arranged in petrological (field and microscopic) order:

1. Greywacke (485)
2. Slightly feldspathised greywacke-granulite (506).
3. Fully feldspathised granulite (507)
4. Opdalitic pod (685/5)
5. Fine-grained opdalite (333)
6. Medium-grained opdalite (532 of Gardiner and Reynolds)
7. Coarse-grained opdalite (18)
8. Potash-feldspar-poor "norite" (206)
9. "Tonalite" (749 of Gardiner and Reynolds)
10. Granite (755 of Gardiner and Reynolds)

For details of these rocks see p. 114.

In Tables 2 and 3:

Summation	6	includes	(Co, Ni)O	0.15
"	9	"	"	0.09
"	10	"	"	0.05

TABLE 1.

Zonal range of graptolites occurring in the Craiglure Old Lodge Shale Quarries.

Sub-zones.	4	5	6	7	8	9	10	11	12	13
Nemag. gracilis						c				
Nemag. pertenuis						+				
Nemag. nitidulus						+				
Dicellog. moffatensis			+	+	?	+	+	+		
Dicellog. divaricatus				+	+	+	+	?		
Dicellog. sextans						c	+			
Dicellog. patulosus							c			
Climacog. bicornis						c	+	c	+	
Climacog. tridentatus							+	+		
Climacog. Schärenbergi			+	+	+	c	c	c		
Diplog. euglyphus					+	c	c	+		
Diplog. foliaceus					c					
Diplog. mucronatus						c	+			
Dicranog. ramosus							r	+	c	
Cryptog. tricornis	+		+	+	+	c	c	c	+	
Leptog. capillaris									+	c
Glossog. Hincksi						+	+	c		

Sub-zones 8, 9, and 10 together constitute the zone of Nemagraptus gracilis.

TABLE 2.

Chemical Analyses

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO_2	68.68	67.79	64.20	60.29	60.06	56.90	55.34	55.78	62.95	70.63
Al_2O_3	12.84	13.83	15.86	17.53	16.14	16.49	16.18	16.36	14.59	14.65
Fe_2O_3	0.16	0.41	0.71	Tr.	0.98	0.98	0.97	0.53	1.00	0.54
FeO	5.58	5.77	4.57	5.31	4.85	5.66	6.13	6.41	3.87	1.93
MgO	2.95	3.03	2.81	4.49	4.65	5.64	6.02	5.42	4.02	1.45
CaO	1.32	1.38	2.35	5.02	5.64	6.14	6.06	7.34	3.81	1.83
Na_2O	2.04	3.06	3.64	2.69	3.43	3.86	3.92	3.32	3.36	3.55
K_2O	1.47	1.96	3.62	2.28	2.04	1.92	2.21	1.78	4.52	4.29
H_2O + 105°	2.98	0.94	0.82	0.36	0.32	0.31	0.36	1.22	0.69	0.42
H_2O -	0.10	0.22	0.16	0.18	0.04	0.18	0.38	0.17	0.22	0.12
CO_2	Nil	Nil	Nil	Nil	Nil	0.40	Nil	Nil	- -	0.18
TiO_2	1.12	0.98	0.96	0.98	1.07	1.13	1.68	1.42	0.73	0.41
P_2O_5	0.17	0.13	0.22	0.20	0.21	0.04	0.25	0.21	0.01	0.07
MnO	0.23	0.27	0.14	0.26	0.26	0.24	0.33	0.31	0.19	0.09
	99.64	99.77	100.06	99.59	99.69	100.04*	99.83	100.27	100.05*	100.21*
Total Fe as FeO	5.72	6.14	5.21	5.31	5.73	6.54	7.00	6.89	4.77	2.42

<u>Norms</u>

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Quartz	40.50	31.23	17.68	15.13	11.67	3.70	0.90	4.37	11.14	26.53
Orthoclase	8.68	11.58	21.37	13.47	12.08	11.35	13.08	10.52	26.71	25.33
Albite	17.29	25.90	30.78	22.75	29.00	32.67	33.14	28.10	28.42	30.02
Anorthite	5.42	6.06	10.17	23.61	22.57	21.98	20.03	24.48	11.39	8.61
Corundum	5.91	4.48	2.23	2.00	- -	- -	- -	- -	- -	1.02
($FeSiO_3$	8.70	9.13	6.47	8.61	6.29	6.90	7.07	7.97	4.43	2.60
($MgSiO_3$	7.35	7.55	7.00	11.18	10.54	12.07	12.90	10.90	8.09	3.61
($CaSiO_3$	- -	- -	- -	- -	1.66	3.42	3.50	4.40	3.10	- -
($FeSiO_3$	- -	- -	- -	- -	0.60	1.18	1.17	1.79	1.05	- -
($MgSiO_3$	- -	- -	- -	- -	0.98	2.06	2.13	2.45	1.89	- -
Magnetite	0.23	0.60	1.05	- -	1.41	1.41	1.41	0.77	1.46	0.79
Ilmenite	2.12	1.87	1.82	1.87	2.03	2.14	3.19	2.70	1.39	0.78
Apatite	0.41	0.31	0.54	0.47	0.51	0.10	0.60	0.51	- -	0.17
Water	3.08	1.16	0.98	0.54	0.36	0.49	0.74	1.39	0.91	0.54
	99.69	99.87	100.09	99.63	99.70	100.02*	99.86	100.35	100.07*	100.23*

TABLE 5.

TABLE 4.

Recalculated Percentages

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO_2	72.11	69.55	65.63	61.60	61.32	58.22	57.01	57.38	64.10	71.42
Al_2O_3	13.48	14.19	16.22	17.91	16.47	16.88	16.66	16.83	14.86	14.81
FeO	6.25	6.58	5.47	5.69	6.12	6.97	7.55	7.41	5.05	2.54
MgO	3.10	3.11	2.87	4.59	4.75	5.77	6.20	5.58	4.09	1.47
CaO	1.39	1.42	2.40	5.13	5.76	6.28	6.24	7.55	3.88	1.85
Na_2O	2.14	3.14	3.72	2.75	3.50	3.95	4.04	3.42	3.42	3.59
K_2O	1.54	2.01	3.70	2.33	2.08	1.96	2.28	1.83	4.60	4.34
	100.01	100.00	100.01	100.00	100.00	100.03	99.98	100.00	100.00	100.02

TABLE 5.

von Wolff values.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Q	44.16	33.52	18.84	16.65	12.36	4.11	0.69	4.47	12.17	28.71
L	35.46	45.71	63.34	58.76	61.00	63.32	63.64	60.40	64.00	62.90
M	20.31	20.59	17.52	24.60	26.26	32.32	35.28	34.91	23.43	8.20
	99.93	99.82	99.70	100.01	99.62	99.75	99.61	99.78	99.60	99.81

Larsen "positions".

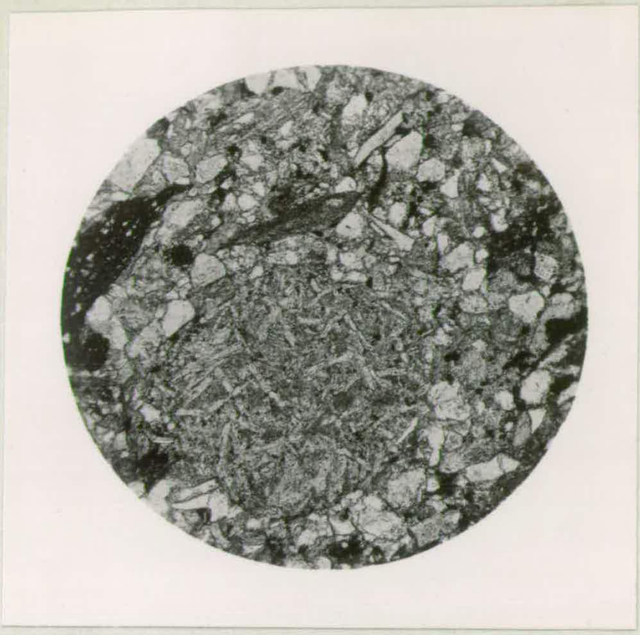
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
+	14.84	14.08	14.84	7.47	5.89	2.35	1.29	0.42	12.91	21.89

EXPLANATION of PLATES 1 - 3.

PLATE 1. (485) Greywacke from Craiglure Hill. Fragments of quartz, muddy material, and muscovite, and a rounded spilitic pebble are seen. P. 16. x 35.

PLATE 2. (685/1) Biotite-cordierite-granulite from Craigbrock. A cordierite crystal occupies a central position. P. 28. x 35.

PLATE 3. (685/1) As Plate 2, but with crossed nicols. x 35.



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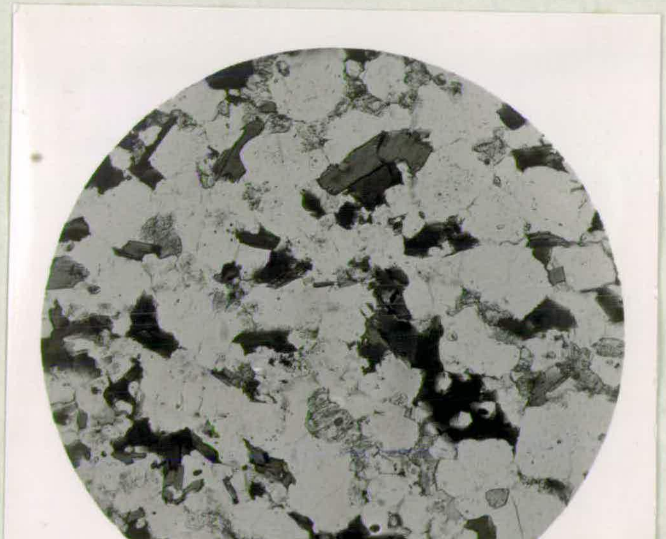

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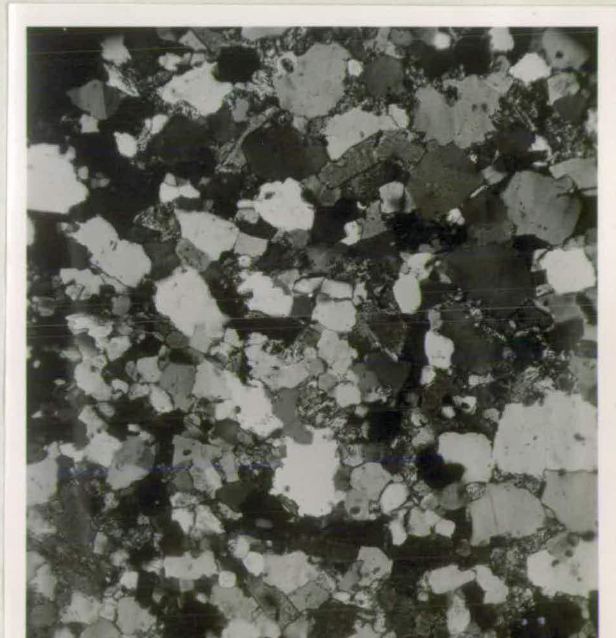

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EXPLANATION of PLATES 4 - 7.

PLATE 4. (509) Biotite-granulite from Cow Craig, with bedding visible. P. 23. x 35.

PLATE 5. (727) Slightly feldspathised biotite-granulite from Cow Craig. P. 26. x 20.

PLATE 6. (400c) Contact on Shepherds' Cairn between slightly feldspathised biotite-granulite and pyroxene-bearing "igneous-looking" rock with plagioclase porphyroblasts. Pyroxene is not seen. P. 34. x 20.

PLATE 7. (685/3) Intensely feldspathised biotite-granulite from Craigbrock. x 35.

4

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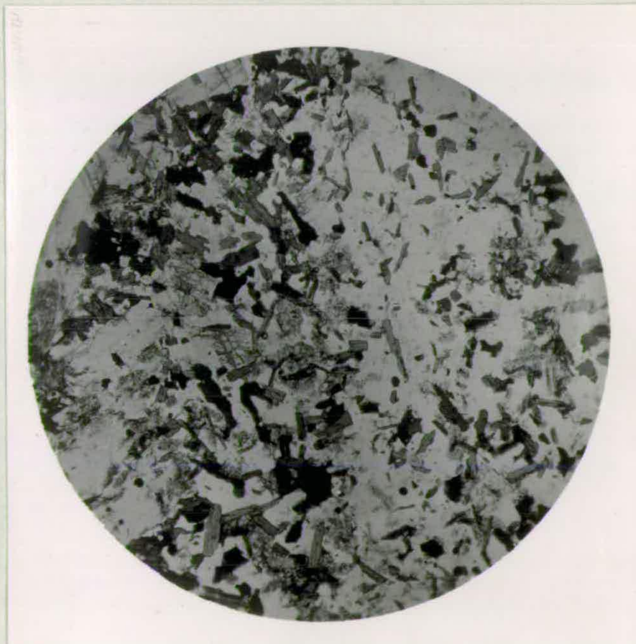

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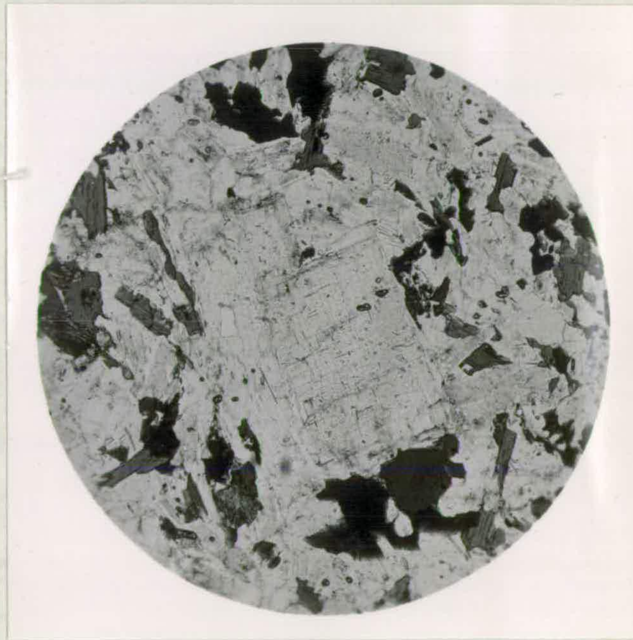

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EXPLANATION of PLATES 8 - 11.

PLATE 8. (509) Biotite-granulite from Craigbrock, with bedding visible. cf. Plate 4. Crossed nicols. x 35.

PLATE 9. (727) Slightly feldspathised biotite-granulite from Cow Craig. cf. Plate 5. Crossed nicols. x 20.

PLATE 10. (400c) Contact on Shepherds' Cairn between slightly feldspathised biotite-granulite and pyroxene-bearing "igneous-looking" rock with plagioclase porphyroblasts. Pyroxene is not seen. cf. Plate 6. Crossed nicols. x 20.

PLATE 11. (685/3) Intensely feldspathised biotite-granulite from Craigbrock. cf. Plate 7. Crossed nicols. x 35.

8

9

10

11

EXPLANATION of PLATES 12 - 15.

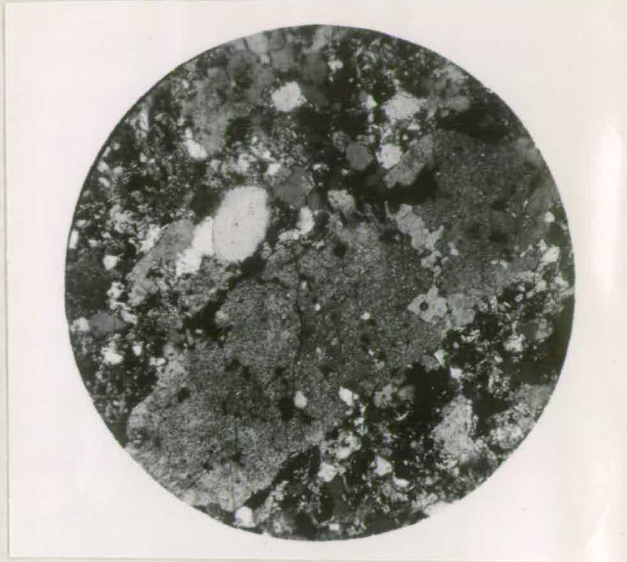
PLATE 12. (727) Plagioclase porphyroblast in biotite-granulite, Cow Craig. P. 26. Crossed nicols. x 20.

PLATE 13. (506) Plagioclase porphyroblast in biotite-granulite, Cow Craig, showing quartz inclusions. P. 25. Crossed nicols. x 35.

PLATE 14. (687) An early stage in the trapping of inclusions by the development of plagioclase porphyroblasts. Craigbrock. Pp. 27, 54. Crossed nicols. x 20.

PLATE 15. (545/6) A further stage in the development of plagioclase porphyroblasts. Craigbrock. Crossed nicols. x 20.

12



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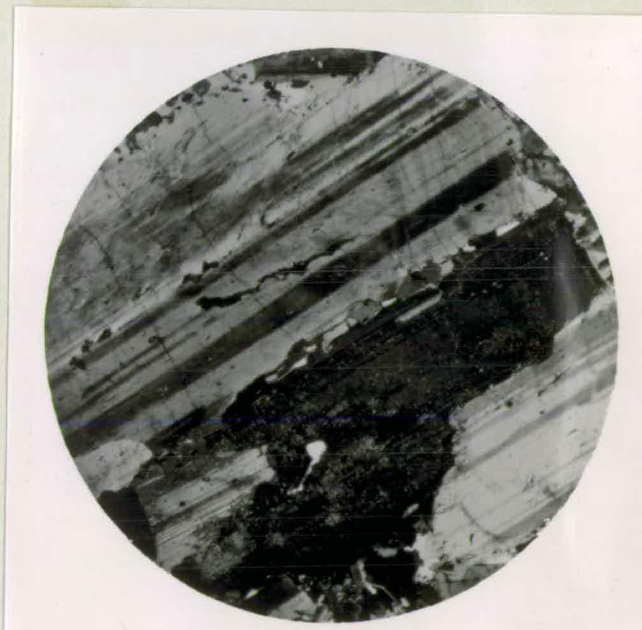

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EXPLANATION of PLATES 16 - 19.

PLATE 16. (507) Inclusions in plagioclase porphyroblast in feldspathised biotite-granulite. Cow Craig. P. 27. x 20.

PLATE 17. (507) As Plate 16, but with crossed nicols. That the line of biotite inclusions is the junction between two individuals in the plagioclase mosaic, is clearly seen. x 20.

PLATE 18. (70) Detail of plagioclase mosaic. Opdalite from N.E. side of Shiel Hill. The two black circles are air-bubbles. P. 54. Crossed nicols. x 35.

PLATE 19. (5) Plagioclase irregularities. Opdalite from N. side of Shiel Hill. P. 54. Crossed nicols. x 20.

16

17

18

19

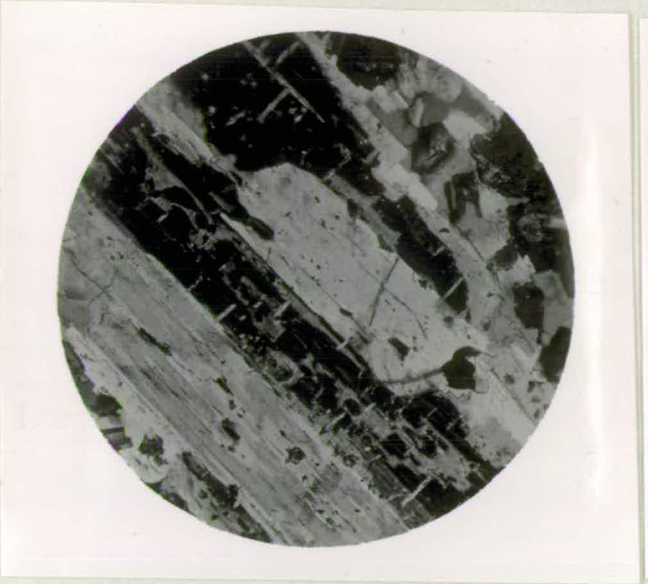
EXPLANATION of PLATES 20 - 23.

PLATE 20. (351) Plagioclase irregularities and inclusions. Opdalite from S. side of Cornish Hill. P. 54. Crossed nicols. x 35.

PLATE 21. (545/12) Plagioclase irregularities. Craigbrock. P. 54. Crossed nicols. x 35.

PLATE 22. (327) Patchiness in plagioclase. Opdalite from Cornish Hill. P. 54. Crossed nicols. x 35.

PLATE 23. (252) Curvature of plagioclase. Pyroxene-biotite-quartz-diorite from S.W. side of Shiel Hill. P. 53. Crossed nicols. x 35.



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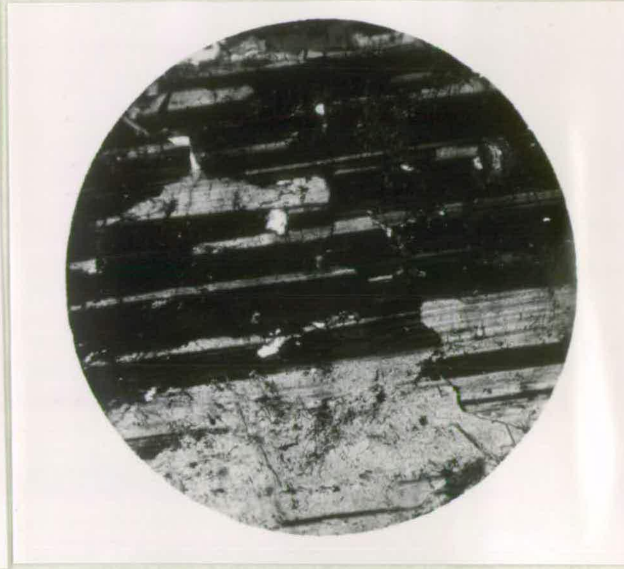

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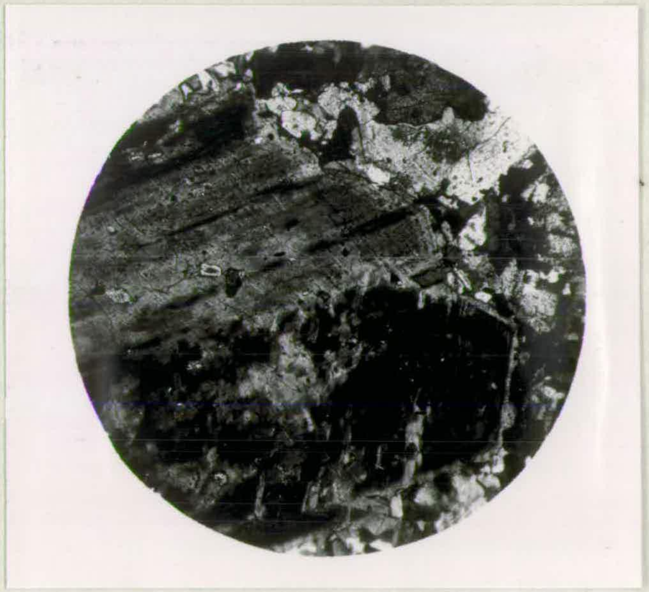

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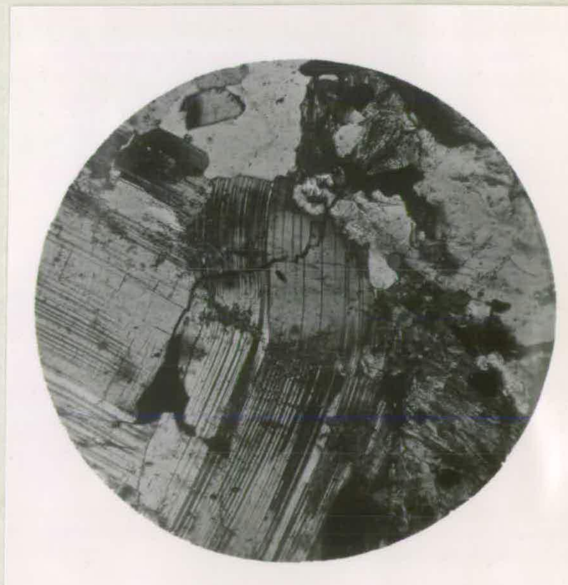


23

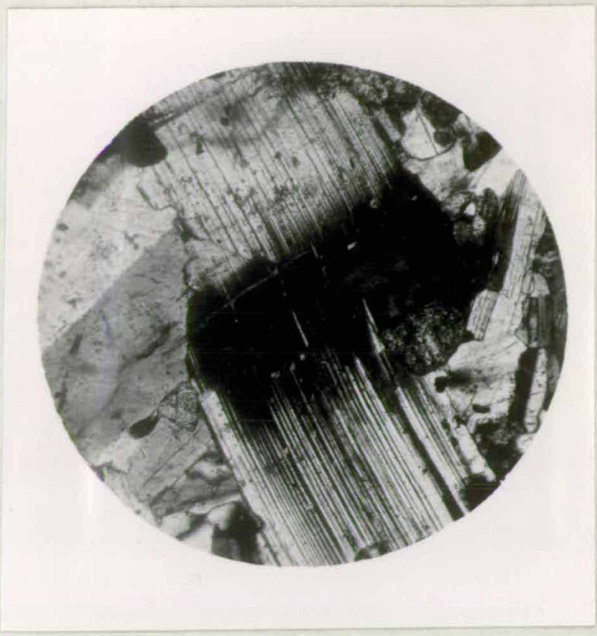
EXPLANATION of PLATES 24 - 27.

PLATE 24. (151) Curvature of plagioclase. Pyroxene-biotite-quartz-diorite from S.E. side of Shiel Hill. P. 53. Crossed nicols. x 35.

PLATE 25. (390) Curvature of plagioclase. Pyroxene-biotite-quartz-diorite from S. side of Cornish Hill. P. 53. Crossed nicols. x 35.

PLATE 26. (334) Plagioclase with a zone of inclusions. These are mainly pyroxene, with some ore and apatite. Opdalite from E. side of Cornish Hill. P. 52. x 30.

PLATE 27. (334) As Plate 26, but with crossed nicols. Oscillatory zoning also seen. x 30.



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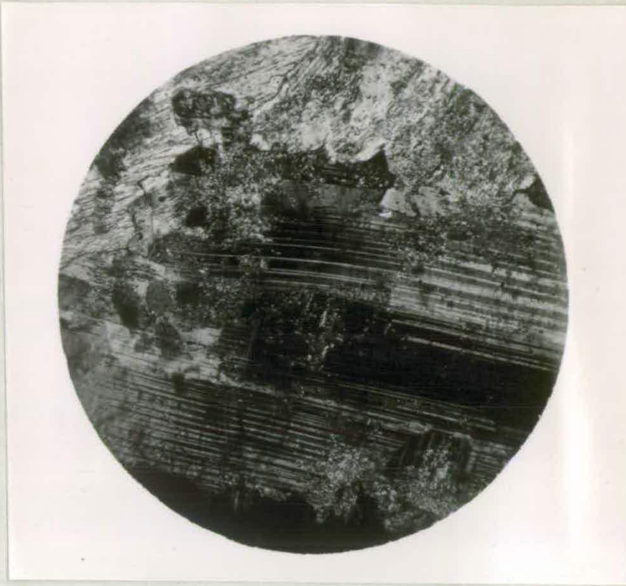

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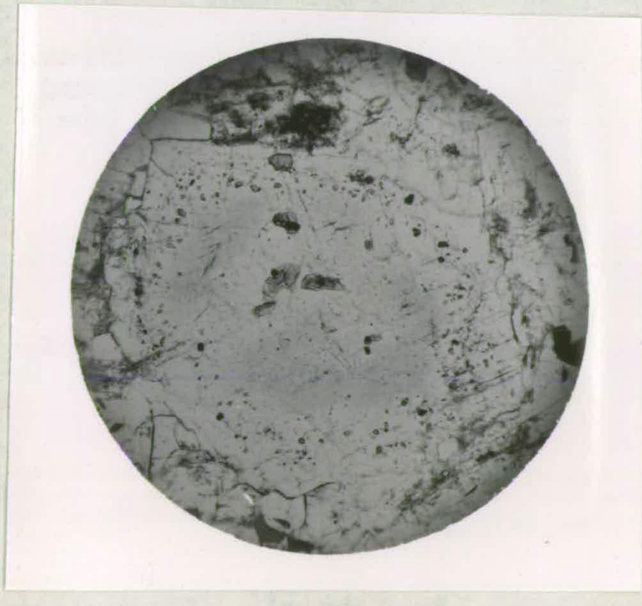

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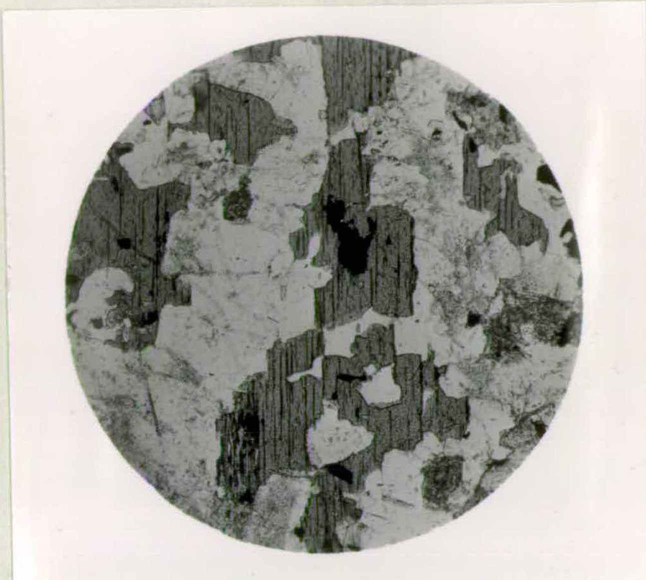
EXPLANATION of PLATES 28 - 31.

PLATE 28. (70) Skeletal biotite. Opdalite from N.E. side of Shiel Hill. P. 55. x 35.

PLATE 29. (188) Skeletal biotite. Pyroxene-biotite-quartz-diorite from S. side of Shiel Hill. P. 55. x 35.

PLATE 30. (401) Highly skeletal biotite surrounding highly skeletal pyroxene. Feldspathised biotite-granulite from Shepherds' Cairn. P. 30. x 35.

PLATE 31. (401) As Plate 30. x 35.



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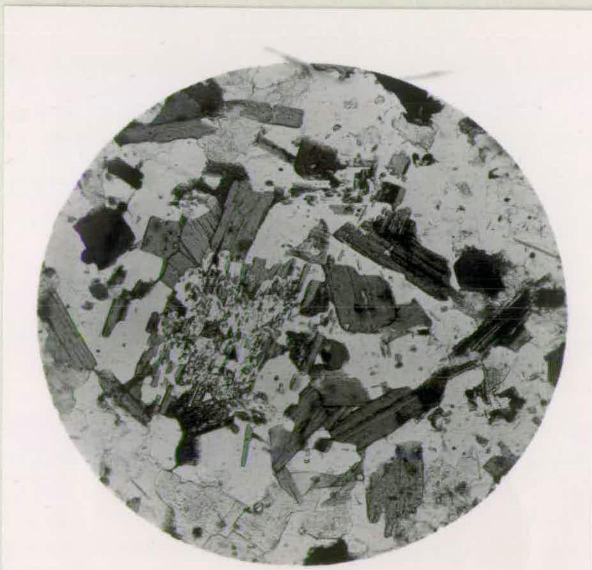

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31

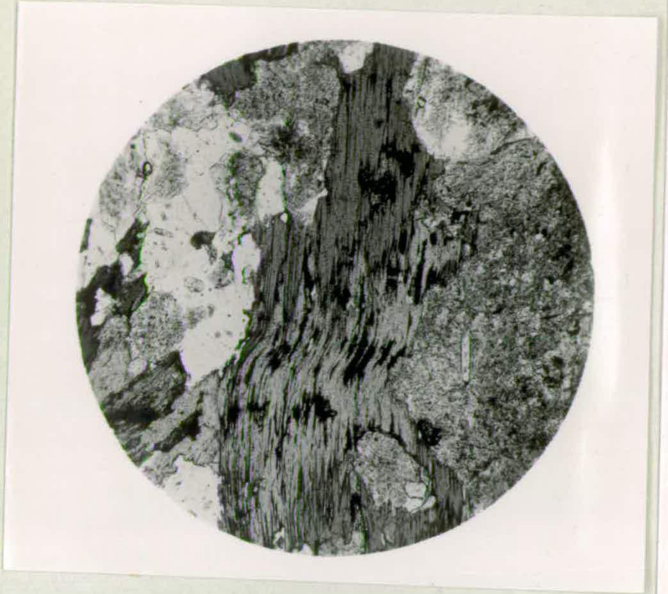
EXPLANATION of PLATES 32 - 35.

PLATE 32. (357) Curved biotite. Opdalite from S. side of Cornish Hill. P. 55. x 35.
N.B. Chlorite at curve.

PLATE 33. (116) Pyroxene rimmed by amphibole rimmed by skeletal biotite. Opdalite from E. side of Shiel Hill. P. 58. x 20.

PLATE 34. (79) Rectangular skeletal crystal of pyroxene. Opdalite from E. side of Shiel Hill. P. 56. Crossed nicols. x 35.

PLATE 35. (79) Sieved pyroxene. Opdalite from E. side of Shiel Hill. P. 56. x 35.



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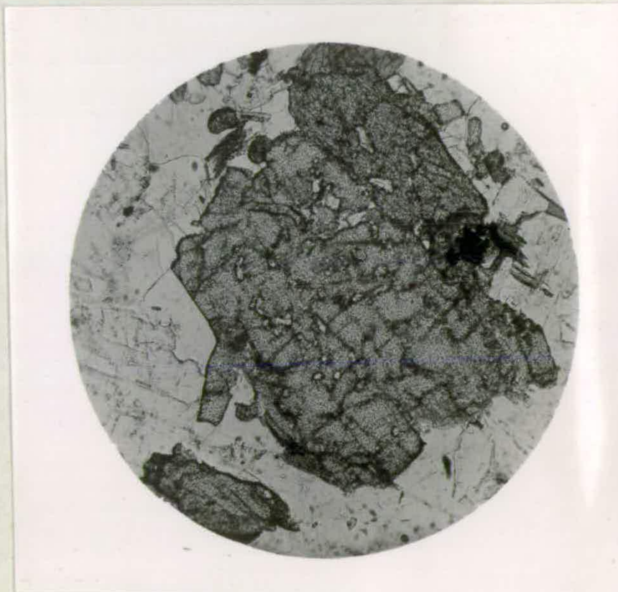

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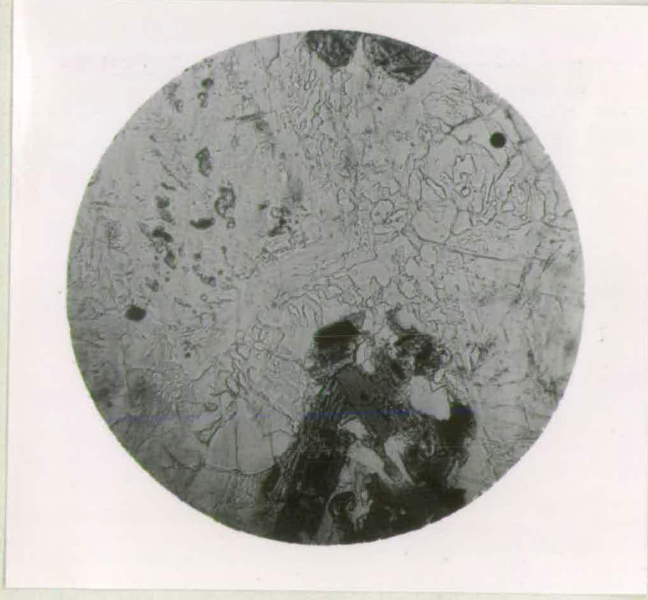
EXPLANATION of PLATES 36 - 38.

PLATE 36. (254) Poikiloblastic potash feldspar in extinction position. Opdalite from S. side of Shiel Hill. P. 54. Crossed nicols. x 35.

PLATE 37. (415) Irregular development of potash feldspar. Opdalite S. of Cornish Hill. P. 54. x 35.
Condenser lowered.

PLATE 38. (415) As Plate 37, but with crossed nicols. x 35.

36



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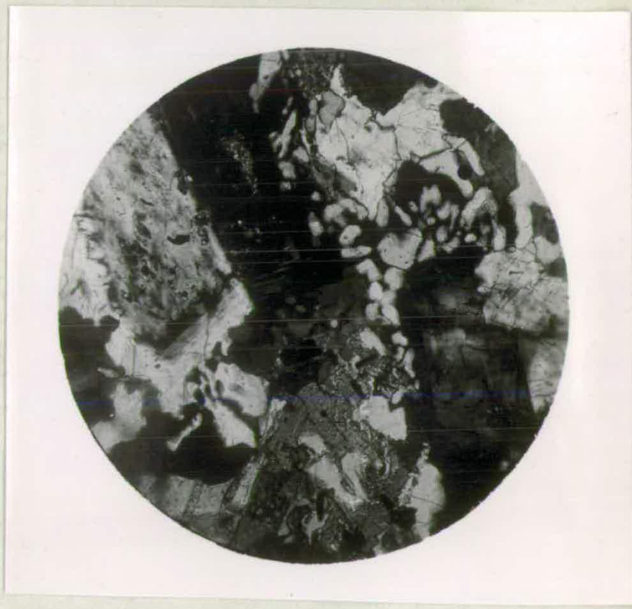


38

EXPLANATION of PLATES 39 - 42.

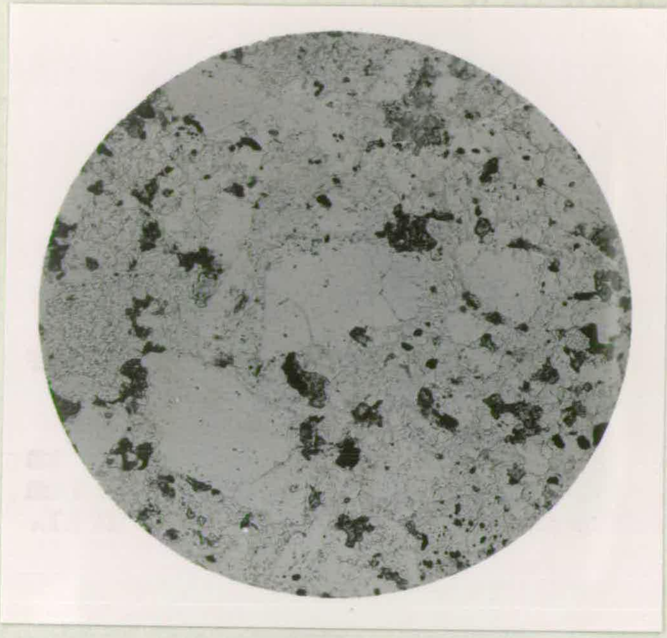
The diopside-hornfels —— opdalite series of inclusions. P.63.

PLATE 39. (24) Angular quartz, granules of pyroxene and ore, in a fine-grained groundmass. Inclusion, 6 ft. in diameter, from N. side of Shiel Hill. x 35.

PLATE 40. (531) Quartz grains, sieved plagioclase, pyroxene granules. 4 ins. inclusion from N. side of Shiel Hill. x 35.

PLATE 41. (118) Pyroxene granules & skeletal pyroxenes. in a plagioclase background with some quartz and potash feldspar. Skeletal-biotite, ore, and apatite needles are also seen. Inclusion, 10 ft. in diameter, from E. side of Shiel Hill. x 35.

PLATE 42. (78) Pyroxene granules and idiomorphic crystals; also plagioclase porphyroblast. 6 in. inclusion from E. side of Shiel Hill. x 35.



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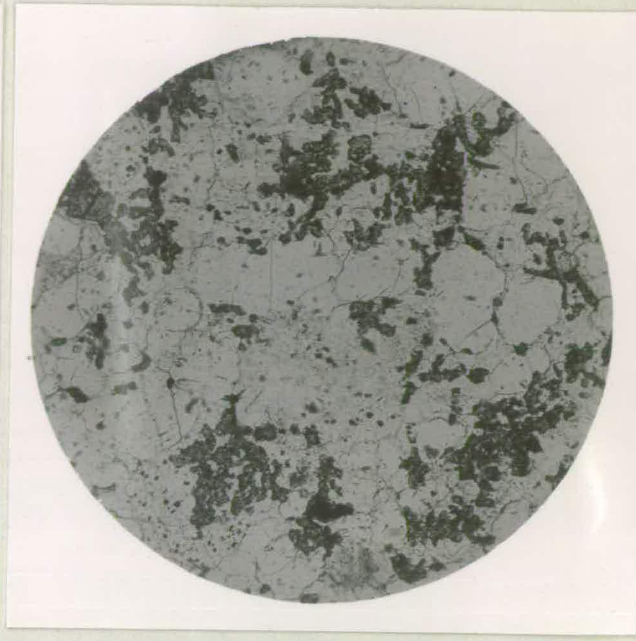

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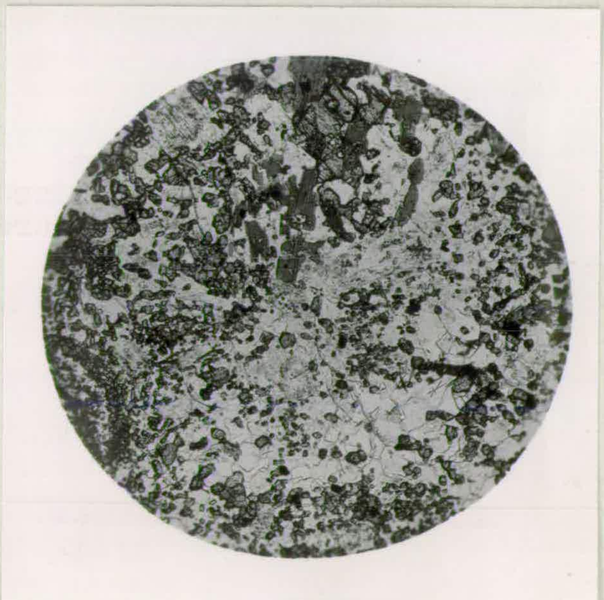

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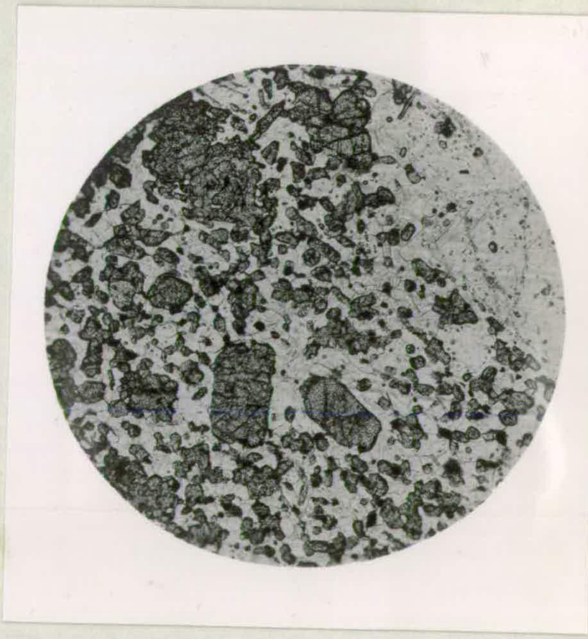


42

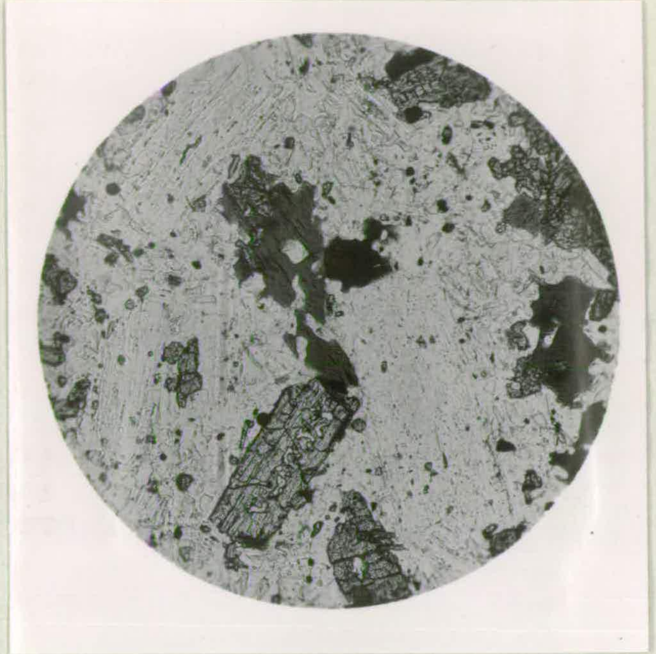
EXPLANATION of PLATES 43 - 46.

PLATE 43. (333) Fine-grained opdalite from E. side of Cornish Hill. Sieved pyroxene, poikiloblastic biotite, inclusions of pyroxene granules in the plagioclase, and irregular potash feldspar are seen. P. 50. x 35.

PLATE 44. (63) Fine-grained opdalite from N.E. side of Shiel Hill. Sieved pyroxene, and irregular potash feldspar are seen. P. 50. x 35.

PLATE 45. (325) Inclusions of pyroxene granules in plagioclase. Fine-grained opdalite from E. side of Cornish Hill. P. 52. x 35.

PLATE 46. (325) As Plate 45, but with crossed nicols. Zoning also seen. x 35.



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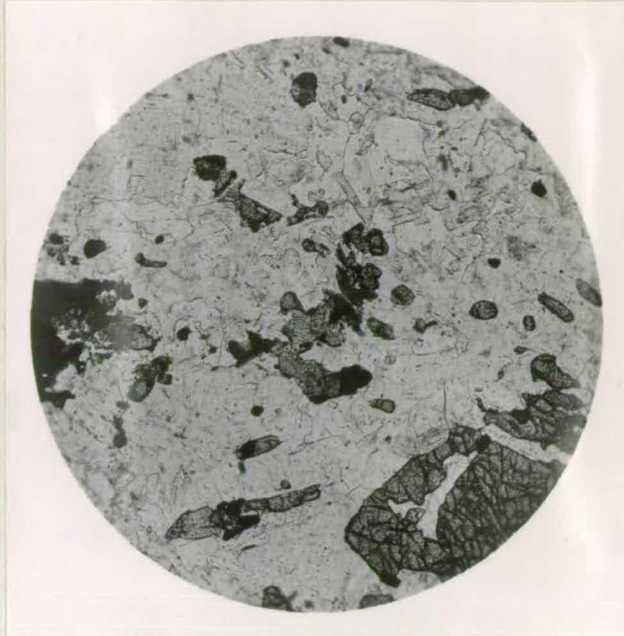

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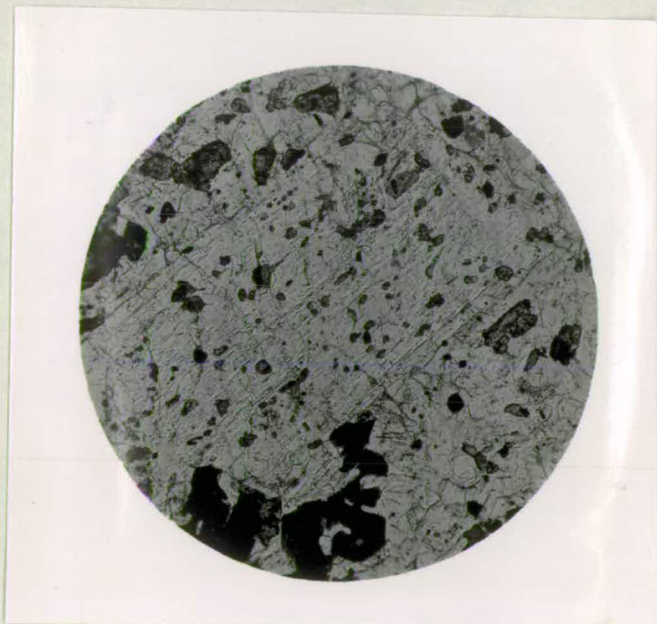

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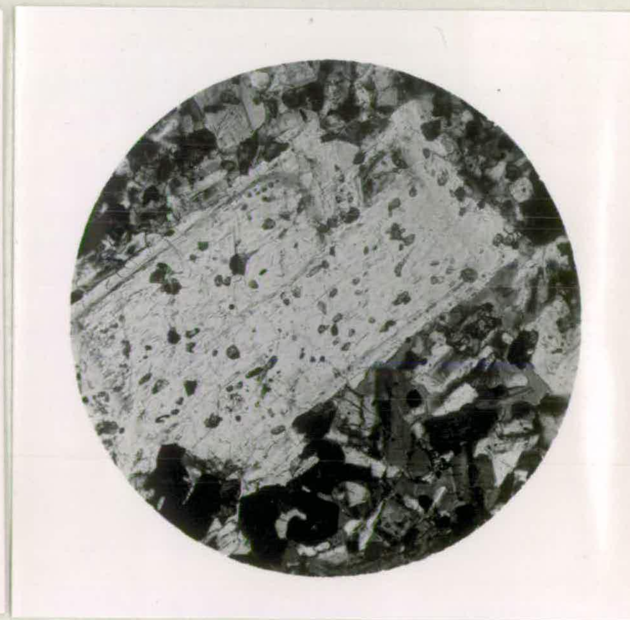


46

EXPLANATION of PLATES 47 - 50.

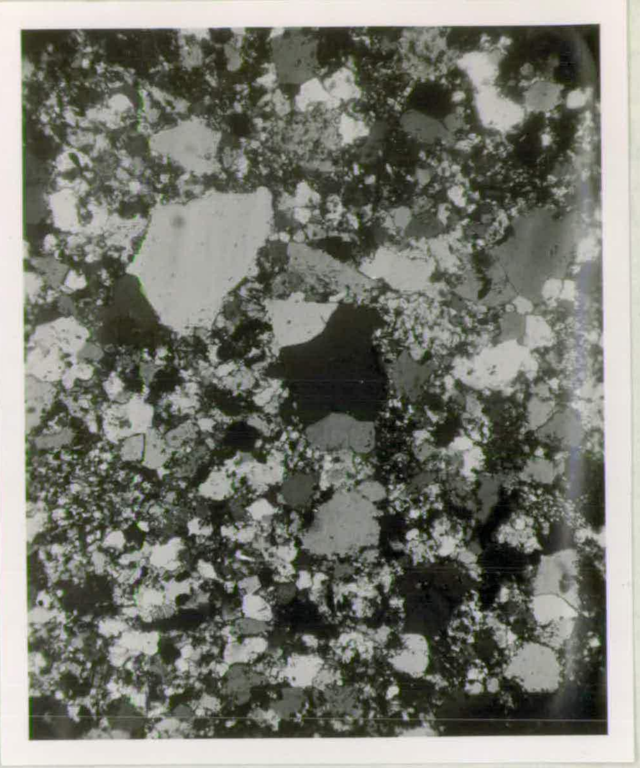
The diopside-hornfels —— opdalite series of inclusions. P.63

PLATE 47. (24) As plate 39, but with crossed nicols.
x 35.

PLATE 48. (531) As Plate 40, but with crossed nicols.
x 35.

PLATE 49. (118) As Plate 41, but with crossed nicols.
x 35.

PLATE 50. (333) As Plate 43, but with crossed nicols.
x 35.



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EXPLANATION of PLATES 51 - 54.

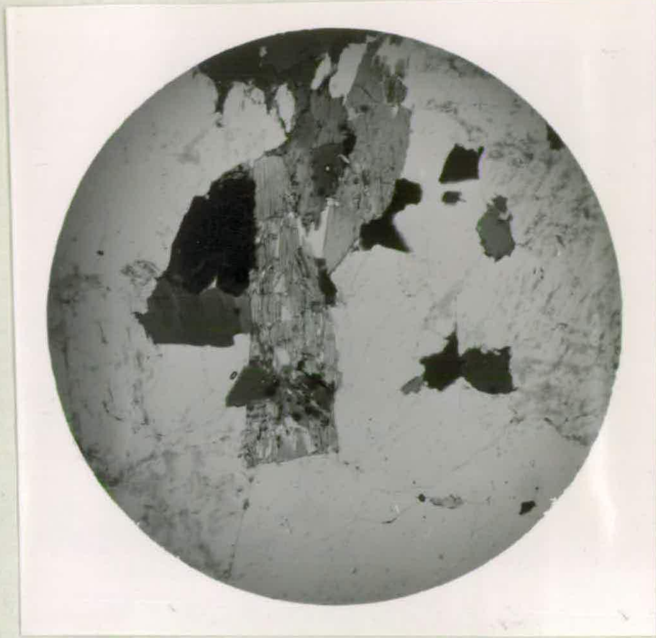
PLATE 51. (63) Fine-grained opdalite. As Plate 44, but with crossed nicols. x 35.

PLATE 52. (702) Sieved hornblende. Quartz, potash feldspar, and biotite also present. Granite from Hoodens Hill. P. 95. x 20.

PLATE 53. (703) Inclusion in granite of Hoodens Hill. Pyroxene granules (a little amphibole), biotite, and feldspar. P. 97. x 20.

PLATE 54. (703) As Plate 53, but with crossed nicols. Poikiloblastic microcline is shown. x 20.

51



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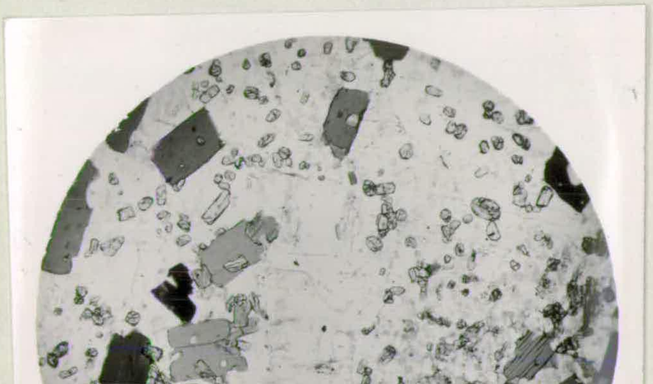

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54

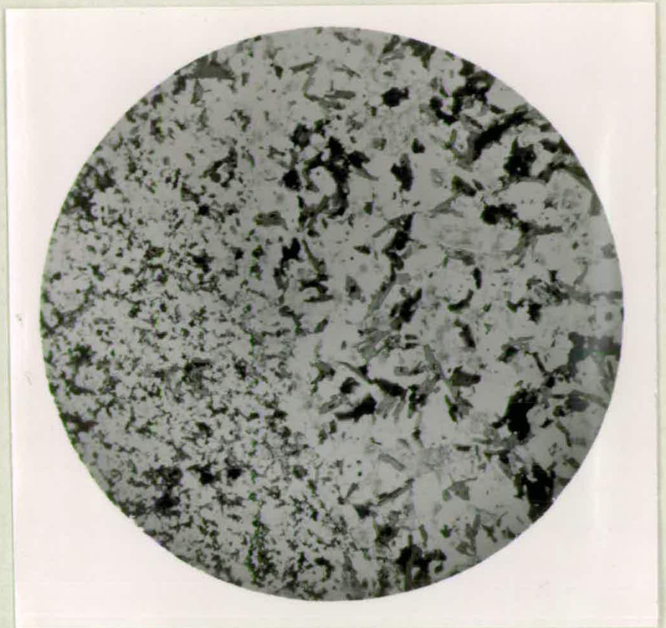
EXPLANATION of PLATES 55 - 58.

PLATE 55. (728) Junction of pseudo-vein. Cow Craig. P. 32. x 20.

PLATE 56. (728) As Plate 55, but with crossed nicols. x 20.

PLATE 57. (738/3) Contact between the fine-grained biotite-granulite, and the coarser and feldspathised biotite-granulite of the Shepherds' Cairn. P. 34. x 35.

PLATE 58. (748) Contact of muscovite — potash feldspar pseudo-vein. Craigbrock. P. 37. Crossed nicols. x 35.



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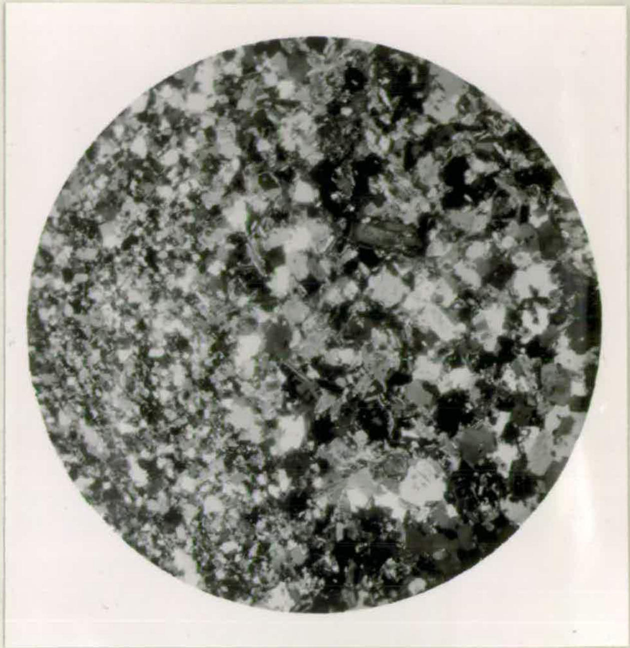

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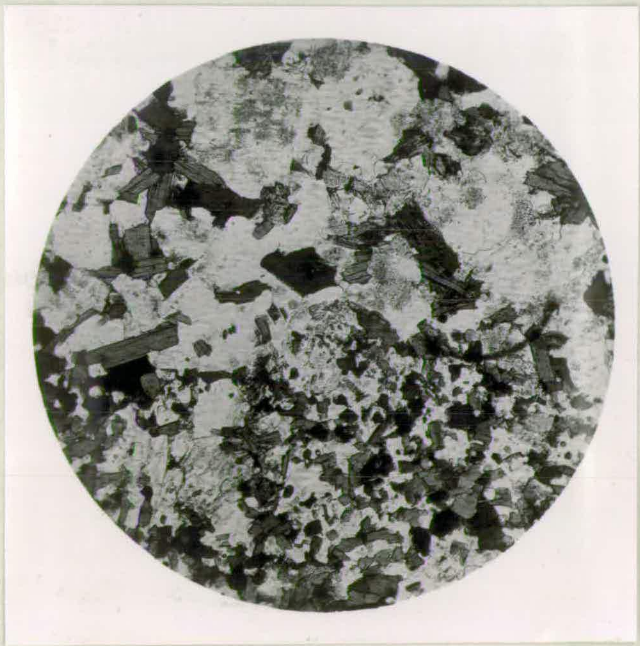

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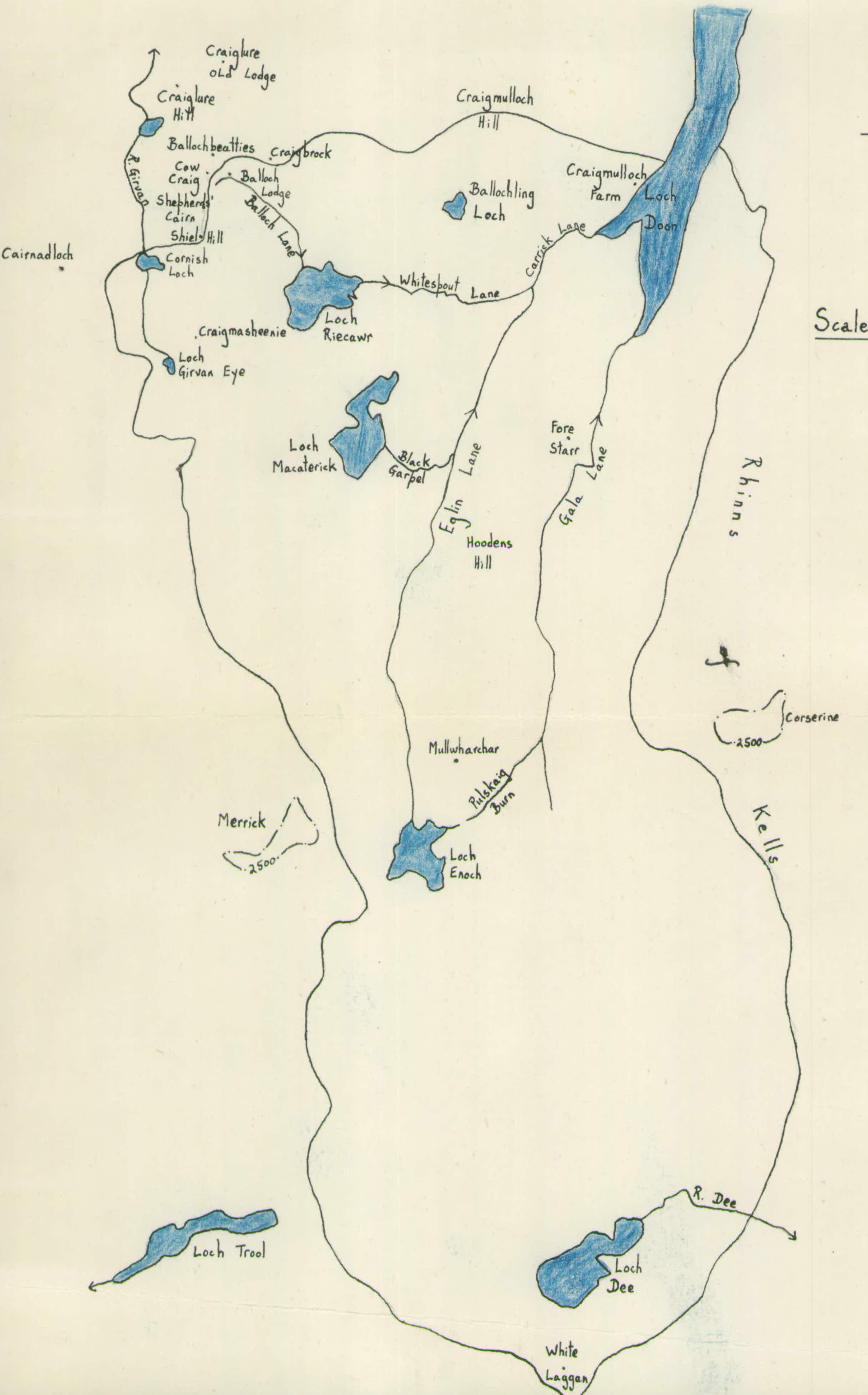
58.



Scale: 1ins. to 1 mile.

Fig. 1.
Map showing inner margin of aureole and localities of places mentioned in text.
[After C.I. Gardiner and S.H. Reynolds]

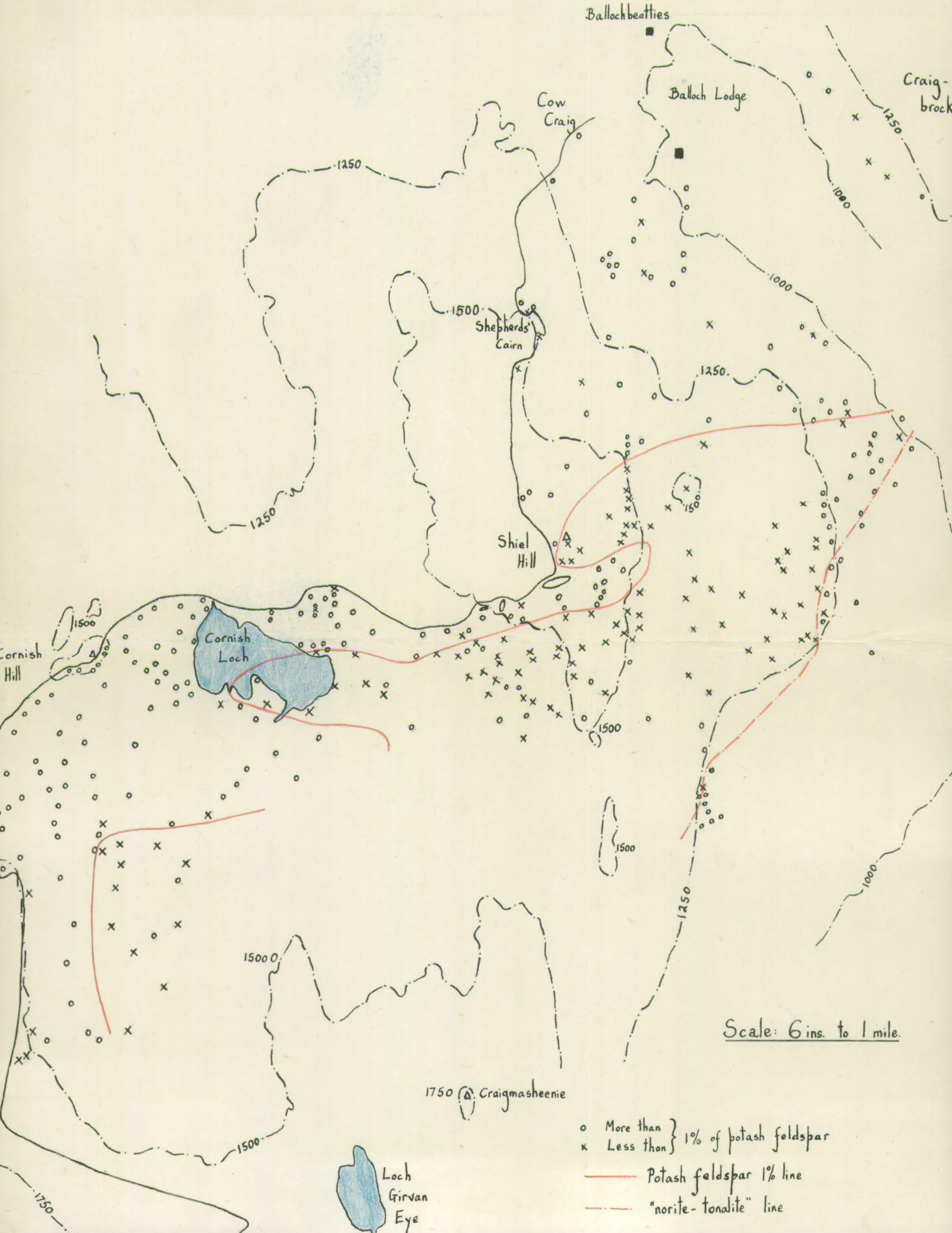

Ballochbeatties
Balloch Lodge
Craig-
brock
Cow
Craig
1250
1000
1500
Shepherds'
Cairn
Shiel
Hill
Cornish
Loch
Cornish
Hill
1500
1750
Craigmasheenie
Loch
Girvan
Eye
Scale: 6 ins. to 1 mile.
More than
Less than
1% of potash feldspar
Potash feldspar 1% line
"norite-tonalite" line

Fig. 3.

Scale: 6ins to 1 mile.

o - More than } 1% of potash feldspar.
x - Less than }

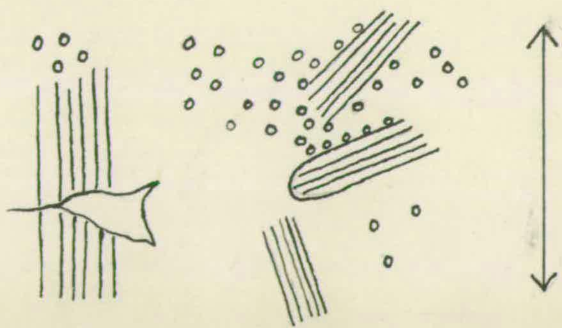
Red line separates the potash feldspar areas.
Broken black lines are 1,500 ft contours.
Full black line is aureole-"norite" contact.
Trig. point 1,665 ft is the summit of Shiel Hill.

Nos. 1-15 (in red) are the localities of specimens after the potash feldspar 1% line (in red) had been drawn.
Nos. 1-3, 10-12, and 15 contain more than 1% of potash feldspar.
Nos. 4-9, 13, and 14 contain less than 1% of potash feldspar.

See page 60.

Fig. 4.

Showing breaking up of bedding by local mobilisation, the distribution of small potash-feldspar - muscovite pods, and one larger pod (irregular). Locality: Craigbrock. See page 37.



1 foot.

Fig. 6.

Diagram showing loci of geochemical culminations and depressions.

Rocks numbered as on tables.

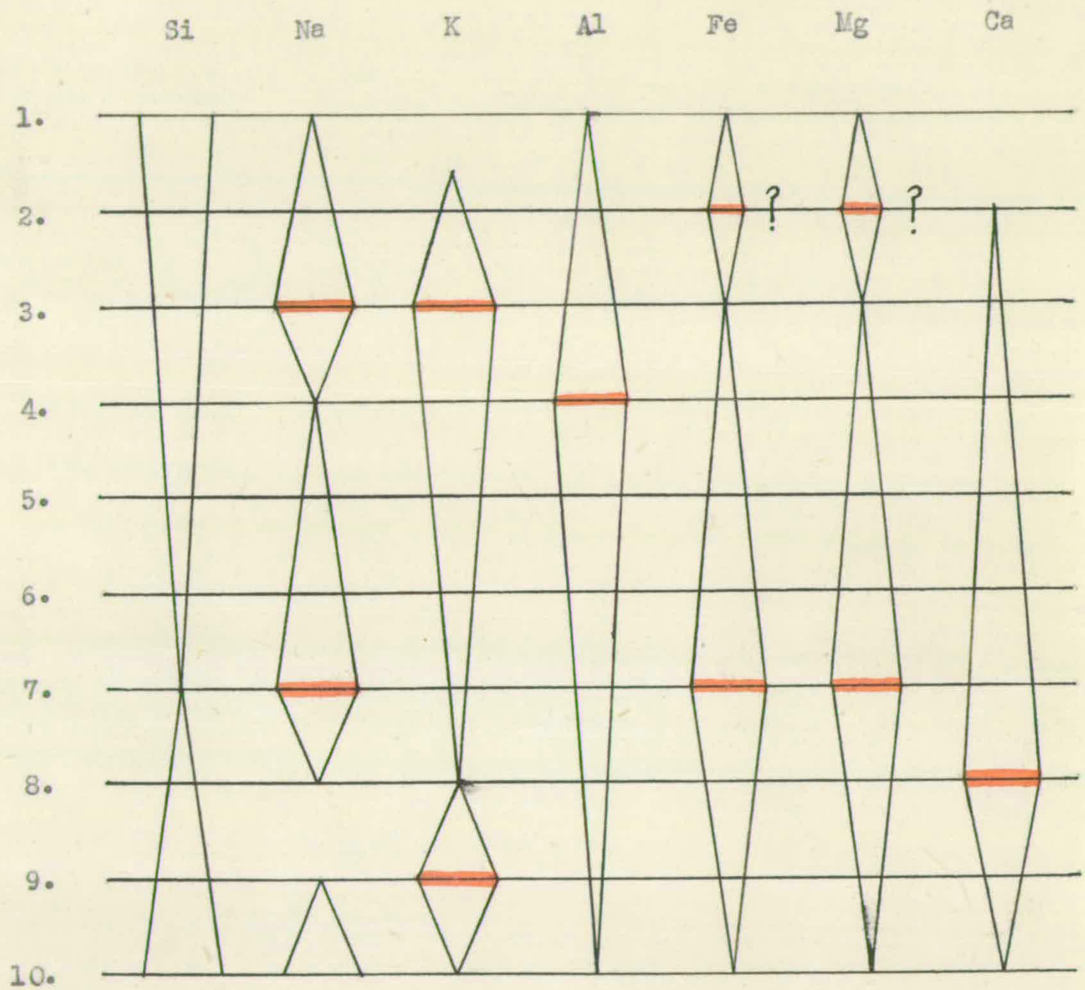
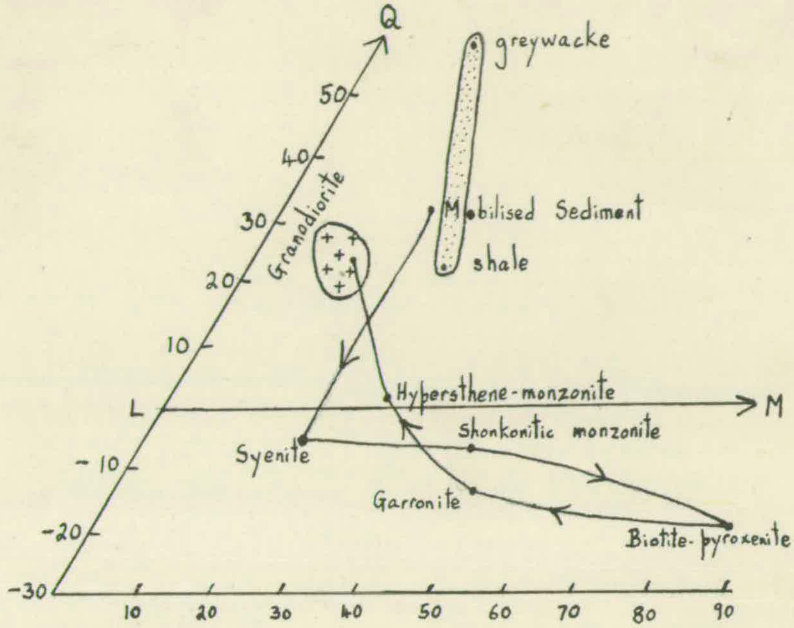
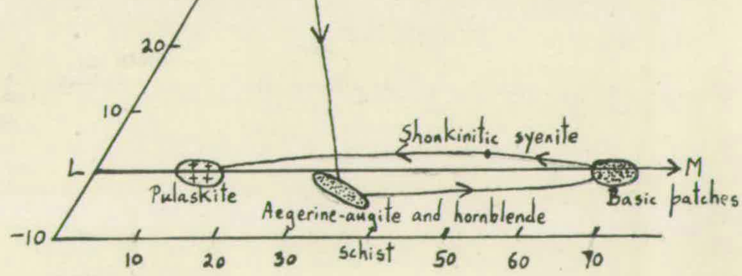


Fig. 8.



Von Wolff diagram of the Newry complex - Doris L.Reynolds

Fig. 9.

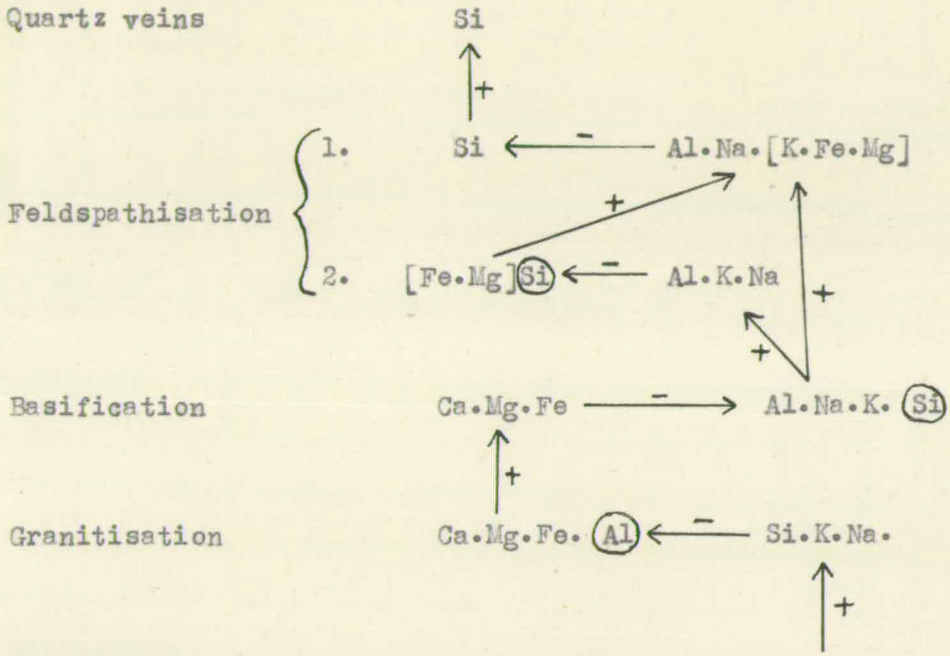


von Wolff diagram of the Cnoc nan Cuilean complex -

B.C.King

Fig. 12.

Geochemical exchanges operative in the Loch Doon complex.
[Generalised]



Symbols:

+ material introduced and fixed.

- material expelled.

X X expelled, but not fixed in the front immediately preceeding.

[Y] Y, in small quantity.