# THE GEOLOGY AND PETROLOGY OF THE ENNERDALE GRANOPHYRE, ITS METAMORPHIC AUREOLE AND ASSOCIATED MINERALIZATION

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by
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# ABSTRACT

The Ennerdale Granophyre occurs in the Lake District between Buttermere and Wasdale. It is a stock shaped, composite intrusion which was emplaced at the close of the Caledonian earth movements. The country rocks of the granophyre are the Borrowdale Volcanic Series and the Skiddaw Slates.

The oldest rocks in the Ennerdale Granophyre are a series of dioritic rocks which have been largely metasomatised by the later granophyre magma into a series of granodioritic hybrids. Eighty percent of the outcrop of the Ennerdale Granophyre is occupied by a fine grained granophyre, the Main Granophyre. The youngest rocks associated with the granophyre are a series of fine aplitic microgranites and rhyolitic felsites.

Metamorphism by the granophyre has been very slight. The main changes in the Skiddaw Slates are a change in colour and an increase in hardness, but the slates in places in Ennerdale have been soda-metasomatised. Macroscopic changes in the Borrowdale Volcanic Series are negligible, but there have been important mineralogical changes within a narrow aureole adjacent to the granophyre.

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# I INTRODUCTION.

## I. Geographical Location

The Ennerdale Granophyre occupies an area of approximately twenty square miles in the western Lake District. It lies within the area covered by the Ordnance Survey Six Inch Sheets NY00/NE; NY0I/SE, NE; NY11/NW, NE, SW, SE; NY10/NW, NE, SW. The intrusion extends from Buttermere in the north to Wastwater in the south (Figure I.). The continuity of the outcrop of the granophyre is interrupted on the north side of Wasdale in the vicinity of Windsor Farm where incomplete erosion of the roof of the intrusion has left a thin skin of volcanic rocks covering the granophyre.

The granophyre has weathered into a group of smooth rounded hills of which the highest is Cawfell, 2200 feet high. These contrast sharply with the crag covered central fells of the Lake District which are made of rocks of the Borrowdale Volcanic Series. The major valleys of Ennerdale, Buttermere and Wasdale, which form the western part of the radial drainage of the Lake District, cross the area under discussion giving it a relief varying from 200 feet O.D. in Wasdale to 2750 feet O.D. on Great Scoat Fell.

The area to be described includes the whole of the outcrop of the Ennerdale Granophyre and its metamorphic aureole, a total area of approximately 40 square miles.

## 2. The Geological Setting of the Ennerdale Granophyre.

A great deal of work on the geology of the Lake District has been published. Mitchell (1956 a.) has given an excellent

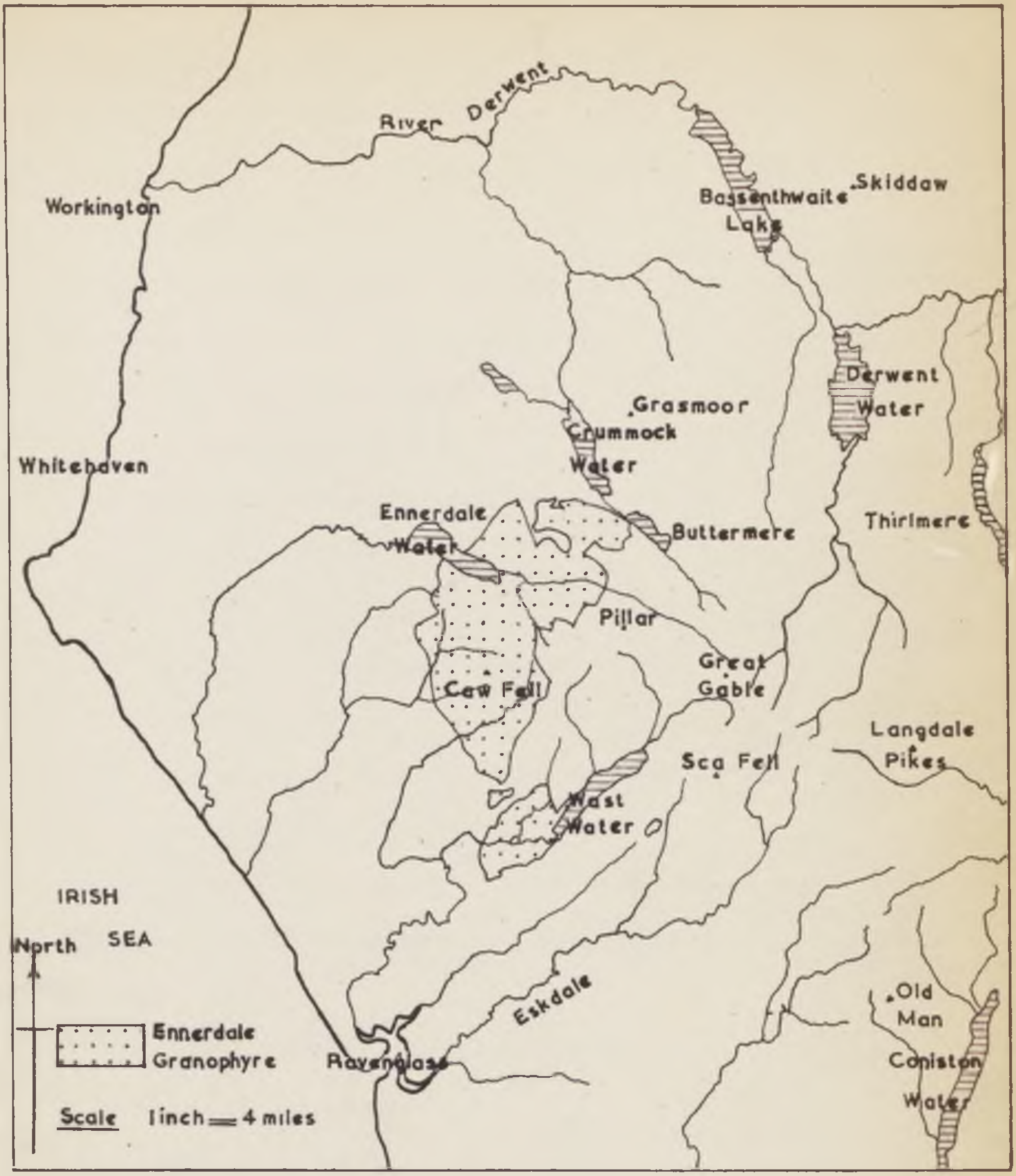


FIG. 1. Location of the Ennerdale Granophyre in the Lake District.

summary of the present state of knowledge of the subject in his paper "The Geological History of the Lake District", and the reader is referred to this paper for a general description of the geology of the Lake District as a whole.

The following stratigraphical succession is firmly established in the Lake District:-

| | |
|---|---|
| New Red Standstone | |
| - Unconformity - | |
| Carboniferous System | |
| - Unconformity - | |
| Silurian Slates | |
| Coniston Limestone Group | Ordovician |
| - Unconformity - | |
| Borrowdale Volcanic Series | |
| Skiddaw Slates | |

The lowest two members only of the above succession occur in the area under discussion. Their outcrops are shown on Figure 2.

The local succession is as follows:-

| | |
|---|---|
| Lower Andesites | Borrowdale Volcanic Series |
| Mottled Tuffs | |
| Latterbarrow Sandstone | Skiddaw Slates |
| Mosser Kirkstile Slates | |
| Loweswater Flags | |

The structure of the Lake District was largely determined during the Caledonian orogeny when the region

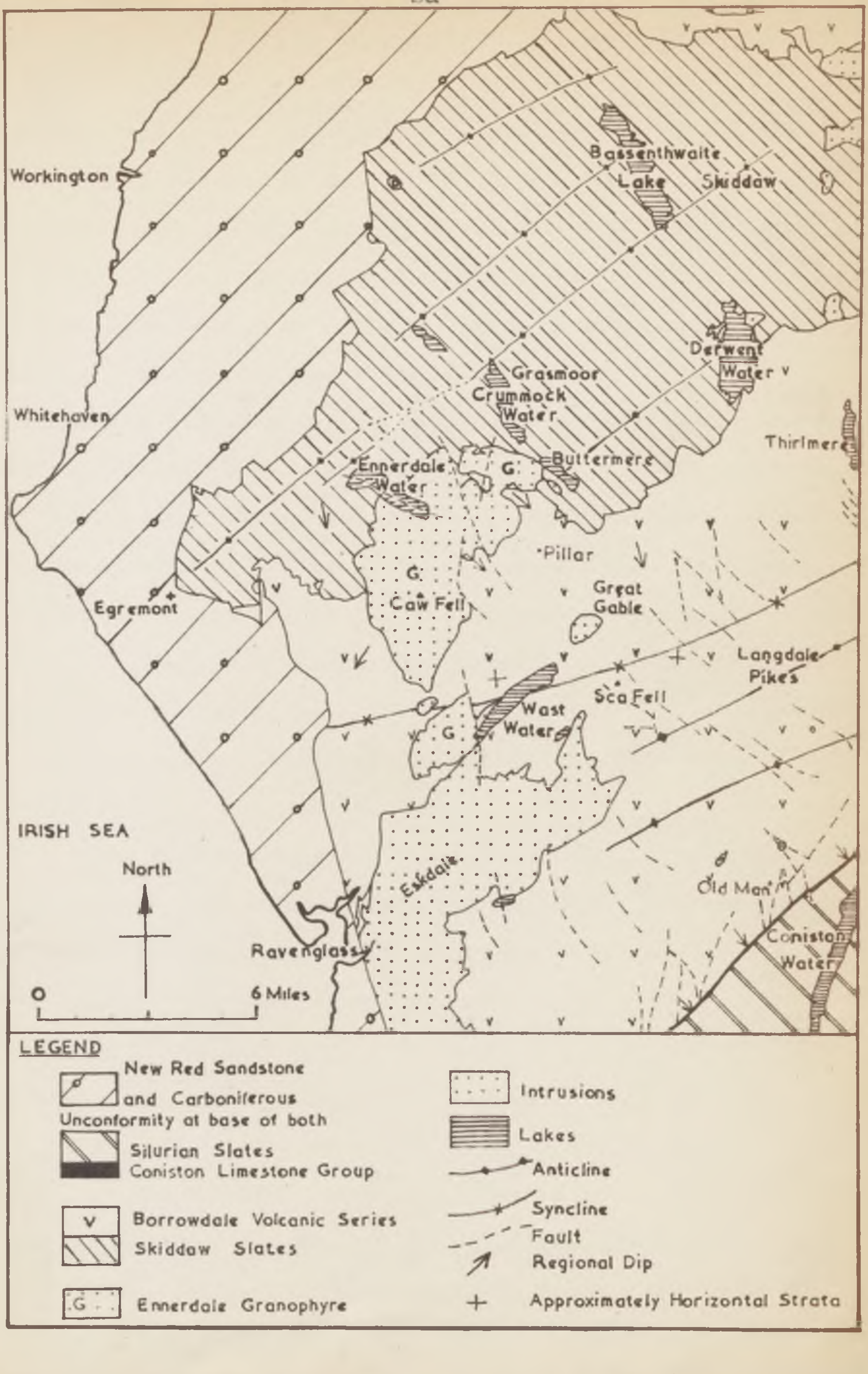


Figure 2. A Geological Sketch-map of the Western Lake District.

was subjected to compressive forces from the south-south-west and north-north-east. The Skiddaw Slates were folded into a complex anticlinorium with the major axis passing through Skiddaw south-westwards almost to Egremont (Fig. 2). The Skiddaw Slates of the area under discussion mainly lie on the south-east flank of this major anticline. The Berrowdale Volcanic Series acted more competently than the Skiddaw Slates and were more gently folded. The junction of the Skiddaw Slates and the Borrowdale Volcanic Series in the Buttermere district is a low angled fault which has cut out several hundred feet of the basal members of the Volcanic Series. The present area is crossed by a number of high angled faults with the north or north-westerly trend characteristic of Devonian faults elsewhere in the Lake District.

The Ennerdale Granophyre is a stock elongated in a north-south direction, which was intruded into the Skiddaw Slates and Borrowdale Volcanic Series after the end of the main Caledonian Fold Movements. The granophyre is cut by several of the high angled Devonian faults that cross the area. It belongs to a suite of late Caledonian acidic intrusions which includes the Eskdale, Skiddaw and Shap Granites (Read, 1960, p.675).

## 3. The General Geology of The Ennerdale Granophyre.

The Ennerdale Granophyre has an oval cross-section approximately nine miles long and four miles wide. Its outcrop covers an area of approximately twenty square miles. The shape of the granophyre outcrop is complex because its roof has not been completely removed by erosion.

The granophyre is a composite intrusion composed of a suite of rocks which, although they are of different compositions, are closely related petrogenetically. These rocks vary from gabbroic to granitic in composition. The following intrusive history of the granophyre has been established during the present work.

vi. Minor Intrusions (mainly rhyolitic felsites)
v. Pegmatites and Metasomatism of Skiddaw Slates in Ennerdale
iv. Porphyritic Fine Grained Microgranite
iii. Main Granophyre
ii. Hybridization of Early Basic Rocks
i. Early Basic Rocks.

The early basic rocks are mainly diorites but a small mass of associated dolerite crops out in Mecklin Wood in Wasdale. The main basic intrusion was probably a sill. The basic rocks have been extensively altered by hybridization and metasomatism until the only unaltered basic rocks are now microdiorites in minor intrusions associated with the granophyre stock.

The hybridization of the basic rocks was probably caused by volatiles rising from the Main Granophyre magma. The major effects on the basic rocks during hybridization were an introduction of potash and silica and a removal of iron, magnesia, lime and soda. The diorites were gradually changed to rocks of a granodioritic composition.

The Main Granophyre occupies over eighty percent of the outcrop of the Ennerdale Granophyre and is responsible for the stock form of the main intrusion. The Main Granophyre is very uniform in macroscopic characters, but varies in texture from a very fine granophyre in the core of the stock to a microgranite beneath its roof.

Late minor acidic intrusions of two ages are associated with the Ennerdale Granophyre. Several irregular masses of porphyritic fine grained microgranite and felsite occur in the Main Granophyre. The last intrusive phase was the emplacement of numerous rhyolitic felsite sills and dykes.

A few small pegmatitic veins from the granophyre crop out in Skiddaw Slates in Ennerdale. These veins are connected with the metasomatism of the Skiddaw Slates in this area. There is a slight indication that the metasomatism and the pegmatites preceded the emplacement of the rhyolitic felsite intrusions.

The Ennerdale Granophyre intrudes and metamorphoses both the Skiddaw Slates and the Borrowdale Volcanic Series. The metamorphic aureole in the Skiddaw Slates varies from a few yards wide to about three miles wide. The major changes in the slates are a change in colour from blue to green, an increase in their hardness and a loss of cleavage. Mineralogical changes are very minor, except in Ennerdale, where the slates have been subjected to soda matasomatism.

The effects of metamorphism on the Borrowdale Volcanic Series appear very slight in the field, but the mineralogy of the rocks has been changed. The greatest changes have been in the ferromagnesian minerals, with pyroxene and chlorite changing to biotite and amphibole in hornfels adjacent to the intrusion.

The position of the Ennerdale Granophyre stock has been governed to a certain extent by the structure of the area. The granophyre is intruded along the axis of a northerly anticline in the Borrowdale Volcanic Series. The Eskdale Granite to the south has been intruded along the axis of the same anticline and also along the Langdale anticline. The intrusions are believed to have been directed into the axes of the anticlines by the inclination of the folded base of the Volcanic Series.

## 4. Aims of the Present Research.

The work of the Geological Survey (Eastwood et al, 1931; Trotter et al, 1937), and the earlier work of Rastall (1906) suggested that the study of the geology and petrology of the Ennerdale Granophyre would be of great interest. The main purpose of the present research was therefore to complete the detailed mapping of the Ennerdale Granophyre and determine its petrological history.

The granophyre has not completely lost its roof and it was hoped that some mineralization associated with the granophyre may be found in the remnants of the roof.

The metamorphic aureole of the granophyre was to be mapped and its petrography studied. The Borrowdale Volcanic Series east of the granophyre had not been mapped in detail. It was hoped to map these rocks during the mapping of the metamorphic aureole, with a view to correlating the volcanics west of the granophyre with those already mapped in the central fells to the east.

# PART ONE: THE COUNTRY ROCKS OF THE ENNERDALE GRANOPHYRE.

## I. THE SKIDDAW SLATES

### I. Introduction.

The following stratigraphical succession within the Skiddaw Slates was established by the Geological Sheets 28 and 37. (Eastwood et al, 1931; Trotter et al, 1937):

Latterbarrow Sandstone
Mosser Kirkstile Slates
Blakefell Mudstone
Loweswater Flags.

This succession has been subsequently modified by Rose (1954) whose work in the Keswick and Buttermere districts showed that the Blakefell Mudstone is not a true stratigraphical unit, but is the rock type of a distinct metamorphic aureole. Rose's ammended stratigraphical succession for the Keswick and Buttermere district is:-

| | thickness |
|---|---|
| Mosser Kirkstile Slates | 2500 feet+ |
| Loweswater Flags | 4500 feet+ |

The Skiddaw Slates have been folded into a series of acute folds trending in an east-north-east direction which make up the Skiddaw anticlinorium (Figure 2). The Loweswater Flags are exposed in the cores of the anticlines and the Mosser Kirkstile Slates are exposed in the cores of the synclines. These two divisions of the Skiddaw Slates therefore outcrop in alternating belts which mark the fold axes (Rose 1954, p.404).

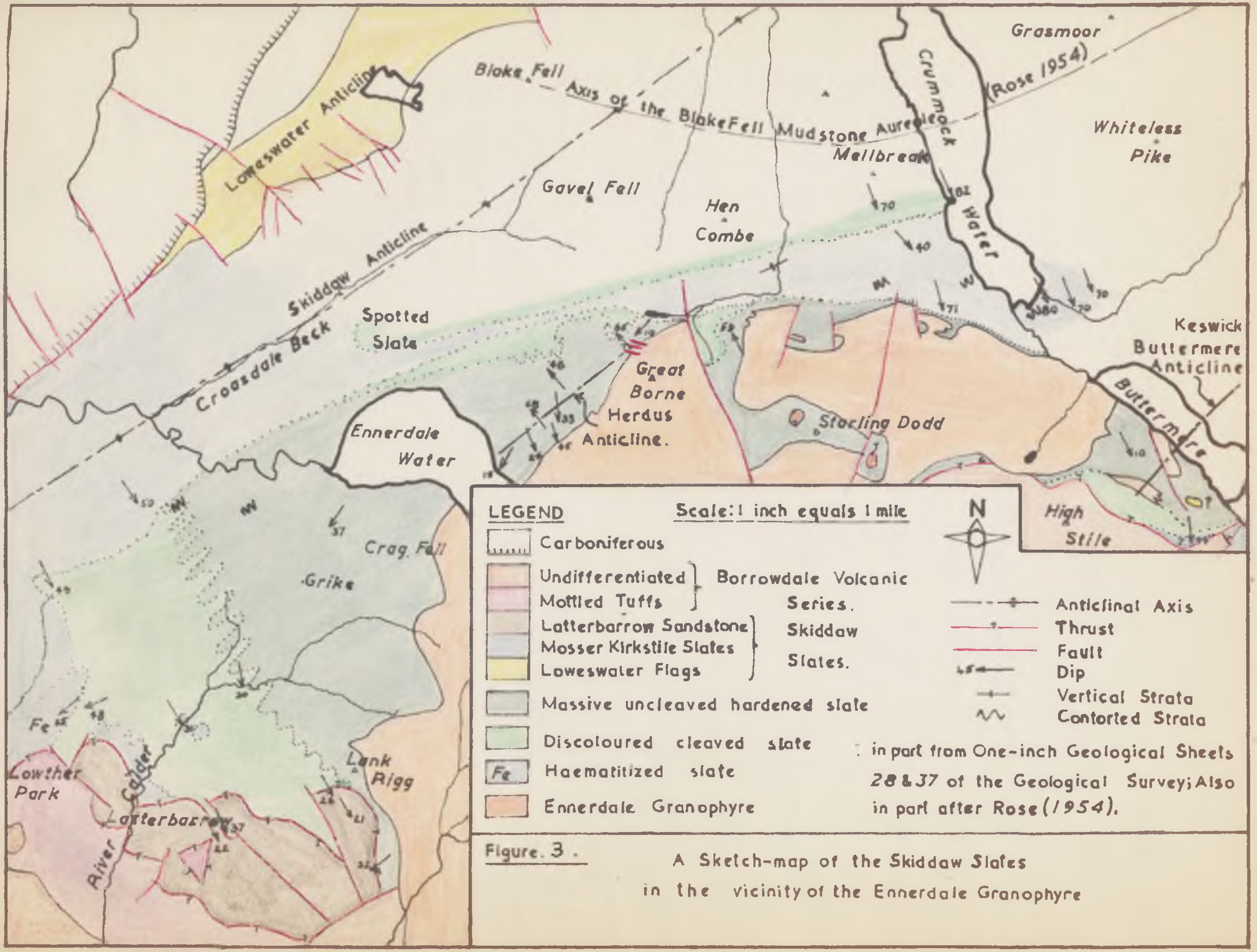


Figure. 3. A Sketch-map of the Skiddaw Slates in the vicinity of the Ennerdale Granophyre

The Skiddaw Slates of the area under discussion occupy a broad synclinal area between the Skiddaw anticline to the north-west and the Keswick-Buttermere anticline to the east (Fig.3). These slates belong to the Mosser Kirkstile Slates, with the exception of the Latterbarrow Sandstone which outcrops west of the Ennerdale Granophyre between the Mosser Kirkstile Slates and the Borrowdale Volcanic Series. The Loweswater Flags do not outcrop within the area except possibly in the Buttermere district.

## 2. The Loweswater Flags.

### A. Field Relationships.

There is no massive development of arenacious beds in the Skiddaw Slates adjacent to the Ennerdale Granophyre comparable with the Loweswater Flags in their type locality. Minor sandstones however occur below Burtness Combe in Buttermere. A line of small crags immediately south-east of Combe Beck at 800 feet O.D. are formed of fine blue sandstones and bluish green sandy slates. The latter form the waterfalls in Combe Beck. The sandstones occur in beds up to six feet thick but their total thickness is not much over forty feet. They are not cleaved but have been crumpled slightly and have a variable dip. There are some slumps in the sandstone which appear to be contemporaneous with deposition. The sandy development as a whole can be traced approximately 400 yards along the hillside and is entirely surrounded by cleaved slates.

These sandstones and associated slates may be transitional beds between the Loweswater Flags proper and the Mosser Kirkstile

Slates, for the locality is close to the Keswick-Buttermere anticlinal axis where Loweswater Flags would most likely occur.

## B. Petrography.

(i) Specimen 225. Section E 9304.

Locality: 270 yards south-east on Combe Beck,
Buttermere, at approximately 800 feet
O.D. G.R. 19411492.

Specimen 225 is a fine hard sandstone which may be taken as typical of the sandstones discussed above. The colour of the rock is a dark greenish grey but there is a blueish tinge produced by the vitreous lustre of the quartz grains. The rock is composed of abundant quartz grains approximately 0.25 mm. in diameter set in a green matrix. Numerous quartz veins cut the rock and pyrite crystals up to 0.5 mm. in diameter occur both in the rock and in the quartz grains.

The sandstone, in thin section, is seen to be well sorted with quartz grains approximately 0.3mm. in diameter set in a chloritic matrix. The composition of the rock is roughly 64% quartz grains and 36% chloritic matrix which puts it in the Sub-Greywacke class of Pettijohns' classification. Except for rare pellets of slate all the sand grains are of quartz, which is often strained and contains liquid inclusions containing gas bubbles. The quartz grains are in general well rounded but their margins are badly corroded, and where two grains are in contact, solution of silica along the contact has led to complex suturing. The matrix is largely made of an almost isotropic, anemalous blue chlorite, most likely penninite, in flakes approximately 0.02 mm. in diameter, but up to 0.2 mm. in diameter. Accessory minerals in the matrix include sericite, rutile, leucoxene, haematite and zircon.

(ii) Specimen 304. Section E9921.

Locality: The base of the falls in Combe Beck in
Buttermere at approximately 650 feet O.D.

Specimen 304 is a massive pale greenish grey sandy mudstone from the sandy slates associated with the sandstones discussed above.

The rock in thin section is seen to be a very fine sandy mudstone with abundant quartz grains up to 0.03 mm. in diameter set in a matrix of sericite and chlorite. The quartz grains are badly corroded around the margins. The sericite in the matrix is generally in minute flakes, but flakes up to 0.2 mm. in diameter do occur. The chlorite is practically all penninite with possibly a few flakes of clinochlore. Opaque grains up to 0.02 mm. in diameter, white in reflected light, which may be leucoxene or organic matter, are scattered in abundance through the matrix. Later minerals include calcite crystals up to 0.2 mm. diameter, occasional veins of quartz, and haematite staining along cracks. The latter is interesting as chlorite is particularly susceptible to the haematite staining which makes it closely resemble biotite in thin section.

## 3. The Mosser Kirkstile Slates.

### A. Field Relationships.

The Skiddaw Slates, adjacent to the Ennerdale Granophyre, with possibly two exceptions, are all in the Mosser Kirkstile Slates. The exceptions are a relatively small outcrop of Latterbarrow Sandstone in the south, and the outcrop described above, which is possibly of Loweswater Flags. The great extent of the Mosser Kirkstile outcrop can be explained by a study of the structure of the Skiddaw Slates. In the north is a broad syncline in which the Mosser Kirkstile Slates are preserved between the Skiddaw anticline in the north-west and the Keswick-Buttermere anticline to the east. A minor anticline passes south-west across Herdus but it has not sufficient amplitude to expose the Loweswater Flags. All the anticlines other than the Skiddaw Anticline appear to end north of Ennerdale. The Skiddaw anticline is the only major fold identified south of Ennerdale and even it must have a reduced amplitude, because the Loweswater Flags are no longer exposed in its core. The only Skiddaw Slates exposed south of Ennerdale, except for the Latterbarrow Sandstone, are therefore Mosser Kirkstile Slates. The apparent thickness of the Mosser Kirkstile Slates south of Ennerdale is 5500 feet + compared with 2500+ in the Keswick and Buttermere area. Unidentified faults or folds could appreciably affect this figure.

South of Ennerdale the Mosser Kirkstile Slates young to the south, and on the east-west line of hills extending from Lank Rigg to Swarth Fell they are overlain by the Latterbarrow Sandstone. Hollingworth, has deduced that the junction between the Mosser Kirkstile Slates and the Latterbarrow Sandstone is a thrust over which the Latterbarrow Sandstone has been carried northwards over the Mosser Kirkstile Slates for a mile or more. (Trotter et al, 1937, pp. 19-20).

West of the road from Calder Bridge over Cold Fell to Ennerdale the geology is now largely obscured by the Forestry Commission's Lowther Park Plantation. Many relevant geological boundaries on Figure 3 have therefore been copied from the Geological Survey, New Series, one inch, Geological Sheet 28. The Latterbarrow Sandstone abruptly dies out a few yards west of the Cold Fell road and in the Lowther Park Plantation the Mosser Kirkstile Slates are overlain by Mottled Tuffs of the Borrowdale Series, all junctions being faulted, (Eastwood et al., 1931, pp. 16; 30). In the Buttermere district the junction between the Mosser Kirkstile Slates and the Borrowdale Series is a low angled fault.

The Mosser Kirkstile Slates are an extremely uniform series of blue laminated slates. The laminae, alternating in colour between dark and light blue, rarely exceed two or three millimetres in thickness. Differences in colour depend on the grain sizes of the laminae, the dark laminae are fine mudstones, the light laminae siltstones. In the silty laminae, especially when they are thicker than normal, examples of small scale false bedding may occasionally be found. Examples of this can be seen on the shore of Crummock Water at Nether How. The laminae are usually very regular and give the rock a distinct striped appearance.

The lithology of the Mosser Kirkstile Slates is remarkably constant with very few variations from the type described above. Several beds of fine blue sandstones up to five inches thick, interbedded with blue laminated slate, crop out on Scale Knott on the south end of Mellbreak overlooking Crummock Water. The sandstones are impersistant and cannot be traced more than a few yards. Their dip of 40 degrees to south 40 degrees east is similar to the regional dip. Isolated outcrops of similar sandstones in slate are common on the hillside above Scale Knott. It is unlikely that these sandstones are related to the Loweswater Flags for they outcrop near the centre of the Mosser Kirkstile syncline.

Silicious concretions are present in the slates but are rather rare. Specimen 306 from the slates below Burtness Combe (G.R. 176150) is three inches wide and seven inches long. The bedding planes of the surrounding slate pass through the concretion. The concretion must therefore have been formed by silicification of the slate and not by deposition of primary silica.

The slates occasionally become more massive and flaggy, as in Lagget Beck near Nannycatch Gorge, but this may be due more to lack of cleavage than to a change in lithology.

A peculiar variation of the Mosser Kirkstile Slates is a rock, conglomeratic in appearance, which is exposed just below the thrust separating the slates from the Borrowdale Volcanic Series north of High Crag near Buttermere. The conglomerate is made of sub-rounded isolated boulders of fine blue sandstone up to nine inches wide and three feet long in blue slate (Photo. 1.). It is probably a 'tectonic conglomerate' produced by the disruption of a bed of sandstone by the movement along the thrust plane above (Pettijohn, p.281 ).

Photo. 1. Tectonic Conglomerate, Buttermere.

Varying intensities of the cleavage affecting the slates, rather than actual variations in lithology are probably responsible for most of the minor variations within the Mosser Kirkstile Slates. Where there is no cleavage or the cleavage is parallel to the bedding, the rock splits easily along the bedding laminae into flaggy slates. This is well seen in the quarry 120 yards north-west of the Buttermere post-office where the slate has been quarried for wall stone.

Five hundred yards below the confluence of Whoap Beck and the River Calder paper shales are exposed in the north bank of the river. These are slates in which there has been a development of micaceous minerals between the individual laminae, which have separated into the leaves of the paper shales. The bedding of the slates, revealed by the laminae, often appears very regular, but there are numerous exposures which show the contorted nature of the slates. The water worn slates on the shores of Crummock Water near Nether How and below Mellbreak reveal good contorted bedding.

The Mosser Kirkstile Slates are often badly altered and haematitized along fault lines. A smash belt passes from Near Thwaites south-westwards into Lowther Park plantation and the shales are smashed, puddled and haematitized along a belt 450 yards wide and over a mile long. The effects of faults are not usually so striking as in the Near Thwaites smash belt, but most of the gullies on the north slope of Grike are cut along similar haematitized smash belts.

## B . Petrography.

(i) Specimen 18. Section E9220.

Locality: 100 yards south of Black Beck, and 300 yards north-east of Scale Force. (G.R.I482, I722).

Specimen 18 is greenish-blue, non-laminated, cleaved mudstone slate. Pyrite crystals up to four millimetres in diameter do occur but are rare. The cleavage surfaces are iron stained.

The rock has a very uniform texture with numerous corroded quartz grains approximately 0.02 mm. in diameter in a matrix of sericite and chlorite. The sericite flakes, up to 0.I mm. in diameter are alligned parallel to each other and largly obscure the quartz grains. Iron ore, apparently fresh in scattered through the rock in grains up to 0.02 mm. in diameter. The slate is veined by chalcedony.

(ii) Specimen 303. Section E9613.

Locality: The east bank of Oxenstone Beck at about
600 feet O.D. (G.R. 06381465).

Specimen 303 is a laminated slate with alternating dark blue mudstone and pale blue siltstone laminae. The laminae in the specimen are contorted and disrupted by small penicontemporaneous slumps in the thicker siltstone laminae. The laminae average about one millimetre in thickness, but one slumped laminais over one centimetre thick.

The silty laminae are formed of quartz grains up to 0.05 mm. in diameter set in a sericitic and chloritic base. The quartz grains tend to be rounded but they have been badly corroded. The sericite flakes may be up to 0.15 mm. long. The dark blue laminae are much less rich in quartz grains. Penninite occurs in veins, lenses and irregular patches tending to outline the disturbed bedding in the slate. Leucoxene in grains up to 0.3 mm. in diameter is common. There are several lenses up to 0.1 mm. long, of spherical bodies 0.01 mm. diameter. The spheres are isotropic, have high relief and are colourless except when iron stained. They are possibly spores.

A chemical analysis of this specimen is given in Table 3.

(iii) Specimen 260. Section E9505.

Locality: A small cliff behind Howside Farm,
Ennerdale (G.R. 09211667).

This is a specimen of a very fine black siliceous concretion in greenish blue slate. The bedding in the slate is parallel to the edge of the concretion and appears to pass through the concretion.

The concretion is a mosaic of quartz and penninite. The grain size of the mosaic is approximately 0.5 mm. diameter but it becomes quite coarse in places with quartz crystals up to 0.6 mm. diameter and penninite flakes up to 0.2 mm. diameter. Leucoxene is present in grains up to 0.02 mm. in diameter, but is not common.

## 4. The Latterbarrow Sandstone.

### A. Field Relationships.

The Latterbarrow Sandstone has been fully described by Hollingworth (Eastwood et al, 1931, pp. 30, 36, 37; Trotter et al, 1937, pp. 9-11, 19-20) and the following notes are largely derived from his descriptions.

The outcrop of the resistant Latterbarrow Sandstone stands out as a line of hills extending from Lank Rigg westwards through Boathow and Latterbarrow to Swarth Fell. The sandstones are several hundred feet thick and their outcrop has been cut into fault blocks by a series of north-west to south-east faults. (Fig. 3.). Each hill now roughly corresponds to a fault block.

The relationships between the Latterbarrow Sandstone, Mosser Kirkstile Slates and the Borrowdale Series are complex. The Latterbarrow Sandstone has been carried a mile or more by a thrust that cuts out the upper part of the Mosser Kirkstile Slates on Lank Rigg. The Mottled Tuffs, the basal member of the Borrowdale Series, have been thrust northwards beneath the Latterbarrow Sandstone. At the north-west end of Lowther Park the sandstone is cut out by a thrust and the Mottled Tuffs rest directly on the Mosser Kirkstile Slates. Half a mile to the west the Mottled Tuffs are also cut out and andesitic lavas rest on the Mosser Kirkstile Slates. Hollingworth also noted that "The sandstone passes up into the basal tuffs of the Borrowdale Volcanic Series by the incoming of andesitic tuff and fragmental sandstone in the sandy matrix." The junction between the Latterbarrow Sandstone and the Borrowdale Series must therefore be conformable when undisturbed.

The Latterbarrow Sandstone is a well bedded, massive, coarse sandstone. Its colour is a greenish grey when fresh but is often yellow or red because of iron staining. Pebble bands, with rounded quartz pebbles up to half an inch in diameter, are common in the sandstone, especially on Latterbarrow. The sandstone has no intercal-ations of slate throughout its whole thickness. Occasional beds of sandstone up to eight feet thick occur but the thickness of the beds is usually between two and four feet. The abundant blocks of sandstone scattered over the outcrops and forming scree slopes testify to the ease with which the Latterbarrow Sandstone breaks up with weathering. Individual beds of the sandstone can often be traced several hundred yards as small scars or lines of scree. This is well seen on Latterbarrow where parallel lines of scree, marking different beds of sandstone, climb up its north flank from the Calder (Photo. 2).

Photo. 2: Latterbarrow and the river Calder.

## B. Petrography.

(i) Specimen 208. Section E9302.

Locality: South side of Lank Rigg at 1300 feet O.D.
(G.R. 09381100).

This specimen is a fine dark green siliceous sandstone sparcely spotted with pink felstic grains.

The rock is a well sorted sandstone with subrounded grains approximately 0.2mm. in diameter in a chloritic matrix. The sand grains are mainly of quartz but there are also numerous grains of felsite and quartzite. The grains are often corroded around their margins, and contacts between adjacent grains are usually sutured. The matrix consists of almost isotropic penninite with very fine grains of quartz, haematite, and zircon as accessory minerals.

(ii) Specimen 223. Section E 9303.

Locality: South side of Lank Rigg at 1300 O.D.
(G.R. 09381100).

The specimen is a coarse grained, badly sorted sandstone with grains from three millimetres to below 0.5 mm. in diameter. The grains appear to be wellrounded and variegated. Quartz is abundant, pink felsitic grains are common and dark green grains of slate are less common. The pink felsitic grains stand out prominently in the dark green grey rock.

Section E3903 is similar in character to E9302. Well rounded sand grains up to 1.5 mm. in diameter are set in a chloritic base. The sand grains are mainly quartz but there are abundant felsite and quartzite grains and less common grains of fine sandstone and slate. The matrix is composed of penninite with small amounts of haematite, sphene and small quartz grains. The composition of specimen 223 is roughly:-

| | |
|---|---|
| Vein-Quartz | 48% |
| Quartzite | 34% |
| Sandstone | |
| Felsite | |
| Slate | |
| Chloritic Matrix | 18% |

The sandstone is, therefore, a sub-greywacke under Pettijohn's classification.

## 5. The Blakefell Mudstone.

### A. Field Relations.

The Blakefell Mudstone was first named by Dixon, who recognized its metamorphic character but believed that it was distinct stratigraphic unit of the Skiddaw Slates (Eastwood et al, 1931, pp. 35). Rose (1954) has shown that the Blakefell Mudstone outcrop transgresses the regional structure and is in fact the metamorphic aureole of a hidden intrusion. He describes the rock of the Blakefell Mudstone as slate "significantly altered to a lighter coloured, hard, brittle rock, usually showing minute darker spots". Rose has traced the aureole from Barrow and Causey Pike in the east, through Grasmoor, to Mellbreak and Blakefell.

North of Ennerdale-Water, a narrow strip of unaltered Mosser Kirkstile Slates is exposed along the line from Gill Beck to Floutern Tarn, separating altered slates within the Ennerdale Granophyre metamorphic aureole from a series of altered slates to the north (Fig. 3). The junction between the unaltered slates of Gill Beck and the altered slates to the north can be traced from Howside in Ennerdale, up Gill Beck, over Floutern Cop to Mellbreak. The altered slates which are pale greenish grey in colour, and in the Howside outcrop coarsely spotted, are most likely Blakefell Mudstones.

Hollingworth and Dixon (Eastwood et al, 1931, pp. 25,29), believe that the hardened slates of Herdus, Crag Fell, Grike and Whoap belong to the Blakefell Mudstone. It is possible, however, that the hardening of these slates was caused by the Ennerdale Granophyre and not by the hidden intrusion responsible for the metamorphism of Blakefell Mudstones.

## B. Petrography.

(i) Specimen 259. Section E 9504.

Locality: The cliff behind Howside Farm, Ennerdale
(G.R. 09201667).

Specimen 259 is a slightly hardened, bluish green, cleaved slate, in which are numerous scattered black spots, about one millimetre in diameter. A small contorted fold is visible as vague bedding lines that are darker than the rest of the specimen.

Microscopically, the rock is a fine slate with occasional quartz grains 0.02 mm. in diameter set in a practically isotropic unresolved matrix. Sericite, in parallel flakes up to 0.5 mm. long is abundant. Much leucoxene in minute grains is scattered through the rock. The section is crossed by close packed cleavage lines coated by sericite and chlorite. The black spots are oval shaped patches about 1.2 mm. long, in which the parallelism of the sericite and the cleavage lines are missing. The dark colour appears to be due to a concentration of chlorite, but in most cases the fine sedimentary structure is unaltered.

The spots in specimen 259 are much coarser than the reported 0.2 mm. diameter spots of the Blakefell Mudstone (Eastwood et al 1931, pp. 38). They are, however, probably metamorphic in origin and associated with the Blakefell Mudstone metamorphism.

# II. THE BORROWDALE VOLCANIC SERIES BETWEEN WASTWATER AND BUTTERMERE.

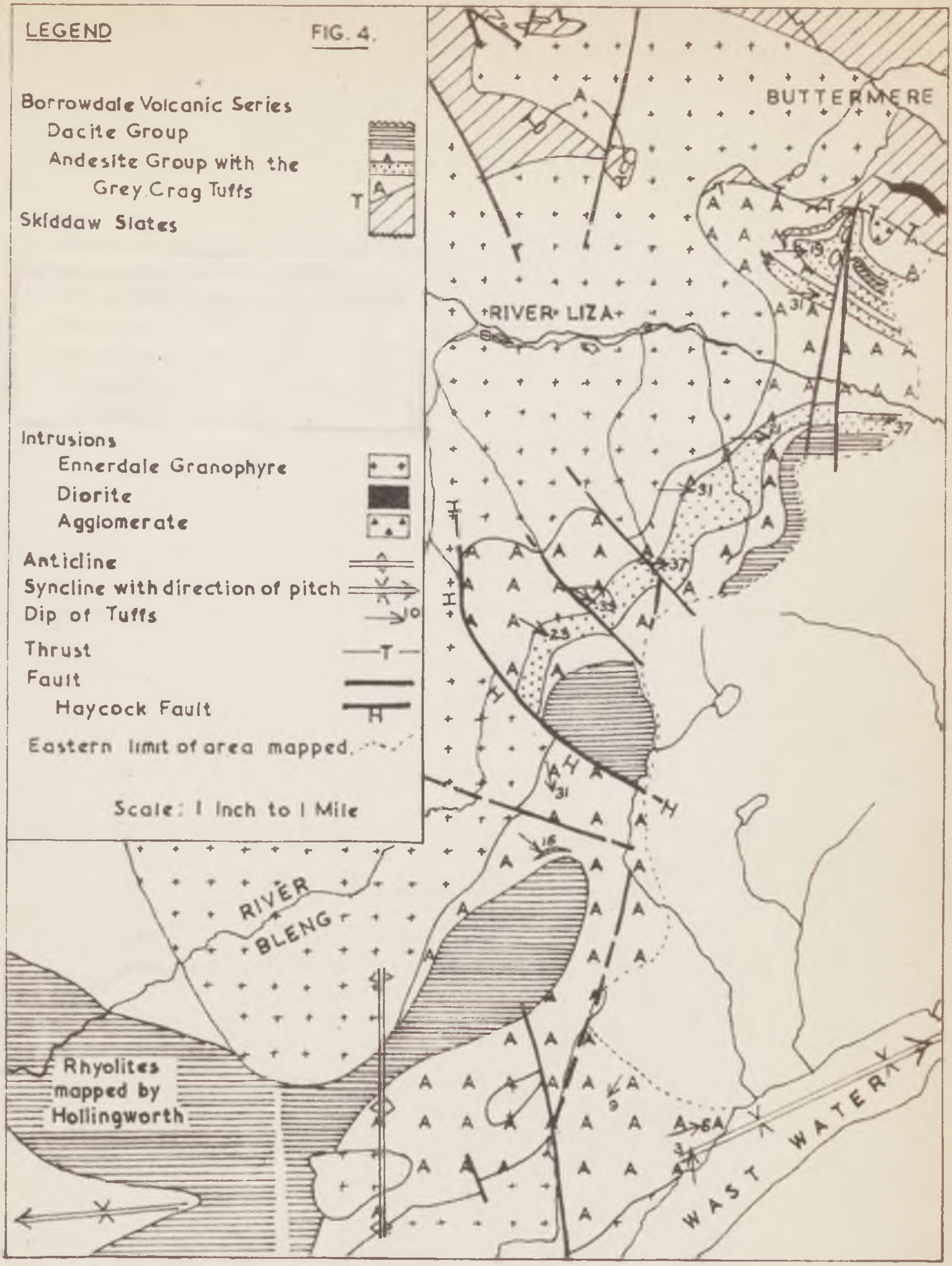
## I. Introduction

The area to be described occupies a belt of country between half a mile and two miles wide, immediately to the east of the Ennerdale Granophyre, (Fig. 4), extending from Buttermere in the north to Wastwater in the south.

This area is almost entirely occupied by rocks of the Borrowdale Volcanic Series. Skiddaw Slates outcrop in the north in the Buttermere valley where they underlie the Borrowdale Volcanic Series. Two small isolated patches of lavas are found resting on Skiddaw Slates on Little Dodd (G.R. 149155) and Starling Dodd (G.R. 141158).

The structure of the area will be discussed in detail later in Chapter VII but a summary is given below. The major structural feature east of the Ennerdale Granophyre is the broad Sca fell syncline pitching to the east-north-east. West of the granophyre the volcanics are more intensely folded with a westerly pitching syncline which closes near Windsor Farm in Wasdale (G.R. 121057), and two very steep tight folds further south trending east-north-eastwards along the floor of Wasdale. These two areas are separated by a northerly striking antiform along the axis of the Ennerdale Granophyre. Steeply inclined faults in the area have two major trends, north and north-west. The Borrowdale Volcanic Series and the Skiddaw

FIG. 4.



The Borrowdale Volcanic Series between Buttermere and Wastwater.

Slates in the Buttermere district are separated by a low angled fault, probably a thrust. The trends of the faults and folds agree with the general pattern of Devonian faulting and folding elsewhere in the Lake District.

The Borrowdale Volcanic Series of the area under discussion was first mapped on a six inch scale by Ward in the early 1870's. Ward's structural mapping is accurate, but his identification of rock types is unreliable. Rocks marked on his maps (Geological Survey, Six inch maps 69 and 74. Old Series) as bedded ash are usually identified correctly, but "altered ash and breccia" may be tuffs, andesites or dacites. Green (1917) has reinterpreted Ward's maps of the northern part of the present area and produced a map which is broadly correct, but inaccurate in detail. He has subdivided the succession as shown below, but his nomenclature is based on incorrect correlations.

Wrengill Andesites
Middle Tuffs
Lower Andesites.

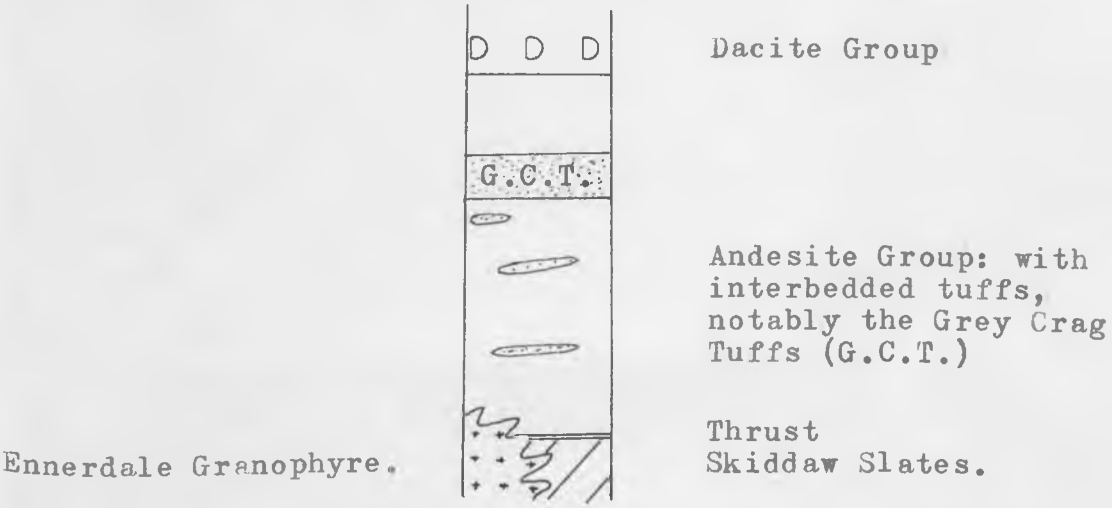
Later, Green (1919, Fig. 25) suggested that in Wasdale, the Ennerdale Granophyre is intruded into the Lower Andesites and that the Middle Tuffs are represented by a thin tuff band running horizontally along the face of Middle Fell at about 500 feet O.D. The latter suggestion has proved to be incorrect.

The area to the west of the Ennerdale Granophyre has been described by Hollingworth (Trotter et al, 1937, pp. 21-39). Hollingworth's work on the Borrowdale Volcanic Series adjacent to the western edge of the granophyre north of Wasdale has been confirmed during the present work. Firman (1957) has described the area to the south of Wastwater, and Oliver (1961) has described the Scafell area to the east. The present area is important because it lies between these three areas and enables correlations to be made between their successions.

## 2. Stratigraphy.

### A. Succession.

The following succession is fairly constant over the whole strip of country under discussion:-

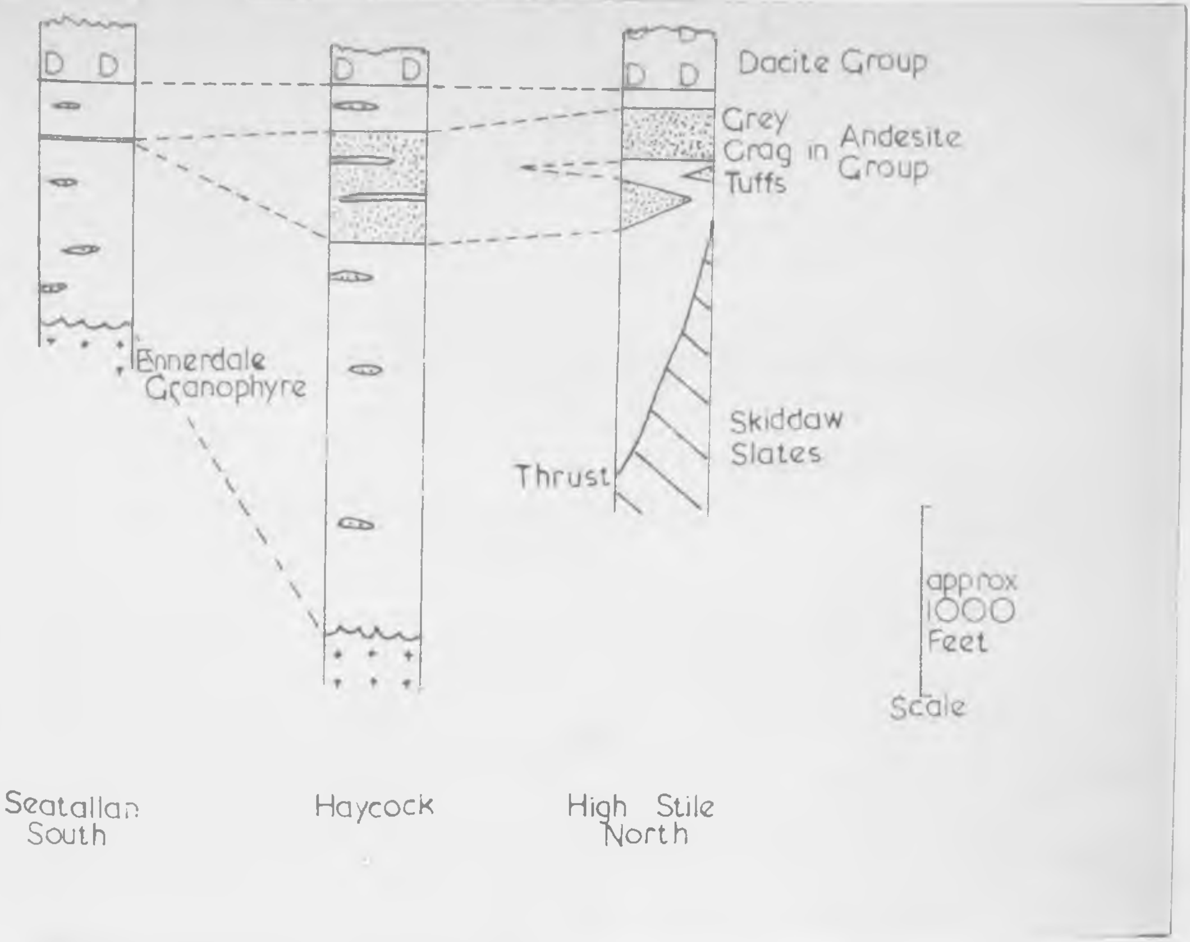


A small circular area of agglomerate occurs in the Andesite Group in Burtness Combe (G.R. 175146). This agglomerate probably marks the site of a volcanic vent.

Local successions from the north, centre and south of the area are given on the next page.

### B Correlations.

The succession in the area under discussion rests directly on the Skiddaw Slates in the Buttermere district and may be correlated with the lower part of Firman's Lower Andesites which also rest on Skiddaw Slates. A comparison of the

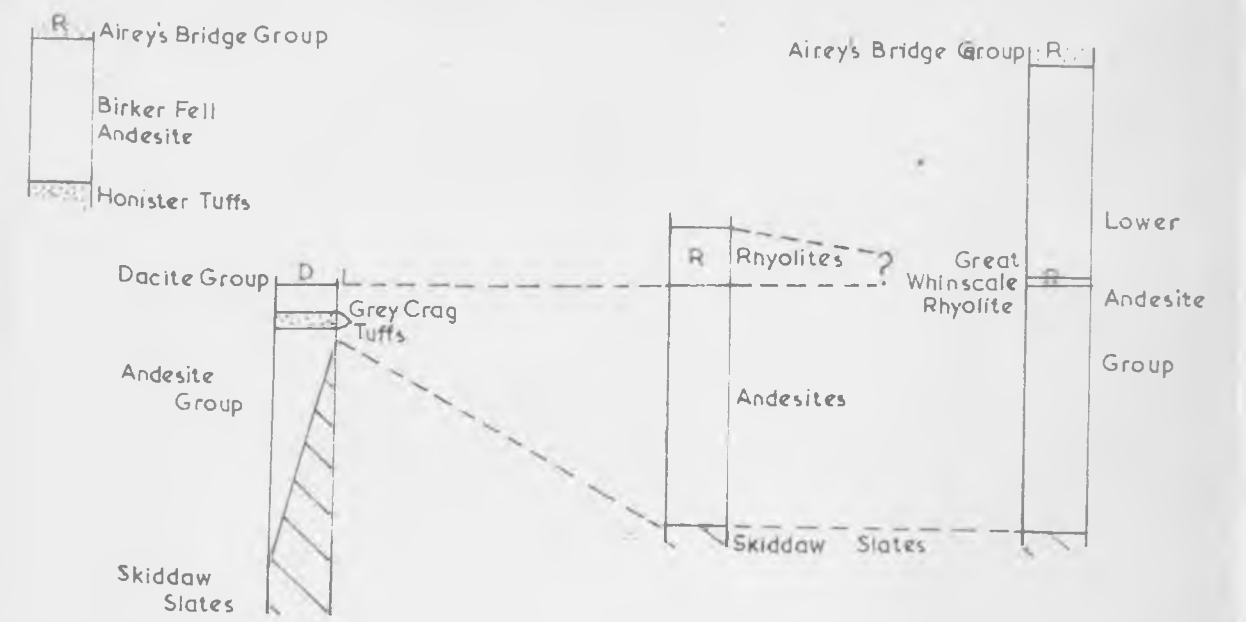


position of the present succession and the Birker Fell Andesite Group of Oliver (ibid, pp. 378) supports this correlation. The present succession is updip from, and therefore, stratigraphically below, the Birker Fell Andesite Group which are correlated with the upper part of the Lower Andesites.

Hollingworth (ibid, pp. 24) correlates a thick development of rhyolites west of the Ennerdale Granophyre with Hartley's (1932) Langdale Rhyolites. The former rhyolites have been proved to be continuous with the Dacite Group of the present area. This shows that the rhyolites west of the granophyre are merely an intercal-ation in the Lower Andesites. They may possibly be correlated with the Great Winscale Rhyolite in the Lower Andesites south of the Esk. (Firman, ibid, pp. 41).

The above correlations are summarized in the diagram below:

Borrowdale Oliver. | Buttermere | Gosforth Hollingworth | Duddon Firman



## C. A Detailed Description of the Succession.

### (i) The Andesite Group.

### a. Field Relationships.

The Andesite Group occupies most of the area under discussion. (Fig. 4). The group rests on the Skiddaw Slates in the Buttermere district, but the junction here is a thrust plane which cuts out over 1000 feet of the Andesite Group on the south side of High Stile. The Andesite Group is in contact with the Ennerdale Granophyre from Buttermere to Wasdale. Over much of this distance the strike of the volcanic rocks is parallel to that of the contact with the granophyre. The maximum thickness seen of the

Andesite Group is of the order of 3000 feet.

The Andesite Group consists of a series of massive andesitic lava flows in which interbedded tuffs are subordinate. The tops of the lava flows are often visible as prominent bedding planes where the less resistant flow brecciated or vesicular surfaces of the flows have been picked out by erosion. Three such bedding planes, crossing Chapel Crags near Buttermere, separate lava flows which are each between 100 and 120 feet thick.

Flow brecciation of the surfaces of the lavas is quite common and is well seen on the ridge between Red Pike and the top of Chapel Crags where the brecciated lavas closely resemble coarse agglomerates. This brecciation rarely affects more than the top few feet of a flow, but flow breccias stand out prominently from the normal fine-grained massive lava of the rest of the flows and appear more abundant than they really are. The bases of the lava flows are also occasionally brecciated. (Photo. 3). Vesicular and amygdaloidal surfaces of flows are not common except in lavas at the top of the Andesite Group.

The andesites between the Grey Crag Tuffs and the Dacite Group in the High Stile area are conspicuously feldsparphyric, amygdaloidal and flow brecciated. This horizon can be followed from High Stile southwards to Haycock, but is not found further south except possibly for a feldsparphyric andesite (E.10119) from Cat Bields (G.R. 13150685). In the vicinity of Windygap Cove on the south side of Ennerdale, the horizon of these amygdaloidal feldsparphyric andesites still underlies the Dacite Group, but is separated from the Grey Crag Tuffs by about 500 feet of more normal andesites.

Photo. 3. Flowbrecciated Base of Andesite Flow Over Bedded Tuffs.

The material infilling cracks in flow brecciated lavas is of variable composition. It is commonly very fine chilled lava (Photo. 3), but can be fine bedded tuff. In the amygdaloidal lavas at the top of the Andesite Group, the cracks are commonly filled with agate or chalcedonic silica. Amygdales are usually filled with quartz with accessory epidote and chlorite, but agate and chalcedony are occasionally found.

The majority of the andesites are definitely extrusive, but an intrusive andesite occurs in the Grey Crag Tuffs on High Stile (G.R. 167148). This andesite superficially looks like a normal lava flow about 20 feet thick, but it cuts across the bedding of the tuffs.

An interesting intrusive structure occurs at the top of a lava flow beneath bedded tuffs on Middle Fell (G.R. 152064). A 'flame' of lava leaves the top of the flow and pierces the tuffs. Apart from this flame structure, whose origin is uncertain, the lava appears to be a normal extrusive lava.

The Andesite Group is notable for the rarity of tuffs interbedded with the lavas. Small lenses of bedded tuffs do occur, however, and become quite common on the lower slopes of Middle Fell in Wasdale. The tuff bands rarely exceed 20 feet in thickness and 200 yards in length. One exception is a tuff band on Long Crag in Wasdale (G.R. 152064) which reaches 100 feet in thickness and over 300 yards in length.

Tuffs reach their greatest development in this area with the Grey Crag Tuffs which occur near the top of the Andesite Group. These tuffs can be traced from the River Liza in Ennerdale for about two miles to Haycock where they abut against the Haycock Fault. They form a bed about 600 feet thick which maintains a constant thickness over this outcrop. Several andesite flows, usually between 20 and 50 feet thick, occur in the tuffs, for example on Haycock. North of the Liza, in the High Stile area, the Grey Crag Tuffs divide into two beds, each approximately 250 feet thick. The upper bed forms Grey Crag in Burtness Combe and the lower bed forms Raven Crag in Ennerdale. A third bed of tuff about 100 feet thick, occurs between the first two on the west side of High Stile. Typical Grey Crag Tuffs are not found south of the Haycock fault, but a band up to 20 feet thick of very fine tuff occurs on Shooting How on Seatallan (G.R.140088) at roughly the same horizon. This tuff band is equated with the Grey Crag Tuffs which must have thinned very rapidly between Haycock and Seatallan.

The tuffs are usually well-bedded in an extremely regular manner, which gives cliffs made of the tuffs a prominent striped appearance, (Photo. 4).

Photo 4. Grey Crag Tuffs, Burtness Combe.

The tuffs often show graded bedding and occasionally current bedding. They can have rapid lateral variations in character, but usually maintain a constant lithology over quite large distances. The regularity of the bedding in tuffs and the localized occurrence of many of the tuff lenses suggest that most of the tuffs were laid down in water.

### b. Petrography

Lavas: In hand specimens the lavas are a uniform series of massive fine dark green rocks in which porphyritic elements are inconspicuous. Prismatic feldspar phenocrysts are quite common in many specimens but are small and rarely exceed two millimetres in length. Femic phenocrysts are less common than the feldspars and are usually smaller. Occasional specimens with conspicuous femic phenocrysts can be found, for example, a specimen (E9932) from Burtness Combe (G.R.17321464) contains numerous femic phenocrysts up to five millimetres in diameter.

Feldspars of the feldsparphyric andesites from the top of the Andesite Group occur as prisms up to 3 x 1 mm. in size in glomeroporphyritic groups up to one centimetre across. The groups of feldspar prisms often have the appearence of asterisks. These andesites are full of amygdules which are often filled with quartz and epidote. The epidote is particularly abundant on High Stile where it has spread from the amygdules to the surrounding rock (E.9927) colouring it a greenish yellow in places.

Lavas exposed on the lower slopes of Middle Fell, from Greendale Gill to the mouth of Nether Beck, show some peculiarities in the hand specimen for they resemble dacites in many respects. Many specimens have a resinous lustre (E.10115) similar to that of the rocks of the Dacite Group. Feldsparphyric specimens are very common (E.10117) but the feldspar phenocrysts do not occur in asterisk forms as do the ones described above. A patchy pink matrix is also common in lavas over much of this area (E.10118)

These andesites are clearly of a much more acid character than the normal andesites of the Andesite Group. Their relatively acid character has been confirmed, for the ground masses of some specimens (E.10118) have been shown to contain potash when stained with sodium cobaltinitrite. The potash is not present in all specimens and is not abundant when present.

Under the microscope plagioclase phenocrysts are usually euhedral or subhedral prismatic crystals, but in badly altered specimens the original form of the crystal may be lost. The composition of the plagioclase varies from $An_{30}$ to $An_{40}$, but alteration of feldspar is so widespread that their composition cannot always be determined.

The original ferromagnesian mineral was probably a pyroxene which, in almost all cases has been replaced by chlorite or hornblende. In some specimens where the original prismatic form of the pyroxene has been maintained, the later mineral has replaced the pyroxene with crystallographic continuity.

The pyroxene phenocrysts in a specimen (E.10354) from Little Gowder Crag (G.R. 14031098) are quite fresh. This pyroxene is almost colourless with a yellowish or pinkish tinge and occurs in abundant euhedral and subhedral prisms up to 0.6 x 0.8 mm. in size. Simple and polysynthetically twinned crystals are common. The pyroxene is optically positive with a 2 V of 57 +/- 1 degree and a maximum extinction angle $z \wedge c$ of 42 degrees which, together with its mode of occurrence suggest that it is augite.

The ground masses of the andesites are variable in composition and texture but are usually largely made up of alteration products. The major component is plagioclase in lath shaped crystals about 0.2 x 0.1 mm in size, but varying from 0.1 x 0.01 to 0.6 x 0.3 mm. in size. The plagioclase occurs as a fine mosaic in badly altered rocks where the original laths have recrystallized. The plagioclase rarely retains any twinning because of the extensive alteration, but that of a few less altered specimens varies in composition from $An_{34}$ to $An_{52}$. The rest of the ground mass is composed of flakes of sericite and chlorite, shreds of hornblende, and grains of epidote, sphene and iron ore which occur either interstitially in a mesh of plagioclase laths or disseminated through a feldspar mosaic. The texture of the ground mass is often trachytic, for example specimen E10343 in which are myriads of parallel feldspar laths about 0.1 x 0.01 mm. in size.

The matrices of the feldsparphyric andesites have a more chaotic appearance than those of the normal andesites. The main constituent is plagioclase in prismatic crystals which vary from less than 0.1 to over 0.5 mm. in length in the same specimen (E9927). The interstices are mainly filled with chlorite and epidote. This matrix is disrupted by amygdules filled with quartz, chlorite and epidote. The epidote has spread from the amygdules and replaced part of the matrix and the feldspar phenocrysts.

The relatively acidic lavas of Middle Fell described above resemble the lavas of the Dacite Group. They contain abundant plagioclase phenocrysts with a composition of approximately $An_{40}$ which are commonly sericitized and epidotized. Very rare femic phenocrysts occur as pseudomorphs in penninite. The ground masses are similar to those of the normal andesites except that quartz occasionally occurs. A distinctive accessory mineral is apatite in stumpy prisms up to 0.2 x 0.1 mm. in size, often containing numerous orientated inclusions. Similar apatite crystals are found in lavas of the Dacite Group. The matrix of a specimen (E.10113) from Long Crag (G.R. 15020658) is an extremely fine mosaic in which flow textures are preserved as trains of sericite swirling around phenocrysts. This matrix is probably a devitrified glass.

Three partial analyses of normal fine grained andesites from the Andesite Group are given below. Average compositions of dacites, andesites and tholeiitic basalts (Nockolds, 1954, p.1007) are given for comparison.

Partial analyses of Andesites, by Clark.

| Silica Percentage | Specimen | Locality |
|---|---|---|
| 55.4 | E 10340 | White Pike (G.R.15981491) |
| 52.1 | E 10350 | Deep Gill (G.R.14371145) |
| 50.3 | E 10121 | Worm Gill. West of the Ennerdale Granophyre. (G.R. 09310946). |

Average Silica content of Dacites = 63.58%
Andesites = 54.20%
Tholeiitic Basalts = 50.83%

These analyses show that the normal andesites vary in composition from average andesites to basalts. The basic character of some of these andesites is also shown by the occurrence of labradorite in specimen E 9221 from Chapel Crags near Buttermere.

The relatively acidic andesites from Middle Fell are intermediate in character between normal andesites and dacites. They may be dacitic in composition but are considered here to be acid andesites.

Tuffs: Tuffs vary from extremely fine flinty tuffs such as specimen E 10107 from Shooting How on Seatallan, to fairly coarse agglomeratic tuffs containing fragments over a centimetre in diameter. The larger fragments in the tuffs are often angular fragments of lavas similar to those of the Andesite Group, but smaller fragments about two millimetres in diameter have often ellipsoidal shapes. Occasionally the tuffs contain rounded pebbles of lava several centimetres in diameter which were volcanic bombs. They depressed the bedding planes of the tuffs beneath them by their impact and were then covered over by further settlement of ash.

Course tuffs frequently show graded bedding but the finer tuffs tend to be well sorted and homogenous. The general colour of the tuffs is dark green and when they lose their striped appearance they closely resemble fine andesitic lavas.

The finest tuffs are crystal tuffs with scattered fragments of euhedral crystals of plagioclass up to 0.4 mm. in diameter, set in a matrix of chlorite and sericite with accessory magnetite, sphene, leucoxene, epidote and quartz. 'Ghosts' composed of sericite, chlorite and occasional quartz show that the matrix in a specimen (E.8760) from Ennerdale (G.R. 16301288), originally contained numerous lithic fragments squashed into lenses about 2 x 1 mm. in size, which have been completely sericitized and chloritized. A crystal tuff (E.9925) from Chapel Crags (G.R. 16531486) contains abundant fragments of partially altered plagioclase up to 0.5 mm. in diameter together with several fragments of a ferromagnesian mineral set in a matrix of alteration products. The ferromagnesian mineral has been pseudomorphed crystal for crystal by chlorite and hornblende. Small stellate groups of amphibole fibres grow in the penninite pseudomorphs, but the larger crystals of hornblende appear to be independent of the chlorite.

The coarser tuffs are more lithic in character. In a specimen from the Grey Crag Tuffs at the foot of Eagle Crag the fragments reach 2 x 1 mm. in size. They are generally ellipsoidal in shape and are flattened parallel to the bedding. Most of the fragments are of fine trachytic lavas containing abundant feldspar laths about 0.2 x 0.05mm. in size, set in a chloritic base, speckled with hosts of granular aggregates of sphene about 0.02 mm. in diameter. The fragments are believed to be lapilli of glassy lava. Besides these trachytic fragments there are numerous fragments of feldspar, quartz and quartzite. The matrix is composed of chlorite and epidote with sphene and granular feldspar.

Agglomerate: A semi-circular outcrop of agglomerate occurs in the Andesite Group in Burtness Combe. The semi-circular shape of this outcrop is caused by one end being removed by the fault at the base of the Borrowdale Volcanic Series. The original outcrop of the agglomerate was probably an oval about 300 x 500 yards in size. The agglomerate is intrusive into the Andesite Group and probably occupies a small volcanic vent.

The relationships between the agglomerate and the surrounding lavas are variable. The andesites occasionally overlie the agglomerate but in most cases the contact is either steep or the agglomerate veins the lavas.

The agglomerate is unsorted (Photo. 5) and composed of material which varies from a fine chloritic matrix to angular fragments of lava up to ten centimetres in diameter. The fragments in the agglomerate are composed of fine basic lavas similar to those in the Andesite Group.

Photo. 5. Vent Agglomerate. Burtness Combe.

### (ii) The Dacite Group.

#### a. Field Relationshipps

The Dacite Group overlies the Andesite Group over the full length of the present area. The base of the group can be followed with little break from Burtness Combe southwards through Haycock to Seatallan. The summit of Seatallan is formed of the Dacite Group which dips down the south-west ridge of the mountain to Hollow Moor where it is continuous with a series of rhyolites mapped by Hollingworth. The top of the Dacite Group is not seen in the area under discussion and the maximum thickness observed is of the order of 300 feet.

Rocks from some parts of the series of rhyolites west of the Ennerdale Granophyre, for example from the region around Guards in Wasdale (G.R.117051) are indistinguishable from those of the Dacite Group. Rhyolites, however, have not been found in the Dacite Group, therefore this acidic intercalation is more acidic in character in the west than in the east. This suggests that the source of the acidic lavas lay to the west of the Ennerdale Granophyre.

The Dacite Group consists of dacitic lavas with no interbedded tuffs and very few lava flows of any other composition. A thin feldsparphyric andesite flow outcrops on High Crag (G.R.176142). The dacites are massive very uniform lavas with no amygdaloidal or flow brecciated types being seen. This uniformity of the dacites makes it extremely difficult to separate individual flows.

The dacites weather to a pale buff colour and the relatively pale coloured cliffs of dacite, for example Black Crag (G.R. 162116), contrast sharply with the much darker cliffs of tuffs and andesites.

The Dacite Group is often separated from the Andesite Group by a prominent bedding plane. A broad ledge marking this plane traverses Burtness Crag in Burtness Combe from White Cove to Eagle Crag.

### b. Petrography.

The dacites are very uniform in hand specimen. Abundant feldspar phenocrysts up to 3 x 1.5 mm. in size are set in an extremely fine, green or brown matrix. The feldspars appear as subhedral prisms usually greenish in colour but occasionally pure white. A freshly broken surface of a dacite is hackly and the brown or green matrix gives the surface a distinctive resinous lustre. In specimens stained with sodium cobaltinitrite the matrix and the pure white feldspars are seen to be rich in potash.

The dacites are also very uniform under the microscope. They are conspicuously feldsparphyric with two types of feldspar phenocrysts set in a very fine matrix. The most common phenocrysts are badly altered prisms of plagioclase, probably of oligoclase composition. Phenocrysts of a clear grey potash feldspar , often perthitic in appearance, are less common. This feldspar is little sericitized, but often contains much epidote.

Ferromagnesian phenocrysts are not common, but occasionally occur as scattered pseudomorphs of chlorite after pyroxene in euhedral prisms upto 1 x 0.5 mm. in size in glomerop-orphyritic groups (E10345). This pyroxene possibly changes into an amphibole before chlorite for the chlorite, which is optically continuous over the whole pseudomorphs, appears to be replacing a fibrous mineral.

The matrices of specimens from the Burtness Combe area (E9930, E9928) are composed of a fine quartzo-feldspathic mos-aic. This mosaic varies in grain size from 0.2 mm. in diameter in coarse grained areas to below the resolution of a microscope in fine grained areas. The coarse and fine grained areas of the matrix tend to be drawn out into 'veins' parallel to the flow direction of the lava. The coarser parts of the matrix are more epidotized than the rest. Accessory minerals in the ground masses include iron ore up to 0.5 mm. in diameter changing to leucoxene, sphene and haematite, abundant granular aggregates of sphene about 0.01 mm. in diameter, and apatite in euhedral prisms up to 0.5 mm. long associated with the epidote, sericite and chlorite.

The matrices of other dacites tend to be similar to those just described, except that quartz is not so evident in many specimens. The matrices are then mosaics of anhedral feldspar grains up to 0.2 mm. in diameter with the usual accessory minerals. The matrix of a specimen (E8674) from the south-west ridge of Seatallan (G.R. 12860662), consists of a mosaic of feldspar anhedra about 0.2 mm. in diameter full of needles 0.1 x 0·01 mm. in size. These needles have a low birefringence, low relief and often grow across feldspar boundaries. Their composition is unknown, but they may be feldspars.

Three partial analyses of lavas from the Dacite Group are given below. The average silica content of andesites, dacites, rhyodacites and rhyolites from Nockolds (ibid) are given for comparison.

Partial analyses of Dacites, by Clark.

| Silica Percentage. | Specimen | Locality |
|---|---|---|
| 66.3 | E 10110 | Near Greendale Tarn.<br>(G.R. 14400772) |
| 65.3 | E 9928 | White Cove. Buttermere<br>(G.R. 17641424) |
| 62.9 | E 9930 | Grey Crag. Buttermere<br>(G.R. 17081476) |

Average silica content of Rhyolite = 73.66%

Rhyodacite = 66.27%

Dacite = 63.58%

Andesite = 54.20%

These analyses show that the lavas of the Dacite Group vary from dacites to rhyodacites in composition. The affinities of these lavas with rhyolites is also suggested by the regular occurrence of much potash feldspar and free quartz in their matrices.

# PART TWO. THE ENNERDALE GRANOPHYRE.

## III. BASIC INTRUSIONS ASSOCIATED WITH THE ENNERDALE GRANOPHYRE.

### 1. Introduction

Metasomatism and hybridization of the basic rocks of the Ennerdale Granophyre by the Main Granophyre have been so intense and widespread that there are now no unaltered basic rocks within the Ennerdale Granophyre stock. The altered basic rocks within the stock will be discussed later in Chapter IV. Basic rocks unaffected by metasomatism and hybridization do occur in minor intrusions in the vicinity of the stock.

The most important of these minor basic intrusions occur in a complex of sills associated with a small laccolith on the Buttermere side of High Stile. This complex has been briefly described by Walker (1904, pp. 83-5) who called it the Intrusive Complex of Burtness Combe. A more detailed description of the complex has been given by Rastall (1906, pp. 261). Numerous basic sills and dykes also outcrop on Bowness Knott and Crag Fell in Ennerdale, and an isolated basic dyke is found on Buckbarrow in Wasdale.

### 2. Field Relationships.

#### A. The Burtness Combe Intrusive Complex.

The Burtness Combe Intrusive Complex is exposed on the lower slopes of High Stile and High Crag, south of Buttermere Lake (Fig. 5). The country rocks of the complex are Skiddaw Slates metamorphosed by the Ennerdale Granophyre.

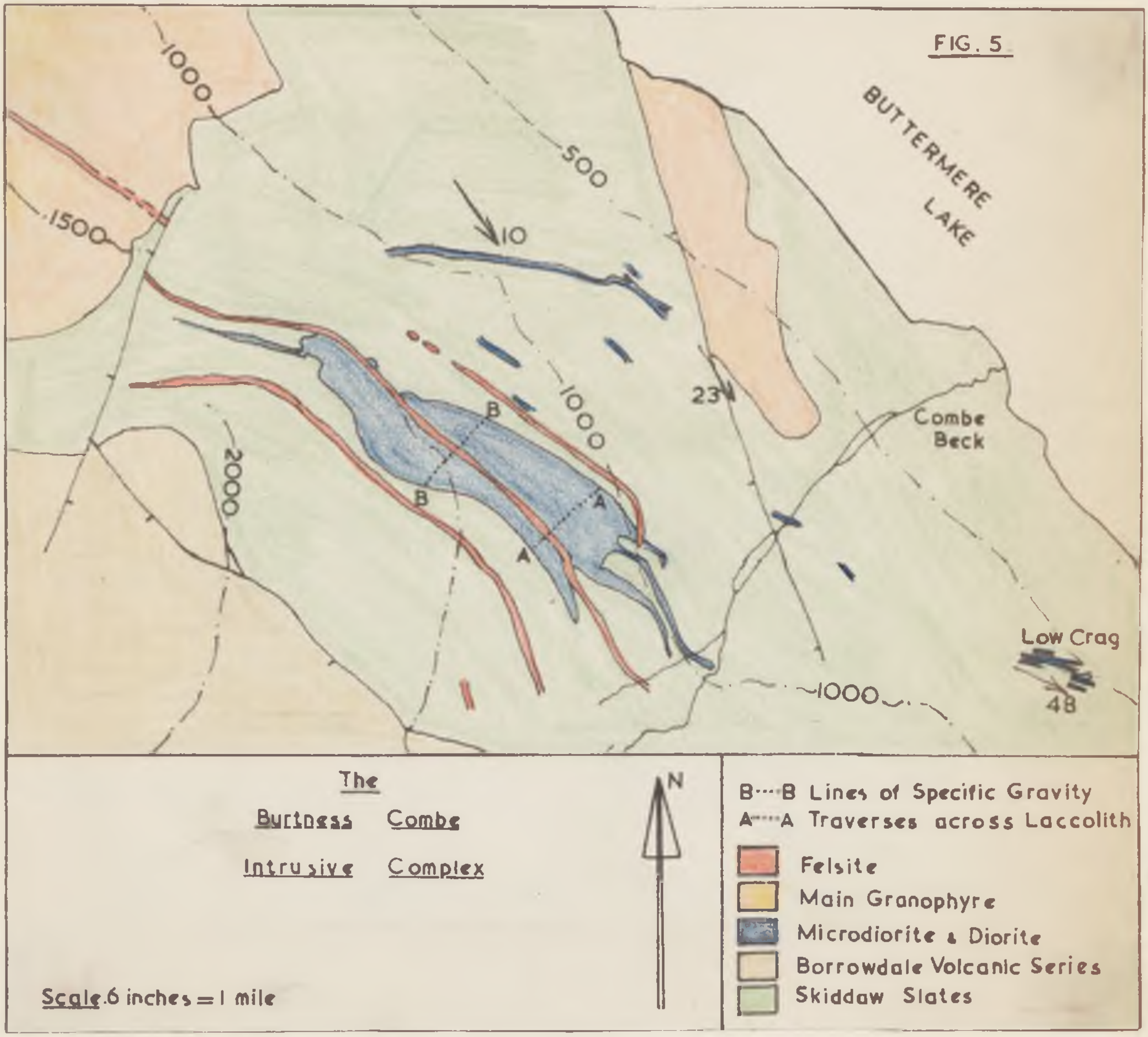


FIG. 5

The Burtness Combe Intrusive Complex

The largest intrusion of the complex is a concordant lensiform, diorite laccolith approximately 600 yards long and with a maximum thickness of 200 feet. The outcrop of the laccolith trends from north-west to south-east, dipping across the front of High Stile from 1750 feet in the north west to 900 feet in the south-east. The laccolith fingers out into four short sills at its south-east end (Photo. 6.) and abruptly thins to a sill about four feet thick at its north-west end. The latter sill can be traced, swelling in places, to 20 feet in thickness, for some 250 yards.

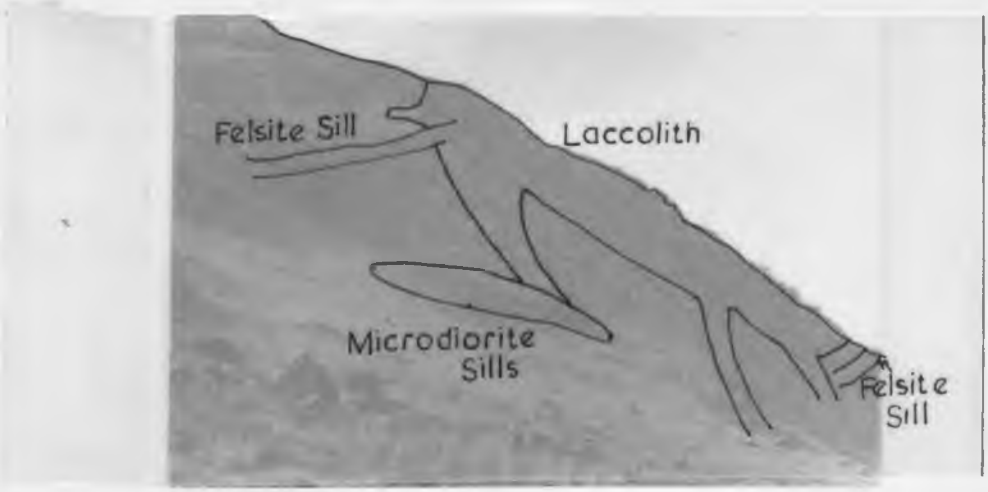


Photo. 6. Diorite Laccolith and Sills, Burtness Combe.

The diorite of the laccolith shows a number of interesting variations in character, The sills given off from the laccolith are composed of a chilled, almost aphanitic, pale greenish-grey microdiorite speckled with numerous femic crystals. The diorite at the base of the laccolith is similar to that of the sills but is a little coarser grained and darker in colour. Above the base of the laccolith the diorite becomes coarse grained, and very dark in appearance. It is very rich in femic crystals about two mm. in diameter which give it a dark green colour. The diorite gradually becomes more leucocratic and ophitic in texture as the abundance of the femic crystals decreases towards the centre of the laccolith. The diorite of the upper part of the laccolith is characterized by an irregular development of pink feldspathic patches. These patches are irregular in shape and vary in size from clots less than a centimetre in diameter to patchy pink areas several centimetres across. The rock close to the upper contact of the laccolith is similar to the chilled diorite at the base, except that it is locally garnetiferous. Garnetiferous diorite has only been found at one locality (G.R.17781508) but is possibly the source of blocks of 'garnetiferous diabase' found in Combe Beck, by Walker (ibid. pp. 85).

Three parallel, flow-banded felsite sills which belong to the last phase of the intrusion of the Ennerdale Granophyre cross the Burtness Complex. The lowest felsite sill cuts across the lowest microdiorite sill at the south-east end of the laccolith. The central felsite sill cuts diagonally across the laccolith, and over much of its course through the laccolith, passes through the zone in which the diorite is characterized by the irregular development of pink feldspathic patches. The contacts between the felsite sills and the diorite are quite sharp.

Numerous previously unrecorded basic sills in the vicinity of the laccolith are believed to have been intruded with the laccolith. The sills are gently dipping, roughly concordant sheets composed of a uniform fine greenish-grey microdiorite. They usually do not exceed four feet in thickness and often cannot be traced for more than a few yards. One sill, approximately three feet thick, can, however, be followed for over 400 yards from a point 300 feet below the west end of the laccolith (G.R.17621545) to a small crag just above Burtness Wood (G.R.1800-1539). The sill there joins three similar sills which can only be traced a few yards. A small but intricate complex of microdiorite sills is well exposed on Low Crag above the south-east end of Buttermere Lake. (Photo. 7).

Photo. 7. Microdiorite Sills. Burtness Low Crag.

## B. The Minor Basic Intrusions of Ennerdale and Wasdale.

The swarm of microdiorite intrusions in Ennerdale is confined to the vicinity of Bowness Knott and Crag Fell. The microdiorite of these intrusions is, in most cases, similar in appearance to that of the Burtness sills. Four vertical dykes between 16 inches and 7 feet in thickness on Bowness Knott, appear to have been injected along sub-parallel south-easterly trending joints in the Skiddaw Slates. A dyke five feet thick and striking at right-angles to these four dykes outcrops on the south face of Bowness Knott at 1000 feet O.D. A small waterfall in Rake Beck at 900 feet O.D. falls over a vertical 16 feet thick basic dyke which strikes north-south. Sixty yards south of the waterfall in Rake Beck, a rather leucocratic sill outcrops. This sill is five feet thick and dips at 20 degrees to the south-south-east. A prominent cliff which swings down the centre of the south face of Herdus is formed by a 14 feet thick sill dipping north 35 degrees west at approximately 40 degrees. Several small concordant lenses of microdiorite occur on the west side of a small crag approximately 200 yards south of Bowness cottage.

A quartz microdiorite sill heads north-westwards from the right-angled bend in Rack Beck at 1000 feet O.D. The sill can be traced for some 60 yards gradually thickening to 15 feet, at which point it is cut by a vertical 15 feet thick felsite dyke striking at 265 degrees. The sill then quickly thickens to approximately 45 feet and the microdiorite becomes much more leucocratic grading into a fine creamy felsite in the thickest part of the sill. After 20 yards the felsitic 'laccolith' thins again to a normal basic sill approximately six feet thick, which can be followed for 60 yards to the north-west.

The microdiorite dykes on Crag Fell vary in thickness from two to twenty feet, but none can be traced for more than a hundred yards. Most of the dykes appear to be confined to the north and east sides of Crag Fell, but this may be due to the lack of exposure on the south and west flanks of Crag Fell rather than the lack of dykes. A basic dyke over four feet thick striking at 340 degrees, which probably belongs to the Crag Fell dykes, is exposed in the south bank of the Calder 400 yards below its confluence with Whoap Beck (G.R. 08041288). A pale greenish-grey microdiorite sill 25 feet thick is exposed in the summit crags of Crag Fell at 1500 feet O.D. (G.R. 09751460).

A microdiorite dyke is exposed on the south face of Buckbarrow in Wasdale (G.R. 13670388). The dyke is four feet thick, strikes approximately north 40 degrees west, and is intrusive into the Borrowdale Volcanic Series and the Ennerdale Granophyre. The rock of the Ennerdale Granophyre on Buckbarrow is the Main Granophyre. The microdiorite dyke is crossed by a felsite dyke but the actual junction is partially obscured. The felsite dyke appears to pinch out on either side of the microdiorite dyke as if the microdiorite has acted as an obstruction to the passage of the felsite during intrusion. This indicates that the microdiorite dyke is younger than the Main Granophyre, but is possibly older than the felsite dyke.

## 3. Petrography.

### A. The Burtness Combe Laccolith.

The sills given off from the laccolith are composed of a very fine grained pale greenish-grey rock, with scattered femic phenocrysts up to 1.5 mm. in diameter, (E 9200). The rock is badly altered with a fine matrix composed of calcic andesine, tremolite-actinolite, penninite and leucoxene. The andesine occurs as decayed laths approximately 0.3 mm. long and as anhedra up to 0.1 mm. diameter, but is almost obscured by the tremolite actinolite, which occurs as a felt of shreds approximately 0.5 mm. long. Leucoxene is scattered through the rock in minute grains and in granular aggregates up to 0.1 mm. in diameter. Ragged phenocrysts of tremolite actinolite up to 0.4 mm. in diameter are quite common.

A specimen taken from the base of the laccolith (E 9201) is similar to the specimen just described but is a little coarser and darker in colour. Tremolite actinolite is abundant in ragged prisms up to 0.8 mm. long. Feldspar crystals up to 2 mm. in diameter have been pseudomorphed by an almost isotropic mineral, possibly serpentine, with shreds of tremolite actinolite and a little recrystallized feldspar. The shreds of tremolite actinolite in these pseudomorphs are orientated in lines in three directions. These lines are possibly along original cleavage directions. The matrix of the specimen is probably a serpentine charged with epidote, leucoxene dust and shreds of tremolite actinolite.

Diorite from approximately 50 feet above the base of the laccolith (E9202) is coarser and more basic in appearance than the specimen from the base. Tremolite actinolite is present as recognizable pseudomorphs of pyroxene prisms up to 2 x 1 mm. in size with very occasional remnants of unaltered pyroxene, probably augite, preserved in their cores. The original ophitic texture of the rock is partially preserved with pseudomorphs after pyroxene embayed by pseudomorphs after feldspar. The pseudomorphs after feldspar and the serpentineous matrix of section E9202 are similar to those of section E 9201. The remanié ophitic texture clearly shows that the peculiar serpentineous pseudomorphs after feldspar really are after feldspar. The altered nature of the specimen makes it difficult to make an accurate estimate of the abundance of the ferromagnesian minerals, but a rough modal analysis suggests that they made up approximately 50 per cent of the original rock. The replacement of the feldspars by ferromagnesian minerals will have appreciably increased this percentage.

The rock close to the centre of the laccolith (Specimen E 9203) is more leucocratic. Calcic andesine is present in fairly fresh prisms up to 3 mm. long but averaging 1.5 x 0.5 mm. in size. Tremolite actinolite occurs in pseudomorphs of prisms of pyroxene and the original ophitic texture of the rock is retained. The edges of the tremolite actinolite crystals are fibrous and ragged, and the amphibole fibres tend to grow into the feldspars. Pseudomorphs after skeletal crystals up to 0.8 mm. in diameter of ilmenite intergrown with magnetite are quite common. These pseudomorphs are now composed of leucoxene in which are set parallel rods of unaltered magnetite alligned in three different directions. These pseudomorphs are often rimmed by granular sphene, The matrix of the rock is serpentineous as in the previous specimens. A modal analysis of section E 9203 is as follows:-

| | Percentage |
|---|---|
| Feldspar (Andesine) | 61 |
| Ferromagnesian Minerals | 38 |
| Iron Ore | 1 |

The rock of the upper part of the laccolith (E9204; E9295) is characterized by the presence of scattered irregular shaped pink patches, as noted above (pp. 48 ). The normal rock is similar to that of E 9203, but is slightly finer grained. The development of the pink patches, due to the influx of a diffuse pink felsitic material, has resulted in the breakdown of the ophitic texture of the rock. The ferromagnesian minerals forced out by this felsitic material are concentrated around the margins of a patch, or in clots near the centre of a patch. A little potash feldspar can be shown in fine intergrowth with quartz in a few pink patches, when stained by sodium cobaltinitrite.

In thin section, the normal rock (E. 9204) is very similar to E 9202 described above. The structure of the pink patch is seen in E 9295, where an influx of quartz and feldspar has driven out all the ferromagnesian minerals and replaced much of the rock by a quartzo-feldspathic micropegmatite.

The feldspar of the micropegmatite is probably andesine-oligoclase. Many calcic andesine prisms from the original rock remain embedded in the micropegmatite, unaltered except for slight corrosion along the edges. The rock around the zone of micropegmatite has been badly altered. The ferromagnesian minerals from the area now occupied by micropegmatite have recrystallized as a halo of penninite around the area. This penninite occupies all the interstitial spaces between the feldspar prisms of the rock, and small clots of penninite riddle the feldspars themselves. Large pseudomorphs of iron ore similar to those described in section E 9203 are quite common in the area around the micropegmatite.

The diorite close to the upper contact becomes finer and more basic and resembles the diorite at the base of the laccolith. It is locally garnetiferous. A specimen from the garnetiferous diorite (E 9296A & B.) is a dark greenish grey, medium grained rock veined by thin quartz veins which appear to be feeders to a white patch-veining in the rock. Numerous yellowish pink spessartine garnets up to 0.5 mm. in diameter occur associated with the veining in the rock.

This specimen has been completely altered. All the ferromagnesian minerals have been changed to penninite and the feldspar sericitized and recrystallized. A patchy development of quartz and feldspar in anhedral crystals up to 0.5 mm. in diameter is present in a matrix of penninite. A quartz, feldspar, pistacite vein crosses section E 9296A and numerous pink spessartine garnets up to 0.4 mm. in diameter are concentrated along the margins of the vein. Their origin appears to be connected in some way with the veining.

The concentration of garnets relative to the vein has been determined by constructing a grid over the section, with the distance between the grid lines equal to the width of the low power field of view of a microscope. The microscope was centred on an intersection of grid lines and the number of garnets visible under low power were counted. The operation was repeated over the whole grid and the results below illustrate the great concentration of garnets along the margin of the vein.

| | | | | | | | Total garnets in each traverse. |
|---|---|---|---|---|---|---|---|
| Vein | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| | 17 | 45 | 10 | 15 | 14 | 15 | 116 |
| | 1 | 3 | 1 | 17 | 11 | 8 | 41 |
| | 0 | 0 | 0 | 0 | 7 | 39 | 46 |
| | 0 | 11 | 0 | 22 | 0 | 0 | 42 |

Section E 9296 B. is similar to E 9296 A., but there is no definite veining. Numerous garnets occur, however, and many are clearly clustered around clots of feldspar. The majority of the garnets are rounded or sub-polygonal, very fresh and set in a chloritic base. The garnet appears to have been the latest mineral to develop. In most cases there appears to be no relationship between the chlorite and the garnets, but a few garnets have irregular outlines and appear to be replacing the interstitial chlorite.

## B. The Other Minor Basic Intrusions.

The majority of the minor basic intrusions are composed of a fine, medium to dark greenish-grey, non-porphyritic, microdiorite. A dyke on Crag Fell (G.R. 09951418) is composed of such a microdiorite in which are scattered euhedral white plagioclase phenocrysts up to 2. x 1.5 mm. in size. (E 9620). The microdiorite of a dyke on the north-west face of Bowness Knott (G.R. 11201565) is coarser and darker in colour than normal (E 9297) A fine pale brownish grey siliceous microdiorite which grades into a felsite occurs in a laccolithic sill near Rake Beck (See pp.50-1).

The normal microdiorites have a uniform appearance in thin section. Feldspar occurs as badly altered basic andesine laths approximately 0.7 mm. long and in anhedral grains. The andesine is extensively altered to sericite and epidote and rarely shows any albite twinning. The ferromagnesian minerals present are chlorite and tremolite actinolite. The chlorite, practically all penninite, varies in abundance from being an accessory to the amphibole (E 9293) to being the only ferromagnesian mineral present (E 8673). Tremolite actinolite is present in ragged crystals varying in size from 0.6 mm. in diameter to single tiny fibres. The larger amphibole crystals appear to be pseudomorphing an earlier mineral, probably a pyroxene. Single small tremolite actinolite fibres are disseminated throughout almost all sections studied. The matrix of the microdiorites is usually a mosaic of anhedral feldspar crystals crowded with amphibole fibres, magnetite, ilmenite changing to leucoxene, sphene, calcite and epidote.

The porphyritic microdiorite from Crag Fell (E 9620) is identical with the above rocks except for the presence of scattered badly decayed feldspar phenocrysts approximately 1.5 x 0.5 mm. in size.

The microdiorite of the dyke on Buckbarrow in Wasdale is similar to the microdiorites described above, except that it is relatively fresh. Andesine occurs in subhedral laths up to 0.6 mm. long and in untwinned crystals. Titan augite is abundant in pale pink anhedral crystals approximately 0.2 mm. in diameter. Some of these crystals are acicular in shape and range up to 1 x 0.2 mm. in size. Penninite, possibly after augite, occurs in interstitial masses as small flakes. Pistacite is common in crystals approximately 0.2 mm. in diameter and is often found in feldspar. Fresh iron ore occurs in branched rods up to 0.4 x 0.01 mm. in size. Sphene is abundant as crusts on the iron ore and as isolated anhedral grains disseminated throughout the rock. A modal analysis of specimen E 10397 gives the following composition:-

| | Percentage |
|---|---|
| Andesine | 34.8 |
| Titanaugite | 26.5 |
| Chlorite | 18.1 |
| Iron Ore | 3.1 |
| Sphene | 9.4 |
| Epidote | 7.9 |
| Total | 99.8 |

The amount of sphene is surprisingly high but the significance of this is not known. Some has been derived from ilmenite, but the percentage of 9.4 appears to be far too high to be accounted for solely in this way. The quantity of andesine is lower than it would be in a fresh rock, for inclusions of epidote, sphene and chlorite have significantly affected the percentage of andesine in the analysis.

A specimen (E 9922) taken from a sill on Low Crag ab-ove the south-west end of Buttermere (G.R.18601487), is a fine greenish-grey microdiorite in which scattered blebs of quartz up to 1 mm. in diameter are visible. This rock is largely composed of roughly parallel andesine laths up to 0.4 mm. long with occasional andesine phenocrysts up to 3 x 1.5 mm. in size. The andesine is badly corroded and sericitized. The only ferromagnesian mineral present is interstitial penninite. Quartz is present in round grains of quartzite up to 1 mm. in diameter. The quartzite grains have in some cases been broken up and partially digested by the microdiorite. It appears likely that some of the interstitial quartz that is present in the rock has been derived from the assimilation of the quartzite grains which have most likely come from a sandstone in the Skiddaw Slates. Quartz microdiorite also occurs in a sill just above Burtness Wood (E. 9293). The basic parts of the Rake Beck laccolithic sill described above also consist of quartz microdiorite (E 9693). Quartz is common as interstitial grains up to 0.2 mm. in diameter in the rock, which grades into a felsite as the percentage of quartz increases and the percentage of ferromagnesian minerals decreases almost to zero. Sphene is common as poikilitic crystals up to 0.5 mm. in diameter. The sphene is of two generations with a core of brown sphene and an overgrowth of pale yellow sphene.

## 4. Age of the Minor Basic Intrusions.

Rastall (ibid) believes that the basic rocks of the Burtness laccolith belong to the same phase of intrusion as the basic rocks within the Ennerdale Granophyre stock. Hollingworth (in Trotter et al 1931, p.59) suggests that the minor basic intrusions of Bowness Knott and Crag Fell belong to the suite of lamprophyric intrusions found elsewhere in the north of England and Scotland, and tentatively suggests that they are post-Triassic in age. The present work shows that Rastall is correct, and that the majority of the basic intrusions are of the same age as the basic rocks in the Ennerdale Granophyre stock.

There are numerous basic intrusions around the periphery of the Ennerdale Granophyre but only one, the dyke on Buckbarrow in Wasdale, cuts the granophyre. The lack of basic sills and dykes in the granophyre supports the conclusion that the main intrusion of the granophyre was later than the emplacement of the majority of the minor basic intrusions.

The original pyroxene of the basic intrusions has been altered by retrograde metamorphism to tremolite actinolite in every case except that of the Buckbarrow dyke, the only dyke proved to be later than the Ennerdale Granophyre. This clearly suggests that the retrograde matamorphism is a thermal effect of the Ennerdale Granophyre.

The basic dyke on Buckbarrow cuts the Main Granophyre and, therefore, must be younger. There is an indication that it is older than the minor felsitic intrusions of the granophyre (pp. 51 ). It is, therefore, probably that although the majority of the basic intrusions were emplaced during the first phase of intrusion of the Ennerdale Granophyre, some were emplaced during the last phase in association with the minor acidic intrusions.

## 5. Petrology.

### A. Classification

Ward (1876, pp. 36) calls the rock of the Burtness laccolith a quartz diorite. Walker (ibid, pp. 83) and Rastall (ibid, pp. 263) both agree that the plagioclase in the rock is oligoclase-andesine, but Walker calls the rock a diabase, while Rastall calls it a dolerite. Hollingworth (ibid pp. 58) classifies the rock of the minor basic intrusions of Crag Fell and Bowness Knott as camptonites.

The normal rock of the Burtness laccolith is a diorite under Johannsen's classification. The plagioclase of the rock contains between 5 and 50 per cent anorthite; quartz and potash feldspar are rare or absent, and the mafic minerals make up less than 50 per cent of the rock. The original ferromagnesian mineral of much of the diorite was a pyroxene, therefore, the diorite was originally a pyroxene diorite. The basic diorite from just above the chilled base of the laccolith is a meladiorite for it contains more than 50 per cent mafic minerals.

The rocks of the other minor basic intrusions practically all fall in the field of medium grained rocks of Hatch, Wells and Well's classification. They are, therefore, microdiorites, or quartz-microdiorites if quartz is present. The dyke on Buckbarrow in Wasdale (E 10397) is composed of augite microdiorite. It is quite likely that many of the microdiorites in which the ferromagnesian mineral is now tremolite actinolite, were originally pyroxene microdiorites.

## B. Differentiation of the Burtness Laccolith.

The diorite of the laccolith of the Burtness Combe complex shows a number of variations in character which are the result of gravity differentation of the original diorite magma. The heavy mafic minerals are concentrated in a meladiorite above the base of the laccolith. As the laccolith is ascended the concentration of the mafic minerals decreases and the rock becomes a normal ophitic diorite. In the upper part of the intrusion the diorite is mottled with numerous patches of pink micropegmatite. The diorites adjacent to the lower and upper contacts of the intrusion are simibar in appearance. They are the chilled edges of the laccolith and probably have a composition close to that of the original magma.

Rastall (ibid, pp. 263) was the first person to note that the diorite at the edges of the laccolith is much more basic than at the centre, attributed this difference to differentiation of the diorite magma. He gives the following partial analyses, together with two provided by Walker (ibid), to show this difference.

| Percentage Silica. | |
|---|---|
| 56.03 | Pink Spotted Diorite. |
| 56.10 | |
| 56.16 | |
| 49.52 | Basic Margin (from Walker). |
| 50.12 | |

Rastall does not believe, however, that differentiation explains the origin of the pink patched rocks, which he wrongly believes to contain much orthoclase as well as quartz. Rastall suggests that the pink patches are derived from a second intrusion of acidic magma which was injected into the centre of the laccolith while the original diorite was still hot and partially molten.

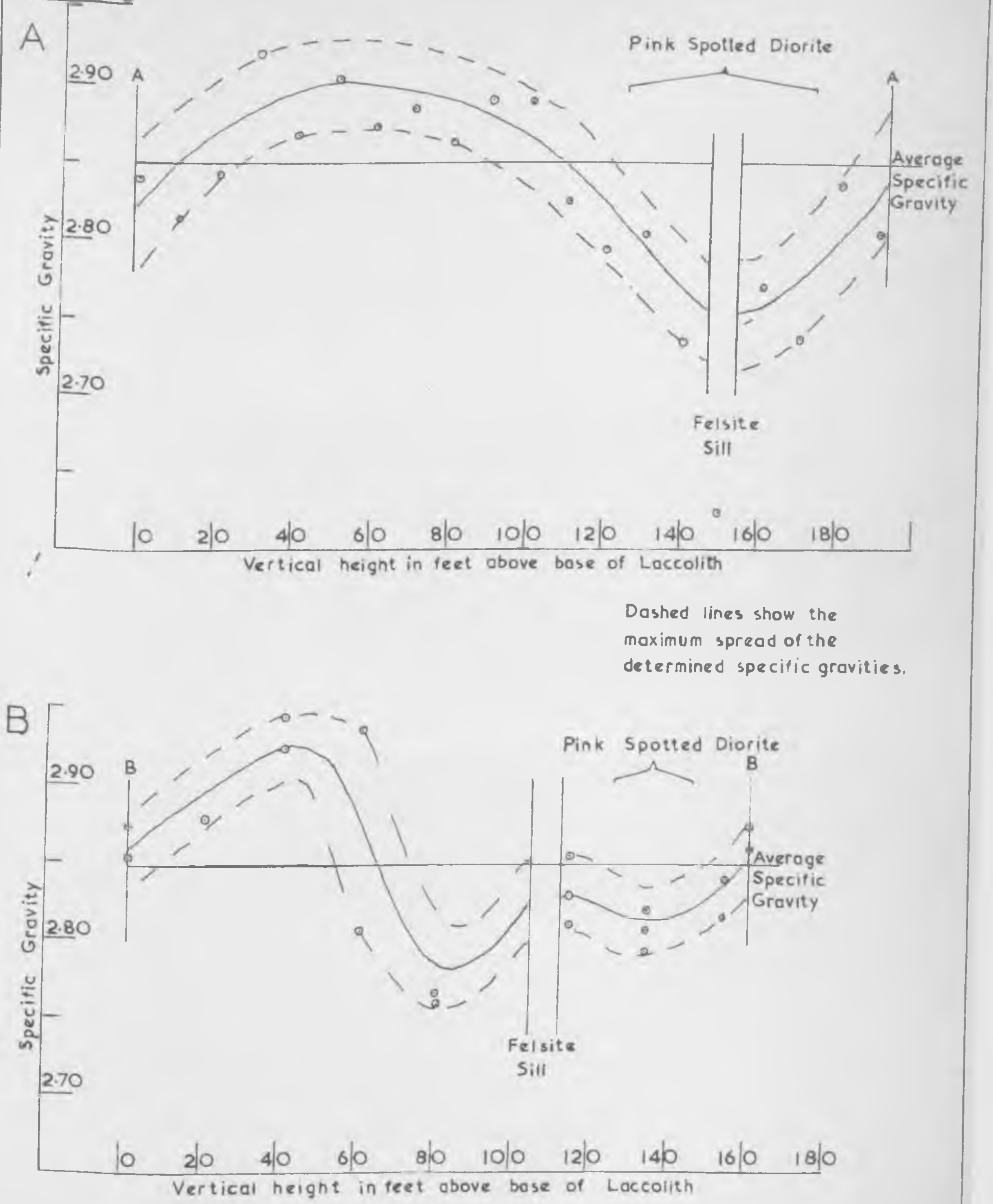
It is now believed that all the phenomena seen in the Burtness Combe laccolith can be explained by the gravity differentiation of a single intrusion. The major argument against Rastall's theory of a second intrusion of an acit magma form the Ennerdale Granophyre is the paucity of potash feldspar in the pink patched rock. Potash feldspar is never found in the normal diorite and only rarely is it found in the pink patches.

The felsitic material of the pink patches would be expected to be much richer in potash felspar if it did come from the granophyre.

The graph of Figure 6A shows the result of a vertical specific gravity traverse through the Burtness laccolith. Specific gravities are high in the more basic diorite of the lower part of the laccolith and low in the upper part of the laccolith. The diorites adjacent to the contact of the laccolith have intermediate specific gravities. This variation is specific gravities is believed to be caused by heavy minerals, mainly pyroxene, sinking under gravity and becoming concentrated in the meladiorite near the base of the laccolith, while the intrusion was still molten. The chilled margins of the laccolith remained unaffected by the differentiation and have specific gravities close to that of the original magma.

In an igneous body that has been differentiated under the influence of gravity the weight of minerals which sink into the lower part of the body must equal the loss of weight from the upper part of the body. This will be shown on the graph of a specific gravity traverse by the area of the graph in which the specific gravity is above that of the original magma, being equal to the area in which the specific gravity is below that of the original magma. The average specific gravity will equal the specific gravity of the original magma. In the case of a multiple intrusion with a second intrusion of acidic magma, the average specific gravity will be less than that of the original basic magma.

FIGURE 6



Dashed lines show the maximum spread of the determined specific gravities.

SPECIFIC GRAVITY TRAVERSES across the DIORITE LACCOLITH of the BURTNESS COMBE INTRUSIVE COMPLEX.

The average specific gravity of the diorites in Figure 6 A, calculated from the form of the graph, closely agrees with the specific gravity of the original magma preserved as the chilled margins of the laccolith. The average specific gravity is well within the observed spread of values of the specific gravities of the chilled margins of diorites of the laccolith. This agreement between the average specific gravity of diorites in Figure 6 A, and the specific gravity of the original magma strongly suggests that the variations within the laccolith are due to differentiation of a single intrusion.

A felsite sill coincides with both the centre of the pink patched zone and the point of lowest specific gravity in the traverse. This suggests that the sill may be the source of the felsitic material in the pink patches, and an important factor in the reduction of the specific gravities in the upper part of the laccolith. A second specific gravity traverse (Figure 6 B), however, shows that the felsite sill is not important.

Figure 6 B has the same major features as Figure 6 A, with high specific gravities in the lower half and high specific gravities in the upper half of the laccolith. This graph has not the perfect sigmoid shape of Figure 6A. The felsite s-ill no longer coincides with either the zone of pink patched rock or the lowest specific gravity on the graph. It may also be noted that much more potash feldspar would be expected in the micropegmatite if it were derived from the potash rich felsite sill. If the pink micropegmatite was derived from the felsite sill the average specific gravities of the traverses would be lower than the specific gravity of the original magma, but this is not so.

It is believed that the removal of pyroxene by crystals settling from the original diorite magma led to the crystallization of a progressively more leucocratic diorite in the rest of the laccolith. The solidification of most of the diorite left a silica rich residuum which crystallized as the micropegmatite. The residuum could apparently migrate through the diorite for it has become segregated in the pink patches and in many of the patches it has attacked and replaced the diorite which had already solidified.

The large amount of pink spotted diorite in the laccolith suggests that the volume of siliceous residuum must have been considerable. This indicates that the original diorite magma may have been slightly over-saturated. The fact that many of the minor basic intrusions associated with the Burtness laccolith are composed of quartz microdiorite supports this idea.

# IV. THE HYBRID ROCKS.

## 1. Introduction.

The Ennerdale Granophyre is not as uniform in character as its name may suggest, for large outcrops of relatively basic rocks occur in several parts of the intrusion. The most important of these outcrops are in Ennerdale on Bowness Knott, Crag Fell and Latterbarrow, in the Bleng Valley, and in Wasdale in the vicinity of Mecklin Wood.

These masses of basic rocks are believed to be the remnants of more extensive basic intrusions, or possibly of a single basic intrusion, which has been so extensively altered by metasomatism that no unaltered basic rocks now occur in the Ennerdale Granophyre stock. This alteration has changed the basic rocks into a series of mixed rocks which vary in composition from slightly acidified dolerites almost to granites. The name 'Hybrid' is used in this work to describe such a mixed rock, and does not necessarily imply an origin by magmatic mixing.

The composition of the rocks from which the hybrid rocks have been derived is uncertain. The least metasomatised hybrid rocks are ophitic dolerites from Mecklin Wood, which suggests that the basic rocks were originally doleritic in composition. There is good evidence, however, that most of the basic rocks were originally dioritic in composition (see pp.105-117 ).

## 2. Hybrid Rocks in Wasdale.

### A. Field Relationships.

#### (i) Mecklin Wood.

The major outcrop of the hybrid rocks in Wasdale occupies an area of approximately a quarter of a square mile in the extreme south-west corner of the Ennerdale Granophyre outcrop in the vicinity of Mecklin Wood. The hybrid rocks of this area overlie the Main Granophyre and separate it from the Borrowdale Volcanic Series. Originally this mass of hybrid rocks extended further to the north-north-east and was connected with small outcrops of hybrid rocks near Strands in Jessie Wood (G.R. 121041) and at Whitesyke (G.R. 121044). The Main Granophyre in the High Coppice area (GR. 120034), between the major hybrid outcrop and these minor ones is discoloured from the normal pink to a purplish colour. This discolouration is believed to have been caused by slight assimilation of the overlying basic rocks.

Prior to erosion the hybrid mass was a flat sheet, wedge shaped in plan, which narrowed from approximately two thirds of a mile wide near Mecklin Wood to nothing at Whitesyke. The top of this sheet, which is coincident with the roof of the granophyre stock, was flat lying, as can be seen from the structure contours of that surface (Map 2). The base of the hybrid mass must also have been fairly flat lying to have discoloured such a large area of granophyre near Great Coppice. The hybrid sheet dipped gently to the south-west resulting in the preservation

The large masses of hybrid rocks appear to be in the form of irregular flat lying lenses. Rastall (1906, pp. 255) has pointed out that their outcrops are associated with the edge of the granophyre. The original basic intrusions may have been sheet-like bodies intruded along a plane, now approximately represented by the roof of the granophyre stock. Marr (1900, pp. 475), was the first to note the presence of distinct masses of basic rocks associated with the Main Granophyre in the Ennerdale Granophyre stock. He suggested that the two rock types were derived by differentiation of one parental magma. Rastall (ibid.) gives a general description of the distribution and petrology of the basic rocks and attributes their peculiar petrology to hybridization between an early basic intrusion and the later Main Granophyre. Hollingworth and Dixon (in Eastwood et al 1931, pp. 47) described the outcrop of hybrid rocks on Crag Fell and mentioned the occurrence of acicular rocks on Latterbarrow to the east. Hollingworth (in Trotter et al, 1937, pp. 41-7) later described in some detail the mixed rocks along the western edge of the granophyre in the vicinity of the Bleng Valley. He believes that the mixed rocks have arisen from reaction between a fine grained dolerite and the Main Granophyre, but he is uncertain whether the reaction took place before or after the intrusion of the basic rocks.

of the south-west end of the sheet in the present outcrop around Mecklin Wood. The thickness of this sheet is uncertain but it probably did not exceed one or two hundred feet in most places. The thickness increased along the length of the sheet from zero near Whitesyke to a maximum at Mecklin Wood.

The main outcrop of hybrid rocks can be divided into three zones which are concentric about the south corner of the outcrop. The inner zone covers an area approximately 170 x 70 yards in size, which is occupied by apparently fresh, coarse ophitic dolerite. This dolerite is best exposed in a small knoll 50 yards south-east of Mecklin Beck and 25 yards south-west of the south-western edge of Mecklin Wood. Rastall (ibid., pp. 268) has described an extremely coarse gabbro from this outcrop which contains crystals of augite and feldspar up to half an inch in diameter and crystals of ilmenite up to one inch in diameter. The coarsest rock found during the present work contains crystals up to three millimetres in diameter.

The dolerite is surrounded by a series of variable rocks which occupy a curved outcrop approximately 200 yards wide, stretching from the south end of High Coppice to the base of Shepherd Crags. The most common rock type is a fine grained resinous basic rock, greenish-grey in colour and much finer grained than the dolerites of the inner zone. The resinous lustre of the rock is due to the presence of quartz. The femic minerals frequently occur in small acicular crystals about one millimetre long. This acicular habit, which is characteristic of the femic minerals elsewhere in the Ennerdale Granophyre, is particularly common in the High Coppice area. Pink feldspathic patches and veins containing feldspar crystals about two millimetres in diameter are quite common. The veins are irregular in shape and distribution and have diffuse edges. The feldspar crystals seem to have grown in situ and are believed to be porphyroblasts of metasomatic origin. The fine basic rocks occasionally grade into granitic rocks as the abundance of quartz and feldspar increases. This is seen at the foot of Latterbarrow (G.R. 122029) where a fine grey rock grades into a medium coarse biotite granite. The basic rocks in places become coarser and then resemble the dolerites of the inner zone.

The outer zone of the hybrid rocks is the most extensive zone, occupying an area about a quarter of a mile wide which extends from High Coppice eastwards to Latterbarrow. This zone is composed of uniform, fine to medium grained, dark greenish grey rocks similar to the fine basic rocks of the intermediate zone. In the field these rocks are seldom obviously affected by metasomatism. They have been metasomatized by large scale introduction of silica and potash which has produced fine grained homogeneous rocks of typical igneous appearance.

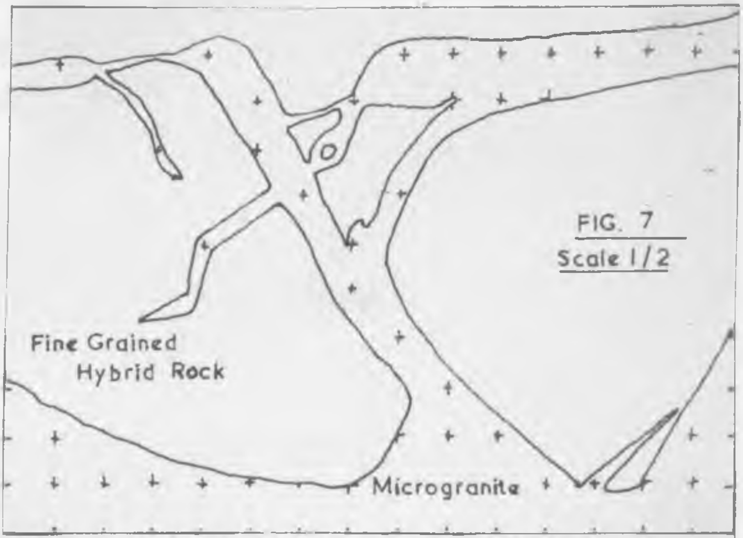
The small outcrops in the vicinity of Strands have been mentioned above. The largest of these outcrops, about 200 yards across, occur in Jessie Wood and near Whitesyke Farm. Several smaller outcrops occur between these two, and one isolated outcrop is found 600 yards north, 30 degrees east of Whitesyke. These minor masses consist largely of fine basic granites, but more basic variaties similar to the rocks of the intermediate zone in the Mecklin Wood outcrop do occur, principally in Jessie Wood.

The field relationships between the three zones in the Mecklin Wood outcrop are uncertain. The outer zone differs from the intermediate zone only in its more homogeneous character. The feldspathic veins and the feldspar porphyroblasts in the intermediate zone have probably been formed in a late, localized phase of the more widespread homogeneous metasomatism. The coarse dolerites of the inner zone differ from the rest of the rocks in the Mecklin Wood area in their coarse grain and relative freedom from metasomatism. Their relationship to the intermediate zone is unknown as the contact between the two zones is not seen. The dolerite mass may be a coarse grained core of the same intrusion as the fine hybrids, or it may be a separate intrusion (see also pp.113 ).

The contact between the hybrid rocks and the Borrowdale Volcanic Series is only exposed in a few places between Mecklin Beck and the base of Latterbarrow. In all cases the contact is a normal sharp intrusive contact. Four large roof pendants of volcanic rocks up to one hundred yards across occur in High Coppice and several masses of volcanic rocks enclosed in hybrid rocks, probably roof pendants, are also found at the foot of Latterbarrow (G.R. 124030).

The relationships between the Main Granophyre and the hybrid rocks are complex. The hybrids are extensively veined by acidic material derived from the Main Granophyre. These veins are clearly intrusive igneous veins (Fig. 7), usually composed of a medium coarse micro-granite. The granite is often rich in femic minerals, particularly biotite, derived from assimilation of hybrid rocks. This is well seen on a small roche moutonnée 270 yards east 10 degrees north of Burnt House (G.R. 12150314). The contact between the hybrid rocks and the Main Granophyre is usually sharp but may be gradational. Veining of the hybrids by the Main Granophyre becomes more intense as the contact is approached. Assimilation of the hybrid rocks by the granophyre is wide spread. Slight assimilation leads to a discolouration of the granophyre as seen in Great Coppice, but more extensive assimilation may lead to the formation of basified granites.

Large acidic intrusions in the hybrids are often composed of fine pink felsite, instead of granite as in the smaller veins. A felsite dyke about a foot thick trending south 20 degrees west, can be followed for 90 yards across the south end of High Coppice (G.R. 116028). A complex of intrusions below Latterbarrow (G.R. 124030) suggests that the felsitic intrusions are later than the Main Granophyre. The Borrowdale Vobanic Series have been intruded by a fine grained basic rock and the later intrusion of Main Granophyre has, in the main, followed the contact between the basic and the volcanic rocks. A later



Microgranite Veining Hybrid Rock. Burnt House.

felsitic intrusion has followed the contact between the Main Granophyre and the basic rocks.

### (ii) Minor Outcrops in Wasdale.

Several small outcrops of hybrid rocks occur in Wasdale, isolated from the main outcrop near Mecklin Wood. These minor outcrops all occur close to the roof of the granophyre, and appear to be connected in some way with that contact.

A line of four small outcrops of hybrid rocks enclosed in granophyre occurs approximately 20 feet below the contact with the Borrowdale Volcanic Series, on the south face of Buckbarrow. The largest of these (G.R. 13960594) is about 20 yards in diameter. The hybrid rocks are medium grained, purplish in colour, rich in quartz and ferromagnesian minerals, and resemble rocks found in the Mecklin Wood outcrop, They are veined by the enclosing granophyre which, in some cases, has broken the mass of hybrid rocks into angular xenoliths.

Hybrid rocks are also found at the east end of the Windsor Farm granophyre outcrop (G.R. 127058), where an area of slabs 50 yards across is exposed. The slabs are largely made up of normal pink granophyre which encloses irregular patches of a fine grey microgranite. The granophyre and the microgranite are both cut by very fine pink microgranite in irregular veins. A more basic rock occurs nearby (G. R. 12730580) in a small patch which has almost been broken into xenoliths by extensive granophyre veining. The basic rock is purplish pink, medium grained, and contains numerous acicular femic crystals.

It is unlikely that these masses of hybrid rocks have been derived from volcanic rocks, although they are associated with the contact with the Borrowdale Volcanic Series. There is no evidence anywhere along the contact of reaction between the granophyre and volcanic rocks. It is doubtful whether the granophyre could half digest a mass of volcanic lava twenty yards across and not affect lavas only twenty feet away. It is, therefore, considered that these hybrid rocks are similar to those of Mecklin Wood, in that they represent original basic rocks that have been acidified.

The Main Granophyre in an irregular area between Woodhow (G.R. 140042) and Ashness How (G.R. 136045) has been discoloured from pink to purple. This discolouration is believed to have been caused by the volcanic rocks above and not by the absorption of hybrid rocks, as in the case of the High Coppice area. The nearest hybrid rocks are at Whitesyke, a mile to the west, while volcanic lavas are exposed just behind Woodhow. This discolouration may be due to slight absorption of lavas or some other contact effect.

## B. Petrography.

The rocks from the inner zone of the Mecklin Wood outcrop appear to be normal coarse ophitic dolerites in hand specimens. One specimen (E 8743) from close to the boundary wall of Mecklin Wood 50 yards south of Mecklin Beck contains irregular patch-veins of coarse grained white feldspar and quartz which look like pegmatitic segregations.

The ophitic texture of the dolerites with euhedral white feldspar prisms up to 3.5 x 1.5 mm. in size intergrown with mafic minerals, is well seen in polished specimens. Staining with sodium cobaltinitrite has shown that the dolerites contain variable amounts of potash. A specimen (E 8742) from the centre of the dolerite mass (G.R. 11830253) contains a little potash irregularly distributed through the specimen, occurring as small patches on the edges of feldspar crystals, or more rarely in their cores. Potash is more abundant in E 8743, but is most abundant in specimen E8740, taken from about ten feet away from E8742. Almost every feldspar crystal contains abundant potash but the distribution of this potash is not uniform through each crystal. Most crystals have a rim of pure plagioclase with a potash rich core, a few have a potash rich rim and some have concentric zones of potash rich and potash poor feldspar.

Under the microscope the dolerites are altered, but their ophitic texture is generally well preserved (Photo. 8). The plagioclase feldspars are extensively altered to sericite, epidote and chlorite, but their rims are often recrystallized to a clear feldspar, free of alteration products. This has led to euhedral crystals of plagioclase with a thin rim of clear feldspar and a completely altered core. With more intense alteration the feldspar prisms tend to lose their euhedral outlines and fuse into each other as sericitic masses. By comparison with the stained specimens the crystals with sericitized cores and clear rims may be equated with the crystals in E8740 with plagioclase rims and potash rich cores. This would lead to supposition that the sericite is the source of the potash, but this cannot be true, for the most sericitized feldspars occur in E8742 which contains least potash. The potash must occur in the altered feldspar in which the sericite is set. The composition of the original plagioclase is difficult to determine because of its alteration. The maximum extinction angle of one specimen suggests a composition of $An_{51}$ but the true composition may be more calcic than this.

Photo. 8. Ophitic Gabbro. Mecklin Wood.

The original ferromagnesian mineral of the dolerites was augite which occurred in crystals up to 3 mm. in diameter in ophitic relationship with the plagioclase prisms. The augite has been largely altered to amphibole but is still reasonably fresh in specimen E 8740. The alteration to amphibole begins along the cleavage planes and edges of the pyroxene crystals and progresses with the development of amphibole in a seive texture in the body of the pyroxene. The amphibole finally pseudomorphs the pyroxene, often with crystallographic continuity.

There are two types of amphibole present, which have been tentively identified as hornblende and tremolite. The hornblende occurs in large crystals replacing the augite crystal for crystal while the tremolite occurs in masses of fibres about 0.2 mm. long. The tremolite is colourless with interference colours up to middle second order and resembles sericite, when en masse. The hornblende is pleochroic from pale yellowish green to deep blue-green, has lower birefringence and slightly higher relief than the tremolite, but has a similar extinction angle $c \wedge z$, of approximately 20 degrees.

The amphibole is occasionally altered to reddish brown biotite, particularly when in association with iron ore. Alteration of amphibole to chlorite is very common. The chlorite is usually green penninite with bright blue anomalous interference colours, but is occasionally almost colourless with grey interference colours. A pale green isotropic interstitial mineral is quite common in E 8740. This mineral is finely fibrous and may be a serpentine.

The perfection of the preservation of the ophitic texture of the dolerite is reduced as the specimens become more altered. The pyroxene is entirely altered to amphibole and the amphibole crystals shown signs of regrowth, often penetrating the feldspar prisms.

Iron ore occurs in very fresh skeletal crystals about one millimetre in diameter which are often covered by a thin skin of sphene. Sphene is characteristically associated with the iron ore, but also occurs separately in crystals about 0.1 mm. in diameter associated with sericite in altered feldspar. Zircons, in square crystals about 0.05 mm. in diameter, occur in the centres of pleochroic halos in amphiboles and chlorite in Specimen E8743.

Quartz occurs in Specimen E 8743 in irregular poikilitic crystals over 1.5 mm. in diameter, in interstitial crystals between subhedral feldspar prisms and in micrographic intergrowth with the feldspars. It appears to be replacing the original interstitial minerals.

Modal analyses of three dolerites are given below:-

| Specimen | E 8740 | E8742 | E 8743 |
|---|---|---|---|
| QUARTZ | | | 4 |
| POTASH FELDSPAR | 20 | 3 | 52 |
| PLAGIOCLASE | 42 | 47 | |
| FERROMAGNESIAN MINERALS | 33 | 45 | 42 |
| IRON ORE | 5 | 5 | 2 |

These analyses take no account of sericite and epidote which are assumed to be alteration products of the feldspars and are included with the feldspars. Sphene is included with the iron ore. The percentage of potash feldspar has been calculated from point counts of stained polished rock slabs and probably includes much microperthite.

The rocks of the intermediate zone of the Mecklin Wood outcrop are variable in character. A specimen (E 8739) from a crag on the wall at the south-east end of High Coppice (G.R.

11690275) is a medium grained, equigranular rock of greenish-grey colour in which occur occasional vein-like lenses, up to 3 x 1 centimetres in size, of quartz and feldspar. The main rock is composed of pale green feldspar prisms about one millimetre long, and dark green femic crystals. Potash feldspar is common in the feldspar prisms in the rock, in overgrowths on euhedral plagioclase prisms up to 2 x 1 mm. in size in the lenses, and as an interstitial mineral.

A medium coarse, very dark green rock containing a patchy development of abundant bright pink feldspar and quartz (specimen E 8738) is exposed on a roche moutonnée approximately thirty yards above the Santon Bridge road (G.R. 11820280). The base rock contains numerous euhedral plagioclase prisms 1.5 mm. long with interstitial femic minerals. The pink feldspar occurs in crystals up to three millimetres in diameter associated with quartz in patches up to six millimetres in diameter. Potash feldspar is very common in interstitial micropegmatite, and as a delicate spotted growth in the pink feldspars, but is less common in the normal rock, where it occurs as an interstitial mineral.

In thin section the two specimens just described are very similar in appearance. The plagioclase prisms are badly altered to sericite and epidote and little of their albite twinning is preserved. The maximum extinction angle of the plagioclase is 19 degrees, and its refractive index is less than that of quartz, suggesting that its composition is albite $An_1$. It is believed, however, that the refractive index of the plagioclase crystals may have been reduced by introduction of potash round their margins, and is anomolous. Their original composition was probably andesine $An_{37}$.

The plagioclase in the lenses in E8739 has probably been formed at two different periods. Most of the plagioclase crystals are residuals from the original rock and are now decayed, overgrown with microperthite and set in a matrix of quartz and microperthite. There are a few crystals, however, which are relatively fresh and grow up to 2 x 1 mm. in size, compared with a maximum of 1.2 x 0.3 mm. in the ordinary rock. These crystals vary in composition from albite $An_9$ to andesine $An_{37}$.

The plagioclase laths are most often surrounded by perthitic overgrowths which, in many cases, have replaced much of the plagioclase. Microperthite also occurs in subhedral crystals up to three millimetres in diameter in specimen E 8738. These crystals are the prominent pink feldspars of the hand specimen. They have grown as porphyroblasts in association with quartz, which occurs in micrographic intergrowth with the perthite around the edges of the crystals. The microperthite is replacing the original rock in places. Similar crystals of microperthite occur in specimen E8739 in the quartz-feldspar lenses. These microperthite crystals orobably began as overgrowths on plagioclase prisms, for remnants of plagioclase are preserved in some of their cores.

Quartz is abundant as an interstitial mineral in poikiloblastic crystals up to two millimetres in diameter. It also occurs in interstitial micropegmatite and in coarse micrographic intergrowth with perthite. The quartz is clearly a later mineral for it veins and replaces later minerals.

Amphibole is abundant in ragged crystals about 0.5 mm. in diameter on the average. The crystals are commonly elongated, reaching 4.6 x 0.4 mm. in size. The amphibole is pleochroic from medium to very pale green and is probably hornblende, although some tremolite actinolite may be present. Penninite replacing the amphibole is very common.

Ilmenite is abundant in skeletal grains and rods up to 0.5 x 0.1 mm. in size which are closely associated with, and being replaced by, yellow sphene. Less skeletal grains of iron ore approximately 0.3 mm. in diameter which are not associated with sp-hene may be magnetite.

Accessory minerals include sphene, zircon and apatite. Sphene is abundant, usually associated with iron ore, but also occurring in skeletal crystals about 0.4 mm. in diameter replacing interstitial amphibole. Zircon occurs in E8738 in stubby prisms up to 0.4 x 0.3 mm. in size and is common in E 8739 in prisms, commonly perfectly euhedral, about 0.2 x 0.1 mm. in size.

The rocks of the outer zone of the Mecklin Wood outcrop are uniform in appearance. They are fine to medium grained, greenish-grey rocks composed of feldspar laths about one millimetre long, set in a dark green matrix. A specimen (E 8741) from near Burnt

House (G.R. 11980291) contains numerous pink spots about two millimetres in diameter in which the feldspars have turned pink. Potash has an irregular distribution in this specimen, but is largely concentrated on these pink spots. The potash first appears as flecks in the plagioclase laths and then progressively blocks out the plagioclase to leave a patch in which the quartz and femic minerals are suspended in a potash rich base. Specimen E 8744, also from near Burnt House (G.R. 12150321), is particularly rich in potash, which occurs replacing plagioclase laths, in overgrowths on the laths and as an interstitial mineral.

Under the microscope the rocks appear badly altered, with the plagioclse altered to sericite and epidote, and very little original albite twinning left. The plagioclase has a similar composition, andesine $An_{36}$, to that of the intermediate zone. The potash rich pink spots in specimen E 8741 are poikiloblastic perthitic feldspar anhedra up to two millimetres in diameter. Perthite is also common in the rock as anhedral crystals about one millimetre in diameter, and as overgrowths on the plagioclase laths.

Quartz is abundant in interstitial crystals and in poikiloblastic crystals up to two millimetres in diameter. It is evidently younger than the perthite for it occurs interstitially between perthite crystals.

Acicular hornblende, possibly including a little tremolite-actinolite, is the most abundant ferromagnesian mineral in specimen E 8741. It occurs in crystals up to 0.4 x 0.1 mm. in size, which are pleochroic from green to greenish yellow. The hornblende is commonly altered to penninite. Brown biotite is rare in E 8741, but is more abundant than hornblende in E 8744 where it occurs in flakes up to one millimetre in diameter.

The iron ore and accessory minerals are similar to those described in rocks from the intermediate zone.

Modal analyses of specimens from the outer zone are given below.

| Specimen | E 8741 | E 8744 |
|---|---|---|
| QUARTZ | 15 | 16 |
| POTASH FELDSPAR | 15 | 23 |
| PLAGIOCLASE | 52 | 38 |
| FERROMAGNESIAN MINERALS | 14 | 20 |
| IRON ORE + ACCESSORY MINERALS | 4 | 3 |

The potash feldspar in these analyses has been calculated from stained polished rock slabs and includes much microperthite.

## 3. Hybrid Rocks in the Bleng Valley.

### A. Field Relationships.

The largest outcrop of hybrid rocks in the granophyre occupies most of the upper Bleng Valley. The outcrop, which covers an area of approximately two square miles, has been divided into three parts by later acidic intrusions. The main outcrop occupies the bottom of the valley, extending in a belt about a mile wide from Stockdale Head to within 150 yards of the western edge of the Ennerdale Granophyre. A small outcrop of hybrid rocks on Stockdale Moor has been described by Hollingworth (Trotter et al, 1937, pp. 44). A thick sill of Main Granophyre at the head of the valley separates a second minor outcrop of hybrid rocks on Brown Band, on the south-west side of Haycock, from the hybrids in the bottom of the valley.

The hybrid rocks on Stockdale Moor occupy a rectangular outcrop about 750 x 400 yards in size, which is elongated in a north-easterly direction. This outcrop is surrounded on three sides by fine pink or grey microgranite and felsite, and is in contact with andesites of the Borrowdale Volcanic Series along its south-west edge. The contact between the hybrid and volcanic rocks is hidden under thick drift. The hybrid rocks are extensively veined by the surrounding microgranite. The microgranite veins have sharp edges and an intrusive appearance. The hybrid rocks in places are also net-veined by acidic veins which have diffuse edges and contain numerous pink feldspar phenocrysts about two millimetres in diameter. These veins appear to have been formed by granitic material diffusing along the veins, and not by igneous intrusion of a granitic magma. The contact between the hybrid rocks and the microgranite is sharp where it is exposed on a small crag at the south-east end of the hybrid mass (G.R. 109085). The hybrid rocks of this outcrop are very variable and include fine basic microgranites, fine and coarse basic rocks rich in acicular femic crystals and the net veined types described above.

The outcrop of hybrid rocks on Brown Band is triangular in shape with the Haycock fault forming the northern edge. Along the western edge of the triangle the hybrid rocks are in contact with andesites but the contact is not exposed. To the west the hybrid rocks overlie the Main Granophyre. The rocks are mainly fine basic microgranites, greenish-grey in colour, containing abundant acicular femic crystals. They are extensively veined by pink granitic veins from the Main Granophyre.

The hybrid rocks of the main outcrop are in contact with andesites of the Borrowdale Volcanic Series for almost a mile along the north-west side of Seatallan at about 1600 feet, but the contact is not exposed. The relationships between the hybrid rocks and the Main Granophyre are complex, for the hybrids have been intruded by the Main Granophyre on a large scale. It is believed that before the intrusion of the Main Granophyre, the hybrid rocks were in contact with the Borrowdale Volcanic Series from Haycock to Stockdale Moor, and as far south as Windsor Farm. A wedge of granophyre has been forced along this contact from the south and now separates the hybrid and volcanic rocks along the south edge of the main hybrid mass. The Main Granophyre is exposed between the hybrid and volcanic rocks in a belt about 150 yards wide extending from the River Bleng southeastwards for half a mile to Hollow Moor, where it swings eastwards and widens out into an outcrop about 750 yards wide and a mile long. This outcrop forms the southern tip of the largest outcrop of the Ennerdale Granophyre. A north-north-easterly dyke 150 yards wide, of fine pink granophyre, extends from this mass through Yokerill Hows as far as the Bleng, almost cutting the outcrop of hybrid rocks in two. Hollingworth, (ibid. p. 45) has compared the marginal belt of granophyre to the ring dykes resulting from cauldron subsidence.

In the north the hybrid rocks probably pass under the main mass of the Main Granophyre which forms Cawfell. The contact between the two rock types runs west-south-westwards from Stockdale Head, beneath Red Crag to Hause, where the Main Granophyre is in contact with an intrusion of fine porphyritic microgranite. A xenolith, approximately twenty feet across, of relatively fresh feldspar-phyric amygdaloidal dolerite occurs in granophyre at 1500 feet O.D. in the east bank of Red Beck. This mass is bounded to the south by a small fault.

The Main Granophyre extends southwards from the Cawfell area in a thick horizontal wedge across the Bleng Valley. The outcrop of this wedge can be followed from Red Crag on the north, around the head of the valley, to Rossy Gill. The granophyre forms the steep wall-like end of the Bleng Valley, and separates the hybrids on Brown Band from their main outcrop in the bottom of the valley. South of Rossy Gill the granophyre thins, and splits into several sills, dykes and irregular shaped intrusions which finally die out near the mouth of Ill Gill.

Over the western half of the northern edge of the hybrid mass the hybrid rocks are in contact with a fine pink porphyritic microgranite which is younger than the Main Granophyre. Similar microgranite occurs between the hybrids and the Main

Granophyre for a few hundred yards on either side of Red Beck.

The rocks of the hybrid outcrop are very varied in character, but a few generalizations on the distribution of rock types can be made. In the area south-east of Raven Crag, between Ill Gill and Swinsty Beck, the rocks are chiefly coarse, purplish-green hybrid rocks, rich in acicular femic crystals which vary in length from about two millimetres to one centimetre. These coarse hybrids often enclose rounded xenoliths of a fine, more basic, rock. The contact between the xenoliths and the coarse hybrid rock may be sharp, but is often diffuse showing that the xenoliths are being acidified and digested

The coarse hybrids grade out into finer grained rocks which occupy the floor of the valley east of the northerly granophyre dyke through Yokerill Hows. These rocks are fine to medium grained and vary from quite basic rocks resembling dolerites, to basic granites. They are generally purplish or greenish-grey in colour and are characterized by the common occurrence of femic minerals in acicular crystals. The hybrid rocks tend to be more acidic or felsic in appearance in the north around Red Beck.

West of the Yokerill Hows dyke the hybrid rocks are fine grained acidified basic rocks, purplish green in colour, which are characterized by the presence of pink feldspar phenocrysts about two millimetres in diameter. These phenocrysts commonly occur in a type of metasomatic patch-veining similar to that described above from Stockdale Moor.

Small scale granitic, igneous veining of the hybrid rocks is extremely common. Intrusions of fine pink granophyre and felsite several feet across, are less common and cannot be traced for more than a few yards. A pinkish-green felsite dyke five feet in diameter, striking east-west, crops out in Swinsty Beck 300 yards below the footpath. Sixty yards upstream from this dyke the hybrid rock is broken into an intrusion breccia by fine pink granophyre. A curious injection 'conglomerate' occurs in an irregular granophyre dyke on the south side of Raven Crag (G.R. 12760842). Rounded xenoliths up to more than 50 centimetres in diameter, of a fine basic hybrid rock are suspended in fine pink granophyre (Photo. 9.)

Photo.9. Intrusion 'Conglomerate' Raven Crag.

The roundness of the xenoliths cannot easily be explained for there is not enough granophyre present to have digested the corners off the xenoliths in situ. They may have sunk into their present position after being rounded by digestion above, or they may have been rounded by digestion or attrition during the intrusion of the granophyre from below. Many other irregular vertical veins and dykes of fine pink granophyre occur on a crag 150 yards south-west of Raven Crag.

## B. Petrography.

The least altered basic rock (specimen E 9619) in the Bleng Valley occurs in the east bank of Red Beck at 1500 feet O.D. It is a medium grained dark green doleritic rock which contains numerous feldspar phenocrysts reaching sizes of 5 x 4 and 8 x 2.5 millimetres. Amygdules up to five millimetres in diameter, filled with calcite and chlorite are common. Skeletal crystals of pyrite up to three millimetres in diameter are present. Potash is very common in the feldspars, particularly in the phenocrysts, which appear to have a perthitic texture.

Under the microscope the rock is seen to be extensively replaced by calcite. Plagioclase is common in large euhedral phenocrysts but normally occurs in prismatic crystals approximately 2.5 mm. in length. The plagioclase, andesine $An_{36}$ in composition, is extensively replaced by calcite, and to a lesser extent by chlorite and sericite. Penninite, which occurs as an interstitial mineral and in amygdules, is the only ferromagnesian mineral present, except possibly for a little serpentine. Iron ore is abundant with ilmenite, partially altered to leucoxene, and magnetite in irregular grains and octahedra up to 0.2 mm. in diameter. Apatite is a rare accessory mineral.

Calcite occurs in amygdules and as a replacement mineral throughout the rock.

The hybrid rocks in the bottom of the Bleng Valley are generally medium grained non-porphyritic rocks. Specimen E8762 from near the mouth of Ill Gill (G.R. 12750983), is a medium grained greenish-grey rock composed of white feldspar prisms about one millimetre long, and interstitial femic crystals. The femic minerals commonly occur in acicular crystals. The feldspar crystals are rich in potash feldspar.

In thin section, the feldspars are badly altered to sericite and epidote. Plagioclase, probably andesine $An_{37}$ in composition, occurs in ragged laths up to one millimetre long in which the albite twinning is almost destroyed. Perthite in anhedral interstitial crystals up to 0.6 mm. in diameter, is very common and quartz is abundant in interstitial crystals up to 0.4 mm. in diameter. Penninite occurs as an interstitial mineral and in pseudomorphs after crystals, which were, in places, acicular. Iron ore is abundant in grains 0.05 mm. in diameter. Accessory minerals include abundant epidote, less common sphene and rare zircon and apatite.

The rocks are coarser, and in general more acidic in appearance, in the area on Seatallan between Ill Gill and Swinsty Beck. A specimen (E 8761) from the junction of the two tributaries of Ill Gill is a coarse purplish-green rock with a pink feldspathic base in which are set numerous white plagioclase prisms about 2 x 1 mm. in size, and acicular femic crystals up to 3 x 0.5 mm. in size. Potash is abundant in the matrix but is not common in the plagioclase crystals.

Specimen E 8761 is coarser grained than E 8762, but in thin section they are very similar in mineralogy and texture. The femic crystals in specimen E 8761 are more conspicuously acicular than those in E 8762, and the interstitial matrix in E 8761, unlike that in E 8762, is largely made up of a micropegmatite of quartz and perthitic feldspar.

The coarse acicular hybrids vary from rather basic types such as E 8761 to more granitic types such as specimen E 8763 from the head of Ill Gill (G.R. 13010864). The pink feldspathic base, which is rich in potash, is more abundant in E 8763 and the general colour of the rock is pink rather than purple. Under the microscope the abundance of perthitic feldspar is very noticeable. Many of the original andesine prisms have been perthitized and most are surrounded by perthitic overgrowths. Perthite, possibly incorporating perthitized plagioclase crystals occurs in crystals up to 3 x 1.5 mm. in size. It also occurs in interstitial micropegmatite with quartz. Iron ore, usually encrusted in sphene, occurs in skeletal acicular crystals up to 1.8 mm. long.

Modal analyses of two coarse acicular hybrid rocks are given below:

| Specimen | E 8761 | E 8763 |
|---|---|---|
| QUARTZ | 12 | 12 |
| POTASH FELDSPAR | 8 | 18 |
| PLAGIOCLASE | 51 | 46 |

| Specimen (cont'd.) | E 8761 | E 8763 |
|---|---|---|
| FERROMAGNESIAN MINERALS | 16 | 15 |
| IRON ORE | 4 | 3 |
| EPIDOTE | 8 | 4 |
| REST | 1 | 1 |

The potash feldspar has been determined by point counts of stained specimens. The epidote is largely contained in the feldspars, and may be added to the feldspar to get a truer value of the total feldspar percentage.

The western part of the major hybrid outcrop is characterized by the development in the rock of bright pink feldspar porphyroblasts about two millimetres in diameter, for example, in E 8678 from Brown Edge (G.R. 11520739). The base rock in which the porphyroblasts grow, is a fine grained purple rock with a matrix composed of pink feldspar laths about one millimetre long, commonly set in radiating groups three to four millimetres in diameter, with interstitial quartz and ferromagnesian minerals. White euhedral plagioclase crystals up to 2 x 0.5 mm. in size and femic crystals up to one millimetre in diameter occur but are not common. The feldspar porphyroblasts commonly occur in a type of net veining in which the veins have no sharp margins. Potash is abundant but does not occur in the porphyroblasts.

The radiating plagioclase prisms of the base rock are very decayed. They contain much epidote, sericite and brown dust and retain very little twinning. Plagioclase also occurs as anhedral crystals up to 0.5 mm. in diameter, many of which look perthitic. Quartz is abundant between the radiating feldspar prisms, and in equigranular relationship with the anhedral feldspar. Hornblende, pleochroic from green to greenish-yellow makes up about five percent of the rock. It usually occurs in fresh euhedral crystals up to 0.4 mm. in diameter but some of the crystals are interstitial to the feldspars. Primary brown biotite is rare, but penninite, after hornblende, is common. Iron ore is abundant in grains up to 0.4 mm., but averaging 0.05 mm. in diameter. Accessory minerals include epidote, zircon, apatite and sphene.

The feldspar porphyroblasts occur in glomeroporphyritic groups. The cores of the porphyroblasts are generally composed of glass-clear plagioclase but the rims are usually full of pink dust, sericite and epidote. The refractive index of this plagioclase is slightly higher than that of balsam, suggesting that its composition is oligoclase, but its 2V, which ranges from 72 degrees positive to approximately 90 degrees, shows that albite is also present.

Specimen E 8754 from Stockdale Moor (G.R. 10890858) is similar to E 8678 in hand specimen and under the microscope, but the acidic veins in the former specimen are more igneous in appearance. The veins reach several centimetres in width and are composed of a pink porphyritic microgranite. The edges of the veins are sharp in some places but gradational in others. The microgranite contains numerous bright pink plagioclase phenocrysts, identical with the feldspar porphyroblasts in E8678, and this suggests that the veins in the two specimens may have a similar origin. The veins in E 8754 may be of igneous origin, but they could represent an advanced stage in metasomatic veining in which some rheomorphic movement has taken place.

## 4. Hybrid Rocks in Ennerdale.

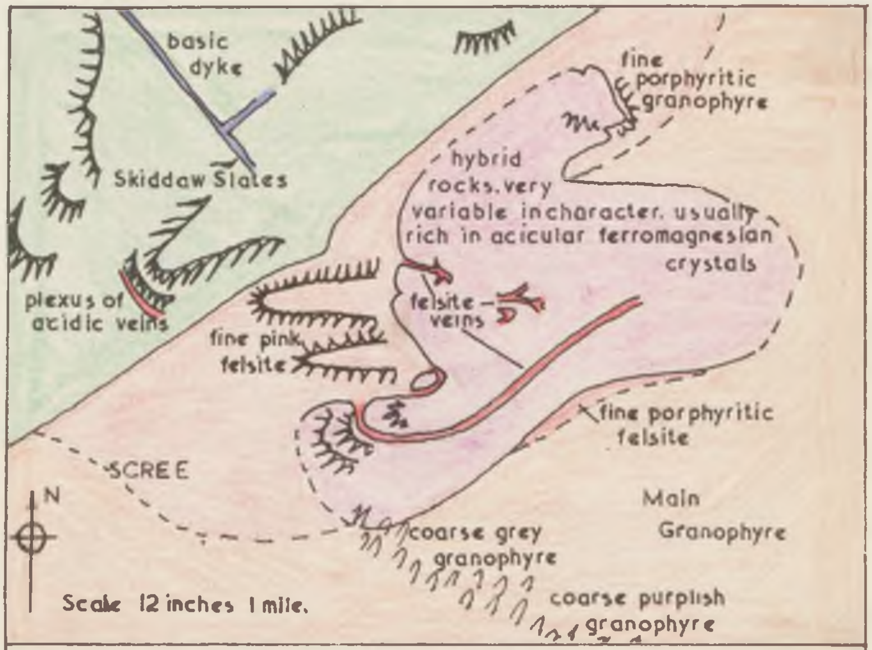
### A. Field Relationships.

Extensive outcrops of hybrid rocks occur in Ennerdale on Crag Fell, Latterbarrow and Bowness Knott. The hybrid rocks on Crag Fell occur in a horizontal sheet about half a mile long, which crops out between 900 and 1250 feet O.D. on the north face of Crag Fell. This sheet is 350 feet thick at its north end (G.R. 101145) and thins south-westwards, ending at the head of Red Beck. Further outcrops of hybrid rocks are found at the same altitude near Boathow, approximately 600 yards south-east of Red Beck. Two small outcrops also occur at 100 feet O.D. in Silver Cove Beck one and a half miles south east of Boathow.

The outcrops of the hybrid rocks in the neighbourhood of Latterbarrow are largely obscured by the dense coniferous Latterbarrow Plantation. On Latterbarrow itself, hybrid rocks occur in an almost horizontal sheet about 150 feet thick. The outcrop of this sheet curves round the western end of Latterbarrow at about 800 feet and then continues eastwards along the south face of Latterbarrow, almost as far as Low Gillerthwaite. A second narrow outcrop of hybrid rocks, 600 to 800 yards long, which may be part of the Latterbarrow sheet that has been displaced by the Red Gill fault, occurs above Gillerthwaite between 600 and 800 feet O.D. Hybrid rocks also outcrop due north of High Gillerthwaite at 900 feet O.D. (G.R. 143 148). A lensiform mass of hybrid rocks about 150 feet thick crops out some 750 yards north of Latterbarrow at 900 feet O.D. This outcrop is over 1200 yards long and stretches from the Bowness Plantation to the Latterbarrow Plantation. Prior to erosion it was probably continuous across Smithy Beck with the Latterbarrow outcrop.

The Crag Fell and Boathow masses consist of hybrid rocks similar to the coarse hybrids in the Bleng Valley. They are coarse grained, purplish-green rocks, containing numerous acicular crystals of femic minerals set in a pink matrix. These rocks do vary in character, but in general they are more homogenous than the coarse hybrid rocks in the Bleng Valley. The hybrid rocks in Silver Cove Beck are finer grained than those from Crag Fell. Those from the Latterbarrow area are similar to the Crag Fell hybrids but are commonly more leucocratic.

The most basic rocks in Ennerdale occur in an irregular shaped outcrop about 350 yards across on the south-east side of Bowness Knot (Fig. 8). The rock types present include fine grained, greenish-grey rocks, similar to those from the outer zone of the Mecklin Wood outcrop, medium coarse, purplish-green doleritic rocks which still retain an ophitic texture although their matrices have turned pink, and more acidic coarse grained types similar to those from Crag Fell.



The Bowness Knott Hybrid Mass FIG 8

The hybrid rocks in Ennerdale are surrounded by later granitic rocks, therefore, their original relationships to the Skiddaw Slates and Borrowdale Volcanic Series is unknown. The hybrid masses of Crag Fell and Bowness Knott, however, were most likely to contact with the Skiddaw Slates originally. The hybrid rocks on Crag Fell are now separated from the Skiddaw Slates by some 60 yards of coarse pink granophyre, and those on Bowness Knott are separated from the Skiddaw Slates by 20 yards of fine pink porphyritic granophyre.

All the outcrops of hybrid rocks in Ennerdale, except that on Bowness Knott, are surrounded by the Main Granophyre. The basic rocks are commonly veined by the granophyre, particularly near their margin. The contact between the hybrid rocks and the granophyre is usually quite sharp but may be gradational in places where the hybrid rock is being absorbed by the granophyre.

The hybrid rocks on Bowness Knott are in contact with the Main Granophyre along the north-eastern and southern margins of their outcrop. This contact may, in parts, be gradational, for the hybrid rocks become coarser and more leucocratic towards the contact and the adjacent granophyre is discoloured to a purple colour. This discolouration continues for over half a mile to the east, almost to Smithy Beck, and it is uncertain whether it is all due to the influence of the hybrid rocks. A later intrusion of fine porphyritic granophyre, felsitic in places, now separates the Main Granophyre and the hybrid mass over much of the contact.

The later granophyre is well exposed in the Bowness Knott cliffs (G.R. 112154) between the Skiddaw Slates and the hybrid rocks. Sheets of fine granophyre and felsite up to three feet thick commonly intrude the hybrid rocks, their emplacement in places being controlled by joints in the hybrid rocks. The age relationships between the three main rock types are shown on a specimen from Bowness Knott (G. R. 11341530), in which a vein of coarse granophyre intruding a hybrid rock is itself cut by a fine granophyre vein.

Hollingworth and Dixon have put forward the theory, that before the intrusion of the Main Granophyre the present outcrop of hybrid rocks in Ennerdale were continuous. This theory is supported by the fact that the hybrid masses, except Bowness Knott, are flat lying sheets and all the outcrops occur at roughly the same altitude. If the theory is correct, then the original hybrid body was a sheet over a mile wide and two miles long. It probably varied in thickness from 400 feet on Bowness Knott, 300 feet on Crag Fell to 150 feet on Latterbarrow.

An isolated exposure occurs on Red Pike (G.R. 157148) of a medium grained hybrid rock very similar in appearance and position to the hybrid rocks on Buckbarrow in Wasdale. This hybrid mass is about 90 yards long, 30 feet thick, and lies 20 to 30 feet below the andesite lavas of the Knorrs, from which it is separated by normal pink granophyre. The origin of this mass is unknown.

## B. Petrography.

The coarse hybrid rocks on Crag Fell, Boathow and Latterbarrow are very similar in hand specimen to those from Seatallan. A specimen (E 8686) from Crag Fell (G. R.10251438) is almost identical in thin section with E 8761 from Ill Gill The acicular femic crystals in E 8686 are almost all altered to penninite but remnants of original hornblende are preserved in a few crystals.

The hybrid rocks of Bowness Knott are more variable in character than those from Crag Fell. Specimen E 8679 (G.R. 11401552) is a fairly fresh looking doleritic rock composed of abundant euhedral white plagioclase prisms up to 1.5 mm. long, interstitial femic minerals and a patchy pink felsitic base. The felsitic base contains a little potash but the rock as a whole contains much less potash than the coarse hybrids of Seatallan. Specimens E 8680 and E 8681 are similar to, but look more altered than E 8679, for the plagioclase prisms have lost their euhedral outlines. There is no potash in E8680 and very little in E8681. A medium grained acicular hybrid similar to E8686 from Crag Fell, except for the fact that it contains no potash, occurs in E8685. This basic rock is in contact with a fine pink granophyre and some potash has diffused up to one centimetre into the hybrid from the granophyre.

Under the microscope the plagioclase prisms of these rocks are extensively altered to sericite and epidote, and retain little of their albite twinning. In specimen E8679 recrystallization of the edges of many of the prisms has produced clear rims (Photo. 10) which are commonly zoned, the plagioclase varying from calcic andesine $An_{46}$ in the core to oligoclase at the edges. Perthite is not common, but occurs in specimen E 8685 as overgrowths on the plagioclase prisms in the area that has been enriched in potash. The ferromagnesian crystals in E8679 are largely composed of fresh amphibole. There may be two amphiboles, hornblende in large twinned crystals which are pleochroic greenish-yellow to green, and tremolite-actinolite in small fibrous crystals with a similar pleochroism but a smaller extinction angle. The amphibole is changing to penninite, and in other specimens the change is practically complete, although remnants of hornblende are preserved in E 8680. Quartz is present in all the hybrid rocks as interstitial mineral, but micropegmatite, which is very common in the Seatallan hybrids has been found on Bowness Knott only in E8679, and then only in small amounts. The iron ore and accessory minerals are similar to those of the Seatallan hybrid rocks. Pistacite, pleochroic from very pale yellow to lemon is abundant in E 8681 in prismatic crystals up to 1.5 x 1 mm. in size.

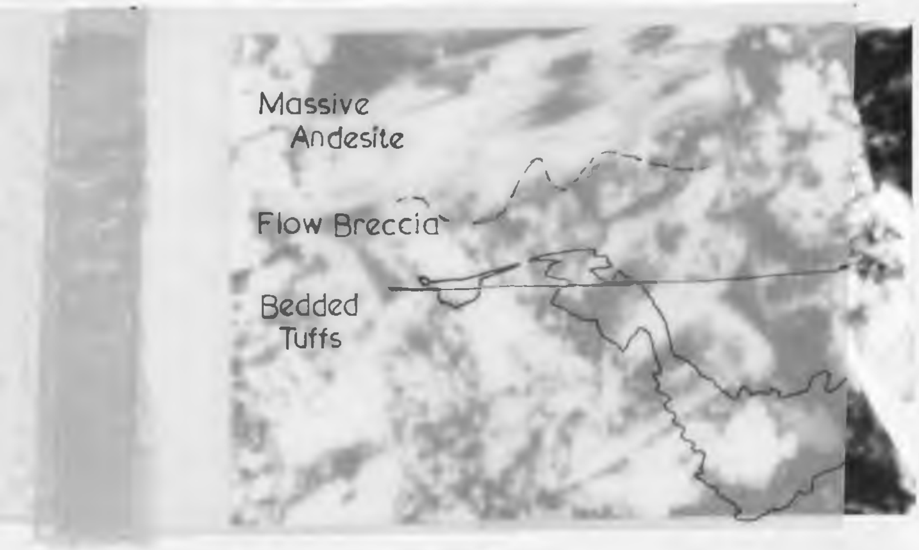


Photo. 10. Hybrid Rock. Bowness Knott.

Fine grained hybrid rocks are common on Bowness Knott. Specimen E 8683 (G.R. 11401555) is a very fine basic rock veined by a porphyritic granophyre. The basic rock is composed of feldspar prisms about 0.2 mm. long, and interstitial femic minerals. The granophyre is largely composed of plagioclase phenocrysts about two millimetres in diameter with a little potash-rich granophyric matrix. The contact between the granophyre and hybrid rock is sharp, but in the hybrid rock, and apparently associated with its contact with the granophyre, are plagioclase crystals identical with the phenocrysts in the granophyre. These crystals are probably plagioclase porphyroblasts of metasomatic origin. Specimen E 8684 is a fine hybrid rock veined by a fine pink granophyre. The hybrid rock is composed of feldspar prisms about one millimetre in length, and interstitial femic crystals. Potash is evenly distributed throughout the hybrid rock, chiefly in the feldspar crystals. The junction between the hybrid and the granophyre is macroscopically sharp but microscopically diffuse.

Apart from the difference in their grain sizes, specimens E 8683 and E 8684 are very similar in thin section. The feldspar prisms, probably andesine $An_{36}$ in composition are very badly altered. The plagioclase porphyroblasts in E 8683 are identical with the phenocrysts in the granophyre which have a composition of approximately $An_{35}$. Quartz is very common as interstitial crystals but there is no micropegmatite. Penninite is abundant but very small remnants of original hornblende are preserved in E 8684. Epidote is abundant in both specimens.

Modal analyses of specimens from Ennerdale are given below:-

| Locality | Bowness Knott | | Crag Fell. |
|---|---|---|---|
| Specimen | E8679 | E8680 | E8686 |
| QUARTZ | 4 | 11 | 13 |
| POTASH FELDSPAR | 7 | 0 | 12 |
| PLAGIOCLASE | 64 | 59 | 51 |
| FERROMAGNESIAN MINERALS | 23 | 20 | 20 |
| IRON ORE | 1 | 3 | 4 |
| EPIDOTE | 1 | 5 | - |
| REST | - | I | - |

## 5. Petrogenesis

### A. Evidence of Hybridization

The hybrid character of the hybrid rocks is suggested by the following evidence. The hybrid rocks are strikingly heterogeneous in composition, mineralogy and texture, with the character of the rock commonly changing very rapidly and irregularly. They vary in composition from slightly acidified dolerites almost to granites. Primary igneous rocks in contrast, are usually characterized by their homogeneity. Many of the rocks found in the hybrid masses have unusual features which are not normally found in igneous rocks, for example the ophitic dolerites from Mecklin Wood (E 8740) in which the plagioclase is rich in potash. Many textures and structures, for example the acicular habit of the ferromagnesian minerals and the acidic veins with gradational margins are characteristic of hybrid rocks rather than normal igneous rocks.

### B. Age of Hybridization.

The greater part of the hybridization took place before the final emplace ment of the Main Granophyre. This is shown by the igneous veining (Fig. 7.) and the large scale intrusion of the hybrid rocks by the granophyre. The hybridization is believed to have immediately preceded the emplacement of the Main Granophyre.

Marginal hybridization by the Main Granophyre is quite common, but this is hybridization of hybrid rocks rather than hybridization of original basic rocks. Potash has migrated from the granophyre into a hybrid rock in specimen E 8686 from

Bowness Knott (pp. 101 ) and oligoclase porphyroblasts, which have developed in a hybrid rock in specimen E 8683 from Bowness Knott, (pp. 103 ) are associated with the contact of the intruding granophyre. The contacts between the hybrid rocks and the granophyre are commonly microscopically diffuse, showing that there has been some mixing of the two rocks. The extent of this hybridization by the Main Granophyre in situ is uncertain but it is not likely to be very great as the effects just noted are marginal in character.

### C. Origin of the Hybrid Rocks.

The hybrid rocks have been formed in one of the following ways:-

1) Masses of basic rocks have been immersed and hybridized in a granophyre magma and then carried passively to their present position during the intrusion of the Main Granophyre.
2) Masses of basic rocks have been hybridized and mobilized at depth and then intruded as hybrid rocks.
3) A basic magma mixing with an acid magma has produced a hybrid magma which has then been intruded.
4) Normal basic intrusions have been hybridized in situ.

The first alternative is very unlikely because the masses of the hybrid rocks would then be surrounded by granophyre whereas they are in contact with the Borrowdale Volcanic Series over large areas. The masses of heavier, basic rock, would also sink through the granophyre, yet they are found associated with its roof.

The major point of evidance supporting the second and third alternatives is that the basic rocks have been intensely altered by hybridization yet the volcanic rocks in contact with the basic rocks are unaltered. It is difficult to envisage a situation where the enormous quantities of silica and potash necessary to effect the hybridization could be transported into the basic rocks without affecting the country rocks, unless the hybridization took place before intrusion. It is possible, however, that the process did take place in situ and the volcanic rocks acted as an impermeable barrier to the metasomatising agents because of their fine grained and massive character.

Hollingworth (ibid. pp. 46) gives a reconstruction of the sequence of intrusion of the Ennerdale Granophyre in which there are two primary magmas, one acid and one basic. The hybrid rocks are shown to be derived from a magma produced by the mixing of the primary magmas. Hybrid rocks that have crystallized from a magma would be expected to be fairly homogeneous. The uniformity of the hybrid rocks on Crag Fell and parts of Seatallan suggest that this is a plausible explanation of their origin. The heterogeneity of most of the hybrid rocks, however, is difficult to explain in this way.

The heterogeneity of the hybrid rocks is consistent with the second possible origin. The intrusion of a mobilized heterogeneous rock would, however, be expected to produce some lineation in the rock, as the residual blocks of basic rocks were orientated parallel to the flow direction, or mobilized basic patches became streaked out parallel to the flow direction. No such lineations are seen in the field.

The minor basic intrusions associated with the Ennerdale Granophyre and the hybrid masses in the granophyre stock are composed of basic rocks of the same age, which would be expected to have similar compositions. The fact that they have not may be the result of the minor basic intrusions being derived from a primary basic magma and the hybrid rocks from a mixed magma. It is a questionable coincidence, however, that without exception all the minor basic intrusion were derived from one magma and all the hybrid rocks of the stock from another. The difference in composition between the normal basic rocks and the hybrid rocks could be better explained if the hybrid rocks were derived from normal basic rocks by hybridization in situ. All the original basic rocks had the same composition but those in the granophyre stock were hybridized while the minor intrusions were shielded by the country rock and remained unaltered.

The dolerites in Mecklin Wood are normal ophitic dolerites in which potash has been introduced into the plagioclase crystals. The introduction of potash clearly took place after the dolerite had solidified and this is an undoubted case of hybridization after intrusion.

The evidence given above does not exclusively support any one possible origin of the hybrid rocks. The observed facts, however, can be best explained by the theory that the hybrid rocks were derived by hybridization of basic rocks after intrusion.

## D. Process of Hybridization.

The hybridization of the basic rocks, as mentioned above, preceeded the final emplacement of the Main Granophyre. The major effect of the hybridization was the introduction of potash and silica, which were probably derived from a granitic magma, and the only granitic magma from which they could come was the acid magma of the Ennerdale Granophyre. The metasomatising agents are envisaged as rising in a metasomatic front, ahead of the Main Granophyre intrusion. Most of the volatiles from the granophyre magma would make up the metasomatic front, but a few would remain in the granophyre. These residual volatiles would produce the small scale marginal metasomatism by the granophyre that has been noted above.

The arrival of the metasomatic front in the basic rocks would raise the temperature of the rock, and the influx of potash and silica would lower its melting point. The hybrid rocks may therefore have been semi-molten when intruded by the granophyre. This would have resulted in gradational, unchilled contacts between hybrids and granophyre. Where the hybrids were less affected by metasomatism they would be solid and their contents with the granophyre would have normal sharp igneous contacts.

The extremely thorough hybridization of the basic rocks shows that the metasomatising agents percolated through the whole rock and were not confined to joints in the rock. The heterogeneity of the hybrid rocks is the result of areal variation in the concentrations of metasomatising agents passing into the rock. Small scale variations in the hybrid rocks may be due to an increase in metasomatism along original lines of weakness such as joints in the basic rocks. This would lead to masses of basic hybrids being surrounded by more acidic hybrid rocks.

The concentrations of the elements introduced into the hybrid rocks vary from place to place. The majority of the hybrid rocks have been enriched in potash and silica. The hybrid rocks of Bowness Knott, however, have been enriched in silica but show little enrichment in potash, and the dolerites of Mecklin have been enriched in potash but not in silica. The porphyroblasts of albite and oligoclase that characterize the hybrid rocks of part of the Bleng Valley (see pp. 94-6) show that there has been an introduction of soda in this area. The porphyroblasts have grown in the normal hybrid rocks, therefore the introduction of soda must have been later than the introduction of potash and silica.

The relative homogeneous character of some of the hybrid masses, particularly the Crag Fell mass is difficult to explain. One would expect a basic rock subjected to potash and silica metasomatism to become gradually more acidic and finally completely granitized. Such an action on a basic mass would lead to a zoning similar to the infiltration zoning described by Korzhinsky (1950, pp. 67). The rocks of the hybrid mass would vary from a granitized hybrid at the margin to unaltered basic rocks in the core. Zoning is not found in the Crag Fell mass.

Hybrids similar in composition and appearence to those on Crag Fell, occur in every outcrop of hybrid rocks and are particularly common on Seatallan. The widespread occurrence of this type of hybrid suggests that it represents an important intermediate stage in the hybridization of the basic rocks.

The abundance of the Crag Fell type of hybrid, and the homogeneity of the Crag Fell mass may be the results of a variation in the rate of hybridization. The initial alteration of the basic rocks would be easy and rapid because of the great disequilibrium between the basic rocks and the granitic metasomatising agents. The rate of hybridization would decrease as the hybrid rocks became more granitic and approached equilibrium with the metasomatising agents. A decrease in the rate of alteration could also be caused by metasomatic overgrowths on primary minerals protecting them from further alteration.

The results of this variation would be that all the basic rocks would be quickly changed into hybrids of granodioritic composition but would then maintain a similar composition for a long period. The hybrid rocks would gradually become more granitic with prolonged metasomatism. In the case of the Ennerdale Granophyre, however, the metasomatism stopped in many areas before the hybrids had changed from the granodioritic composition.

The mineralogical variations within the hybrid rocks are shown in Fig. 9. The amount of quartz and potash feldspar in a specimen is taken to indicate its degree of hybridization, and is plotted against the mineral composition of the specimen. The modal analysis of an unaltered microdiorite (Specimen E9203) from the Burtness Combe laccolith (see pp. 53 )is included for comparison. This graph shows several features which throw light on the process of hybridization.

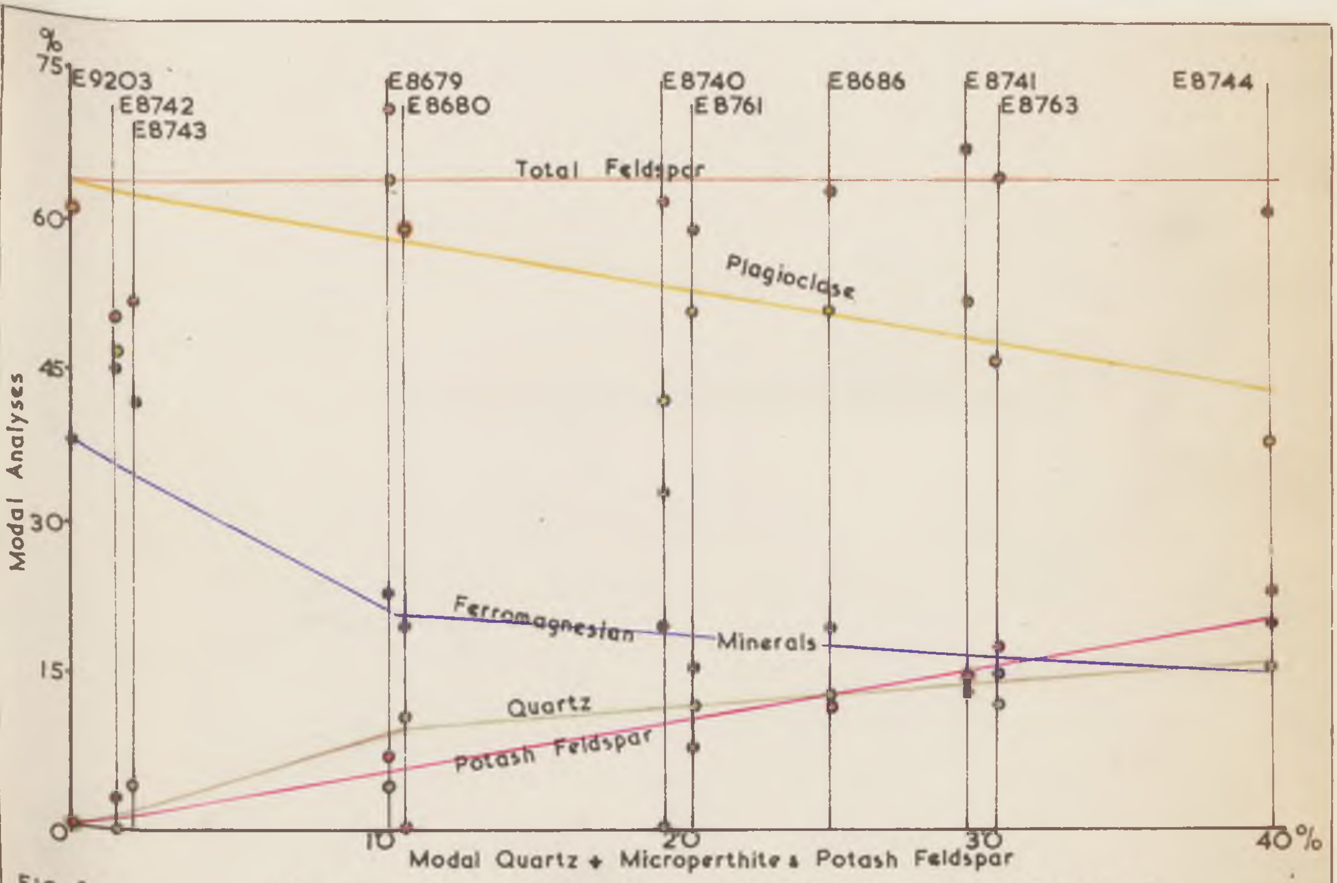


FIG 9

Mineralogical Variations in the Hybrid Rocks of the Ennerdale Granophyre

The percentage of plagioclase in the hybrid rocks decreases as the degree of hybridization increases. The plot of this variation is a straight line which, if projected back to the line of alteration, almost coincides with the percentage of plagioclase in the microdiorite from Burtness Combe. The only three points which differ greatly from the straight line plot are the plots of three dolerites from Mecklin Wood. This strongly suggests that the hybrids have been derived from dioritic rocks and not from dolerites and that the dolerites from Mecklin Wood are fundamentally different from the rest of the hybrids.

The percentage of potash feldspar in the hybrid rocks increases uniformly as the degree of hybridization increases. This change is complementary to the reduction in the amount of plagioclase, the total feldspar percentage remaining approximately constant, suggesting that the potash feldspar is replacing the plagioclase. This is supported by petrographic evidence, for the perthitization of primary plagioclase crystals is very common in almost every specimen.

The graph shows a similar complementary relationship between the quartz and ferromagnesian minerals. The percentage of ferromagnesian minerals drops sharply from 38 to 20 and then slowly decreases to about 16. The percentage of quartz rises sharply from 0 to 10 and then gradually increases to about 16. This complementary relationship is also revealed in petrographic studies, for ferromagnesian minerals are the main interstitial minerals of the microdiorites but are partially replaced by quartz in the hybrids. In the dolerites of Mecklin Wood where there has been an introduction of potash but very little quartz, the percentage of ferromagnesian minerals remains high. The difference of some six percent between the fall in the ferromagnesian percentage and the rise in the quartz percentage is probably due to the replacement of some of the ferromagnesian minerals by alteration products such as sphene and epidote.

The theory concerning the rate of hybridization of the basic rocks is supported by Figure 9, if the degree of alteration of a rock is assumed to be roughly proportional to the length of time the rock has been subjected to metasomatism. In the initial phase of rapid change the amount of ferromagnesian minerals in the rocks drops from about 40 to 20 percent and the amount of quartz rises from 0 to about 10 percent. Potash feldspar gradually replaces the plagioclase in this period and finally makes up about 6 percent of the rock. In the second phase of less pronounced alteration the percentage of ferromagnesian minerals drops very slowly and the percentage of quartz rises very slowly. The major change during this period is the continued gradual replacement of plagioclase by potash feldspar. The rocks appear to remain almost unaltered during this phase because the relative amounts of quartz, ferromagnesian minerals and total feldspar only change slowly. The differences in the degree of replacement of the plagioclase by potash feldspar is not obvious in hand specimens or under the microscope unless the specimens are stained. This stage, therefore, produces a series of rather uniform hybrid rock; the Crag Fell type of hybrid.

The chemical exchanges that occurred during hybridization must have been extremely complex. During the replacement of andesine by potash feldspar, potassium and silica were introduced and calcium and sodium removed. The introduction of water was necessary to change theprimary pyroxene to amphibole. Silica was introduced and calcium, magnesium, iron, aluminium and water removed during the replacement of the ferromagnesian minerals by quartz. The major changes in the rock were, therefore, the introduction of potassium, silica and water, and the removal of calcium, sodium, magnesium, aluminium, iron and water. Some of the elements lost during this interchange may have been used in the formation of alteration products, calcium, iron and aluminium in epidote, calcium with titanium in sphene and sodium in sericite. The fate of the excess of these elements is unknown.

## 6. The Original Basic Rocks.

### A. Composition.

The rocks of the inner zone of the Mecklin Wood outcrop were undoubtedly normal dolerites before they were hybridized. They have been little affected by metasomatism and still retain their original ophitic texture and contain primary augite and labradorite.

The primary character of the rest of the hybrid rocks is less certain. Almost every specimen contains decayed and altered plagioclase laths which look as though they are primary crystals.

The plagioclase is usually within the andesine range, about $An_{36}$ but reaching $An_{46}$ in specimen E 8679. The constancy of the composition of the plagioclase in the hybrid rocks suggests that andesine was their original composition. If this is correct, then the hybrid rocks were originally diorites.

This is supported by a comparison with the minor basic intrusions associated with the Ennerdale Granophyre (see Chapter 3). These intrusions are the same age as the basic rocks within the granophyre stock and would be expected to have a similar composition. They are composed of diorites and microdiorites. A comparison of the modal analyses of the hybrid rocks with those of dolerites from Mecklin Wood and a microdiorite from the Burtness Combe laccolith also suggests that the hybrid rocks have been derived from diorites rather than dolerites (see Fig. 9, pp. 112).

The plagioclase of the original basic rocks may have been enriched with soda during their hybridization and changed from labradorite to andesine. Rastall (ibid. pp.265 ) records basic labradorite from Bowness Knott, but no labradorite has been found in hybrid rocks other than the dolerites from Mecklin Wood. It is believed that the balance of evidence points to an original dioritic composition for the basic rocks apart from the Mecklin Wood dolerites.

The primary ferromagnesian mineral of the Mecklin Wood dolerites was augite but the identity of the primary ferromagnesian mineral of the diorites is uncertain. Rastall (ibid.pp265-7 believes that it was augite and records remnants of primary augite in secondary hornblende crystals from Bowness Knott and Wasdale. No augite has been observed in any hybrid rocks except the Mecklin Wood dolerites. The occurrence of augite in the rocks of the related minor basic intrusions, however, suggests that it might have been a primary mineral in the diorites of the stock.

## B. The Form of the Original Basic Intrusion.

Any attempt to reconstruct the form of the original basic intrusion must be highly speculative because of the wide separation of the present masses by the Main Granophyre. It is not known whether the present masses of hybrid rocks are remnants of one intrusion, or several intrusions.

Each of the major hybrid masses may be the remnant of a single early basic intrusion. The main hybrid mass in Wasdale is in the form of a flat sheet (pp. 70 ), and the hybrid masses in Ennerdale are believed to be parts of a similar sheet, that has been disrupted by the intrusion of the Main Granophyre. The form of the Bleng Valley hybrid mass is uncertain, but is likely to be a sheet, also, for the widespread veining and large-scale intrusion of the hybrid rocks by granophyre, for example the Yokerill Hows dyke (pp. 87-8 ), suggests that the hybrid mass is underlain by granophyre. It is likely, though uncertain, that the sheet form of these hybrid masses is a reflection of the form of the original intrusions.

The roofs of the basic intrusions of Wasdale and the Bleng Valley are formed of rocks of the Borrowdale Volcanic Series.

These two sheets or sills must have been intruded along a plane that is now marked by the roof of the Ennerdale Granophyre stock. This raises the problem of the small masses of hybrid rock, for example those on Buckbarrow (pp. 75 ), which are also associated with the roof of the granophyre stock. These may be remnants of small basic masses intruded along the same plane as the Wasdale and Bleng Valley intrusions, but this idea presents a questionable coincidence.

The present hybrid masses may be remnants of a single early basic intrusion. This basic intrusion, most likely a sill, was intruded, in part at least, along the plane now represented by the roof of the Ennerdale Granophyre. The small masses of hybrid rocks mentioned above are possibly small remnants of this single large intrusion. This reconstruction of the basic mass is shown in Fig. 10.

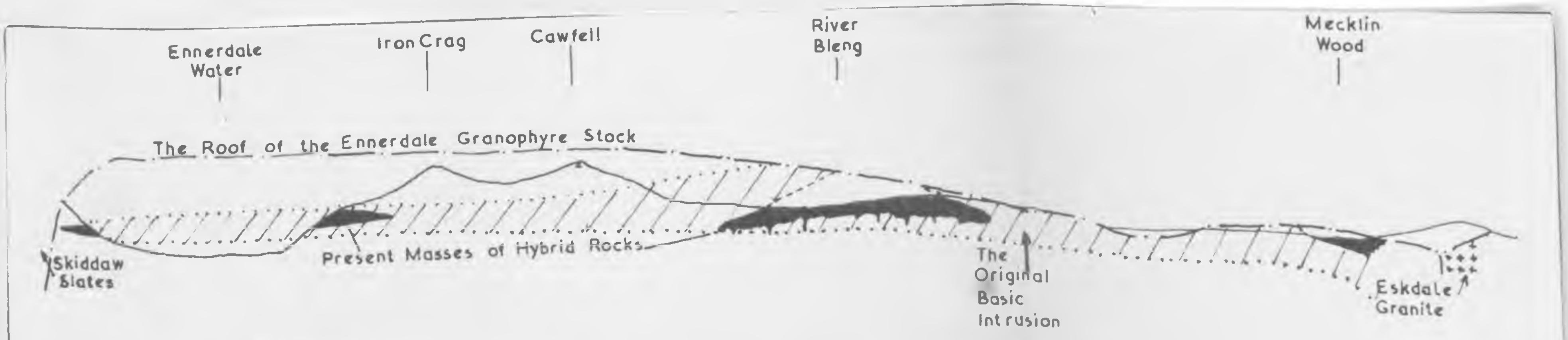


FIG. 10. A Restoration of the Original Basic Intrusion of the Ennerdale Granophyre: Semi-diagrammatic.

The relationships between the dolerite of Mecklin Wood and the rest of the basic rocks are unknown. The original basic intrusion may have been a multiple intrusion, with a separate dolerite intrusion in the main diorite intrusion.

## C. Age of the Original Basic Intrusion.

The basic intrusion is older than the Main Granophyre and it has been unaffected by the Caledonian fold movements. The basic rocks are still fresh compared with the rocks of the pre-Caledonian intrusions (Appendix 2A). The intrusion must, therefore, immediately pre-date the Main Granophyre which is itself immediately post-Caledonian in age. It is believed that the intrusion of the basic rocks was the first phase in the intrusion of the Ennerdale Granophyre stock.

# V. THE MAIN GRANOPHYRE.

## 1. Introduction.

The Main Granophyre makes up the bulk of the exposed Ennerdale Granophyre stock. It occupies over eighty percent of the granophyre outcrop. It is a fine pink granophyre which is extremely uniform in the field. The majority of the variations in the granophyre that are obvious to the naked eye are colour changes associated with the edges of the intrusion. There are, however, regional variations in the texture of the granophyre which can be observed on closer examination, particularly microscopic examination.

The edge of the Ennerdale Granophyre which, over most of its distance is also the edge of the Main Granophyre, was first accurately mapped by Ward and others in the 1870's (Geological Survey, One Inch Sheets 101 SE 99NE, 98NW and 101SW Old Series). The margin of the granophyre was re-examined by Rastall (1906) and later, the western edge of the granophyre from Routern southwards to the Bleng Valley was surveyed again by the Geological Survey (Eastwood et al 1931; Trotter et al 1937).

Petrological variations within the Ennerdale Granophyre were first described in any detail by Rastall who showed that the Main Granophyre, or normal rock, and the hybrid rocks belonged to different intrusions. He, and later, officers of the Geological Survey noted regional variations within the

Main Granophyre itself.

## 2. Field Relationships.

The present survey of the edge of the Ennerdale Granophyre has confirmed Ward's survey, except for a few details. Ward shows a large granophyre dyke heading north-eastwards from Starling Gill to the summit of Starling Dodd. In the mapping of this 'dyke' Ward connected an exposure of white granophyre at the head of Starling Gill to an outlier of andesitic lavas near the summit of Starling Dodd.

According to Ward's mapping, the outcrop of the Main Granophyre in the vicinity of Windsor Farm in Wasdale extends westwards as far as Turdypack Gill. The present work shows that Ward misidentified rhyolitic lavas near Yewtree as granophyre, because the granophyre outcrop only extends about 100 yards west of Windsor.

An inlier of granophyre in volcanic rocks is shown by Ward in Windgate Wood (G.R. 112033) about 500 yards west of the edge of the main outcrop of granophyre. Normal granophyre, however, has been found in Stonehow Wood (G.R. 114036), and it is believed that the granophyre outcrops of Windgate and Stonehow Woods are actually in the main granophyre outcrop. The edge of the granophyre passes from Windgate Wood northeastwards to Kidbeck How, almost parallel to the margin mapped by Ward but about 500 yards to the north-west.

Rastall in his description of the edge of the granophyre suggests that the faults on Haycock and Tewit How mapped by Ward are non-existent. This view, however, is incorrect. The detailed description of the western edge of the Ennerdale Granophyre by the Geological Survey has also been largely confirmed by the present work.

The Main Granophyre is intrusive into the Skiddaw Slates, the Borrowdale Volcanic Series and the hybrid rocks of the Ennerdale Granophyre. The contact between the Main Granophyre and the Skiddaw Slates is well exposed on the south side of Herdus and in places along the north side of Gale Fell. The Skiddaw Slates are veined by the granophyre, the veining commonly being controlled by cleavage planes in the slates (Fig. 11.).

The Main Granophyre in contact with the Borrowdale Volcanic Series is best exposed along the south face of Buckbarrow, but can also be seen in some rivers, for example the Liza and Low Beck in Ennerdale. Several horizontal lenses of lavas occur in the Main Granophyre on High Birkhow (G.R. 141043). These lenses are believed to be the remnants of the volcanic roof of the granophyre which has been separated into wedges by sills of granophyre.

The relationships between the Main Granophyre and the hybrid rocks of the Ennerdale Granophyre are fully discussed in Chapter IV.

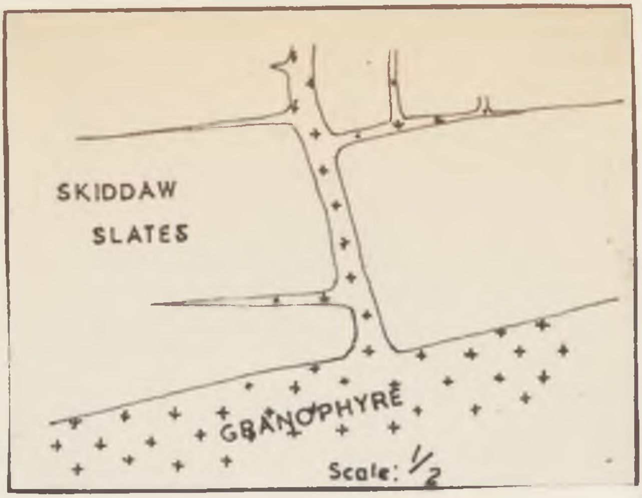


Fig. 11. Veins of Granophyre intruded along Joints in Skiddaw Slates, Herdus.

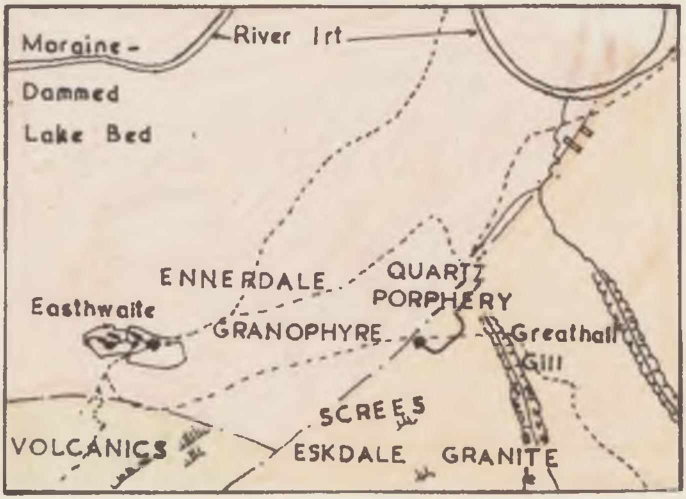


Fig. 12. Geological map of the Vicinity of Easthwaite Farm, Wasdale.

Scale. Six inches equals one mile.

The Main Granophyre has been intruded by the late acidic intrusions of the Ennerdale Granophyre (Chapter VI). There is some evidence that east of Easthwaite Fram in Wasdale the Eskdale Granite also is intrusive into the Main Granophyre. Unaltered Eskdale Granite is exposed in Greathall Gill and on the hillside to the west (Fig. 12). One hundred and twenty yards west of Greathall Gill shattered quartz porphery, a marginal variant of the Eskdale Granite crops out in the Easthwaite path. Main Granophyre crops out 120 yards further west in the path and 60 yards to the north-west below the path. The quartz porphery is believed to be a selvage of the Eskdale Granite chilled against the Ennerdale Granophyre. Similar marginal quartz porphyry is found to the east, adjacent to the Pens End Fault.

Additional evidence that the Eskdale Granite is intrusive into the Ennerdale Granophyre is provided by the way that the edge of the granite cuts across the contact between the Main Granophyre and the Borrowdale Volcanic Series at right angles. The only other way these relationships could be explained would be if the edge of the Eskdale Granite was a fault.

The outcrop of the Ennerdale Granophyre has been divided by remnants of its roof into three main parts; The Buttermere, the Main or Ennerdale, and the Wasdale outcrops. Rastall has described a series of regular variations in the granophyre from each of the outcrops (ibid. pp. 270); "Near the margin of the laccolite the rock shows a structure nearly approaching that of the normal acid plutonic rocks with scarcely a trace of graphic intergrowth; a short distance from the margin graphic structure begins to make itself manifest, at first very imperfect and irregular type; and, as we approach the centre of the visible mass, this intergrowth becomes continuously finer in texture, and of increasingly perfect micropegmatitic structure."

Rastall believed that each outcrop represented a separate laccolith and that the variations in the Main Granophyre were due to laccolithic differentation in these laccoliths. His interpretation of the structure of the Ennerdale Granophyre is incorrect, for the intrusion is a stock (see pp. 198 ). The texture of the Main Granophyre actually varies from coarsely micrographic at the edge to finely micrographic in the core of the stock. The finest granophyres are, therefore, found in the most deeply eroded parts of the stock.

The granophyre in the Buttermere outcrop, when examined in the field, is a uniform fine pink rock containing numerous white feldspar phenocrysts about 2 x 1 mm. in size. It is commonly discoloured to a pale grey colour near the margins of the outcrop, for example near Scale Bridge. The granophyre at the north-west side of Gale Fell (G.R. 136 169) is a dark purplish-grey colour and is much more basic in appearance than normal.

The Buttermere outcrop is largely composed of a coarsely micrographic granophyre, but in Ling Comb, where the granophyre has been deeply eroded, the texture of the granophyre is much finer. The dark purplish-grey granophyre on Gale Fell is a coarse granophyre in which the feldspars have been altered to sericite. Rastall (ibid. p. 261) called this rock a greisen. The small mass of granophyre in Burtness Wood is also composed of a coarsely micrographic granophyre. A true microgranite with no micrographic texture has not been found in the Buttermere outcrop. A specimen (E 9210) from 200 yards west of Scale Force shows the Main Granophyre, here a coarsel-y micrographic granophyre, in contact with the Skiddaw Slates. A contact selvage of the granophyre about three millimetres wide and small veins from the granophyre are microgranitic in texture.

The Ennerdale outcrop is composed of a uniform rock similar to that of the Buttermere outcrop. Variations in the granophyre, other than in colour, are rare. Much of the granophyre on Side in Ennerdale is a pale grey colour, while that on Lingmell is a particularly bright pink. Rastall has described fel-sitic variations from Silver Cove and Revlin Crag, but these are most likely the late fine grained microgranites of Deep Gill, and the Anglers Crag dykes. The granophyre adjacent to the contact across the summit of Herdus is a white microgranite. Veins of similar rock trending parallel to the contaot occur in normal pink granophyre some sixty yards from the contact (G.R.121163).

Hollingworth (in Eastwood, et al, 1931, pp. 48) points out that the Main Granophyre on the summit ridges of Boathow, Iron Crag and Cawfell is a distinctly porphyritic microgranite. He suggests that this microgranite is a marginal facies of the Main Granophyre that was formed just under the granophyre roof. The microgranite actually grades down into coarse granophyre and the edge of the microgranite outcrop cannot be mapped in the field with any accuracy. Its approximate extent, determined by microscopic examination of selected specimens is shown on Map 1. The summits of Silver Cove and Boathow Crag are composed of very coarsely micrographic granophyre.

The Main Granophyre in the area between Silver Cove and Stockdale Head, including the summit plateau of Cawfell is commonly finer grained than normal. This fine grained granophyre, in most places, appears to be merely a variant of the normal granophyre but below Red Crag a fine granophyre is veining the normal granophyre. The fine grained granophyre resembles some of the late fine grained microgranites (see pp.146-9) and may possibly be related to them.

Erosion of the Main Granophyre has been greatest in Ennerdale. Granophyre at the head of Ennerdale Water is over 1000 feet below the roof of the stock and is close to the centre of the stock. As one may expect the finest micrographic texture in the Ennerdale Granophyre is found in this area. The micrographic texture of the granophyre becomes progressively coarser as the margin of the granophyre is approached. The texture of the granophyre over most of the Ennerdale outcrop is medium to coarsely micrographic. The complete loss of micrographic texture appears to be restricted to places under the roof, for example Herdus and Iron Crag. A continuous section showing the range in texture from the finest micrographic to a microgranitic texture is displayed in Ennerdale between Mart Knott and the summit of Iron Crag. The granophyre adjacent to the walls of the stock tends to be a fairly coarsel-y micrographic granophyre.

The Main Granophyre of the Wasdale outcrop and the smaller outcrops near Windsor Farm and on Buckbarrow Moss has been hardly eroded at all. It mainly consists of microgranite and coarsely micrographic granophyre. The granophyre near Wasdale Hall and at the junction of the two main roads (G.R. 151054) has lost its primary texture due to intense granulation related to fault movements. Wasdale Hall is almost along the line of the Fens End - Greendale fault and the granophyre at the road junction is traversed by numerous north-west, south-east crush belts.

## 3. Petrography.

The appearance of the Main Granophyre in hand specimens is very uniform and is barely affected by its microscopic textural variations. It is a fine pink granitic rock sparsely flecked with a dark green chloritic mineral. Stout prisms of white feldspar about 2 x 1 mm. in size which tend to stand out against the fine pink matrix are very common. Small grains of yellowish-green epidote are common in most specimens. The major macroscopic variations within the Main Granophyre, which are mainly variations in colour, have been described with the field relationships.

The variations in the textures of the Main Granophyre can be easily seen in polished specimens stained with sodium cobaltinitrite. Potash feldspar is bright yellow and picks out any micrographic intergrowth present. The white feldspar phenocrysts are chiefly plagioclase for they are not stained.

Microscopically, the Main Granophyre, as described above, varies from an extremely fine granophyre to a microgranite in texture. The fine granophyre has a matrix largely made up of an extremely fine micrographic intergrowth of quartz and feldspar in which are set numerous feldspar crystals. Scattered through the matrix are irregular clots of ferromagnesian minerals and iron ore.

The majority of the feldspar crystals are subhedral prisms up to three millimetres long, but averaging 1.5 mm. in length, commonly occurring in glomeroporphyritic groups. The feldspar crystals are not true phenocrysts for the feldspar in the micrographic intergrowth in the matrix is optically continuous over areas as large as the crystals. The crystals vary in composition, some are composed of plagioclase, others are composed entirely of microperthite.

The feldspars from the Main Granophyre are dealt with in some detail in Appendix ~~2~~ 3. The plagioclase is dominantly oligoclase, about $An_{27}$, but albite is probably also present. High temperature oligoclase probably occurs in the cores of some crystals. There appears to be two generations of plagioclase crystals in the granophyre. The younger generation are very fresh and have clear twinning, while the older generation are corroded, have thick mantles of perthite and their twinning is faded. The potash feldspar is mainly microperthite but orthoclase may occur, and there is some indication that anorthoclase is also present in a few crystals.

The mantles and crystals of microperthite were partially formed by metasomatism of primary plagioclase crystals, but it is likely that some are primary. This feldspar is commonly in optical continuity with that of the micropegmatite, suggesting that the crystals formed centres of crystallization for the micropegmatite. The interfaces between the microperthite crystals or mantles and the micropegmatite are commonly perfectly euhedral. The feldspar of the micropegmatite around some crystals can be seen to be assuming an euhedral outline, apparently expelling quartz from the micropegmatite to form a crystal edge. (Photos. 16 and 17). Some of the perfectly euhedral crystal faces may have formed in this way.

The matrix of the granophyre consists predominantly of micropegmatite, together with small crystals of quartz and feldspar. The feldspar in the micropegmatite is a microperthite. The micrographic intergrowth of quartz and feldspar is extremely fine in places and possibly becomes sub-microscopic. There are three main types of intergrowth:-

i) Parallel plates or rods of quartz and feldspar which give a herring-bone effect when two crystals meet.

ii) Orientated triangles or hexagons of quartz in feldspar.

iii) Irregular cellular intergrowths.

Almost all the quartz in the granophyre occurs in the micropegmatite , but a little occurs in anhedral crystals between 0.I. and 0.8 mm. in diameter. These crystals occur in groups which tend to be interstitial to the feldspar crystals and the areas of micropegmatite. Their interstitial occurrence suggests that they represent the last siliceous residuum of the granophyre magma. The quartz is full of liquid cavities about 0.005 mm. in diameter, containing gas bubbles and crystals. The liquid cavities tend to be arranged in lines and Rastall (ibid. pp. 258) suggests that the lines are parallel throughout all the quartz crystals in a specimen. This is not very obvious.

The ferromagnesian minerals occur in clots about one millimetre in diameter. The commonest ferromagnesian mineral is brown biotite, in flakes about 0.2 mm. long, altered to varying degrees to green chlorite. A green amphibole, probably hornblende occurs in crystals about 0.3 mm. in diameter, but is comparatively rare. The biotite is clearly a late mineral and is probably derived from an earlier mineral, possibly augite, as suggested by Hollingworth (1931, pp. 52). The biotite appears very rarely to be pseudomorphing a prismatic mineral.

Iron ore, in anhedral crystals up to 0.2 mm. in diameter, is commonly altered to leucoxene and haematite. This shows that both ilmenite and magnetite occur as primary ores. Rastall and Wilcockson (1917) give the characteristic iron ore of the granophyre as pyrrhotite, but no pyrrhotite has been found, despite an intensive search of thin sections, polished specimens and heavy mineral separations.

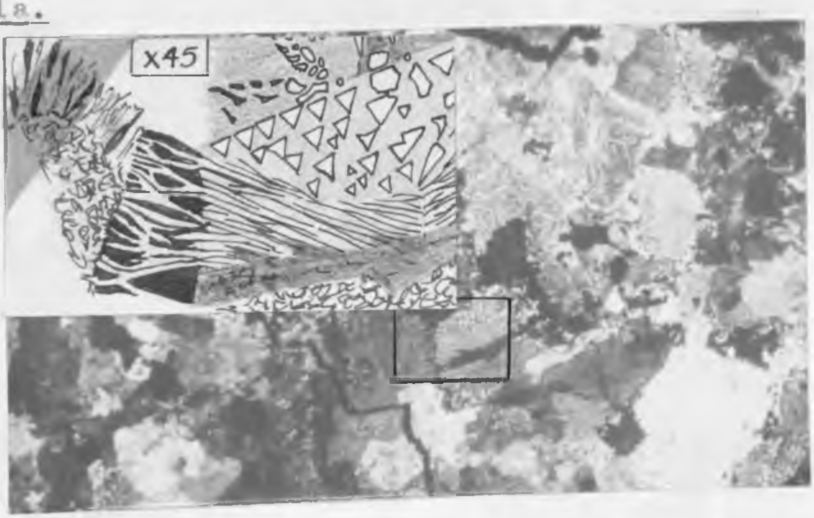
Accessory minerals of the granophyre include epidote, sericite, apatite, zircon and sphene. The epidote, sericite and sphene are alteration products and vary in abundance with the degree of alteration of the specimen. The apatite, zircon and iron ore are characteristically associated with the ferromagnesian minerals, and the minerals of this association are believed to have been the first to crystallize. The later growth of the feldspar crystals and micropegmatite pushed the early minerals aside until they were concentrated in the present interstitial clots.

There is a continuous textural variation in the Main Granophyre from the finest granophyre described above to a microgranite. In a section through the textural series the fine granophyre gradually gives way to an intermediate granophyre in which the micropegmatite is coarser and there is little difficulty in differentiating between its component minerals. The intergrowth of quartz and feldspar, however, remains fairly complex. This intermediate granophyre is the commonest rock type in the Main Granophyre (Photo 11b).

The micropegmatite becomes still coarser and the intermediate granophyre changes into a coarse granophyre (Photo. 11c). The micrographic intergrowth is no longer centred on feldspar crystals and is relatively simple. As the intergrowth becomes simpler the texture of the rock becomes microgranitic.

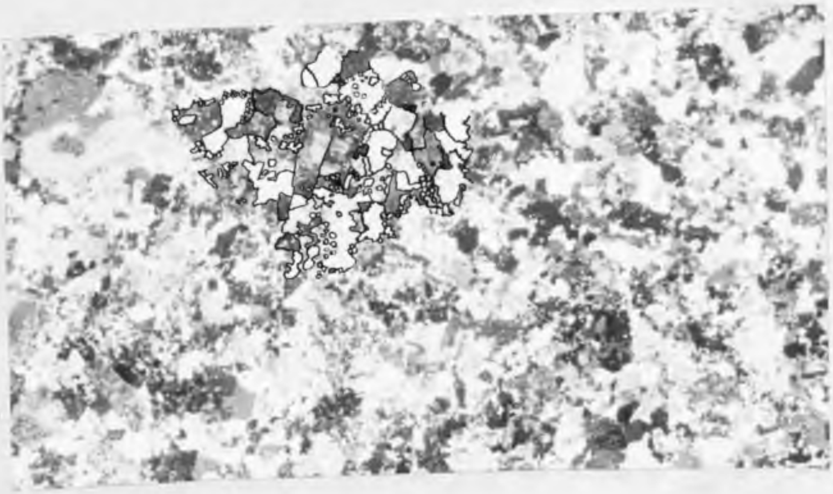
The microgranites (Photo. 11d) are slightly porphyritic with feldspar phenocrysts about 2 x 1 mm. in size set in a matrix of quartz and feldspar crystals about one millimetre in diameter. Clots of ferromagnesian minerals and iron ore are scattered through the rock. The matrix is largely composed of anhedral crystals of microperthite, plagioclase and interstitial quartz with some subhedral prisms of plagioclase. The phenocrysts are composed of a core of plagioclase mainly oligoclase, with a thick mantle of microperthite. The ferromagnesian minerals are similar to those in the fine granophyre except in specimen E 8769 from Windsor Farm, where clots of small green biotite

Photo. 11a.



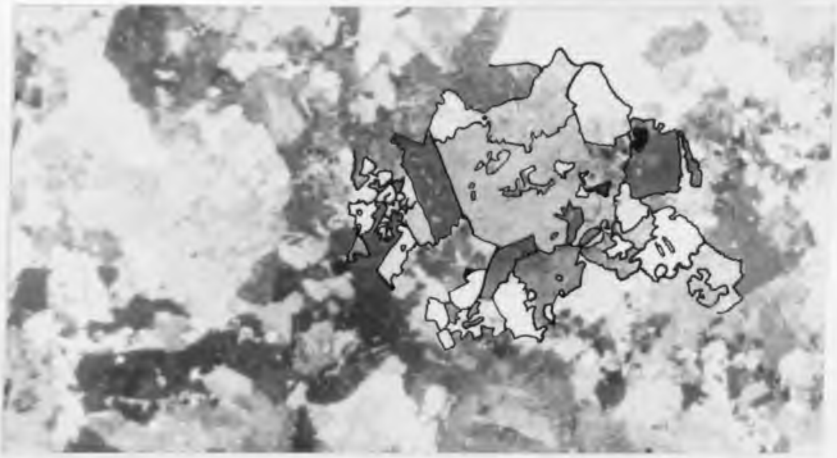
Fine Granophyre. Stair Knott, Ennerdale. E 8757.
Note the fine complex micrographic intergrowth of quartz and feldspar.

Photo. 11b.



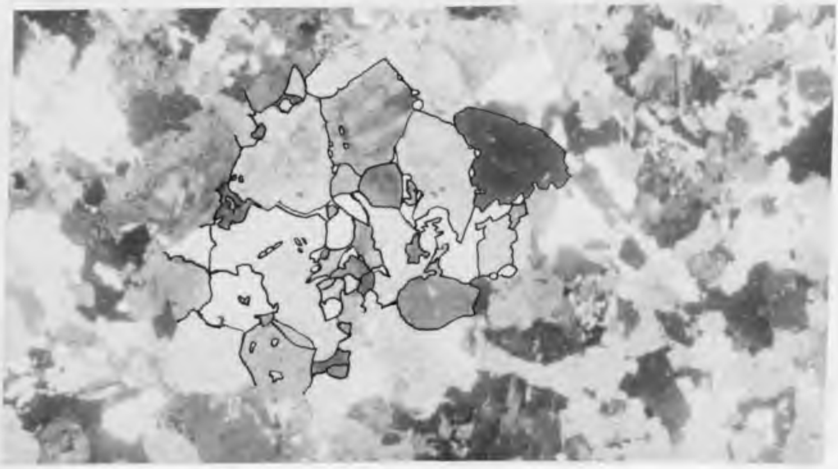
Intermediate Granophyre, Bleaberry Tarn, Buttermere E 9207.
The micrographic intergrowth of quartz and feldspar is coarser and simpler than in Photo. 11a.

Photo. 11c.



Coarse Granophyre. Burtness Wood. Buttermere. E 9313.
The intergrowth of quartz and feldspar is very simple.

Photo. 11d.



Microgranite. Iron Crag E9312
The intergrowth of quartz and feldspar is almost absent.

## TABLE I

| | FINE GRANOPHYRES | | | INTERMEDIATE GRANOPHYRES | | | MICROGRANITES | | |
|---|---|---|---|---|---|---|---|---|---|
| | E8757 | E8758 | E8759 | E8768 | E92I3 | E93I5 | E8769 | E9305 | E93I2 |
| Quartz | 29.6 | 28.5 | 27.5 | 29.9 | 28.2 | 34.5 | 27.I | 3I.9 | 28.8 |
| K. Feldspar + Perthite | 59.I | 63.9 | 53.9 | 64.7 | 65.I | 45.9 | 56.4 | 45.6 | 54.9 |
| Plagioclase | 7.0 | 5.3 | I3.3 | 2.9 | I.7 | I5.9 | I0.7 | I8.7 | I2.8 |
| Ferromagnesian Minerals | 5.0 | I.8 | 4.0 | 0.9 | 2.7 | I.5 | 4.4 | 0.9 | 2.6 |
| Iron Ore | I.0 | 0.9 | 0.9 | 0.9 | I.8 | 0.7 | 0.9 | - | 0.8 |
| Epidote | | 0.6 | | 0.7 | 0.2 | I.4 | 0.5 | 0.5 | 0.2 |
| Sericite | | | | | | | | 2.4 | |

| | | |
|---|---|---|
| E8757 | Stair Knott, Ennerdale. | G.R. I26II353 |
| E8758 | Sail Hills, Ennerdale. | G.R. I240I3I3 |
| E8759 | Woundell Beck, Ennerdale. | G.R. I320I372 |
| E8768 | Boathow Crag, Ennerdale. | G.R. I075I332 |
| E92I3 | Far Ruddy Beck, Buttermere. | G.R. I602I660 |
| E93I5 | Buckbarrow Farm, Wasdale. | G.R. I3530438 |
| E8769 | Windsor Farm, Wasdale. | G.R. I2I4057I |
| E9305 | Herdus, Ennerdale. | G.R. I2III639 |
| E93I2 | Iron Crag, Ennerdale. | G.R. I253II43 |

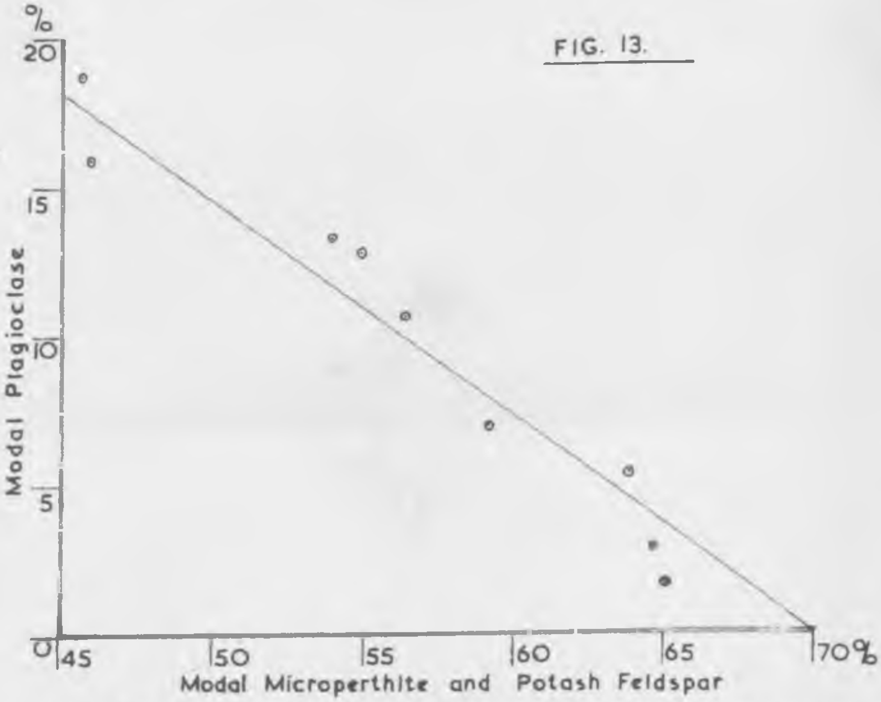
flakes have largely changed to green penninite and then changed back to brown biotite around the margins. This regeneration of biotite may have been caused by reheating by a local resurge of the granophyre magma.

The mineralogy of the Main Granophyre has been little affected by the variation in texture. Modal analyses of several specimens of Main Granophyre are given in Table 1. The major changes in the mineralogy are in the feldspars. The amounts of microperthite and plagioclase vary inversely, the amounts of total feldspar remaining approximately constant (Fig. 13). This is the result of the plagioclase in the phenocrysts being changed to perthite in the formation of perthite mantles and crystals. The amount of plagioclase in a specimen is dependent on the intensity of this perthitization.

Rastall (ibid. pp. 261) has described a greisen from the Main Granophyre at the west end of Gale Fell. In hand specimens the rock is coloured a dark purplish-green, but under the microscope it can be seen to be a normal coarse granophyre in which the feldspars are altered to sericite. The degree of sericitization is variable, but in places it is complete. The plagioclase was more susceptible to sericitization than the perthitic feldspar and some crystals have sericitized plagioclase cores and unaltered perthitic margins. The clots of ferromagnesian minerals in these rocks (E 9205; E 9206) are commonly crossed by lines of leucoxene dust orientated in three directions.

These directions are believed to be the relics of crystallographic directions, cleavage or twinning, of the original ferromagnesian mineral.

FIG. 13.



Variation of Plagioclase with Microperthite and Potash Feldspar in the Main Granophyre

## TABLE 2

| CHEMICAL ANALYSES | | | NORMATIVE ANALYSES | | | MODAL ANALYSES | | |
|---|---|---|---|---|---|---|---|---|
| | 6IO | 6II | | 6IO E8757 | 6II E93I2 | | 6IO E8757 | 6II E93I2 |
| $SiO_2$ | 72.84 | 73.I4 | Quartz | 27.24 | 29.0 | Quartz | 29.6 | 28.8 |
| $TiO_2$ | 0.24 | 0.36 | Orthoclase | 29.4 | 29.6 | Perthite | 59.0 | 54.9 |
| $Al_2O_3$ | I3.95 | I3.I3 | Albite | 34.7 | 33.8 | Plagioclase | 7.0 | I2.8 |
| $Fe_2O_3$ | I.43 | 0.98 | Anorthite | 4.5 | 2.2 | | | |
| FeO | | 0.8I | Corundum | 0.2 | 0.3 | | | |
| MnO | 0.05 | 0.04 | Hypersthene | I.4 | I.2 | Ferromagnesian Minerals | 5.0 | 2.6 |
| MgO | 0.43 | 0.42 | Magnetite | I.0 | I.4 | Iron Ore | I.0 | 0.8 |
| CaO | I.04 | 0.6I | Ilmenite | 0.5 | 0.7 | | | |
| $Na_2O$ | 4.I0 | 4.00 | Apatite | 0.2 | 0.3 | Rest | | 0.2 |
| $K_2O$ | 4.98 | 5.0I | | | | | | |
| $H_2O$ + | 0.78 | 0.98 | | | | | | |
| $H_2O$ - | 0.I2 | 0.27 | | | | | | |
| $P_2O_5$ | 0.I0 | 0.I2 | | | | | | |
| Total | I00.05 | 99.87 | | | | | | |

Chemical Analyses by Margaret H. Kerr.

Specimen E9757. 6IO. Fine Granophyre from Stair Knott, Ennerdale. The ratio FeO:$Fe_2O_3$ could not be determined. In calculating the normative analyses it has been taken as 50:50, similar to analysis 6II.

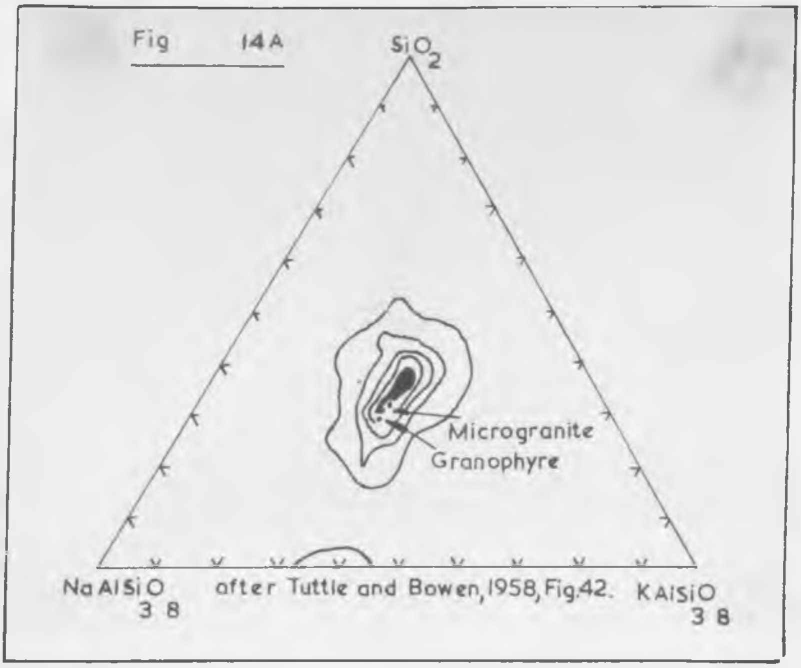
Specimen E93I2. 6II. Microgranite from Iron Crag, Ennerdale.

## 4. Petrochemistry.

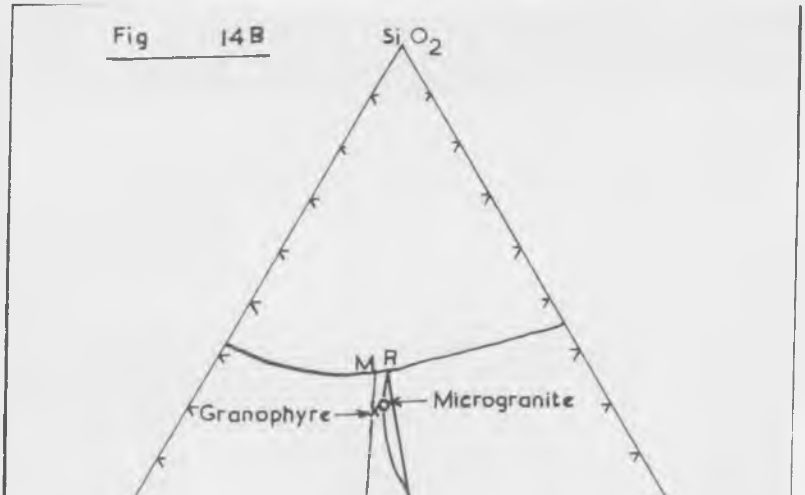
The chemical, normative and modal analyses of specimens of fine granophyre and microgranite, are given in Table 2. The analyses show that ther e is no significant difference between the two rocks. The high normative and low modal plagioclase figures are due to much of the plagioclase occurring in microperthite.

The close chemical resemblance between the two rocks, and their geat textural differences raises the problem of the origin of the textures. The origin of micropegmatitic texture is in some dispute, but it is generally assumed to be formed by simultaneous crystallization of quartz and feldspar under some type of cotectic conditions (see Firsman, 1931, pp. 86-97). The difference between the textures of the granophyre and microgranite of the Main Granophyre, however, cannot be explained simply by a difference between cotectic and none-cotectic compositions, for these rocks have practically the same composition.

The compositions of the microgranite and granophyre from the Main Granophyre are shown in Fig. 14A, on a contour diagram illustrating all the analysed plutonic rocks in the Washington's Tables that carry more than 80% Ab + Or + Q (after Tuttle and Bowen, 1958, pp. 79). This shows the similarity



A Contour Diagram illustrating the distribution of normative Albite, Orthoclase and Quartz in all (571) the analyzed plutonic rocks in Washington's Tables that carry 80% or more normative Ab Or Q. Contours more than 1,2,3,4,5,6-7%. 0.25% Counter.



Isabaric equilibrium curves for water vapour pressure of 1000 Kg/cm$^2$ in the system Na $AlSi_3O_8$ - $KAlSi_3O_8$ - $SiO_2$ - $H_2O$. Relations projected onto an hydrous base of tetrahedron.

between the granophyre and microgranite, and the similarity between these two, and the majority of other acidic plutonic rocks. In the light of this similarity of compositions of acid plutonic rocks, their textures clearly cannot be dependant on compositional differences.

The crystallization histories of the specimens of the Main Granophyre, assuming that their analyses represent the composition of the original magma, are shown in Fig. 14B (after Tuttle and Bowen, Fig. 31). The microgranite would precipitate feldspar crystals with an Or content greater than T(54%) and the composition of the liquid would change along the line Or to R. At R the feldspar of composition T would crystallize out with quartz, and the liquid would change its composition to M. Herefeldspar of composition N(54%Or) would crystallize out with quartz until the liquid was exhausted. The granophyre would crystallize, precipitating feldspar of composition N until the remaining liquid reached M, when quartz would also crystallize until the liquid was exhausted.

The range of compositions of the theoretical microperthites from below 46% up to 55% Ab agrees very well with the observed range in composition of microperthites in the Main Granophyre (Appendix III 2).

The ratio of modal quartz to modal feldspar in the micropegmatite of the fine granophyre is approximately 42.3 to 57.7, which corresponds with the theoretical ratios of mixtures of the ternary eutectic M at low hydrostatic pressures. The theoretical ratios are (ibid. Figs. 22, 23 and 24):-

$pH_2O$ 500 Kg/Sq.Cm. Quartz: Feldspar 39.5 : 60.5
$pH_2O$ 1000 Kg/Sq.Cm. Quartz: Feldspar 37.2 : 62.8
$pH_2O$ 2000 Kg/Sq.Cm. Quartz: Feldspar 34.5 ; 65.5

The difference between the modal ratio and the theoretical ratio at 500 Kg/Sq.Cm. is probably within the experimental error of the point counting to find the modal ratio.

The experimental work of Tuttle and Bowen does not explain why the primary phenocrysts are of oligoclase-andesine composition. At high pressures there are separate potash and soda feldspar fields (ibid. pp. 71) but the Main Granophyre falls in the potash feldspar field and would be expected to precipitate potash feldspar phenocrysts, not plagioclase.

The above experimental work shows that there has been no great difference in the crystallization histories of the granophyre and microgranite. The cause of the differences in their textures must therefore be something that does not show in such experiments. Two such factors are the rate of cooling of the rocks and the quantity of volatiles in the rocks.

The rate of cooling of an igneous body would be expected to be roughly proportional to their sizes, yet the Ennerdale and Eskdale intrusions of similar size, have completely different textures. In general, both intrusions with granitic and granophyric textures have a wide range in size. The rate of cooling in the rocks is, therefore, unlikely to be the cause of this difference in texture between the granophyre and the microgranite of the Main Granophyre.

If this is so, then the main factor affecting the texture of granitic rocks must be the concentration of volatiles in the rock. A high concentration of volatiles in a magma could act in two ways. It could encourage, or it could inhibit the magma from crystallizing in a granophyric texture. The characteristic occurrence of granophyric texture in the late acidic differentiates of basic intrusions, where one would also expect a concentration of volatiles, suggests that volatiles encourage a rock to crystallize as a granophyre.

This is also supported by the zoning of the Main Granophyre. During the solidification of a granitic intrusion one would expect the volatiles in the magma to be gradually concentrated in the magma still remaining liquid, until they were released to form pegmatites or metasomatizing agents. The core of an intrusion would be the last to solidify and in the Ennerdale Granophyre it is the centre of the stock that is composed of the most finely grained granophyre. The small amount of microgranite in the Ennerdale Granophyre suggests that the initial concentration of volatiles in the magma was almost high enough to promote crystallization in a granophyric texture.

The zoning of the Main Granophyre could, however, be taken to support the opposite view that the presence of volatiles inhibits the formation of granophyric texture, and that the texture of the microgranite under the roof of the Ennerdale

Granophyre is the result of such an enrichment in volatiles. The volatiles of an intrusion may diffuse through the magma prior to solidification and become concentrated under the roof in a similar manner to the concentration of volatiles from petroleum under the roof of an oil trap.

The method of control of the texture of granites by volatiles is unknown.

# VI. THE LATE MINOR ACIDIC INTRUSIONS OF THE ENNERDALE GRANOPHYRE.

## 1. Introduction.

Numerous fine grained acidic intrusions occur associated with the Ennerdale Granophyre. The rocks of these intrusions include microgranites, felsites and granophyres. The relationships between the various minor intrusions are uncertain, but the intrusions are discussed together because they are all younger than the Main Granophyre.

The largest of these intrusions occur within the Ennerdale Granophyre stock. A marginal intrusion of porphyritic fine grained microgranite crops out in the vicinity of Stockdale Moor between the Main Granophyre and the Borrowdale Volcanic Series. An irregular mass of similar microgranite with a core of fine felsite is exposed in Deep Gill in Ennerdale. Hollingworth (Eastwood et al, 1931, pp. 53), has described a series of microgranite dykes on Stair Knott and Mart Knott in Ennerdale. Late intrusions of felsite or fine granophyre are associated in places with the junction between the hybrid masses and the Main Granophyre, for example on Bowness Knott.

Late acidic sills and dykes are usually composed of rhyolitic felsite. They do occur within the granophyre stock, but are most common around the edge of the stock. They are concentrated in three areas, in the Burtness Intrusive Complex, on Bowness Knott and Crag Fell, and on Middle Fell in Wasdale.

## 2. The Fine Grained Microgranites.

### A. Field Relationships.

The largest outcrop of fine microgranite in the Ennerdale Granophyre occurs in the vicinity of Stockdale Moor. The microgranite lies between the Main Granophyre and the Borrowdale Volcanic Series in a wedge shaped outcrop which extends from the Bleng Valley, north-north-westwards to Worm Gill. The area between the Bleng Valley and Cawfell Beck has been described by Hollingworth (in Trotter et al, 1937, Fig. 6), who has sub-divided the microgranite into four types, a marginal porphyritic microgranite, a semi-marginal porphyritic granophyre, a fine grained microgranite, and a massive granophyric felsite. No evidence has been found during the present work to differentiate between the first three types.

The microgranite is best exposed in Cawfell Beck where it extends from the Main Granophyre, approximately 400 yards below Pearson's Fold, to the Borrowdale Volcanic Series some 1100 yards down stream. A porphyritic, fine grained, purplish-grey microgranite, similar to that in Cawfell Beck crops out at the junction of Worm Gill and Long Grain, and in a small stream 540 yards to the south (G.R. 10201075). There are no exposures in the area between Worm Gill and Cawfell Beck, but the microgranite is assumed to extend from Cawfell Beck, northwards into the Main Granophyre, in a wedge which pinches out near the Intake Works in Worm Gill.

The outcrop of microgranite extends southwards in a belt that gradually widens from half a mile at Cawfell Beck to almost a mile in width in the Bleng Valley. A roof pendant of andesitic lavas, approximately 300 yards across, is enclosed in the microgranite in Caw Gill (G.R. 104091), and on Stockdale Moor the microgranite almost surrounds a mass of hybrid rocks (see pp. 86 ). The belt of microgranite ends against the main outcrop of hybrid rocks in the Bleng Valley along a north-easterly line along the north side of the valley.

The microgranite changes its character on Stockdale Moor, north-east of the hybrid mass on Hause. The microgranite becomes pink in colour and a little coarser grained so that it looks like a fine grained variant of the normal granophyre. South-east of the hybrid mass on Stockdale Moor the rock is a pink porphyritic felsite.

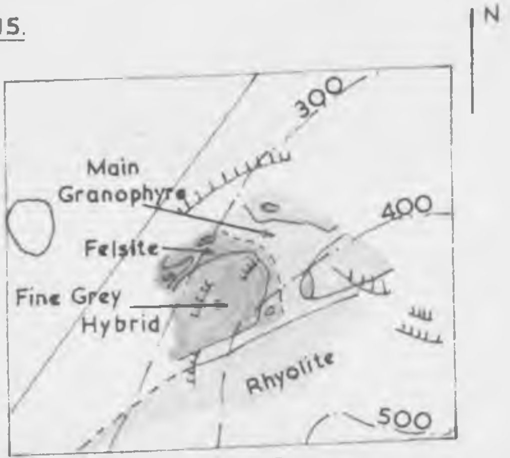
The relationships between the various rock types are difficult to determine because of the poor exposures in the area. The microgranite is in contact with the Borrowdale Volcanic Series for over a mile on Stockdale Moor, but their contact is only exposed in Cawfell Beck. The microgranite here is veining an andesitic lava that has been metamorphosed to a biotite hornfels. The hybrid rocks on Stockdale Moor and in the Bleng Valley are veined and dyked by microgranite. No contact between microgranite and the Main Granophyre is exposed north of Cawfell Beck but the shape of the microgranite outcrop suggests that it is intrusive into the granophyre. On Hause, the junction between the microgranite and the granophyre is difficult to define because of the resemblance in this area between the two rock types.

The Main Granophyre in the area around the Stockdale Head and on Cawfell is characterized by the occurrence of irregular areas of fine granophyre very similar in appearance to the pink microgranite on Hause. There are usually no sharp contracts between the fine granophyre and the normal granophyre, but in places, for example below Red Crag (G.R. 131097), the fine granophyre veins the normal granophyre. Fine microgranite which may be related to the microgranite on Stockdale Moor, crops out in a strip 60 yards wide between the hybrid rocks and the Main Granophyre in Red Beck. This strip extends about 300 yards on either side of Red Beck.

A late fine grained granitic intrusion occurs associated with the hybrid rocks on Bowness Knott. This intrusion, which varies from a fine distinctly porphyritic granophyre to a pink felsite, crops out between the Main Granophyre and the hybrid rocks. The reason for the association of the late intrusion with the hybrids is uncertain, but the fine granophyre may be occupying fractures which have developed between the Main Granophyre and the hybrids because of the different reactions of the rock types to cooling stresses. The fine granophyre veins the hybrid rocks, and this veining appears to have been controlled in part, by joints in the hybrid rock. A very fine porphyritic felsite which may be related to the fine granophyre crops out behind a sheep pen on Brown How (G.R. 118158) where it is veining the Main Granophyre.

Fine pink felsitic microgranite is found on Latterbarrow in Wasdale (G.R. 124030), in a similar geological situation to the late intrusion on Bowness Knott. The fine hybrid rocks in this area formerly enclosed roof pendants of volcanic lavas. Normal granophyre has been intruded along the contact between the hybrid and volcanic rocks. A later intrusion of pink felsitic microgranite now separates the normal granophyre and the hybrid rocks (Fig. 15). Other small masses of felsite, for example a pink felsite dyke one foot thick trending north 20 degrees east across the south end of High Coppice, or an irregular mass of pink felsite in hybrid rocks near Great Coppice, (G.R. 12180324) may be of a similar age to the Latterbarrow felsite.

FIG. 15.



The Latterbarrow Complex
Scale 1inch 100yards

Three parallel dykes of fine whitish-grey microgranite striking 8 degrees north of west, crop out between 600 and 900 feet O.D. on Stair Knott in Ennerdale. These three dykes which are approximately 20 yards thick and 90 yards apart, cut a fourth similar dyke which is striking south 47 degrees east. These dykes were first mentioned by Rastall (1906, pp. 261) and have been described by Hollingworth (in Eastwood et al, 1931, pp.53). Their parallelism suggests that they have been intruded along joints in the granophyre.

A fine porphyritic pink microgranite, very similar to the pink microgranite on Hause is exposed in an irregular shaped outcrop about half a mile across in the vicinity of Deep Gill. The edges of this outcrop are not well exposed, but when seen the contact with the surrounding granophyre is usually sharp. In the middle of the microgranite outcrop is a lenticular outcrop some 300 yards long, of porphyritic brick-red felsite. The felsite is exposed in the bed of Deep Gill from 1100 feet to 1350 feet O.D. The junction between the microgranite and the felsite is diffuse where it is exposed at 1350 feet O.D. in Deep Gill.

## B. Petrography.

The microgranite from Cawfell Beck is a very fine purplish-grey rock containing abundant prominent subhedral prismatic feldspar phenocrysts. The phenocrysts occur in glomeroporphyritic groups up to three millimetres in diameter, but the individual phenocrysts rarely exceed two millimetres in length. The phenocrysts, which are commonly zoned with pink cores and white rims, are set in a pinkish-white felsic base speckled with abundant femic crystals. Rounded clots of a fine basic rock up to one centimetre in diameter are occasionally found in the micrggranite.

In specimens stained with sodium cobaltinitrite potash feldspar is seen to be abundant in the matrix. The plagioclase phenocrysts are commonly rimmed by potash feldspar.

Microgranite from Caw Gill (E8753), is very similar to that from Cawfell Beck (E 8750); (E7851; E8752), but is less conspicuously porphyritic. The matrix is greener in colour and the rock appears to be slightly more basic than the Cawfell Beck microgranite.

These microgranites are very uniform in appearance in thin section. The matrix is mainly composed of quartz, microperthite and plagioclase, with a subhedral granular texture. Microperthite occurs in anhedra and subhedral prisms averaging 0.3 mm. in diameter, but reaching 0.5 mm. in diameter. Plagioclase, oligoclase in composition is common in subhedral prisms up to 0.3 x 0.15 but averaging 0.2 x 0.1 mm. in size. Micro-granite (E 8753) from Caw Gill contains more plagioclase than the other microgranites. Many of the subhedral microperthite prisms have developed by the introduction of potash into plagioclase crystals. Quartz occurs in irregular anhedral crystals, commonly interstitial between the feldspar prisms.

The ferromagnesian minerals usually occur in irregular clots in association with iron ore and accessory minerals. Primary biotite does occur (E 8751, E 8752), but it is most commonly altered to penninite. Iron ore, including both magnetite and ilmenite appears as scattered grains about 0.05 mm. in diameter which reach 0.3 mm. in diameter when associated with the ferromagnesian minerals. The magnetite is fresh, but the ilmenite is commonly altered to leucoxene. Accessory minerals include epidote, calcite, sphene, zircon, apatite and rare tourmaline. Epidote is very common as tiny granules in the feldspar and as pistacite grains up to 0.1 mm. in diameter in the matrix. The zircon and apatite are almost completely confined to the clots of ferromagnesian minerals.

The plagioclase phenocrysts are altered to sericite, calcite, pistacite and chlorite. Determinations of their refractive indices, extinction angles and optic signs suggest that most are oligoclase-andesine but albite may be present.

The felsitic variant of the microgranite which crops out on Stockdale Moor (E8755; G.R. 10940974) is a porphyritic very fine pink felsite. Set in a fine pink matrix are numerous white plagioclase phenocrysts up to three millimetres in diameter, and numerous small femic crystals. Rounded intrusions of fine basic rock occur but are not common.

The matrix of specimen E8755 is chaotic in appearance under the microscope. Plagioclase occurs in thin laths up to 0.2 mm. long. Microperthite occurs in irregular anhedra, in intergrowths with quartz and as laths after plagioclase. Quartz is also present in anhedra up to 0.2 mm. in diameter. Most of the matrix is made up of a very fine cellular intergrowth of microperthite and quartz, and the intergrowth commonly being in the form of feathery spherulites. The ferromagnesian and accessory minerals are similar to those in the microgranite from Cawfell Beck. The plagioclase phenocrysts are fairly fresh and occur both in interpenetrating glomeroporphyritic prisms and as single subhedral prisms. They are mainly oligoclase-andesine in composition.

The microgranite from Hause is a similar porphyritic spherulitic felsite except that it contains more phenocrysts and is coarser grained. Specimen E9307 (G.R. 1123098) also contains numerous crystals of fresh plat-y magnetite. Perthite is more abundant in E 9307 than E 8755. It occurs as rims around the phenocrysts, replacing the pheno-crysts, replacing plagioclase in the matrix and in fine cellular and feathery intergrowths with quartz.

The fine porphyritic microgranite from Deep Gill (E 9507; G.R. 13821234) is practically identical in hand specimen and thin section with the microgranite from Cawfell Beck. The porphyritic red felsite from Deep Gill (E 9499; G.R.1398-1205) is very similar to the felsite on Stockdale Moor (E8755) apart from its deeper colour. Microscopically the spherulitic nature of the matrix is more pronounced in E 9499 than E 8755. The spherulites are approximately 0.6 mm. in diameter and usually have a core formed of a small feldspar prism. Some of the spherulites are composed of radiating feldspar but most are composed of feathery intergrowths of quartz and feldspar.

The microgranite dykes of Mart Knott are composed of a porphyritic greyish-white fine rock (E 9625; G.R. 12701350), in which white glomeroporphyritic plagioclase crystals are scattered through a pinkish white base speckled with femic crystals. The phenocrysts, up to 2.8 mm. long, in groups three millimetres in diameter, are composed of altered andesine $An_{33}$. The matrix is largely composed of ragged plagioclase laths of both albite and andesine compositions, and a cellular intergrowth of untwinned plagioclase and quartz. Some of the feldspar looks perthitic, but staining has shown that there is no potash feldspar in the rock. The usual accessory minerals are present.

The rocks of the late fine grained intrusions on Bowness Knott (E9314) are granophyres very similar to the normal granophyre of the Main Granophyre (see Chapter V.) in hand specimen and microscopically. The plagioclase phenocrysts in the late granophyre are more widely separated than in the normal granophyre so they stand out prominently against the fine pink matrix. The felsite on Brown How (E 8682) is composed of rounded glomeroporphyritic groups of oligoclase-andesine prisms set in a quartzo-feldspathic mosaic. The crystals in the mosaic are rounded, 0.2 mm. in diameter, and have very complex sutured edges.

Modal analyses of microgranites from Cawfell Beck and Deep Gill are given below:-

| | Cawfell Beck E 8750 | Deep Gill E 9507 |
|---|---|---|
| Quartz | 25.3 | 28.8 |
| Microperthite | 55.2 | 57.4 |

| | Cawfell Beck<br>E 8750 | Deep Gill<br>E 9507 |
|---|---|---|
| Plagioclase | 12.9 | 8.7 |
| Ferromagnesian Minerals | 3.8 | 2.8 |
| Iron Ore | 0.6 | 1.5 |
| Rest | 2.2 | 0.9 |

## 3. Felsitic Sills and Dykes.

### A. Field Relationships.

Rastall (ibid., p. 269) has remarked on the scarcity of acid minor intrusions associated with the Ennerdale Granophyre stock. In the present survey, however, over fifty felsite dykes and sills associated with the granophyre have been recorded, many for the first time. These felsitic intrusions are concentrated in three main areas, in the Burtness Combe Intrusive Complex , on Bowness Knott and Crag Fell and on Middle Fell in Wasdale.

Three parallel felsite sills which cross the Burtness Combe Intrusive Complex have been briefly described above (pp. 48 , Fig. 5). The sills vary in thickness, but are usually between fifteen and twenty feet thick. The lowest sill forms a marked feature about 50 feet below the base of the dolerite laccolith in the complex (Photo. 12). Rastall (ibid., Fig. 2) shows this sill joining the middle felsite sill and then continuing onto the Main Granophyre outcrop. The lower sill, however, is well exposed at its north-west end pinching out and ending in two small felsite lenses in the slates. The middle sill is well exposed from close to the granophyre outcrop until it disappears under moraines near Combe Beck. The high sill has been shown in part by Ward and Rastall. It can be traced from just north of Combe Beck at 1250 feet, north-westwards round the nose of High Stile and it is well exposed in the slate cliffs on the north face of High Stile at about 2000 feet. An intrusion of massive pink felsite some twenty feet exposed near Combe Beck (G.R. 177751480) may be part of a fourth sill.

Photo. 12. Felsite Sill. Burtness.

Ward and Rastall both show a felsite sill extending south-eastwards from the south-east end of the laccolith. This sill has not been seen in the present survey, but it may be a continuation of the upper sill that is now covered by scree. Wards has mapped another felsite sill a few feet below Low

Wax Knott, but Rastall suggests that this sill is not related to the Burtness Sills. The south-east end of the sill, however, is a grey flow-banded spherulitic felsite sill, fourteen feet thick, which may well be related to the Burtness Sills. The north-west end of the sill is a porphyritic volcanic lava that Ward has mistakenly connected with the felsite.

A 21 feet thick sill of flow-banded spherulitic felsite cutting the Main Granophyre can be followed from Dodd (G.R. 167159) south-westwards across Sourmilk Ghyll, almost to the edge of the granophyre. This sill has been mapped by Ward as relict bedding in the granophyre. It does not appear to be continuous with any of the Burtness Sills but is believed to be part of the middle felsite sill that has been displaced by a fault.

The sills are composed of pale grey or pink felsite, with chilled edges of a greenish-grey vitreous rock. The felsite is usually prominently flow-banded, and is commonly spherulitic, with the spherulites arranged along the flowbands. Theymay be regular and parallel to the edge of the sill, or irregular and contorted (Photo. 13). The regular flowbanding is most common close to the contact of the sill. A section across the middle Burtness sill is as follows:-

| | |
|---|---|
| Diorite | |
| Regular Flowbanding | 1 foot 8 inches |
| Irregular Flowbanding | 6 feet |
| No Flowbanding | 7 feet |

| | |
|---|---|
| Irregular Flowbanding | 2 feet |
| Regular Flowbanding | 1 foot 4 inches. |
| Skiddaw Slate | |

The regular flowbands of the sill suggest that they dip south-westwards at about 40° to 50° degrees.

Photo. 13. Contorted Flowbanding in Felsite Sill, Burtness.

A series of vertical felsite dykes crop out near Bowness Knott and on Crag Fell in Ennerdale. They are usually between five and ten feet wide and trend between east-west and north-east, south-west. The felsite is pink, flowbanded and spherulitic. Similar felsite also occurs in sills, for example in Rake Beck (G.R.11451604) a sill, dipping at 70 degrees towardx 146 degrees, gives the following section:-

| | |
|---|---|
| Slate | |
| Very Fine Flowbanded pink and green rhyolitic rock | 6 inches |

| | |
|---|---|
| Coarsely Spherulitic Pink Felsite | 3 feet |
| Flowbanded Spherulitic Felsite | 8 feet |
| Slate | |

A plexus of felsite sills and veins in Skiddaw Slates are exposed at the foot of Bowness Knott (G.R.11101540). Many of the veins have been injected along cleavage planes in the slates. A fine pink felsite sill in which the spherulitic structure and flowbanding are particularly well developed can be followed for almost a mile across Scaw on the south side of Great Borne. Its arcuate trend, approximately east five degrees north, suggests that it is a sill rather than a dyke.

A vertical spherulitic felsite dyke near Rake Beck (G.R. 11541597) cuts across a quartz vein in the Skiddaw Slates. The quartz vein is probably associated with the quartz feldspar pegmatite veins of Brown How (see pp.228-9 ). This strongly suggests that the pegmatitic phase of the Ennerdale Granophyre predated the emplacement of the felsite dykes.

Numerous pink felsite dykes are exposed on Middle Fell between Greendale Gill and Nether Beck. Several of these dykes have been mapped by Ward (Six Inch Map LXXIV). The felsite of the dykes have commonly flowbanded but is rarely spherulitic. The majority of the dykes are between five and fifteen feet thick, but the largest dyke, which can be followed from Goat Gill northwards almost to Nether Beck, is sixty feet wide at the foot of Goat Crag. The dykes on Middle Fell form a recti-linear dyke swarm, for they have been intruded along two sets of joints in the Borrowdale Volcanic Series trending south-eastwards and south-westwards respectively.

Hollingworth (1937, pp. 62.) has suggested that the dyke plexus on Yewbarrow is also derived from the Ennerdale Granophyre. The proximity of Middle Fell to Yewbarrow and the similarity between the felsites from the Middle Fell and Yewbarrow dykes supports this suggestion.

Dykes of fine pink felsite are quite common in the vicinity of Buckbarrow. Those exposed in Greendale Gill (G.R. 14370658) and Tongue Gill (G.R. 14140632) are clearly connected with a small outcrop of granophyre on Buckbarrow Moss. Similar dykes near Cat Bields and Glade How are probably derived from the Main Granophyre a short distance below. Two flowbanded grey felsite dykes which cut both the volcanic rocks and the Main Granophyre are exposed in the Buckbarrow cliffs. These dykes are irregular in form because of the control exerted on their intrusion by joints in the volcanic rocks. A six feet wide flowbanded felsite dyke which also cuts the Main Granophyre crops out near Scale (G.R.13390460)

Four previously unrecorded dykes of pink felsite, flowbanded and spherulitic in places, cut the volcanic rocks on the north slopes of Pillar (G.R. 1317). These dykes have been intruded along joints in the volcanic rocks and strike roughly north-south. A similar dyke crops out on Raven Crag on the south side of High Stile.

Hollingworth (ibid), has described two dykes from Cawfell Beck which trend north-west parallel to the margin of the granophyre. A third pink felsite dyke with a similar trend crops out in Cawfell Beck about 100 yards below the margin of the granophyre.

B. Petrography.

The majority of the felsitic intrusions, for example, those in the Middle Fell dyke swarm are composed of pink felsite, but some, the sills of Burtness for instance, are composed of grey felsite. The felsites vary in grain size from extremely fine rhyolitic rocks as seen in specimen E9624 from a sill in Goat Gill (G.R. 0881487) to fine grained felsites as found in the Burtness sills.

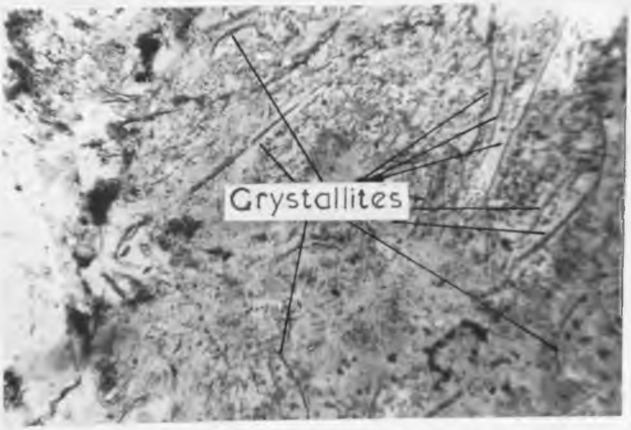
Flowbanding is very common in the felsitic intrusions. The flowbands in Specimen LC2 from the lower Burtness sill are about three millimetres broad and, on a fresh surface, appear as parallel dark and light grey stripes across the rock. The dark grey bands weather out more easily than the light grey bands so that the banding is emphasized on weathered surfaces. Flowbands in specimen LC 430 from Nether Beck (G.R. 147087) appear as fine parallel yellow lines in a pink flinty matrix. Extremely regular flowbanding occurs in the felsite from the sill on Scaw, giving it the appearence of a varved rock. Alternating bands of flesh coloured felsite, one and two millimetres wide respectively, are separated by fine lines of dark felsite.

Spherulitic structures in the felsites are common. The spherulites which vary in size from less than one millimetre to about 2.5 millimetres in diameter, are usually arranged in lines parallel to the flow structures. The spherulites in specimen LC 225 are bright pink with pale cores and darker rims. Those in specimen E 9624 have flesh coloured cores and yellow or black rims. The spherulites in the sill on Scaw grow across flow lines in the felsite and must have formed later than the flow lines.

Porphyritic elements are rare in the felsites. An east-west dyke on Angler's Crag (G.R. 10061502) is made of a porphyritic rock very similar in appearance to the granophyre and may be an apophysis of the granophyre. A second dyke on Angler's Crag (E 9612, G.R. 10051499) is composed of a fine pink porphyritic felsite.

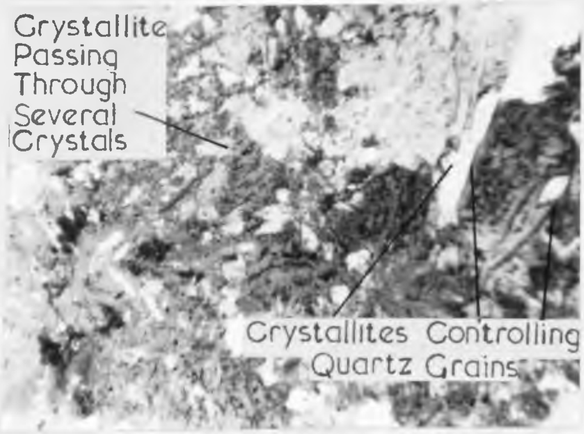
The distribution of potash in the felsites is irregular. It is absent from specimens E 9612, LC2, LC329 from Buckbarrow (G.R. 13600576), and specimen E 8687 from Angler's Crag (G.R. 10061502). The matrix of LC 430 is rich in potash but the fine flow lines are not, and similarly the matrix of LC225 is rich in potash, but not the spherulites. The matrices of specimens E 9624, LC 365, from Pillar (G.R. 168128) and LC 301 from Crag Fell (G.R. 098143) contain little potash, but the spherulites from these specimens are rich in potash. The potash in LC 301 is concentrated around the periphery of the spherulites. Potash is common throughout specimen LC 8 from the middle Burtness sill (G.R. 17841506).

Photo 14a. Normal Light.



Relict Crystallites in Felsite. Goat Gill, Ennerdale.

Photo 14b. Crossed Nicols.



Note: The crystallite in the top right corner forms the edge of two quartz crystals. Others have no effect on the crystals in the felsite.

Microscopically the spherulites in the felsite from Scaw are seen to be composed of a very fine quartz rich quartzo-feldspathic mosaic containing a few flakes of sericite. The grain size of this mosaic is approximately 0.05 mm. in diameter. The spherulites are set in a coarser mosaic 0.5 mm. in diameter grain size in places, which is very rich in sericite, particularly around the spherulites.

Specimen E 9624 from Goat Gill is similar to LC 225 in thin section. The quartz and feldspar in some of the spherulites have grown in fibrous crystals radiating from their centres. The mosaic in the spherulites is usually much finer grained just around their periphery, and this may be the cause of the rims on the spherulites in hand specimens. Threads up to 0.6 mm. in length, composed of chlorite and sericite are common. These threads have controlled the growth of crystals in the matrix in places for they form the edges of some crystals (Photos. 14c and 14b). In most cases, however, the threads pass through the rock irrespective of crystal edges, spherulite edges, or any change in texture. They are believed to be remnants of crystallites from the original glassy rock which has recrystallized into the present felsite.

A similar devitrified glass (E 8687) is found at the tip of the granophyre dyke on Angler's Crag. Numerous corroded phenocrysts of plagioclase, altered to epidote and sericite, are set in a very fine mosaic of feldspar, quartz and epidote. Numerous tiny, parallel acicular crystals of apatite pass through this mosaic irrespective of crystal boundaries. The apatite crystals show the flow directions of the original glassy rock.

A white felsite from the lower Burtness sill (LC2) is coarser than the felsites just described. It is formed of a quartzo-feldspathic mosaic with a grain size of about 0.2 mm. diameter. The crystals have complex sutured margins and they commonly grow in radiating groups to form crude spherulites. Chlorite is much more common than in the other felsites and is concentrated along bands that appear dark grey in hand specimen. Specimen E 9612 from Angler's Crag is very similar in thin section to LC 2. Numerous rounded glomeroporphyritic crystals of oligoclase altered to calcite and sericite are set in the matrix.

### 4. Origin of the Late Acidic Intrusions.

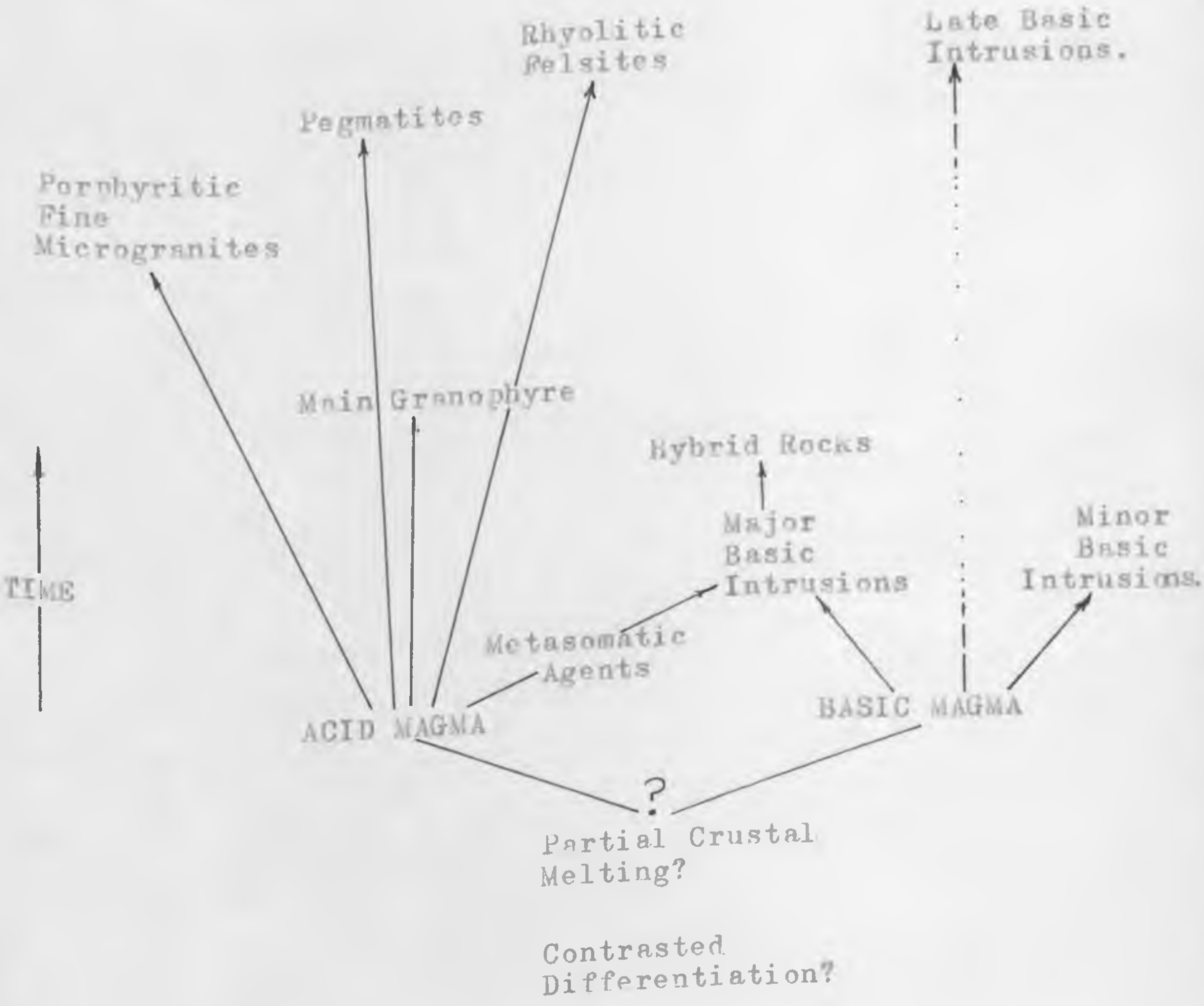
The minor acidic intrusions are younger than the Main Granophyre and represent the last phases in the intrusive history of the Ennerdale Granophyre. The relationships between the different types of these intrusions is unknown, but they must all have been derived from the unsolidified core of the granophyre stock.

The porphyritic microgranites of Cawfell Beck, Deep Gill and Mart Knott, resemble the Main Granophyre in their mineralogy. They were probably derived from the same magma as the Main Granophyre, and were intruded shortly after the solidification of the granophyre. Their fine grained character has probably been caused by chilling against the Main Granophyre. The late intrusion of fine granophyre on Bowness Knott is possibly of a similar origin.

The fel-sites of the sills and dykes associated with the granophyre differ from the microgranites in that they contain very few, if any, feldspar phenocrysts. The two porphyritic dykes on Angler's Crag are the only exceptions to this rule. This lack of feldspar phenocrysts in the felsites suggests that they may come from a different source to that of the porphyritic microgranites. The felsites are younger than the microgranites, for a felsite dyke cuts the microgranite in Cawfell Beck (Hollingworth, in Trotter et al, 1937, pp. 62), The felsites are also younger than the pegmatites associated with the Ennerdale Granophyre.

## PETROGENESIS.

The genesis of the various rock types making up the Ennerdale Granophyre is summarized below.



The association of basic and acid magmas in the Ennerdale Granophyre is similar to that found in numerous intrusive complexes, the best known being in the Tertiary Igneous Province of Scotland. Opposing theories concerning the origin of this association have been put forward by Nockolds (1934; 1936) and Holmes (1931; 1936). Nockolds proposes the theory of contrasted differentiation, believing that differentiation of a basic magma is the main factor in the formation of an acid magma. Holmes believes that acid magmas are mainly formed by refusion of the earth's granitic crust, and differentiation is relatively unimportant.

In the case of the Ennerdale Granophyre the great bulk of acidic rocks compared with basic rocks favours Holmes's theory rather than Nockold's.

# VII STRUCTURE.

## I. FOLDING.

### A. Introduction.

The major structural features in the Lower Palaeozoic rocks of the central Lake District were produced during the Caledonian Orogeny. Important folds of two ages, Pre-Bala and Devonian, have been identified. No folds of post-Devonian age have been recognised within the central Lake District.

The Pre-Bala fold movements have resulted in the unconformity that separates the Borrowdale Volcanic Series and the Coniston Limestone Series. This unconformity is best seen in the Duddon and Coniston districts where the strikes of the two series are almost at right angles, (Mitchell, 1940, 1956; Firman, 1957). Mitchell (1940, pp. 313) estimated that in less than three miles between Coniston and High Pike Haw the base of the Coniston Limestone Series transgresses over two thousand feet of the Borrowdale Volcanic Series. The Pre-Bala movements and the subsequent denudation must have been quite considerable to have produced such an unconformity. The Pre-Bala folds have been recognized elsewhere by their effect of altering the pitch of later Devonian folds which cross their axes, (Mitchell, 1956, pp. 431; Firman, 1957, pp. 56; Oliver, 1961, pp. 384.). The trend of the Pre-Bala axes is east-north-east in the Kentmere district (Mitchell, 1929, pp. 30-33) and north-north-east in the Duddon district (Firman, 1957, pp. 56).

The main fold movements affecting the Lake District were of Devonian age. Their lower age limit can be fixed by the fact that they affected all rocks up to and including those of Ludlow age. The Mell Fell Conglomerate, possibly of Lower Old Red Sandstone age (Capewell, 1955), resting with strong unconformity on the strata folded by these movements gives them an upper age limit. The Skiddaw Slates and the Borrowdale Volcanic Series reacted differently during the Devonian earth movements. The Skiddaw Slates acted incompetently and were crumpled into a series of very tight, often overturned folds, which trend approximately west 40 degrees south. The slates were intensely cleaved and often disrupted by thrusting. The Borrowdale Volcanic Series reacted much more competently and were folded into relatively open folds trending approximately west-south-west.

## B. The Folding of the Skiddaw Slates in the Vicinity Of The Ennerdale Granophyre.

The Skiddaw Slates have been folded into a series of tight folds with axes trending approximately west 40 degrees south. Rose, (1954, pp. 405) gave the lines of two anticlinal axes which pass close to the thesis area as "Barf, Whinlatter Pass, Whiteside, Grisedale Pike and Brackenthwaite," and "Newlands, Cat Bells, Little Dale, Robinson and Buttermere," (see Fig. 3). The first axis is continuous with the anticlinal axis through Skiddaw (Geological Survey One Inch Geological Sheet 23, New Series.) and the axis along Croasdale Beck to Dent (Eastwood et al, 1931, pp. 14). This axis is named the Skiddaw anticline on Fig. 3.

The structure described above is very generalized, for when examined in detail the structure is complicated by the common occurrence of overfolding, thrusting and isoclinal folding (Rose, 1954, pp. 404). In such an area the knowledge of the true dip of the beds is important and criteria such as current bedding, for the determination of the true top and bottom of the beds are necessary before any detailed structure can be worked out.

North of Ennerdale the Skiddaw Slates of the thesis area lie in a syncline between the two anticlines described above. The regional dip, however, is constantly to the south-south-east at about seventy degrees in the Buttermere district. The simplest structure that is possible in the area is, therefore, an isoclinal syncline overturned to the north-north-east. Unfortunately this structure could not be confirmed during the present work, as no criteria for the determination of the true top and bottom of beds were found. A minor anticline trending east thirty-five degrees north passes through Herdus on the north side of Ennerdale, but quickly dies out in both directions (see Fig. 3).

The Skiddaw anticlinal axis passes along Croasdale Beck south-westwards to Dent. The Skiddaw Slates south of Ennerdale, south-east of this axis have a reasonably constant dip. Their dip is usually within a few degrees of south, but most often it is a few degrees east of south. The structure appears to be simply a uniformly dipping limb of an anticline but this may be deceptive. The lack of variation in lithology of the slates of the entire area (see pp. 13-6 ) would make the identification of isoclinal folding, faulting or thrusting, very difficult.

Assuming that the structure south of Ennerdale is as simple as it appears, that is, there are no overfolds, faults or thrusts, the apparent thickness of the slates can be determined. A line of section from between Fellend Farm and Oxenstone Beck, near Ennerdale, along a bearing south twenty degrees east to the base of the Latterbarrow Sandstone is, within a few degrees, along the dip of the Skiddaw Slates. The amount of dip varies from thirty degrees to fifty degrees. Assuming the Skiddaw Slates have a dip of thirty degrees along the line of section, their apparent thickness is 5,500 feet. This thickness is entirely in the Mosser-Kirkstile Slates and is not the full thickness of the Mosser-Kirkstile Slates, as their base is not reached by the section. The apparent thickness of 5,500 feet plus for the Mosser-Kirkstile Slates south of Ennerdale may be compared with the thickness of 2,500 feet plus in the Keswick and Buttermere district (Rose, 1957, pp. 403).

### C. The Folding of the Borrowdale Volcanic Series in the Vicinity of the Ennerdale Granophyre.

The major structural feature of the Borrowdale Volcanic Series in the vicinity of the Ennerdale Granophyre is the Scafell Syncline. This syncline has been traced from Ullswater, (Moseley, 1960) through Helvellyn (Hartley, 1941) to Scafell (Oliver, 1961). The axis of the syncline trends approximately west-south-west.

The outcrop of the Borrowdale Volcanic Series is almost cut in two by the outcrop of the Ennerdale Granophyre. In the Scafell region the Scafell syncline is a simple, broad, shallow syncline pitching to the east-north-east (Oliver, 1961, pp. 383). The south-easterly regional dip between Great Gable and the eastern edge of the Ennerdale Granophyre shows that this syncline continues as far as the granophyre (Geological Survey, one inch Geological Sheet. 101 S.E. Old Series).

West of the granophyre the folding is more complex (Hollingworth, in Trotter et al, 1937, pp.8). A syncline pitches to the west with its axis trending almost due west from near Windsor Farm to the Bleng Valley. The pitch of this syncline is clearly shown by the easterly closure of the V shaped outcrop of a series of rhyolites and dacites on Hollow Moor (G. R. 108056, Geological Survey, Geological Sheet 37, New Series). This syncline is succeeded to the south by a very tight steep anticline which in turn is succeeded by a tightly folded syncline (see section 2, Geological Sheet 37.) The axis of the latter two folds trend approximately east-north-east, the anticline through Wrighthow and the syncline through Craghouse.

The relationships between the folds on either side of the Ennerdale Granophyre are difficult to determine. The northerly syncline west of the granophyre is continuous with the Scafell syncline to the east because the rhyolite and dacite group mentioned above can be traced without a break from the north limb of the syncline in the west to the north limb of the Scafell syncline. The southern syncline to the west of the granophyre may be the result of a bifurcation of the Scafell syncline, or it may be independent of the Scafell syncline, either hypothesis being impossible to prove or disprove.

The Scafell syncline to the east of the Ennerdale Granophyre pitches to the west. The culmination of the pitch of the synclinal axis almost coincides with the present outcrop of the granophyre. From a study of the strike of the base of the Dacite Group on Seatallan the culmination appears to be approximately half a mile north-east of Cat Bields (G.R. 134076). The culmination in the synclinal axis is caused by an anticline crossing the syncline. The Borrowdale Series on either side of the Ennerdale Granophyre dip into the synclines on the respective sides. The axis of the anticline must, therefore, pass along the present outcrop of the granophyre in an approximately north-south direction. The anticline looks as though it is due to an uplift by the intrusion of the Ennerdale Granophyre. The pitch of the Scafell syncline, however, continues unchanged as far as Ullswater, fifteen miles away, and is independent of the granophyre. The writer believes that the anticline is, in fact, older than the Scafell Syncline, possibly of pre-Bala age.

## 2. FAULTING.

### A. Introduction.

A prominent pattern of high angled faults has been recognized by all the people who have worked on the Borrowdale Series. The major fault directions are approximately north-north-east and north-west (Fig. 2). Many of the north-westerly faults have a horizontal displacement and are tear faults rather than normal faults (Mitchell, 1956, pp. 405; Moseley, 1960, pp. 72). It is seldom possible to distinguish high angled Devonian faults from high angled faults of a later age when the faults were confined to the Lower Palaeozoic rocks.

Low angled faults or thrusts can be considered, with some certainty, to be of Devonian age as such faults are not found in the Carboniferous or younger rocks of the western Lake District (Hollingworth, in Trotter et al, 1937, pp,9). Large scale thrusting occurs at two horizons, at the junction between the Skiddaw Slates and the Borrowdale Series, and in the Stockdale Shales which overlie the Conniston Limestone Series. The Stockdale Shales are notably incompetent shales and the Skiddaw Slates are incompetent in comparison with the Borrowdale Series. It is believed that the great compressional forces involved in the Devonian fold movements were partially relieved by movements along these imcompetent horizons (Mitchell 1956, pp. 442). The thrusting must therefore have been, in part at least, contemporaneous with the folding.

Many of the north-westerly high angled faults have been shown to stop at the thrust within the Stockdale Shales. Mitchell (1956, pp. 445), from evidence at Coniston and in the Dunnerdale Fells, suggested that both sets of faults were approximately contemporaneous, with the thrusts being formed a little later than the north-west tear faults. Moseley (1961, pp 79) stated that in the Ullswater district the initial thrusting was contemporaneous with the fold movements. After the folds had formed, a system of north-west wrench faults associated with renewed thrusting was initiated.

The youngest group of faults are the north-north-easterly or northerly suite of high angled faults (Hartley, 1932, pp. 60; Moseley, 1960, pp. 79). The age of these faults is uncertain, they may be Devonian, Hercynian or Alpine in age (Mitchell, 1956,b, pp. 442). Many Devonian faults have probably been rejuvenated during the later Hercynian or Alpine earth movements, so complicating the crosscutting relationships on which their relative ages are based.

## B. High Angled Faults.

### (i) The Nature of the Fault Planes.

The high angled faults of the area under discussion fall into three sets trending approximately west-north-west, north-west, and north; or north-northeast. The first two sets are probably tear faults (see below, p.173 )but there is very little evidence on the actual fault planes to show whether they are tear or normal faults.

A fault passing through the granophyre would be expected to leave some slickensides showing the direction of movement along the fault plane. This may have happened, but the granophyre along most fault planes is now weathered to a rough surface showing no slickensides. The Combe Beck Fault (G.R. 182150) trending north-north-west, has a footwall dipping west at between forty and eighty degrees which is grooved. The grooves dip south at about twenty degrees suggesting that there was a large element of strike slip in the fault movement. Actually it is the mineralized zone along the original fault that has been grooved, therefore, the only thing the grooving indicates is that the last movement along the fault had a large element of strike slip.

There are several places where the rejuvenation of a fault can be proved. Combe Beck Fault described above has clearly had at least two periods of movement separated by a period of mineralization. Similarly many faults have deposits of haematite along their courses and later movements along the faults have brecciated the primary haematite. Examples of brecciated heamatite can be found on almost all spoil tips of the iron ore mines in Ennerdale.

Faults have affected the granophyre in several ways. Movement along the Scale Beck Fault (Map 2 ) near Buttermere has induced jointing in the granophyre parallel to the fault line. Scale Beck, taking advantage of the well jointed rock, has cut a deep gorge along the fault line between two prominent joint faces. Scale Force is a waterfall at the head of this gorge. Faults within the granophyre sometimes have no apparent effect and cannot be traced, The Haycock Fault on the south slopes of Ennerdale (G.R. 133118) cannot be traced three hundred yards after the granophyre is exposed on both sides of the fault plane. A small fault at the west end of Gale Fell (G. R. 135167) and Combe Beck Fault in Burtness Combe are marked by prominent angular fault breccias with a pure quartz cement. Occasionally the rock is finely brecciated so that it is reduced to a granular aggregate of quartz, feldspar and ground rock loosely cemented together. At the west end of Silver Cove Crags (G.R. 127110 ) such a rock is rapidly breaking up into a fine gravel as the component parts separate.

A fault through the rocks of the Borrowdale Series usually induces parallel jointing within the rocks, or brecciates the rock in a narrow smash belt. In either case the lines of weakness are quickly eroded out and the fault lines are marked by gorges or gullies. The gullies at the head of Mirklin Cove in Ennerdale are cut along fault lines. There is little difficulty in following faults through the Borrowdale Series because of the erosion of gullies along their courses and the readily recognizable displacement of marker horizons in the Borrowdale Series by the faults.

The hardened Skiddaw Slates within the metamorphic aureole of the Ennerdale Granophyre are usually smashed by faults, in places, as in Red Gill (G. R. 128170), upto ninety yards from the fault plane. The smash belts have commonly been later mineralized by haematite. Faults are very difficult to trace through the soft unaltered Mosser Kirkstile Slates. They apparently produce a gouge along the fault plane which welds up the fault and leaves no line of weakness for either mineralization or erosion to follow. The difficulty is also increased by the uniformity of the Mosser Kirkstile Slates for there are no marker horizons to help locate a fault. It is this difficulty in identifying faults rather than true lack of faults that has led to the apparently unfaulted character of the Mosser Kirkstile Slates on many maps of Skiddaw Slates (see the Geological Survey, Geological One Inch Sheet 28, New Series). Another result of this difficulty in identifying faults is the way in which many faults apparently die out on entering the Mosser Kirkstile Slates, for example all the faults which cut the Latterbarrow Sandstone apparently stop on entering the Mosser Kirkstile Slates to the north.

### (ii) The North-North-Easterly Faults.

The north-north-easterly faults tend to be insignificant, the most important being the Greendale Fault, the Scale Beck Fault and the Grey Crag Fault Belt (Map. 1). Several small northerly faults cut the contact of the Ennerdale Granophyre along its northern edge in the Buttermere valley. The vertical throw on all these faults is small.

The Greendale Fault displaces the contact of the granophyre from near Countess Beck, 1100 yards to the north up Greendale. The actual vertical throw of the fault, however, is probably not more than one hundred feet, the great horizontal displacement being due to the fact that the morphology of the present landscape at this point is very similar to that of the surface of the granophyre. On the west side of the Greendale Fault the roof of the granophyre has just been eroded away, exposing the granophyre while on the east side of the fault a thin skin of volcanic rocks is still covering the granophyre.

The Grey Crag Fault Belt is very impressive on the ground, (Photo. 15), but the vertical throw of the fault belt as a whole on Grey Crag is less than one hundred feet. On the south side of Ennerdale below White Pike, the total throw of the fault belt appears to be approximately three hundred feet.

The Scale Beck Fault, despite the deep gorge cut along its fault plane, has a vertical throw of less than fifty feet.

There is no evidence upon which to decide what type of faults the north-north-easterly faults are. If Scale Beck Fault was a tear fault of any great importance, then a much greater displacement of the contact of the granophyre would be expected. The Grey Crag Fault Belt is a fault complex in which, in the High Stile area at least, the country is broken into a large scale 'breccia'. Such a thorough shattering of the area suggests that the movement along the faults was not

Photo. 15.

Burtness Combe.

just a simple downthrow of a hundred feet. There have probably been repeated movements, possibly downthrowing in different directions, with different movements, subjecting the rocks to a grinding motion.

### (iii) North-Westerly Faults.

The north-westerly faults are the most important high angled faults of the area under discussion. There are several north-westerly faults with small or undetermined throws such as the fault along Deep Gill in Ennerdale and the group of faults which cut the Latterbarrow Sandstone (Figure 3). The most important of this suite of faults are the Haycock Fault, and the Red Gill Fault.

The Haycock Fault can be traced from Waver Beck (G.R. 148096) north-westwards below Gowder Crag onto the ridge at the head of Silver Cove. The line of the fault swings almost due north on crossing the ridge and can be followed as far as an old level above Silver Cove Beck (G.R. 133199). The swing of the fault line on the ridge is due to the low dip of the fault, which actually strikes approximately north 38 degrees west and dips at 30 degrees to the north-east. A study of Map 2 suggests that this fault is probably a tear fault. The flat dome of the roof of the intrusion, possibly dipping eastwards, occurs to the west of the north end of the Haycock Fault. East of the fault at this point the roof of the intrusion is dipping south at ten degrees. The only part of the roof of the intrusion, west of the fault, with a similar southerly dip, is a mile to the south-east. This fact cannot be explained by a purely vertical throw of the fault. The east side of the fault must have moved to the north-west with respect to the west side. There was probably also a vertical component in the fault movement downthrowing to the east. The correctness of this interpretation depends entirely on the accuracy of the structure contours on Map 2.

The Red Gill Fault can be traced from near Floutern Tarn south-south-eastwards into Ennerdale, where it is almost certainly continuous with the fault that passes on the north-east side of Tewit How into Mirklin Cove. The fault downthrows approximately 250 feet to the west in the Tewit How area while in the Red Gill area it downthrows to the east. North of Ennerdale the Red Gill Fault shows several interesting features. It displaces the contact of the Ennerdale Granophyre on its west side from Starling Gill over a mile north-north-westwards to Red Gill, while the edge of the metamorphic aureole of the granophyre on the west side of the fault is displaced fifteen yards to the south-south-east. The metamorphic aureole near the mouth of Red Gill is approximately 15 yards wide on the west side of the fault and over a mile wide on the east side. The slight south-south-easterly displacement of the edge of the metamorphic aureole on the upthrow side of the Red Gill Fault can only be explained if the east side of the fault has mo-ved north with respect to the west side of the fault. It is impossible, however, to decide how much movement has taken place along the fault from the displacement of the edge of the metamorphic aureole. This displacement is dependent on the relationship between the resultant of the vertical and horizontal movements along the fault, and the dip of the edge of the metamorphic aureole. If the resultant of the vertical and horizontal movements along the fault was parallel to the dip of the edge of the aureole, then there would be no displacement of the edge of the aureole, whatever the throw of the fault. The narrowness of the aureole along the north flank of Gale Fell suggests that the great width of the aureole east of the Red Gill Fault is anomalous. The surface of the granophyre is most likely close to the present surface over much of the area and the throw of the fault is probably not very great.

### (iv.) The West-North-Westerly Faults.

A tear fault trending approximately west-north-west passes through the col between Bowness Knott and Brown How in Ennerdale. The vertical contact of the granophyre on the north side of the fault is displaced approximately 120 yards to the east-south-east (Hollingworth in Eastwood et al, 1931, pp. 50). A similar tear fault along Ennerdale Water has displaced the contact of the granophyre on its north side approximately 350 yards to the east-south-east (see Map. 2). On top of Boathow Crag (G.R. 109134) a fault trends west 30 degrees north and dips to the north at 80 degrees. There is a prominent belt of jointing in the granophyre parallel to the fault line. No definite evidence is available to show whether this fault is a tear fault or not, but its west-north-westerly trend suggests that it does belong to this suit of tear faults.

## C. Low Angled Faults.

### (i) The Contact Between the Borrowdale Volcanic Series and the Skiddaw Slates.

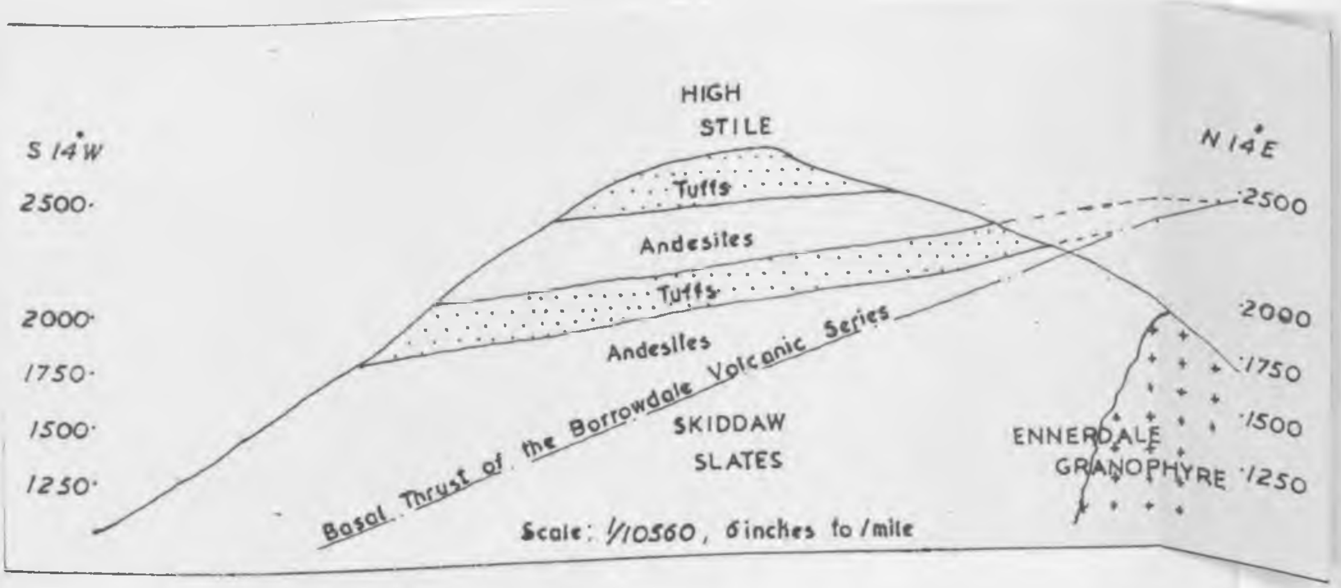
#### (a) The High Stile Area.

The junction between the Skiddaw Slates and the Borrowdale Volcanic Series in the High Stile area is a low angled fault. The presence of this fault is revealed by the divergence of the strike of the Borrowdale Volcanic Series and the junction between the Borrowdale Series and the Skiddaw Slates. The strike of the Borrowdale Series on the High Stile ridge is a few degrees west of south. The strike of the junction of the Borrowdale Series and the Skiddaw Slates is variable; on High Stile it is a little north of west, while on Fleetwith Pike to the east of the present area (Geological Survey Six Inch Geological Sheet LXIX Old Series), it is east 30 degrees south.

The dip of the fault plane is difficult to determine, but assuming that the dip on High Stile is a little west of south, then it must exceed 15 degrees, for the Skiddaw Slates do not outcrop in the bottom of Ennerdale. The way that the outcrop of the fault plane climbs gently up hills and then drops down to the south in intervening combs suggests that the dip of the fault plane is quite low, probably not exceeding 30 degrees. The junction between the Borrowdale Series and the Skiddaw Slates from the bottom of Burtness Combe almost to the top of High Stile is practically vertical. This contact is believed to be a high angled fault and not the low angled fault.

The result of the divergence in strike between the low angled fault plane and the Borrowdale Series is most noticeable in the High Stile area where the two strikes are practically at right angles to each other. The lower members of the Borrowdale Series are cut out to the north by the rising fault plane (Fig. 16). The basal member of the Borrowdale Series in this area, a series of fine blue andesites, is exposed along the ridge overlooking Bleaberry Tarn in a continuous dip section for over half a mile. The thickness of andesites in this section is approximately 1000 feet, yet on the north nose of High Stile, only half a mile to the north, these andesites are entirely cut out by the fault. The fine blue andesites reappear again east of High Stile in Burtness Combe.

The junction between the Skiddaw Slates and the Borrowdale Series is exposed for three hundred yards on the north side of High Crag (G.R. 182146). There is little evidence at the junction of the presence of this fault. The Borrowdale Series appear to be unaffected, but a 'tectonic conglomerate' is exposed in the Skiddaw Slates below the junction (see pp. 14-15 ).



Vertical Section of High Stile.

### (b) Relationships between the Contact in the High Stile Area and the Contact Further East.

The contact between the Borrowdale Series and the Skiddaw Slates was believed by Ward (1876a, pp. 46) to be faulted over all its outcrop shown on the Geological Survey One Inch Geological Sheet 101 S.E. Old Series. This was later disputed, particularly by Green (1920) who suggested that there was a conformable passage from the Skiddaw Slates to the Borrowdale Series. Recent work at Ullswater (Moseley, 1960, pp. 70) supports Ward's interpretation by proving that the contact is a thrust which has cut out up to 3500 feet of the basal members of the Borrowdale Series. Moseley thought that the thrust was "a thrust of modified decollement type, largely due to the disharmonic relation between the two groups". The mapping by Ward has also been verified to a large extend by the present work in the High Stile area. The general accuracy of Ward's mapping of the Borrowdale Series in contact with the Skiddaw Slates has, therefore, been verified over six miles of contact and it appears likely that his mapping of the faulted contact will be similarly correct over the rest of its outcrop (Rose, 1954, pp.406). The entire contact from High Stile to the Ullswater district is, therefore, believed to be a thrust which, over much of its outcrop, has removed the basal members of the Borrowdale Series.

### (c) West of the Ennerdale Granophyre.

The complex relationships between the Borrowdale Series and the Skiddaw Slates west of the Ennerdale Granophyre have been fully described by Hollingworth (in Trotter et al, 1937, pp. 8-12). The youngest unit of the Skiddaw Slates, the Latterbarrow Sandstone, has been thrust a mile or more to the north over the Mosser Kirkstile Slates. The Mottled Tuffs have been thrust northwards under the Latterbarrow Sandstone. The junction between the Mottled Tuffs and the overlying andesitic lavas may be normal, an overthrust, or a fault.

### (d) Origin of the Basal Thrust of the Borrowdale Volcanic Series.

It is generally accepted that the thrust at the base of the Borrowdale Series originated during the Caledonian Fold Movements and is connected with the relative competencies of the Borrowdale Series and the Skiddaw Slates. The effect of compressional forces during orogenies is to decrease the lateral extent and increase the vertical thickness of any beds under compression. Rocks under such pressures can respond in three ways, by being folded, disrupted by thrusting, or cleaved.

The Skiddaw Slates have reacted incompetently relative to the Borrowdale Series under the compressive forces of the Caledonian orogeny. They have been tightly folded, thrusted and cleaved. The decrease in their lateral extent, calculated from a section by Rose (1954, facing pp. 404) is of the order of 30%. Many of the faults on this section are normal faults which increase the lateral extent of the slates, so that the decrease due to folding alone must be greater than 30%.

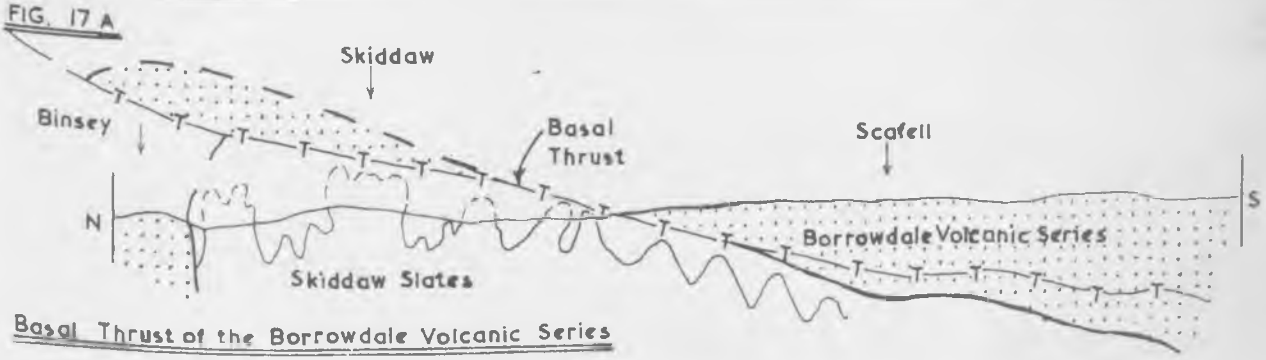
The Borrowdale Series have been folded into broad folds of relatively long wave length and small amplitude. The reduction of their lateral extent, calculated from five sections by Hartley (1925; 1932) is in the order of 10%. This leaves a difference of approximately 20% between the relative reductions of the lateral extent of the Skiddaw Slates and the Borrowdale Series.

The sections on which the above calculations are based take into account both the folding and the cleavage of the rocks. Assuming that the lateral extent of the Skiddaw Slates and Borrowdale Volcanic Series have been reduced by the same amount, the difference of some twenty percent in their apparent reductions must be explained by thrusting in the Volcanic Series. There have, however, been very few thrusts identified in the Borrowdale Series, therefore the Borrowdale Series must have moved as a unit over a single basal thrust. The vertical, or near vertical, dips of the Borrowdale Series in the Binsey area of the northern Lakes District (section in Eastwood, 1946, pp.16) suggest that the Borrowdale Series may have been folded into a large asymmetric anticline over the Skiddaw Anticlinorium, which broke at its crest as its south limb was thrust northwards, (Fig. 17. a).

If it were possible for the Borrowdale Series to have remained a relatively rigid block while the incompetent Skiddaw Slates were folded beneath it, then a dislocation would take place at the base of the Borrowdale Series. The dislocation would, in this case, be a décollement dislocation

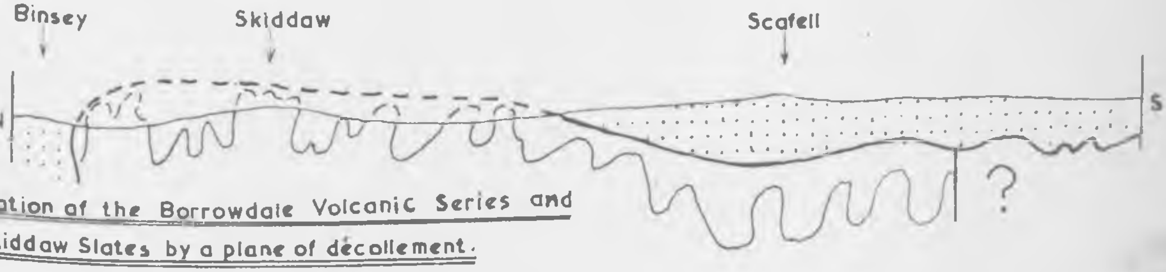
(Fig. 17.b). The plane of separation would, however, be expected to be found below, rather than in, the Borrowdale Series. Wedges from the base of the Borrowdale Series may have been torn off by the movement of the Skiddaw Slates underneath, but this effect would be locallized and not as extensive as the proven basal thrust of the Borrowdale Series.

FIG. 17 A



Basal Thrust of the Borrowdale Volcanic Series

FIG 17 B



Separation of the Borrowdale Volcanic Series and the Skiddaw Slates by a plane of décollement.

Scale. 1/4 inch = 1 mile.

The form lines in the Skiddaw Slates are diagrammatic

The writer believes that the evidence available at the present time supports the first hypothesis rather than the second. It is quite likely, however, that both pure thrusting and pure décollement movement have played a part in the formation of the basal thrust.

### (ii) The Floutern Crag Thrusts.

A suite of small thrusts displacing the contact of the Ennerdale Granophyre are exposed on Floutern Crags near Buttermere (Fig. 18). Three of the thrust planes have the following dips:-

60 degrees at 172 degrees; 58 degrees at 147 degrees and 47 degrees at 172 degrees.

These thrusts cannot be associated with the basal thrust of the Borrowdale Series because the latter is earlier than the Ennerdale Granophyre which is cut by the Floutern Crag thrusts. They may have been produced by fold movements later than the main Caledonian fold movements, or they may be marginal upthrusts associated with the intrusion of the granophyre (Balk, 1948, pp. 101-6). The displacement of three feet or more by marginal upthrusts mentioned by Balk, however, suggest that the Floutern Crag thrusts, with displacements of 150 yards, are too large to have originated in this way.

## (3) The Age Relationships of the Ennerdale Granophyre and Neighbouring Structures.

### (A) Folding.

The direction and form of the Caledonian fold axes in the Skiddaw Slates are not affected in any way by the Ennerdale Granophyre. Similarly the Ennerdale Granophyre and its metamoprhic aureole are not affected by the Caledonian folds.

If the intrusion of the granophyre had predated the Caledonian fold movements the granophyre may be expected to have acted as a rigid block and deflected some of the orogenic forces to give the Caledonian fold axes within its zone of influence some arcuate form which would have shown the effect of the intrusion. Folds, such as the Herdus anticline, which cross the metamorphic aureole would be expected to have affected its outline. The fact that no such effect can be detected suggests that the intrusion post dates the main Caledonian fold movements.

Numerous minor intrusions of greater age than the fold movements have been identified in the Skiddaw Slates (Appendix 2A). These pre-Caledonian intrusions clearly precede the major fold movements, for they have been extremely altered, folded and disrupted , together with the Skiddaw Slates in which they occur. The minor intrusions associated with the Ennerdale Granophyre, however, are fresh and unaffected by the fold movements.

The cleavage of the Skiddaw Slates is greatly reduced in intensity in the hornfelsed zone of the granophyre's metamorphic aureole. Rastall, (1906, pp. 269) believed that the intrusion of the granophyre preceded the major fold movements during which the mass of the granophyre protected the Skiddaw Slates from the forces from the south-east so that they were little cleaved. The low degree of cleavage was attributed by Green, (1917, pp. 15) to the resistance of the Ennerdale Granophyre and its hardened aureole to the cleavage forces. The low degree of cleavage can also be explained if the intrusion post-dated the fold movements, for the metamorphism by the granophyre would tend to weld the previously cleaved slates into massive hornfels.

The Skiddaw Slates are veined by fine granitic veins from the granophyre close to its contact on the south side of Herdus (Fig. 11). These would most likely have been disrupted if the intrusion was earlier than the fold movements.

The contact of the granophyre and the Borrowdale Series between Burtness Combe and Haycock is remarkably parallel to the bedding of the Borrowdale Series. Green (1917, pp. 15) believed that this proved that the intrusion preceded the fold movements. This parallelism is, however, readily explicable if the intrusion was later than the fold movements (see below, pp. 198-200).

The Ennerdale Granophyre clearly truncates the folds in the Borrowdale Series in Wasdale on its west side. The intrusion must, therefore, be later than the folds.

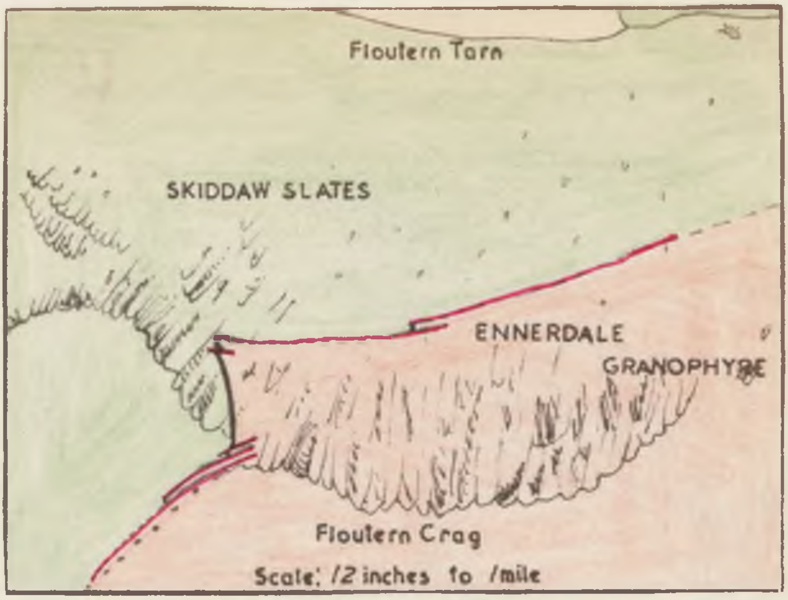
The Scafell syncline is crossed near Catbields on Seatallen by a northerly anticline (see p. 172). The anticline was possibly in existance before the initiation of the major Caledonian fold movements and is probably of pre-Bala age.

There is a well developed reticulate dyke swarm on Middle Fell in Wasdale. The dykes, associated with the Ennerdate Granophyre, are intruded along prominent joints in the Borrowdale Series. The dykes must, therefore, be later than the joints. The dykes trend in two directions, approximately parallel to the strike and dip of the Barrowdale Series. This suggests that the joints were formed in association with the folding of the Borrowdale Series and were later filled with the dykes. The dykes from the Ennerdale Granophyre are, therefore, probably later than the folds.

Some of the evidence discussed above is ambiguous, some is rather hypothetical, but in balance, the evidence supports the theory that the intrusion of the Ennerdale Granophyre postdated the main Caledonian fold movements.

### (B) Faulting.

The basal thrust of the Borrowdale Series can be followed westwards from High Stile, dipping gently down, across Bleaberry Combe to its contact with the Ennerdale Granophyre under Red Pike. There the thrust plane is bent abruptly upwards and it climbs over Red Pike, separated from the granophyre by a thin wedge of Skiddaw Slates. A mile to the west of Red Pike lavas of the Borrowdale Series occur resting at a gentle angle on Skiddaw Slates, in the roof the granophyre on Little Dodd and Starling Dodd. The intrusion of the granophyre has lifted its roof on Red Pike approximately 300 feet producing a sharp monocline in the basal thrust of the Borrowdale Series. The granophyre must, therefore, be later than the thrust and the earth movements that produced the thrust. It could be argued however, that the same monocline would be produced by a deflection of the thrust plane by a massive intrusion before the fold movements.



Thrusts on Floutern Crag, Herdus.

The Ennerdale Granophyre is cut by numerous high angled faults of three main trends, north-west, east-south-east, and north, or north-north-east (see above). By comparison with other areas of the Lake District most of these faults are believed to be of Devonian age. The granophyre is, therefore, older than the late Caledonian faulting.

The Herdus thrusts (p 189) and the brecciation of the granophyre along its contact in Low Beck may be due to low angled movements initiated during the final phases of the fold movements.

Evidence provided by the faulting shows that the intrusion of the Ennerdale Granophyre postdated the major thrusting but predated the phase of high angled faulting. The intrusion may have taken place before the end of all the fold movements.

## (4) The General Relationships of the Ennerdale Granophyre to the Structure of the Western Lake District.

A glance at a geological map of the western Lake District will reveal a remarkable parallelism between the outcrop of the eastern edges of the Ennerdale Granophyre and the Eskdale Granite and the outcrop of any particular horizon, for example the top of the Lower Andesites, in the Borrowdale Series (Fig. 19). The concordance between the Ennerdale Granophyre and the Borrowdale Series is most perfect from Burtness Combe to Haycock (see also Ward, 1876, pp. 15).

The outcrop of the Ennerdale Granophyre is elongated along the northerly pre-Bala anticline that crosses the Scafell syncline on Seatallan. The Eskdale Granite outcrop is elongated along the Langdale anticline and, near Muncaster, it is elongated parallel to the north south trend of the Borrowdale Series (Rose, in Trotter et al 1937, pp. 52).

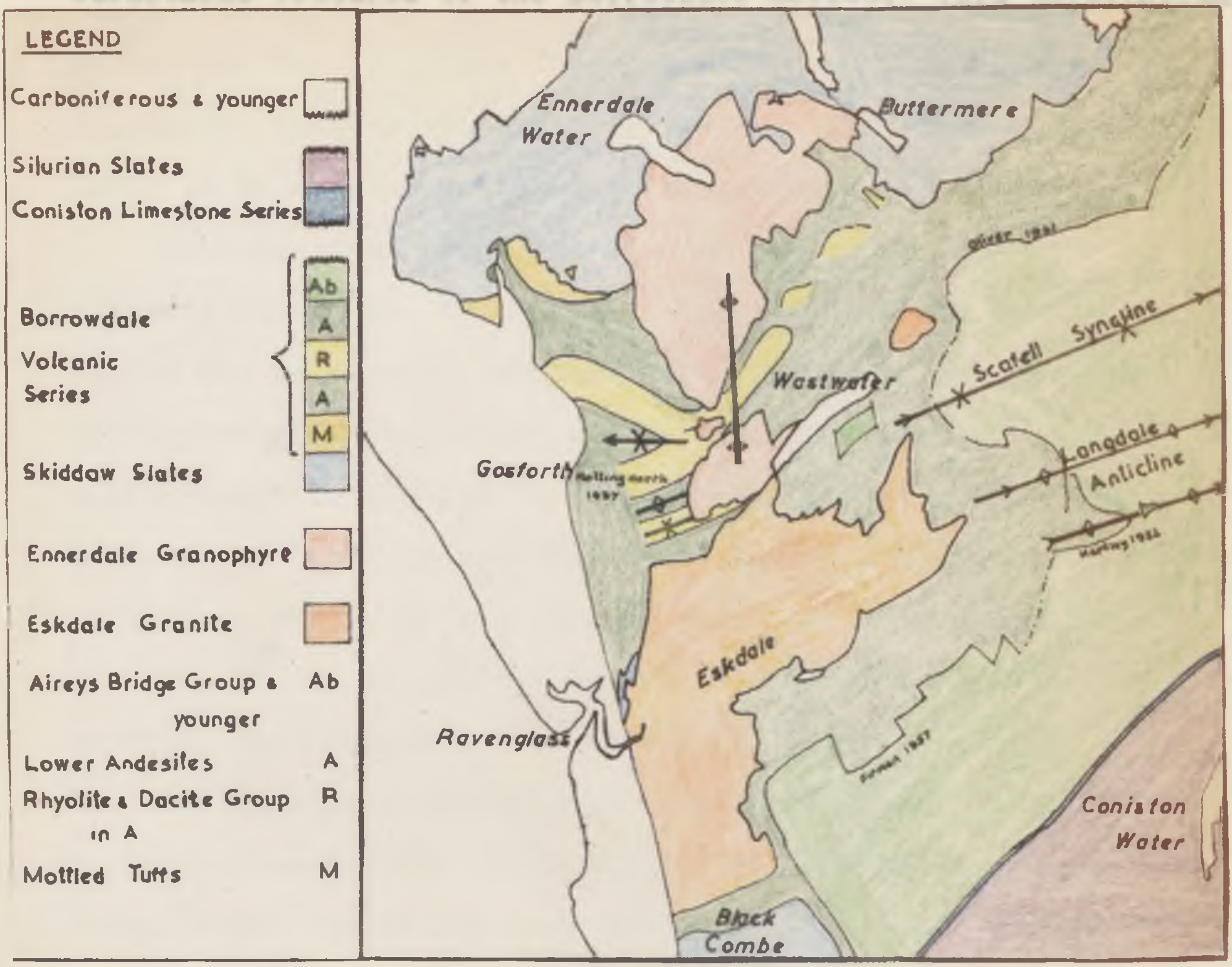
The coincidence of the two intrusions with major structural elements in the Borrowdale Series can be explained in three ways:-

(i) It is a coincidence of no significance.

(ii) It is due to a control of the structure of the Borrowdale Series by the intrusions.

(iii) It is due to a control of the intrusions by the structure of the Borrowdale Series.

The parallelism between the eastern edges of the Eskdale and Ennerdale intrusions and the top of the Lower Andesites is



Geological Sketch Map of the Western Lake District.

Scale: $\frac{1}{4}$ inch – 1 mile.

a result of the coincidence of the intrusions with the major structural features of the Borrowdale Series. This parallelism exists for over 15 miles from Buttermere to Black Combe. It is, in the writers opinion, too perfect over too great a distance to be a coincidence of no significance.

Assuming that the Ennerdale and Eskdale masses were intruded before the major fold movements then the Borrowdale Series may be expected to have been 'moulded' over the forms of the pre-existing intrusions by the fold movements. This would result in the form of the folds being related to the form of the intrusions. The outcrops of the contacts of the intrusions would, in general, be parallel to the outcrops of the beds of the Borrowdale Series. There is much evidence, however, that suggests this theory is wrong.

The Eskdale Granite is believed to be later than the major Caledonian Fold movements in the area (Rose, in Trotter et al, 1937, pp. 51; Firman, 1957, pp. 62). The Ennerdale Granophyre is also believed to be later than the major fold movements. The intrusions, therefore, could not affect the structure of the Borrowdale Series. The present outcrop pattern of the Borrowdale Series is due to the north-north-easterly pitch of the Scafell syncline and the Langdale anticline (Fig. 19). The pitch of these folds is constant for a distance of ten miles or more from the intrusions, far outside their zone of influence. The pitch of the folds is, therefore, independent of the intrusions and the outcrop pattern of the

Borrowdale Series must also be independant of the intrusions. The form of the Caledonian folds in the Borrowdale Series, therefore, must have exerted a control over the emplacement of the Ennerdale and Eskdale intrusions.

The Eskdale and Ennerdale intrusions are in close proximity to the junction between the Borrowdale Series and the Skiddaw Slates. The Ennerdale Granophyre cuts across this junction between Worm Gill and Buttermere. The Skiddaw Slates are exposed west of the Eskdale Granite at Muncaster (Rose, in Trotter et al, 1937, pp. 18) and south of the Eskdale Granite at Black Combe. The similarity between the distance from the top of the Lower Andesites to their base in the Thirlmere to Buttermere area, and the distance of the top of the Lower Andesites to the eastern edge of the Esdale and Ennerdale intrusions suggests that the eastern edges of the Eskdale and Ennerdale intrusions are close to, and parallel with, the base of the Borrowdale Series. (Fig. 19).

The proximity of the Ennerdale and Eskdale intrusions to the base of the Borrowdale Series was noted by Marr (1900, pp. 449) who believed that the Ennerdale Granophyre was a laccolith intruded along the lag plane that he thought separated the Skiddaw Slates and the Borrowdale Series. Green (1917, pp. 1-30) further emphasized the coincidence of the intrusions and the base of the Borrowdale Series, suggesting that the intrusions were sheets intruded along the junction between the Skiddaw Slates and the Borrowdale Series. The present work confirms Marr's and Green's opinion that the junction between the Skiddaw Slates and the Borrowdale Series acted as an important structural control during the intrusion of the Eskdale and Ennerdale masses. It disagrees with them however on the nature of this control.

Hollingworth (Eastwood et al, I93I, pp. 47-50) has demonstrated that the Ennerdale Granophyre is a stock. The stock form of the intrusion is clearly shown on a structure contour map of its surface (Map 2). The vertical sides of the stock are well exposed in Ennerdale and Buttermere but are not seen further south. The roof of the stock is much more irregular than suggested by Hollingworth, with two domes on Cawfell and Red Pike, and a great roof pendant of uncertain form above Ennerdale Water. The roof slopes gently southwards from its highest point on Cawfell to Wasdale. On the north side of Wasdale the roof dips more steeply and then forms the present flat floor of Wasdale.

## (5) The Intrusion of the Ennerdale Granophyre.

The mechanism of the intrusion of the Ennerdale Granophyre and the Eskdale Granite is not known. It may have been stoping but the paucity of the xenoliths in the Ennerdale Granophyre casts some doubt on this method of intrusion. An alternative however, is difficult to envisage.

The intrusion sequence of the Ennerdale and Eskdale intrusions is believed to be as follows:-

The magma was initially rising through the Skiddaw Slates. The advancing magma eventualby reached the base of the Borrowdale Series, which, being massive and relatively unbroken, presented a barrier to the rising magma. The magma first reached the Borrowdale Series at the base of the synclines (Fig. 20. stage 2) and the easiest passage for further advance was into the shattered Skiddaw Slates in the anticlinal axes. The magma flow, therefore, tended to be deflected into the anticlines (Fig. 20. stage3) and the whole intrusion tended to move sideways underneath the anticlines. (Fig. 20, stages 4 and 5). When the magma had filled the anticlines the surface of the intrusion was a cast, except for minor irregularities, of the base of the Borrowdale Series. The only direction left for further advance of the magma was into the Borrowdale Series. The main magma flow and intrusive force had already been deflected into the anticlines in stage 3, therefore, the main intrus-ion into the Borrowdale Series tended to be along the anticlines. Minor exceptions to the above rule, such as the Wasdale Head Granite in the Scafell syncline, do occur.

The theory described above can explain several features found in the Eskdale and Ennerdale intrusions:-

(i) The concordance between the contacts of the intrusions and the beds of the Borrowdale Series (Fig. 20. point X).

(ii) The intimate relationship of the intrusions and the base of the Borrowdale Series.

(iii) The concentration of the intrusions along the anticlines in the Borrowdale Series (Fig. 20, point Y).

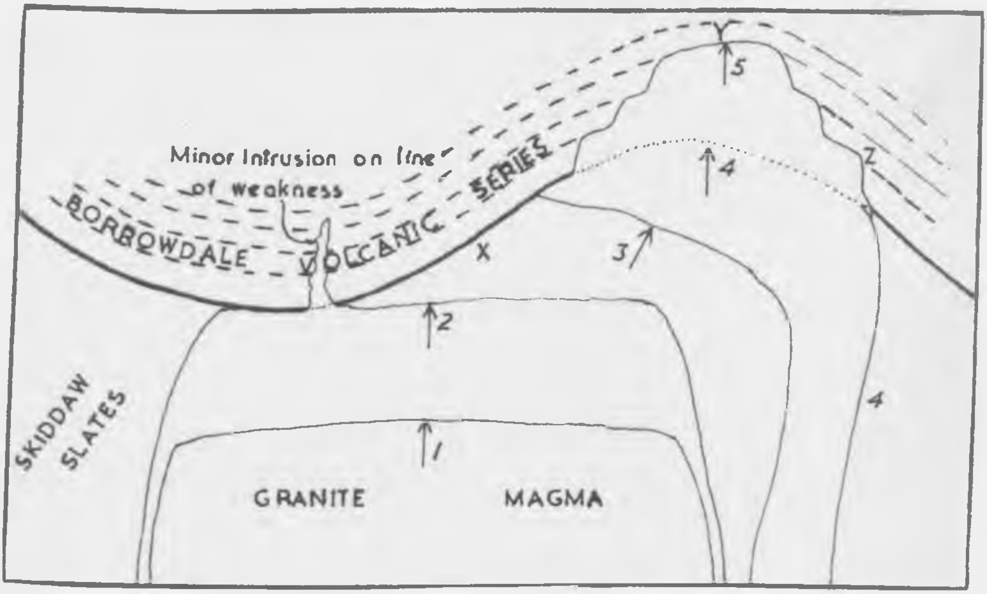
(iv) The concordance between the contacts of the intrusions and the Borrowdale Series in the roofs of the intrusions giving way to discordant steep walls of the intrusions at depth. (Fig. 20, point Z).

The control of the intrusions by the folds in the base of the Borrowdale Series could, of course, only affect the course of the intrusions after they had reached the base of the Borrowdale Series. The control was, therefore, relatively superficial.

## (6) Age of the Ennerdale Granophyre.

The lower age limit of the Ennerdale Granophyre is provided by the Borrowdale Series into which it is intruded. Its upper age limit is fixed by a pebble of Ennerdale Granophyre found in the conglomerates at the base of the Carboniferous Limestone at Hodbarrow, Millom (Mitchell, 1956, pp. 406). The relationship of the Ennerdale Granophyre to the structure of the surrounding area helps to fix the age of the granophyre more closely. The Ennerdale Granophyre was intruded after the Main Caledonian fold movements, which are themselves post-Ludlow and pre-Old Red Sandstone in age.

The Floutern Crag thrusts and the shattered contact in Low Beck suggest that the intrusion of the granophyre may have taken place before the fold movements had completely ceased. The granophyre is cut by several high angled faults of Devonian age. The age of the granophyre is, therefore, either late Silurian or early Devonian, but is perhaps best expressed as late Caledonian.



Intrusion of the Ennerdale Granophyre. Diagrammatic.

## IX. THE METAMORPHIC AUREOLE OF THE ENNERDALE GRANOPHYRE.

### I. Introduction.

The Ennerdale Granophyre intrudes and metamorphoses rocks of both the Skiddaw Slates and the Borrowdale Volcanic Series. The effect of the thermal metamorphism is different in both of these rock series. The major effects on the Skiddaw Slates are a change in their colour from blue to green, an appreciable hardening of the slates and a reduction in their fissility. The greatest alteration has taken place on Crag Fell and Herdus in Ennerdale, where the slates have been extensively recrystallized, and in places soda metasomatized. The metamorphic aureole in the Skiddaw Slates is remarkable for the variation in its width, which is only a few yards near Scale Bridge in Buttermere, but almost three miles just south of Ennerdale.

The macroscopic effects of the metamorphism of the Borrowdale Volcanic Series are very slight. The rocks tend to be darker in colour adjacent to the granophyre due to the formation of biotite and amphibole hornfels. The major changes in these rocks have occurred in the ferromagnesian minerals. There is a zoning in the aureole with a narrow zone of biotite hornfels and localized patches of pyroxene hornfels adjacent to the granophyre, surrounded by a wide zone in which chlorite is the major ferromagnesian mineral. Amphibole occurs throughout the aureole but is most common near the granophyre.

Dixon and Hollingworth, (in Eastwood, et al 1931, pp. 34-41) have described the metamorphism of the Skiddaw Slates west of the Ennerdale Granophyre in some detail. They have identified three periods of metamorphism, a metamorphism by a hidden intrusion which has produced the spotting in the Blakefell Mudstones (see Chapter 1), a thermal metamorphism by the Ennerdale Granophyre, and a hardening of the slates independent of the hidden intrusion and the Ennerdale Granophyre. The present work suggests that this hardening of the slates ascribed to a separate metamorphism was in fact caused by the thermal metamorphism by the Ennerdale Granophyre.

Hollingworth (in Trotter et al, 1937, pp. 38) has described the metamorphic aureole within the Borrowdale Volcanic Series west of the granophyre. This description has been confirmed during the present work and the mapping of the aureole within the Volcanic Series has been continued along the eastern edge of the granophyre.

## 2. The Metamorphic Aureole Within the Skiddaw Slates.

### A. Field Relationships.

The metamorphic aureole of the Ennerdale Granophyre within the Skiddaw Slates is shown in Figure 3. The most striking point about this aureole is the great variation its width, which as mentioned above, varies from a few yards at Scale Bridge in Buttermere to nearly three miles on the west side of the granophyre south of Ennerdale. East of the granophyre, on the south side of Buttermere Lake, the aureole is over a mile wide.

Dixon and Hollingworth believed that the great width of the aureole in the Ennerdale area was not caused by the Ennerdale Granophyre. Herdus, Crag Fell, Grike and Whoap were believed to be formed of Blakefell Mudstones that had been hardened independently of both the thermal effects of the Ennerdale Granophyre and the hidden intrusion that had caused the spotting in the Blakefell Mudstones. The altered slates south of Ennerdale were also believed to be silicified independently of the Ennerdale Granophyre.

The present work suggests that the whole of the aureole of altered slates around the granophyre is the result of metamorphism by the granophyre. Dixon's and Hollingworth's main reason for believing that the hardening of the slates was independent of this metamorphism, was that the hardening extended much further from the granophyre than appeared likely if it were caused by the granophyre. It is equally unlikely, however, that the hardening has been caused by an independent hardening agency from an unknown source. A similar hardening agency would also have to be invoked to explain the mile wide aureole on the south side of Buttermere Lake. The slates south of Ennerdale do not appear to have been silicified as described, for analyses of slates from this area (Table 3) show that no silica has been introduced into the rocks.

The relationship between the Ennerdale Granophyre and the intrusion producing the Blakefell Mudstone aureole is uncertain. The separation of the two aureoles by a narrow strip of unaltered slates suggests that the two intrusions may be adjacent cupolas on one large intrusion. The Blakefell Mudstone aureole however is characterized by the presence of minute spotting (Rose 1954) and no such spotting is found in the Ennerdale Granophyre aureole. This suggests that there may be a fundamental difference between the intrusions.

The variation in the width of the aureole of the granophyre is not related to the inclination of the walls of the intrusion. The contact of the granophyre is exposed in Far Ruddy Beck near Buttermere, dipping outwards at about 50 degrees and the aureole in this area is only about 50 yards wide. The contact of the granophyre across Ennerdale and south of Buttermere Lake is practically vertical, but the aureole is over a mile wide in each case.

The intensity of metamorphism is not related to the distance from the granophyre contact, therefore, it must be related to some anisotropic factor in the slates. The most obvious anisotropic factors, and probably the only ones great enough to have produced the large variation in the width of the aureole, are the bedding and the cleavage. The most important of these is the bedding.

The aureole is widest in the east and west and narrowest in the north. This east-west extension of the aureole is almost parallel to the east-north-east to west-south-west strike of the bedding planes in the slates. It is believed that when the bedding planes in the slates are cut by the granophyre they give easy access to metamorphosing agents and give rise to a wide aureole. The ease of access into the slates south of Buttermere Lake is shown by the great number of sills in this area. The passage of the metamorphosing agents across bedding planes, however, will be restricted by the bedding lamellae, therefore, when the bedding planes are parallel to the edge of the granophyre the aureole will be narrow.

The anisotropy in the slates may have been emphasised a little by the intrusion of the granophyre. The distortion produced by the intrusion would tend to close bedding planes parallel to the contact and open those at right angles to the contact.

There are two major objections, however, to this theory. South of the line of fells from Crag Fell to Blakely Raise the aureole narrows again, yet the relationships between the edge of the granophyre and the strike of the slates remains constant. The second objection is that along the northern contact of the granophyre the slates dip south at 40 to 90 degrees and the granophyre contact dips north at 50 degrees. The two planes are almost at right angles and there seems to be no reason why the aureole is not much wider.

The main metamorphic agents w-ere probably heat and water. The anisotropy of the slates would affect the conduction of heat but probably not to the extent indicated by the variation in extent of the aureole. The passage of water or other volatiles would, however, be greatly influenced by the anisotropy, for their passage would be almost restricted to the partings in the slates. Much of the heat lost from the intrusion would be carried in the volatiles or pass by convection through the volatiles. The importance of volatiles in the metamorphism is shown by the widespread metasomatism on Crag Fell and Bowness Knott.

The aureole of the Ennerdale Granophyre can be divided into two zones, an outer and an inner zone. The outer zone is quite narrow over most of the aureole, but is about a mile wide in the west around Blakely and Latterbarrow. The slates in the outer zone closely resemble the normal Skiddaw Slates, except they are yellowish-green in colour instead of dark blue. The colour change from blue to green is distinct and sharp so that the outer edge of this zone can be mapped with some accuracy. Hollingworth (Eastwood, et al, 1931, pp. 36) believes that the wide zone of discolouration in the slates is caused by superficial weathering.

The inner zone occupies most of the aureole, and is practically the same as the aureole mapped by Dixon and Hollingworth. The slates of the inner zone are usually olive green in colour except when stained by haematite, in which case they may be a purplish colour. They have lost much of their fissility and are much more massive than the normal slates. The original bedding planes in the slates are preserved as laminae in the hornfels. Original structures in the slates are also preserved, for example small scale zig-zag folding in hornfels above Burtness Wood (G.R. 17781543).

The inner zone increases in extent with depth. The hornfels on the summit ridge of Grike are more fissile than the massive hornfels in the cliffs lower down the north slopes of the hill. Fissile hornfels on the outer zone extend up the north shoulder of Herdus as if the slope of the north end of Herdus is coincident with the junction between the outer and inner zones. A similar increase in extent of the inner zone of the aureole with depth is seen south of Buttermere Lake.

Rastall (1906, pp. 296) and later Green (1917, pp. 15) remarked on the lack of cleavage in the slates adjacent to the granophyre and suggested that the hardening of the slates by metamorphism had protected them from cleavage. It has been shown however that the fold movements that produced the cleavage preceded the intrusion of the granophyre. The cleavage and the bedding planes of the slates of the inner zone of the granophyre aureole must, therefore, have been destroyed by the metamorphism.

The hornfels on Crag Fell and Grike are commonly a pink colour, and in places resemble fine felsites. The pink hornfels do not occupy a well defined zone, but in general they are confined to the north slopes of Grike and Crag Fell east of Goat Gill, and are commonest close to the edge of the granophyre.

The whole rock may be pink over quite large areas, for example on the east wing of Anglers Crag. In many places, however, the pink felsitic hornfels occur as selvages on either side of joints in the normal green hornfels. This suggests that the pink colour has been caused by solutions passing along the joints. A dyke-like mass of hornfels which resembles fine pink felsite very closely, is marked by a line of prominent pinnacles on Crag Fell(G.R. 09581475). This mass is about 200 yards long, 30 yards wide, and has vertical contacts. It is cut by numerous quartz and pegmatitic veins. The 'dyke' may mark the site of a major fracture or joint in the hornfels.

An analysis of a specimen (E 9616) of pink felsitic hornfels from Crag Fell Pinnacle shows that it has been considerably enriched in soda when compared with the normal hornfels and unaltered Skiddaw Slates ( Table 3.) The pink felsitic character is, therefore, believed to be the result of soda metasomatism. The metasomatism of normal hornfels along the edges of joints shows that the metasomatism took place after the hornfelsing.

A small area about 150 yards across, of whitish-grey felsitic hornfels occurs just north-east of Brown How (G.R. 117159). This area of white hornfels is surrounded by olive green hornfels 'veined' by white hornfels. The white hornfels veins which form a rectilinear pattern, are sometimes cored by quartz and are actually metasomatised selvages along the edges of joints in the green hornfels.

The similarity, apart from their colour, between the felsitic hornfels of Brown How and Crag Fell suggests that they are of similar origin. White felsitic hornfels occur as selvages to pegmatitic quartz and feldspar veins on Brown How. This suggests that the metasomatic hornfels and the pegmatites were formed at the same time. The sodic feldspar in the pegmatites certainly show that the solutions passing along the pegmatite veins were sodic in character.

Two thin sills of white porcellaneous felsite containing numerous phenocrysts of white feldspar in glomeroporphyritic groups up to three millimetres in diameter, are exposed on Bowness Knott (G.R. 10751536; G.R. 11181555). The felsite does not resemble the rock of any minor intrusions associated with the Ennerdale Granophyre but does closely resemble the white felsitic hornfels on Brown How. The contacts of the sills in places are sharp but elsewhere the felsite grades insensibly into the normal green hornfels over a distance of a few inches.

These sills are believed to be of metasomatic origin and to represent a further stage than the white felsitic hornfels of Brown How in the metasomatism of the Skiddaw Slates. They may have been included by Hollingworth (ibid., 1931, pp. 45) in minor felsitic intrusions associated with the granophyre.

## B. Petrography

### i. The Outer Zone of the Aureole.

The slates are very similar to the normal dark blue laminated slates, except that they are a yellowish-green colour and are a little harder. In thin sections, (E 9218, E9219, E 9220) they are indistinguishable from normal Skiddaw Slates (E 9613, see Chapter I). The sericite in the hornfels shows signs of recrystallization, for it loses its parallel orientation and in places is coarser than normal. It occurs in specimen E 9219 from 140 yards from the contact with the granophyre, 200 yards west of Scale Force, in radiating groups of flakes about 0.15 mm. long.

Specimens of Latterbarrow Sandstone (E 9302, E 9303) taken from Lank Rigg (G.R. 09381100) 300 yards from the granophyre show no metamorphic effects in hand specimen or in thin section. A fine sandstone from Burtness Low Crag (E 9304; G.R. 18411492) similarly shows no effects of metamorphism, although it is actually in the inner zone.

## ii. The Inner Zone of the Aureole.

The greater part of the inner zone is composed of rocks somewhat similar to those in the outer zone, but more massive and darker green in colour. In hand specimens they are fine, hard, massive olive-green rocks, commonly laminated parallel to the original bedding. They are very finely granular in texture in places, particularly on the cliffs on the Ennerdale side of Crag Fell and Grike.

The hornfels vary in appearance in thin section. The majority have retained much of their original clastic appearance and closely resemble the hornfels of the outer zone. Chlorite pseudomorphs after biotite crystals up to 0.2 mm. in diameter occur in some specimens but are only common very close to the granophyre.

Specimens E 9614 and E 9615 from Ben Gill and Goat Gill in the cliffs on the Ennerdale side of Grike are more altered in appearance. The original laminated clastic structure of these rocks is partially obscured by a patchy development of sericite and chlorite. The sericite is concentrated in spheres about 0.4 mm. in diameter, while the chlorite occurs in the interstitial areas between the spheres. The spheres in specimen E 9615 have coalesce-d and the chloritic areas are preserved as patches in the sericitized rock. The spheres may have produced the finely granular texture of the hand specimen.

The hornfels of the inner zone becomes felsitic in character in places on Crag Fell and Bowness Knott. Specimen E 9616 from the Crag Fell Pinnacles (G.R. 09521477) is a fine felsitic rock striped pink and yellow, the stripes picking out the broad bedding lamellae. There are rare femic clots up to one millimetre in diameter scattered through the rock. Fine pink felsitic hornfels in specimens E 8772 and 10009 from the same locality is veined by quartz, feldspar pegmatite.

The felsitic hornfels are composed of a quartzo-felspathic mosaic about 0.05 mm. in grain size. Anhedral crystals of feldspar up to 0.4 mm. in diameter have grown in this base and the high soda content of specimen E 9616 (Table 3) suggests that this may be albite. Sericite occurs in flakes scattered through the matrix and in clots up to 1.3 mm. in diameter. Chlorite is present and is fairly common close to the pegmatite veins. Accessory minerals include schorlite in prisms 0.2 x 0.1 mm. in size in clumps up to 0.5 mm. in diameter, leucoxene, rutile, sphene, apatite and rare zircon.

The metasomatic porphyritic felsite sills on Bowness Knott (E 9288; E 9299) are composed of very fine white felsite containing numerous white feldspar phenocrysts up to 2.5 mm. in diameter in glomeroporphyritic groups up to 4 mm. in diameter. Clots of a dark green mineral up to 2.5 mm. in diameter occur sporadically in the felsite. The felsite commonly changes to a pink colour along fractures.

The matrix of these felsites is a quartzo-feldspathic mosaic with a grain size of 0.1 to 0.2 millimetres in diameter. The crystals in the mosaic have complex sutured margins and are very irregular in shape. The phenocrysts are glomeroporphyritic plagioclase prisms which are full of sericite but still retain very faded twinning. The plagioclase is probably oligoclase but the extensive alteration makes its determination uncertain. Penninite occurs in scattered irregular patches in the matrix. Accessory minerals include leucoxene, sphene, calcite and rare zircon.

Staining of specimens of felsitic hornfels from Crag Fell and specimens of porphyritic felsites from Bowness Knott show that potash feldspar is almost absent from both.

## C. Petrochemistry.

Three chemical analyses of Skiddaw Slates have been made in order to study the chemical changes that have taken place during the metamorphism of a normal Skiddaw Slate to a massive hornfels and then to a felsitic hornfels. The specimens for analysis (Table 3) have been taken as close as possible from along the strike of the Skiddaw Slates, in order to ensure that their original compositions were similar.

The unaltered slate (E 9613) is a dark blue laminated mudstone from Oxenstone Beck (see p.17 ). The massive hornfels (E 9614) has been taken from the head of Ben Gill gorge (G.R. 08851476) and the felsitic hornfels (E 9616) comes from the Crag Fell Pinnacles.

The chemical changes in the change from an unaltered slate to a massive hornfels are not great. The carbon has been expelled from the slate and the water content has been reduced. The percentages of CaO, $Na_2O$, and $K_2O$ have risen appreciably and the amount of MnO in the rock has been reduced by half. The hornfels has not been silicified for the $SiO_2$ percentage has been slightly reduced.

The change from massive hornfels to felsitic hornfels has involved important chemical changes. The amount of soda has increased almost five fold to almost eight percent, and the amount of total iron has been reduced by the same amount. The percentage of $H_2O$ and MnO in the rock have been greatly reduced. The amounts of TiO2, $Al_2O_3$ and CaO have increased a little and MgO and $K_2O$ fallen a little.

These analyses show that the change from an unaltered slate to a massive hornfels does not involve any important chemical changes and must be mainly a process of recrystallization. The production of a felsitic hornfels, however, involves the replacement of iron by soda by a process of soda metasomatism. This is seen in the rock as a great reduction of iron ore and ferromagnesian minerals and a development of sodic

# TABLE 3

CHEMICAL ANALYSES

| | 505<br>E96I3 | 506<br>E96I4 | 507<br>E96I6 |
|---|---|---|---|
| $SiO_2$ | 59.89 | 59.39 | 58.76 |
| $TiO_2$ | I.02 | I.I2 | I.29 |
| $Al_2O_3$ | I8.82 | I8.99 | 23.04 |
| $Fe_2O_3$ | 0.95 | I.09 | 0.37 |
| $FeO$ | 7.55 | 6.80 | 0.84 |
| $MnO$ | 0.I3 | 0.07 | 0.0I |
| $MgO$ | 2.I2 | 2.06 | I.98 |
| $CaO$ | 0.50 | I.03 | 2.39 |
| $Na_2O$ | 0.66 | I.64 | 7.66 |
| $K_2O$ | 2.54 | 3.28 | I.5I |
| $H_2O+$ | 4.89 | 3.95 | I.62 |
| $H_2O-$ | 0.70 | 0.II | 0.I9 |
| $P_2O_5$ | 0.28 | 0.36 | 0.24 |
| C | 0.I2 | | |
| Total | I00.I7 | 99.89 | 99.90 |

SPECTROGRAPHIC ANALYSES (IN P.P.M.)

| | S809<br>E96I3 | S8I0<br>E96I4 | S8II<br>E96I6 | | S809<br>E96I3 | S8I0<br>E96I4 | S8II<br>E96I6 |
|---|---|---|---|---|---|---|---|
| Ba | 550 | 700 | 300 | Ni | 75 | 85 | 45 |
| Be | II | 9 | 5 | Pb | <I0 | <I0 | <I0 |
| Co | I0 | I0 | <I0 | Rb | I80 | 200 | 75 |
| Cr | 95 | I30 | I70 | Sc | I5 | I5 | I5 |
| Ga | 27 | 23 | 30 | Sr | I20 | I40 | 400 |
| La | <I00 | <I00 | <I00 | Ti | >3000 | >3000 | >3000 |
| Li | I20 | 50 | II0 | V | I20 | I80 | I70 |
| Mn | I800 | 600 | 70 | Y | 65 | 60 | 30 |
| Mo | 7 | 5 | <3 | Zr | 300 | 300 | I70 |
| Nb | 60 | 60 | 30 | | | | |

Chemical analyses 505 and 506 by Margaret H. Kerr.
Chemical analysis 507 by Joy R. Baldwin.
Spectrographic analyses by Joan M. Rooke.

E96I3.505.S809. Skiddaw Slate. Oxenstone Beck, Ennerdale.
E96I4.506.S8I0. Hardened Skiddaw Slate. Ben Gill, Ennerdale. 6885 1476
E96I6.507.S8II. Felsitic Skiddaw Slate. Crag Fell, Ennerdale.

plagioclase. The percentage of MgO has only fallen slightly suggesting that the greatest changes has been in the removal of iron ore. Iron may have been removed from the ferromagnesian minerals changing them to magnesian minerals. The $TiO_2$ in the felsitic hornfels chiefly occurs as rutile and sphene. This $TiO_2$ may have been partially derived from original il-menite but the abundance of rutile in associated pegmatites suggests that some has been introduced.

The identification of the soda metasomatism associated with pegmatites suggested that there may be some enrichment in trace elements in the felsitic hornfels. Spectrographic analyses of the above specimens, however, shows no significant enrichment in any trace element. The most striking change in the specimens is the reduction of manganese from 1800 p.p.m. in unaltered slates to 70 p.p.m. in felsitic hornfels.

## 3. The Metamorphic Aureole within the Borrowdale Volcanic Series.

### A. Introduction.

The metamorphic aureole within the Borrowdale Volcanic Series cannot be mapped in the field because the effects of metamorphism in hand specimens are very slight. The volcanic rocks tend to be darker in colour and have a purplish tinge close to the granophyre because of their change to biotite and amphibole hornfels. The outer limit of these effects cannot be determined in the field.

A microscopic examination of volcanic rocks that have been metamorphosed by the Ennerdale Granophyre shows that the major changes produced by the metamorphism have been in the ferromagnesian minerals. Pyroxene has changed to amphibole, biotite and chlorite, and chlorite has changed to biotite and amphibole. The metamorphic aureole can, therefore be mapped by microscopic examination of chosen specimens. The accuracy of the mapping will depend on the number and scatter of the chosen specimens.

The delimitation of the metamorphic aureole in the above manner is not as simple as it at first appears. Secondary alteration in the volcanic rocks is common, and the cause of any specific alteration is often difficult to determine, for the rocks have been subjected to at least three different periods of alteration. These are deuteric alteration during eruption and for a short period after eruption, regional alteration during the Caledonian earth movements and thermal metamorphism by the Ennerdale Granophyre. Similar secondary alteration has been described by Hollingworth (ibid. pp. 27-39) in the Borrowdale Volcanic Series west of the Ennerdale Granophyre, and by Firman (ibid. pp. 45) in the Lower Andesites adjacent to the Eskdale Granite.

## B. Field Relationships.

The general distribution of the ferromagnesian minerals in the Borrowdale Volcanic Series adjacent to the Ennerdale Granophyre is shown in Fig. 21. The ferromagnesian minerals in the aureole show some zoning, but the boundaries of the

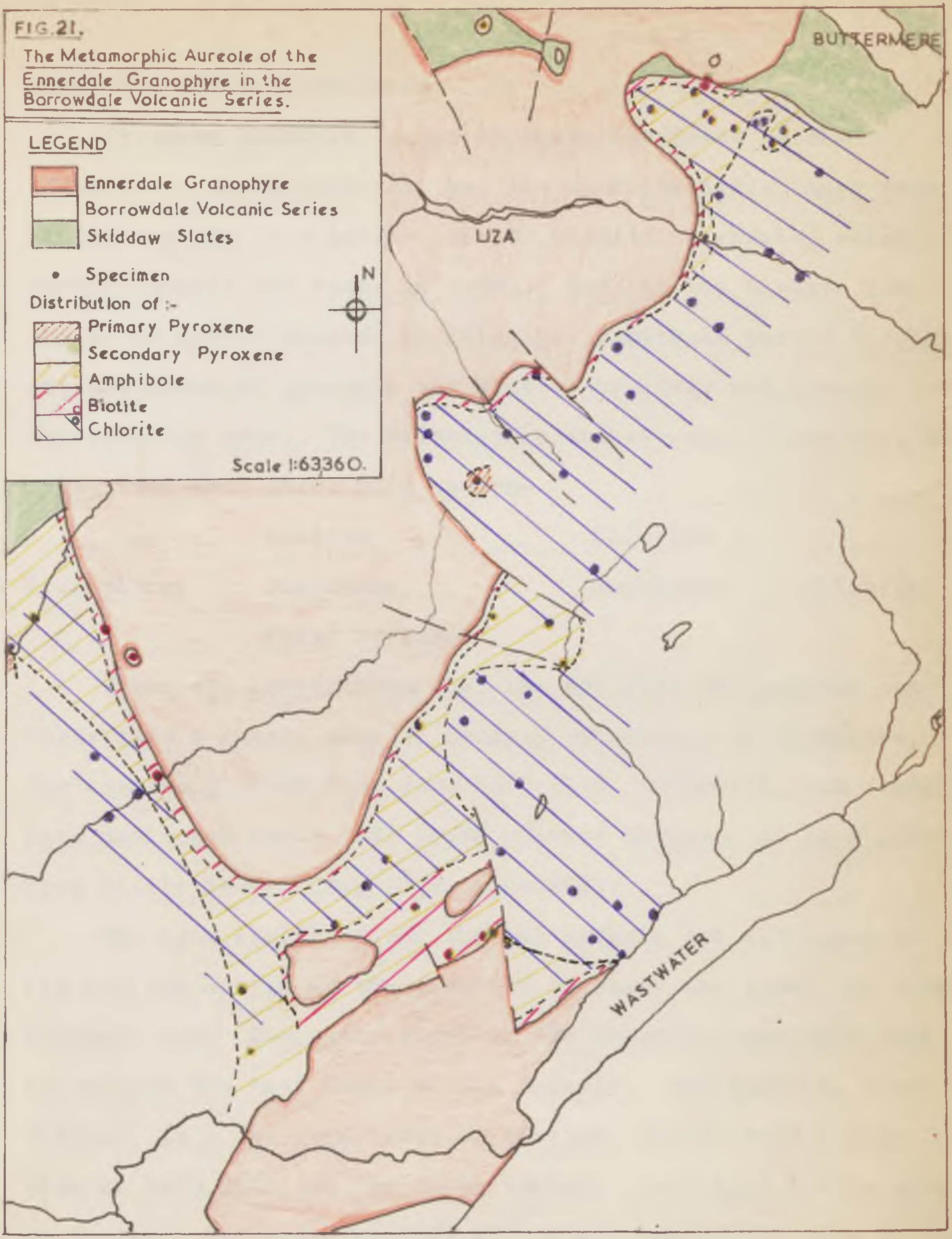


FIG. 21.

The Metamorphic Aureole of the Ennerdale Granophyre in the Borrowdale Volcanic Series.

zones are not well defined.

Pyroxene hornfels occur in small localized patches adjacent to the granophyre, but the characteristic inner zone of the aureole is a narrow zone of biotite hornfels, which rarely exceeds 200 yards in width. Outside the biotite zone the major stable mineral is chlorite. Amphibole occurs throughout the zones of pyroxene and biotite hornfels and extends into the chlorite zone. The metamorphic aureole may, therefore, be subdivided into three main zones:;-

| | | | | | |
|---|---|---|---|---|---|
| | Biotite | | Chlorite | | |
| Granophyre: | Amphibole | : | Amphibole | : | Chlorite |
| | Local Pyroxene | | | | |

There are indications that the chlorite zone passes outwards into a narrow zone of primary pyroxene with amphibole, for example E 10220 from Worm Gill (G.R. 08980919), and finally into unaltered rocks with fresh primary pyroxene as in E 10354 from Little Gowder Crag (G.R. 14041098).

The true limits of the thermal aureole are difficult to fix for the origin of the minerals on which the limits are based is uncertain. The outer limit of the chlorite-amphibole zone is perhaps the best limit of the aureole. The aureole, thus defined, is a few yards wide on Steeple, almost half a mile wide in Worm Gill and the Bleng Valley, about half a mile wide in Burtness Combe and at Pots of Ashness and a mile wide on the south end of Seatallan. This aureole is based on the assumption that the chlorite which occurs outside the zone of secondary hornblende is not connected with the granophyre and is probably of deuteric origin. If the chlorite is a product of retrograde metamorphism, then the aureole is much wider.

## C. The Secondary Alteration in the Borrowdale Volcanic Series.

The recrystallization and alteration of feldspar to epidote and sericite is widespread. This alteration varies from slight alteration with a few crystals of epidote or sericite in the feldspar to complete replacement of the feldspar. It is impossible to decide how much epidote in any specimen has been produced by alteration of the feldspars in situ and how much has been introduced during the epidotization of the rock as a whole.

Epidote, mainly pistacite, is abundant in feldspar crystals but is also common in veins or cracks (E 9924), amygdules (E 9927) and in the matrices of almost all specimens. The abundance of epidote appears to be governed by the nature of the rock. It is most abundant in ves-icular lavas as an amygdule mineral, in sheared rocks along cracks and in tuffs. It is least abundant in massive, fine or aphanitic lavas. The epidote is most likely of several generations for its abundance in amygdules suggests that some may be of deuteric origin, but its frequent occurrence on joint planes shows that much is of later origin. Hollingworth and Firman note that the intensity of epidotization increases as the Ennerdale and Eskdale intrusions are approached. They suggest that the epidotization is in part due to thermal alteration by the granitic intrusions.

This effect has not been observed in the present area but it is likely that some epidote has been produced by metamorphism by the granophyre. The present area may be coincident with the area of epidote enrichment and the concentration of epidote may well fall away from the granophyre.

The iron ore in almost all specimens has been badly altered. Ilmenite has usually been changed to leucoxene and secondary sphene. Magnetite is usually fresher than ilmenite but has been changed to haematite in some specimens. The ferromagnesian minerals in an andesite from a roof pendant in Caw Gill (G.R. 10350911) have exsolved iron as magnetite which now ghosts the ferromagnesian crystals as dense clouds of tiny crystals. This may explain the abundance of fine magnetite in other specimens (E 10123; E 9309).

Quartz is present in the matrices of a few specimens such as specimen E 9920 from Starling Dodd. The origin of this quartz is uncertain, but it may have been introduced during deuteric alteration, during silicification by the Ennerdale Granophyre, or it may be primary quartz. Hollingworth notes that silicification is quite common in the more acidic lavas, particularly in regions adjacent to the Ennerdale Granophyre, and suggest that some of the silicification is connected with the intrusion of the granophyre.

Many of the changes in the ferromagnesian minerals have been caused by thermal metamorphism by the Ennerdale Granophyre. The original ferromagnesian mineral of the lavas was probably a pyroxene similar to the augite from Little

Gowder Crag (E 10354). This original pyroxene has been extensively altered to chlorite, biotite and hornblende. The stable feromagnesian minerals adjacent to the granophyre are pyroxene, amphibole and biotite, but over much of the present area the only stable ferromagnesian mineral is chlorite (Fig.21).

Practically all the chlorite has a very low birefringence and anomalous blue polarization colours which suggest that it is penninite. Pyroxene phenocrysts have often been pseudomorphed by penninite which is optically continuous over the whole crystal. In some specimens, for example specimen E 9924 from High Stile, the chlorite in the pseudomorphs appears to be replacing a fibrous mineral, possibly an amphibole. The original pyroxene had possibly changed into an amphibole before the chlorite. Chlorite is also abundant in small flakes in feldspars, amygdules, veins and in the matrixes of rocks.

Some of this alteration to chlorite may have taken place during retrograde metamorphism by the Ennerdale Granophyre but much is believed to predate the intrusion of the granophyre. Small fibres, and in some cases, larger crystals of amphibole, are commonly found growing in chlorite in amygdules or pseudomorphs (E 9926). The amphibole is believed to have been produced by metamorphism by the granophyre, therefore, the chlorite must predate the granophyre. An andesite close to the contact of the granophyre in Greendale Gill (G.R. 14250609) contains numerous amygdules which are now filled with hornblende and a pyroxene, probably augite. The hornblende and augite are believed to have been derived through metamorphism by the granophyre from chlorite which originally filled the amygdales.

Pyroxene occurs in localized patches of pyroxene hornfels very close to the Granophyre, where the lavas have been most intensely metamorphosed. A specimen (E 9221) from the base of Chapel Crags in Buttermere, is netveined by poikiloblastic crystals of hypersthene up to nine millimetres across. The specimen from Greendale Gill mentioned above is a pyroxene amphibole hornfels. Augite occurs in the centres of a few amygdules in anhedral crystals approximately 1.5 mm. in diameter. The rest of the amygdales are made up of hornblende in spherulites of acicular crystals up to 0.5 millimetres long which appear to be replacing the augite. Hornblende is also abundant through the rest of the specimen in crystals up to 0.2 mm. in diameter.

Biotite is the characteristic mineral in the hornfels in contact with the granophyre. The biotite usually occurs as a cloud of brown flakes between 0.1 and 0.2 mm. in diameter disseminated through the rock. The flakes are commonly concentrated in clots, but they do not pseudomorph any earlier minerals . Biotite hornfels are well seen at several points along the contact, for example Cawfell Beck (E 9309), Buckbarrow (E 8745) and Chapel Crags (E 9222).

Hornblende is present over much of the metamorphic aureole of the Ennerdale Granophyre. It is associated with pyroxene in hornfels from Greendale Beck, but also occurs alone in amphibole hornfels from High Pike Haw (E 10357).

Hornblende is common in biotite hornfels on Buckbarrow, but is also common outside the biotite zone in association with chlorite. The hornblende commonly occurs as pseudomorphs after pyroxene (E 9926) in which one crystal of pyroxene has been replaced by one crystal of amphibole. It is also present as small crystals disseminated through many specimens as in specimen E 10119 from Cat Bields (G.R. 13150685), and in ragged fibrous crystals or masses of fibres replacing interstitial chlorite as in specimen E 9920 from Starling Dodd.

The secondary pryoxene and biotite have been formed by progressive thermal metamorphism by the Ennerdale Granophyre. The wide range of the hornblende through the metamorphic aureole of the granophyre suggests that it was stable over a wide range in temperature and that temperature was not the sole factor promoting its growth. The hornblende occurs far outside the biotite zone in regions where thermal effects would be expected to be negligible. Firman describes a similar phenomenon in the Eskdale Granite aureole where secondary hornblende characteristically occurs outside the biotite zone. This has been confirmed by Oliver (1961, Fig. 3). The factors other than temperature which promote the development of the hornblende are unknown.

### D. A comparison of the Aureole of the Ennerdale Granophyre with The Aureoles of other Intrusions in the Lake District.

The mineralogical changes in the aureole of the Ennerdale Granophyre are very similar to those described by Firman (1957, pp. 45) from the much wider aureole of the Eskdale Granite, where the biotite zone is approximately a mile wide over most of its outcrop (ibid. Fig. 3).

Metamorphism of the Skiddaw Slates by the Skiddaw Granite (Rastall, 1910) is extremely intense when compared with the effect of the Ennerdale Granophyre on these beds. The slates in the aureole of the Skiddaw Granite include such rock types as chiastolite slates and cordierite andalus-ite hornfels while the slates over much of the Ennerdale Granophyre aureole are barely altered. Thomas and Hollingworth ( in Eastwood, et al, 1931, pp. 41) suggests that andalusite may occur in some hornfels adjacent to the Ennerdale Granophyre.

The mineralogical changes in andesitic lavas in the Shap Granite aureole (Harker and Marr, 1891) are similar to those in the Ennerdale Granophyre aureole, except that at Shap, biotite occurs towards the outer edge of the aureole. The metamorphism around the Shap Granite has been more intense than around the Ennerdale Granophyre, and metasomatism has played an important part in the mineralogical changes (Firman, 1954.)

Metamorphism by the Threkeld microgranite intrusions is very slight.

The variation in intensity of metamorphism, and in the types of metamo-rphism, by the Lake District granites must be the result of either a variation in the granite masses, or a variation in the rocks being affected. Very similar rocks have been metamorphosed with very different results by different granites, for example Skiddaw Slates by the Skiddaw Granite and the Ennerdale Granophyre, or andesitic lavas by the Ennerdale Granophyre, Eskdale Granite and Shap Granite. The variation is, therefore, most likely in the intrusions themselves.

The most obvious variables in a granitic body that could affect its metamorphic action are its temperature, its rate of cooling and the abundance of volatiles in the granite. The temperatures of the intrusions cannot be determined but it is unlikely that they varied much.

The rate of cooling of an intrusion will depend on its depth of burial and its size. The depths of burial of the Lake District granites would probably be similar for they are of similar age, are close together, and reach similar elevations at the present time. The larger granites should cool more slowly and have wider aureoles than the smaller granites. The Ennerdale Granophyre is one of the largest intrusions in the Lake District, but has one of the narrowest aureoles.

The amount of volatiles in an intrusion will be reflected in the intensity of its hydrothermal, pegmatitic and metasomatic effects. The Skiddaw Granite is noted for the Grainsgill greisen and the associated mineralization. Firman has described the metasomatism in the aureole of the Shap Granite, which suggests that volatiles may be the most important factor in the metamorphism. The Ennerdale Granophyre, however, was also rich in volatiles, for the Main Granophyre has metasomatized large masses of diorite in the granophyre, and also areas in the Skiddaw Slates in Ennerdale. The Main Granophyre at the west end of Gale Fell has been converted into a fine grained greisen. The effect of volatiles on the width of the granophyre aureole has already been noted (pp205-7 ). but the volatiles do not appear to have affected the metamorphic grade of the rocks in the aureole.

An important factor affecting the grade of metamorphism may be the temperature of the country rocks into which the granite is intruded. A granite that intrudes rock that is already hot will have a greater metamorphic effect than a granite intrusive into a cold rock.

The reason for the variations in the aureoles in the Lake District granites is unknown. It is probably a combination of the factors discussed above.

# IX. MINERALIZATION.

## II. Mineralization Related to the Intrusion of the Ennerdale Granophyre.

Four pegmatitic quartz and feldspar veins cross Brown How in Ennerdale, striking approximately east-west. Their dip is variable, but is usually steep and to the north. These veins are believed to represent the pegmatitic phase of the Ennerdale Granophyre because of their proximity to the granophyre and their association with soda-metasomatism of Skiddaw Slates by the granophyre.

The veins are composed of stringers of massive quartz with lenses and veins of coarse creamy feldspar. The hornfelsed slates adjacent to the veins are usually discoloured to a white or pinkish-grey colour and lenses of discoloured slate are commonly enclosed in the veins, The discoloured slate usually can only be distinguished from the creamy feldspar by the difference in their grain size.

The feldspar of the veins is a sodic plagioclase of albite or oligoclase composition which occurs in crystals up to a centimetre in diameter. The discolouration of the adjacent slates is probably due to soda metasomatism by solutions passing along the veins, for the slates resemble the soda metasomatized slates of Crag Fell (see Chapter IIX). The permeating solutions must have been rich in soda to have produced the sodic feldspars.

FIG.22.

Polished Specimen of Apatite-bearing Pegmatite: Brown How.
Full Size

The largest vein on Brown How is of interest, for on the south-east side of the hill (G.R.11551581) it is associated with a quartz vein which contains abundant crystals of apatite. The apatite is creamy in colour, and occurs in hexagonal prisms up to one centimetre in diameter and four centimetres long. The prisms are orientated haphazardly in the quartz (Fig. 22). The apatite has been susceptible to weathering, and on the weathered surface the prisms are now represanted by hexagonal cavities. This vein was probably the source of an apatite pegmatite found by Hollingworth (Eastwood et al, 1931, pp. 54-5) in a fallen block on the south side of Bowness Knott.

A line of prominent pinnacles at about 1200 feet on Crag Fell marks the position of a dyke-like mass of pink felsitic hornfelsed slates (G.R. 09581475). This mass of hornfels is traversed by numerous quartz veins up to about two feet in diameter which are probably of similar pegmatitic origin to the veins on Brown How.

The quartz in places is associated with coarse creamy feldspar and chlorite. The feldspar is plagioclase which probably varies in composition form albite to oligoclase. The relatively high birefringence of the chlorite suggests that it is clinochlore. The chlorite is remarkable for the abundant prismatic crystals of rutile about one millimetre in diameter that it contains.

The feldspar and chlorite may also occur without quartz, in small veins along joints in the hornfels. These veins swell in places into small pods about five centimetres in diameter. The minerals in the pods have a zonary arrangement as follows:-

Margin ⟶ Core.

| | | | |
|---|---|---|---|
| Hornfels: | Chlorite<br>Rutile | : Albite<br>Oligoclase | : Calcite |

No apatite-bearing pegmatite has been found on Crag Fell.

## 2. Mineralization Unrelated to the Intrusion of the Ennerdale Granophyre.

Mineralization is relatively sparse in the area between Buttermere and Wasdale. Postlethwaite (1913) on his map of the Lake District mining field shows no mines in this area. Small mines and trials, mainly for haematite are, however, quite common in the area around Ennerdale.

## A. Haematite.

Ennerdale lies on the fringe of the west Cumberland haematite field. Haematite is common coating joints in the rocks, and is particularly common along fault lines and smash belts. The rock may be haematitized for several yards on either side of a fault line. This is particularly noticeable in the Skiddaw Slates, for example the slates alongside the Red Gill fault are haematitized for some ninety yards from the fault. The haematitized smash belt that passes near Thwait~~s~~e is approximately 450 yards wide.

Trials for haematite have been made at the following places:-

| | |
|---|---|
| Red Gill | Along the Red Gill Fault |
| Clews Gill | |
| Gale Fell | On small faults |
| Scale Force | On the Scale Force Fault |
| Iron Crag | |
| Crag Fell | Probably along a fault |
| Grike | Along several smash belts. |

The majority of these trials were barren. The most successful mines were the Crag Fell and Iron Crag mines. Four hundred tons of haematite were removed from the Iron Crag mine in 1882, but the mines were only short lived (Smith, 1924, pp. 171).

The haematite occurs in massive, reniform and specular habits. Vughs in the ore are commonly lines with drusy quartz, and less commonly calcite. Rare small grains of chalcopyrites have been found in the haematite from Scale Force and Clews Gill. The occurrence and origin of the west Cumberland haematite has been fully discussed by several authors, the most important being Postlethwaite (1913), Smith (1924) Dixon and Smith (1928) and Trotter (1945).

## B. Lithiophorite: First Record in Great Britain.

A manganese oxide mineral from Clews Gill in Ennerdale has been shown by Xray defraction to be lithiophorite. This mineral has been found in a small spoil tip from a haematite trial in Clews Gill at 1450 feet O.D. (G.R. 13251595). It occurs as black films or manganese stains on joint surfaces of fragments of granophyre that has been brecciated by the Red Gill Fault.

The films of lithiophorite may be several centimetres across, but rarely exceed one millimetre in thickness. The lithiophorite is finely botryoidal but no crystalline texture can be observed and it appears to be a dull black amorphous wad. Its hardness varies but it is usually about three.

The crystalline character of the mineral is shown by its Xray defraction pattern which is closely comparable with those given by lithiophorite from White Oak Mt., Bradley Co., Tennessee (Fleitscher and Richmond, 1943, pp. 282), and Gloucester South Africa (Wadsley, 1950, pp. 494).

| South Africa | | Tennessee | | Clews Gill. | |
|---|---|---|---|---|---|
| D A$^o$ | I/I$_i$ | D A$^o$ | I/I$_i$ | D A$^o$ | I/I$_i$ |
| 9.45 | 50 | 9.407 | 90 | 9.66 | 27.0 |
| | | 5.13 | 10 | | |
| 4.70 | 100 | 4.70 | 100 | 4.75 | 100.0 |
| 3.12 | 35 | 3.13 | 30 | 3.16 | 9.5 |
| 2.39 | 35 | 2.48 | 10 | 2.51 | 9.5 |
| | | 2.35 | 90 | 2.31 | 43.2 |
| | | 2.27 | 10 | | |
| | | 2.12 | 10 | | |
| | | 2.04 | 10 | | |
| 1.88 | 35 | 1.87 | 80 | 1.89 | 41.9 |
| 1.51 | 20 | 1.55 | 60 | 1.58 | 12.2 |
| 1.46 | 10 | 1.44 | 70 | 1.45 | 14.9 |
| 1.45 | 10 | | | | |
| 1.40 | 10 | 1.38 | 50 | 1.40 | 10.8 |
| 1.23 | 20 | 1.23 | 60 | 1.24 | 12.2 |
| 1.17 | 10 | 1.18 | 20 | | |
| 1.15 | 10 | 1.14 | 20 | | |
| Fe $K\alpha$ | | Fe $K\alpha$ Mn Filter | | Cu $K\alpha$<br>Sensitivity 2%<br>Scale $10^4$ x 4<br>Attenuator 10 x 1<br>Discriminator<br>Difference 5 x 10 | |

A partial analysis of the mineral from Clews Gill with parts of analyses of specimens of lithiophorite from South Africa and Saxony for comparison are given below:-

| | i | ii | iii |
|---|---|---|---|
| $Na_2O$ | 0.08 | 0 | 0 |
| $K_2O$ | 0.13 | 0 | 0.73 |
| $Li_2O$ | 0.19 | 3.3 | 1.23 |

i from Clews Gill, Ennerdale; Analyst L. Clark.

ii from Gloucester, South Africa; Analyst C.F.J. van der Walt (J.E. De Villiers, 1945, pp. 632).

iii from Schnee-burg, Saxony; Analyst Winkler (Dana's System of Mineralogy I, 1947, pp. 568).

The lithia content of the specimen from Clews Gill is very low and the soda and potash content high, when compared with the other specimens.

Wadsley (ibid. p. 496) suggests that the manganese oxide minerals have formed by the substitution of metallic ions in a hydrous oxide formed by the oxidation of $Mn(OH)_2$ or else by the oxidation of mixed sols of $Mn(OH)_2$ and other hydroxides. In the formation of pure mineral species only ions of one element are substituted but there is no reason why more than one element cannot be substituted. This will lead to a wide variety of compositions in any one mineral species as has been suggested for lithiophorite by Fleitscher.

Wadsley suggests that the lithium in lithiophorite may be substituting for aluminium according to the formula $(Li, Al)MnO_3 . H_2O$ or $(Li, Al)_2Mn_2O_6 . 2H_2O$. The low lithia content of the Clews Gill lithiophorite may well be due to a relatively minor substitution by lithium. The high soda and potash contents suggest that the place of some of the lithium may have been taken by the other alkalies.

A qualititive Xray spectrographic examination of the Clews Gill specimen by Dr. G. Hornung has shown that it contains in the region of one percent each of iron, cobalt, nickel and zinc. Cobalt and iron are common accessory constituents of lithiophorite (Wadsley, pp. 492) and nickel is recorded in analyses of lithian wad quoted in Dana's System of Mineralogy, Vol. I, pp. 568.)

## C. Lead and Copper.

A copper bearing vein that may be related to the rich copper veins of Dale Head and Goldscope of the Keswick mining area, crops out on the south shore of Buttermere in Burtness Wood. The vein lies along a fault striking north 18 degrees west, which dips to the west at between 40 and 80 degrees. The mineralized zone along the fault is grooved along the strike, with the grooves dipping about 20 degrees to the south.

The vein is largely made up of a quartz breccia which is well seen close to the path through Burtness Wood (G.R.18041550). Small masses of copper and lead minerals up to one inch in diameter occur sporadically infilling vughs in the quartz breccia. They may be found in a small spoil tip on the lake shore (G.R. 17971572) or in situ about 40 yards east of Combe Beck at 800 feet O.D. (G.R. 18201500).

Minerals recorded include quartz, pyrite, chalcopyrite, malachite, chrysocolla, galena, hydrocerrusite, pyromorphite and wulfenite. Apart from quartz, the commonest mineral present is malachite. The wulfenite is of interest because of its rarity in the Lake District. It has only been recorded previously from Brandy Gill and Driggeth near Carrock Fell and Hartsop Hall, near Ullswater (J. Hartley; personal communication). The wulfenite occurs in single, resin coloured, tabular tetragonal crystals about one millimetre in diameter. They are most commonly formed simply of four prisms and two pinacoids, but dipyramidal faces occur in some crystals. The derivation of the molybdenum in the Buttermere wulfenite is unknown.

The order of formation of the secondary minerals, as far as can be observed, is malachite-chrysocolla, pyromorphite, wulfenite.

# PART THREE: APPENDICES

## APPENDIX I.

## GLACIATION

### I. The Glacial History of the Western Lake District.

The detailed glacial history of the western Lake District is now well known through the researches of Smith (1912; 1932), Dixon (1922), Eastwood et al (1931), Trotter et al (1937), and numerous earlier workers. A summary of the glacial history is given below.

There have been three major periods of glaciation identified during the glacial history of the western Lake District. Each of these glacial periods was followed by a period of glacial recession during which the glaciers disappeared from the Lake District. The glacial periods are:-

(i) The Scottish Readvance Glaciation.

(ii) The Main Glaciation.

(iii) The Early Scottish and Lake District Glaciation.

The evidence of the Early Scottish and Lake District Glaciation is sketchy in the western lake district, and is confined, in the main, to the low coastal area. The Main Glaciation has had the greatest effect on the region. The glacially influenced topography of the Lake District is believed to be almost all the result of the Main Glaciation. The Scottish Readvance Glaciation ice sheet only encroached onto the coastal areas of of the western Lake District.

At the zenith of the Main Glaciation the Irish Sea was filled with an ice sheet flowing south from Scotland. The Lake District was covered by an ice sheet, the lower layers of which flowed down the valleys. The flow of the upper layers of this ice sheet was independent of the topography and the ice frequently crossed the topographical divides.

The ice sheets retreated from their position of maximum extent as the Main Glaciation waned. The Irish Sea ice tended to retreat northwards and westwards, while the Lake District ice retreated northwards and eastwards. There was, therefore, a northerly recession of ice as a whole, but the two major ice sheets split as they retreated to the Irish Sea.basin and the Lake District hills, respectively. The split first appeared in the south and gradually spread northwards (Trotter et al, 1937, pp. 97). Glacier lakes, impounded against the Irish Sea ice, were established in the valleys of the vacated ground between the two ice sheets and overflowed southwards, either along the sides of the ice sheets or through gaps in the valley sides.

The Irish Sea Ice receded from the mouths of Ennerdale and Wasdale. At that point the recession of ice stopped temporarily and the ice sheet readvanced into the mouths of the two valleys. (Dixon, 1922; Eastwood et al 1937). After this temporary readvance the Irish Sea Ice retreated from the area and the glacier lakes drained away into the Irish Sea. The

Lake District Ice sheet quickly diminished into valley glaciers which receded to their sources at the heads of the valleys.

Valley glaciers possibly occupied the valleys of the Lake District during the Scottish Readvance Glaciation but there is no evidence to prove this. Manley (1961) suggested that the wettest parts of the Lake District were subjected to a 'Corrie' glaciation in post-Allerod times. He attributed the present combes and associated moraines in the Lake District to this glaciation. Gresswell (1962 , p 83) attributed the final sculpturing of the combes of the Coniston district into the forms they have today to the post-Allerod 'Corrie' glaciation. He also suggested (pp. 90) that a Highland Readvance Glaciation occurred between the Scottish Readvance Glaciation and the post-Allerod 'Corrie' Glaciation in the Coniston district.

## 2. Glacial Studies of the Present Work.

### (A) Introduction.

The glacial history of the western Lake District has been worked out in detail by previous workers (see above). The results of earlier surveys have been confirmed by the present survey at all points where the surveys coincide. The results of the work in previously surveyed areas are, therefore, not discussed as they are merely repetitive. The present work adds little to our knowledge of the glacial history of the Lake District, but several points of interest have been noted.

The area to be discussed lies east of the area over-ridden by the Irish Sea Ice Sheet and has not been directly affected by that ice sheet, therefore, evidence concerning the early Scottish and Lake District Glaciation and the Soottish Re-advance Glaciation is missing. The effects of the Main Glaciation, however, are evident on all sides, while the freshl glaciated appearance of the combs provides evidence of a late independent 'Corrie' glaciation.

(B) The Main Glaciation.

The approach of the Main Glaciation was marked by the onset of cold conditions with an increase in the precipitation of snow. Corrie glaciers formed as the increase in precipitation of snow exceeded its removal by ablation and melting. As the corrie glaciers increased in size, they flowed from the corries into the main valleys to fuse into valley glaciers. The valley glaciers, increasing in size, eventually filled the valleys and submerged the ridges between the valleys. Many of the peaks in the Lake District became covered with ice and the valley glaciers merged across the intervening ridges to form the Lake District Ice Sheet. The Main Glaciation reached its maximum development with the formation of the Lake District Ice Sheet.

The Lake District Ice Sheet at its maximum extent covered all the lower hills of the western Lake District. Many of the hills clearly show the results of the scraping and smoothing action of the ice. Seatallan, Cawfell, Iron Crag, Great Borne, and others have been scraped bare of any superficial deposits and have often incipient roches moutonnés on their summit ridges.

A train of boulders of Ennerdale Granophyre can be followed from the summit ridge of Iron Crag westwards to Blakely Raise revealing the path of a westerly flowing ice sheet which passed over the summits of Iron Crag, Grike and Blakely Raise. Sedgwick (1825, from Ward 1873) was one of the first to notice the anomalous position of boulders of Ennerdale Granophyre on the summit of Starling Dodd. These boulders rest on Skiddaw Slates which are topographically higher than the surrounding granophyre. Sedgwick and Ward, believing that the boulders were dropped from icebergs, thought that this proved a marine submergence of over 2000 feet. It is now believed that the erratics on Starling Dodd were left by ice that flowed over the Starling Dodd ridge. The direction of flow of this ice appears to have been northwards, for the abundance of granophyre erratics and the lack of volcanic erratics suggests that the erratics came from Ennerdale, south of Starling Dodd. The northerly flow of the ice from Ennerdale, to Buttermere, is also suggested by the spread of abundant volcanic erratics between Scale Beck and Lincombe Edge extending northwards from the col between Red Pike and Little Dodd.

On a north-south traverse from Great Borne to Seatallan all the summits are ice smoothed and all are approximately 2000 feet in height. The surface of the ice sheet along this line of traverse must, therefore, have been above 2000 feet in altitude. Great Borne clearly shows the influence of ice erosion Herdus, immediately to the west of Great Borne, has a flat summit plateau which shows relatively little sign of ice action. It is thought that the mass of Great Borne split the west or north-westerly flowing ice sheet and largely protected Herdus from the effects of ice abrasion. Ice certainly passed over Great Borne but the successful protection of Herdus suggests that the ice sheet was quite thin.

The part of the ice sheet above the level of the summits of the Lake District could move more or less independently of the underlying topography. The flow of the lower part of the ice sheet, however, was strictly controlled by the topography and glacier flow was directed down the valleys. There must have been some mixing of the upper and lower parts of the ice sheet, for the erratics which show the direction of the movement of the upper part of the ice sheet have been derived from the eroding lower part.

The valley glaciers, as they reach their maximum development, occasionally developed distributaries which flowed over cols into adjacent valleys. The distributaries deepened the cols and gave them a U shaped profile. An offsheot of the Buttermere glacier flowed up Black Beck into the head of Mosedale where it join-ed the Mosedale Glacier. Dixon (1922) showed that a glacier passed along Gill Beck from Floutern to Ennerdale. The westerly flow of the Gill Beck Glacier may have been due to the westerly thrust of the Black Beck Glacier or the blocking of the exit from Floutern Tarn into Mosedale by the Mosedale Glacier. The Nether Beck Glacier, which flowed into Wasdale, overfloweed across the low col at Pots of Ashness into the Bleng Glacier and over the col south of Seatallan into Greendale.

The direction of ice flow has been determined by the direction of glacial striae (Ward 1873, pp. 82-84; Smith, 1932, Pl. VII), the form of roches moutonnées and the distribution of glacial erratics (Marr, 1916, pp. 143-155).

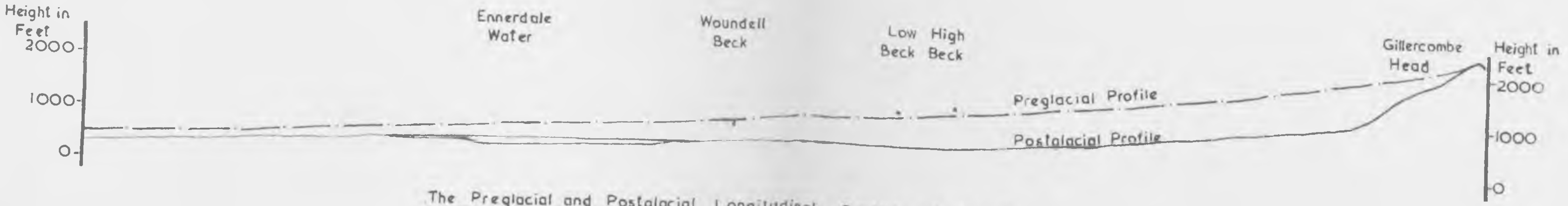
## (C) Erosion During the Main Glaciation.

The recognition and study of numerous late Tertiary marine erosional platforms between Wasdale and Buttermere has led Hollingworth (1937) to conclude that the level of the Lake District as a whole has not been greatly reduced by the Pleistocene Ice Sheet. The major erosion during the glaciation was affected by valley glaciers which deepened and widened the pre-existing valleys. The hills merely had their cover of weathered rock removed and their underlying solid rock rounded and smoothed.

The amount of vertical erosion by the valley glaciers can be calculated from a comparison of the pre-glacial and post-glacial longitudinal profiles of a valley. The pre-glacial profile of a valley can be reconstructed by using the profiles of tributary hanging valleys. The upper part of a hanging valley is presumed to have remained graded to the level of the pre-glacial major valley. The profile of the hanging valley is projected into the major valley until it intersects the mid line of the major valley. The point of intersection is a point on the pre-glacial longitudinal profile of the major valley. A series of hanging valleys along the sides of a major valley enable a series of such points to be determined and the

FIGURE 23.

The Preglacial and Postglacial Longitudinal Profiles of Eskdale.



The Preglacial and Postglacial Longitudinal Profiles of Ennerdale.

Horizontal Scale 1 inch = 1 mile

profile to be reconstructed.

Marr, (1906, Fig. 8) gives the pre-glacial profile of Borrowdale reconstructed in this way. The longitudinal profiles of pre-glacial Eskdale and Ennerdale are shown in Fig. 2B. Eskdale has been chosen because its numerous hanging valleys enable several points along its pre-glacial profile to be determined. The reconstructions of profiles of pre-glacial Eskdale and Borrowdale are typical profiles of graded fluvial valleys. The perfection of these reconstructed profiles appears to justify the use of the above method in the reconstruction of the pre-glacial profiles of other valleys, for example Ennerdale, in which hanging valleys are less numerous.

A comparison of the pre-glacial and post-glacial longitudinal profiles of a valley clearly shows that vertical glacial erosion has not been constant over the full length of the valley. The thickness of strata removed by vertical erosion is very small at the mouth of the valley, but gradually increases to the head of the valley. The maximum thickness of rock removed by vertical erosion is of the order of 750 feet near the head of the Ennerdale.

The pre-glacial relief, calculated using the preglacial valley profiles, was surprisingly high. The preglacial relief at Gillerthwaite in Ennerdale for example, was approximately 1100 feet compared with 1600 feet at the presant time. The preglacial valleys must have been deep, V shaped, almost gorge-like valleys.

Lateral erosion by the valley glaciers has oversteepened the valley sides and bevelled off many valley spurs. The occurrence of numerous truncated spurs, for example Long Crag on Steeple, High Stile and High Crag shows that the preglacial valleys were not as straight as the present valleys and probably zigzagged between overlapping spurs.

The preglacial topography of the Ennerdale district with its high relief contrasts with the mature preglacial topography of rounded hills described by Marr (1916, pp. 140) and Mitchell (1931) from the eastern Lake District.

Valley glaciers have excavated rock basins in the floors of the Wasdale, Buttermere and Ennerdale Valleys. These rock basins are now occupied by Wastwater, Buttermere and Ennerdale Water. The present level of Wastwater is contained by moranic obstructions, but the moraines have merely raised the water level, for Wastwater, with its floor at-150 feet O.D. would, in any case, be dammed by bed rock. Ennerdale Water and Buttermere are most likely similar to Wastwater, in that morainic dams have merely raised the level of lakes that would in any case be impounded by rock dams.

The deep trench of Wastwater has probably been excavated along a shatter belt. The Ennerdale Water basin may have been in part excavated along a tear fault. The occurrence of lakes in most of the major Lake Districts valleys shows, however, that the sites of the lakes are not entirely structurally controlled. Almost all the lakes have a rock dam close to the valley mouth, just before the valley opens out onto the coastal plain. The origin of these rock dams can be explained by Penck's Law of adjusted cross-sections for glaciated valleys (1905). If a valley widens out, then according to the law it must become less deep. When the Lake District valleys widen out onto the western coastal plain they must decrease in depth. Their floors will rise as rock steps across the mouth of the valley and lakes will be impounded behind these steps.

### (D) The Retreat of the Main Glaciation.

Three glacial periods later than the Main Glaciation have been recognized in the Lake District (Gresswell, 1962, pp. 90). These are the Scottish Readvance, the Highland Readvance, and the post-Allerod Glaciations. It is possible that glaciers occupied the Buttermere, Ennerdale and Wasdale valleys during the first two of these glaciations, although deposits associated with them have not been identified. It is possible, therefore, that retreat phenomena attributed to the Main Glaciation actually belong to a later glaciation.

The Lake District Ice Sheet, after parting from the Irish Sea Ice, quickly diminished to a series of valley glaciers. The valley glaciers then receded to their sources.

Smith (1932, pp. 71) describes a series of terminal moraines in Wasdale stretching from Easthwaite Farm to Strands. These moraines have been deposited in Glacier Lake Wasdale from the snout of the Wasdale Glacier. A series of five terminal moraines marking a slightly later halt in the retreat of the Wasdale Glacier than the Easthwaite-Strands moraines encircle the foot of Wastwater. They extend in an arc from the mouth of the River Irt, through Low Wood to the Wasdale Road. These moraines originally damned up Wastwater raising its level to about 230 feet O.D. The lake then flooded the land to the north of High Birkhow and overflowed westwards down Cinderdale Beck. The overflowing water cut a channel about 90 yards west of Scale Farm with an inflow at 230 feet O.D. and an outflow at 200 feet O.D. The channel was vacated, except for the present Cinderdale Beck, when Wastwater cut through the moraines.

The recession of the Bleng Glacier has left a series of well preserved moraines. Yokerill Hows are a line of large morainic mounds with their crests at about 900 feet O.D. along the south side of the Bleng Valley. The boulders in the moraines are largely of Ennerdale Granophyre with an admixture of volcanic rocks. This line of moraines, parallel to the length of the valley, is most likely a lateral moraine of the Bleng Glacier. The glacier at this stage could not have been much more than 200 feet thick as the bottom of the valley is only 140 feet below the crest of the lateral moraine. The lateral moraine of Yokerill Hows, at Swinsty Beck, joins on to a terminal moraine which forms the Step Hills. This terminal moraine held back a lake which extended almost a mile up the Bleng Valley with its water level just below 900 feet O.D. The bed of this lake is now a flat swamp through which the River Bleng meanders. Remnants of a terminal moraine occur at the head of the valley below Red Crag. Thick morainic deposits of uncertain origin are heaped against the end of the valley below High Pike How. These moraines may be the last terminal moraine of the Bleng glacier or they may have fallen from a hanging corrie glacier under Gowder Crag.

No retreat stages of the Ennerdale and Buttermere Glaciers are preserved in the lower reaches of the valleys. This suggests that the glaciers receded up the valleys without a pause.

The retreating glaciers filled the valley bottoms with thick deposits of boulder clay left as ground moraines. The post-glacial rivers now meander over flat alluvial straths which have been incised into these ground moraines. The ground moraines are left as benches, sometimes over 30 feet high, along either side of the valleys (Photo. 2).

### (E) The Post-Allerod Corrie Glaciation.

Hollingworth (in Eastwood et al, 1931, pp. 240) considers the possibility of an independent corrie glaciation in the Ennerdale District. Manley (1961) suggests that the combes in the Lake District were occupied by corrie glaciers in post-Allerod times. He attributes the present form of the combes and the moraines within the combes to this post-Allerod Corrie Glaciation.

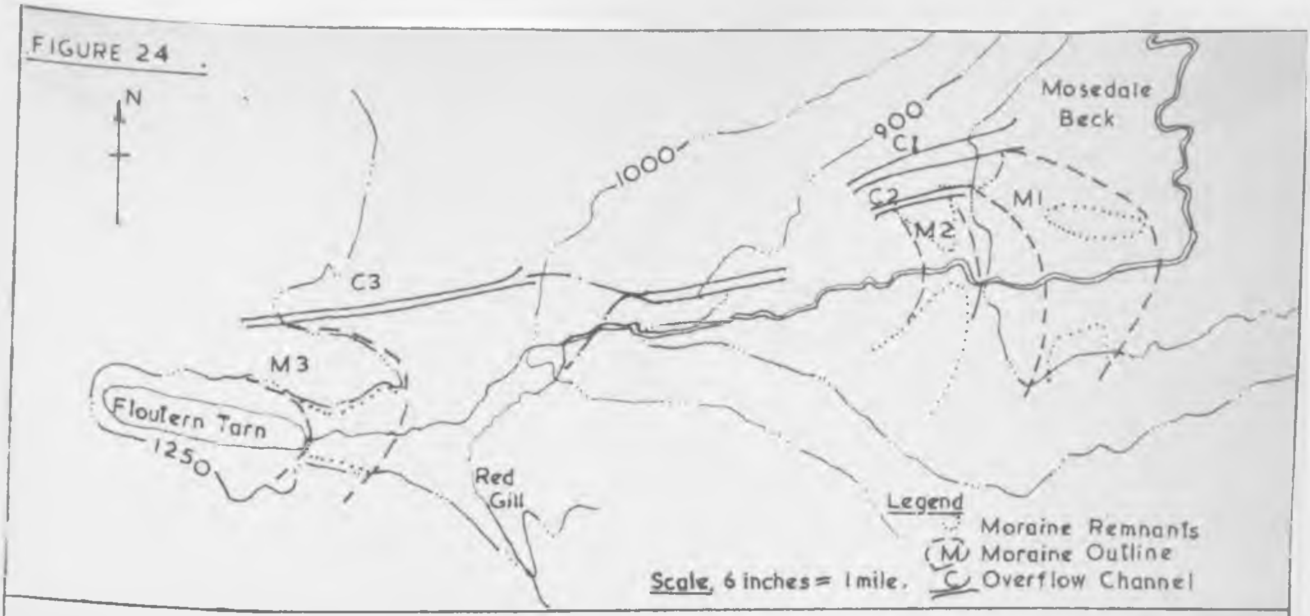
A characteristic feature of many combes in the Lake District, for example Bleaberry Combe in Buttermere, is the terminal moraine at their lip. These terminal moraines do not appear to be associated with any other moraines in the main valleys. The combes themselves, for example Burtness Combe, often have a very freshly glaciated appearance. The moraines in the combes and the final sculpturing of the combes are possibly caused by a post-Allerod Corrie Glaciation.

Combes are found in various stages of formation. Open combes, in which the classic amphitheatre form has not been developed, are common, particularly on the outcrop of the Ennerdale Granophyre. The floors of such combes are flat benches below such cliffs as Boat How crag and Seatallan crag. The benches are probably remnants of the pre-glacial erosional platforms described by Hollingworth. This suggests that the corrie glacier has only given the cliffs their final sculpturing for they were already present as steep features backing the benches before the glaciation. The immature form of the open combes suggests that their corrie glaciers were short lived.

Burtness Combe is a much more advanced combe in which the corrie glacier has sapped back into the summit plateau of High Stile (Photo. 15) and given the combe a deep amphitheatre form. Burtness Combe is backed by the cliffs of Eagle and Grey Crags which are over 300 feet high. Similar magnificent combes are found along the south side of Ennerdale from Pillar Cove to the Great Cove.

Bleaberry Combe in Buttermere is a good example of a combe in which the corrie glacier has gouged out the floor of the combe into a rock basin which is now occupied by a tarn.

FIGURE 24.



Moraines and Overflow Channels in the Vicinity of Floutern Tarn

A series of terminal moraines marking the retreat of a possible corrie glacier occur at Floutern Tarn (Fig. 24). The remnants of a terminal moraine (M1) cross the Mosedale Valley at the point where Mosedale Beck, flowing from Floutern Tarn, turns sharply to the north. This moraine dammed back a small lake which overflowed through a channel (C1) at the north end of the moraine. A second moraine (M2) occurring just above the first at 800 feet O.D. also held back water which cut a small channel (C2) at the north side of the moraine. A third moraine (M3) which looks much fresher than the other two, is found around the eastern end of Floutern Tarn. An overflow channel (C3), now dry, has been cut at the north end of the moraine, with an inflow at 1250 feet O.D. and an outflow at 1000 feet O.D. The two lower moraines possibly belong to an earlier glaciation than the corrie glaciation.

There has been a marked climatic control over the development of the combes. The development of combes has been much favoured on the shaded north facing slopes of the mountains. This is particularly marked on the ridge between Ennerdale and Buttermere, where there is a line of six large combes on the north side and none on the south side.

The combes of the region appear to mouth at distinct altitudes as shown below:-

| Approximate height in feet | Name of Combes. |
|---|---|
| 2000 | Scoat Tarn, Iron Crag, Tewit How Tarn, Silver Cove, Mirklin Cove. |
| 1750 | Low Silver Cove, Seatallan. |
| 1500 | Lincombe, Bleaberry Combe, Burtness Combe, Wind Gap Cove. |
| 1250 | Low Burtness Combe, Floutern Tarn, Boathow Crag. |
| 1000 | Low Lincombe. |

The concentration of the combes at the above heights suggests that there has been an altitude control over the positions in which the combes originated. The various levels could well mark persistent snow lines on which the combes were initiated.

## APPENDIX III.

## INTRUSIONS UNRELATED TO THE ENNERDALE GRANOPHYRE.

### I. Pre Caledonian Intrusions.

#### (A) Introduction.

Small intrusions which are older than the major Caledonian fold movements are quite common in the Skiddaw Slates of the Ennerdale district. Smith and Hollingworth (in Eastwood et al 1931, pp. 56) have identified many of these early intrusions on Dent. The 'Dent Group' of intrusions occurs in two swarms trending between northeast to south-west, and east-west, one on the south-eastern, and the other on the north-western slopes of Dent. The composition of these intrusions is said to vary from keratophyric, through andesitic to basaltic.

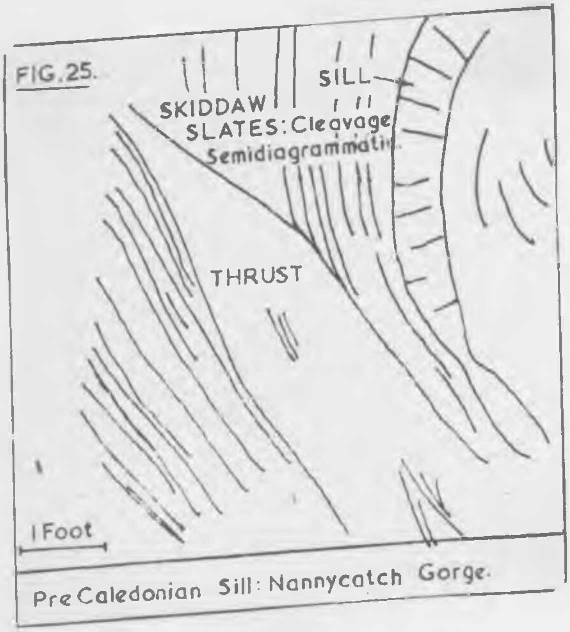
Similar intrusions are shown by Ward (One Inch Geological Sheet 101, S.E. Old Series) on the south end of Mellbreak and in Mosedale Beck about a quarter of a mile east of Floutern Tarn.

#### (B) Field Relationships.

The pre-Caledonian intrusions occur as minor sheets whose relationships with the surrounding slates are difficult to determine because of the cleavage of the slates. These intrusions are very common in Nannycatch Gorge and on the south end of Mellbreak east of Floutern Tarn. The strike of the intrusions is usually between south-west and west, but may be a few degrees north of west.

The intrusions vary from a few inches to over 50 feet in thickness, but usually cannot be traced for more than a few yards. The majority of the intrusions appear to be lensiform masses, for example an intrusion on Raven Crag in Nannycatch Gorge (G.R. 055129) and a mass just north of Black Beck near Crummock (G.R. 148174). On the south end of Mellbreak overlooking Crummock Water a few of these intrusions have a typical dyke form. Small sheets often appear to be concordant sills. (Fig. 25.)

FIG. 25.



Pre Caledonian Sill: Nannycatch Gorge.

Smith and Hollingworth suggest that the 'Dent Group' of intrusions are a series of flat sided rod-like lenticles of variable hade intruded parallel to, or along the axes of minor pitching folds in the slates. This implies that the intrusions were emplaced after the major fold movements although Smith and Hollingworth do state that the intrusions are probably older than the cleavage in the slate. Fig. 25 shows a thin concordant sill in Nannycatch Gorge (G.R. 05751360) which has been folded and faulted with the Skiddaw Slates. This sill was clearly intruded before the major earth movements.

It is believed that these early intrusions were in place before the major Caledonian fold movements. The impersistent lensiform character may have been caused by the disruption of normal elongate intrusions by thrusting and folding during the earth movements.

## C. Petrography.

In hand specimens the rocks are rather uniform fine to medium grained greenish-grey rocks. Many are vesicular with the vesicles filled with quartz. The vesicles of a dyke on Mellbreak (G.R. 151180) are occasionaly filled with chalcopyrite and malachite. Phenocrysts in the rocks are rare.

Under the microscope the rocks are very badly altered. Considerable portions of a specimen taken from Mosedale Beck at 900 feet O.D. (E 9301) have been replaced by calcite. The matrix of the rock is composed of feldspar laths approximately 0.3 mm long and chlorite, mainly clinochlore with little penninite. The feldspar laths have been almost completely replaced by calcite. Quartz is very common in rounded grains up to 0.5 mm. in diameter which have been partially replaced by calcite. A micaceous mineral, possibly biotite, is quite common in crystals up to 0.4 mm. in diameter. These crystals have been replaced by calcite, sericite, chlorite and quartz but still retain their pleochroism. Pseudomorphs of leucoxene after skeletal crystals of ilmenite approximately 0.2 mm. in diameter are abundant. Fresh pyrite occurs in fresh skeletal crystals up to 1 mm. in diameter. This rock originally had a trachytic texture with the feldspar laths in sub-parallel orientation.

Another specimen from Mosedale Beck, at 1000 feet O.D. (E 9300) is finer grained than the first specimen. A fine matrix of quartz, chlorite and feldspar is replaced over much of the section by calcite in crystals up to 1.5 mm. in diameter. Quartz and feldspar occur in crystals up to 0.2 mm. in diameter but these are often replaced by calcite. Chlorite, both penninite and clinochlore, is abundant.

An intrusion in Oxenstone Beck just below the Cold Fell road (G.R. 06221455) consists of a rock (E 9617) which is similar to those in Mosedale Beck, but contains little calcite. Quartz and feldspar occur in a felsitic mosaic which is often obscured by a development of abundant penninite. The feldspar is badly sericitized. Quartz filled vesicles occasionally occur.

A specimen from Raven Crag in Nannycatch Gorge (E 9618) has a fine matrix of sericitized feldspar laths, penninite, sericite and quartz. Abundant leucoxene grains up to 0.1 mm. in diameter are scattered throughout the rock. Quartz grains up to 0.3 mm. in diameter are quite common. Penninite is abundant, frequently occurring in lenses up to 3 mm. long. Quartz filled vesicles are common.

The specimens described above are so badly altered that their original identity has been lost. Quartz is present in every specimen and is probably a primary constituent of the rocks.

## 2. The Hole Gill Porphyry.

The Hole Gill Porphyry crops out in an exposure about four feet across in the south bank of Hole Gill on the east side of Lank Rigg at 1400 feet O.D. (G.R. 09661166). The Main Granophyre is exposed in Hole Gill approximately five yards on either side of the porphyry, but the two are not seen in contact. The porphyry is a fine grained rock containing large euhedral tabular feldspar phenocrysts. The tabular crystals are alligned roughly parallel to a vertical east-west plane, as if the porphyry has been intruded as a dyke.

The matrix of the porphyry is composed of a very soft creamy coloured clay substance liberally speckled with a dark greenish-grey material. The phenocrysts are about one millimetre thick, but some exceed a centimetre in diameter. They are all perfectly euhedral, but the original feldspar has been replaced by a white clay mineral.

In thin section the rock can be seen to be entirely altered. The phenocrysts are composed of clay minerals and sericite. The matrix has a base of clay minerals, sericite and a little chlorite and quartz, in which are set irregular masses of white leucoxene and red haematite associated with fresh magnetite. The magnetite occurs in rod-like, skeletal and octahedral crystals. The leucoxene and iron ore is the greenish grey material speckling the rock in hand specimens.

The Hole Gill Porphyry is unlike any other rock in the vicinity. It is younger than the Main Granophyre and yet it is entirely altered while the granophyre is fresh.

## APPENDIX III

## MINERALOGY.

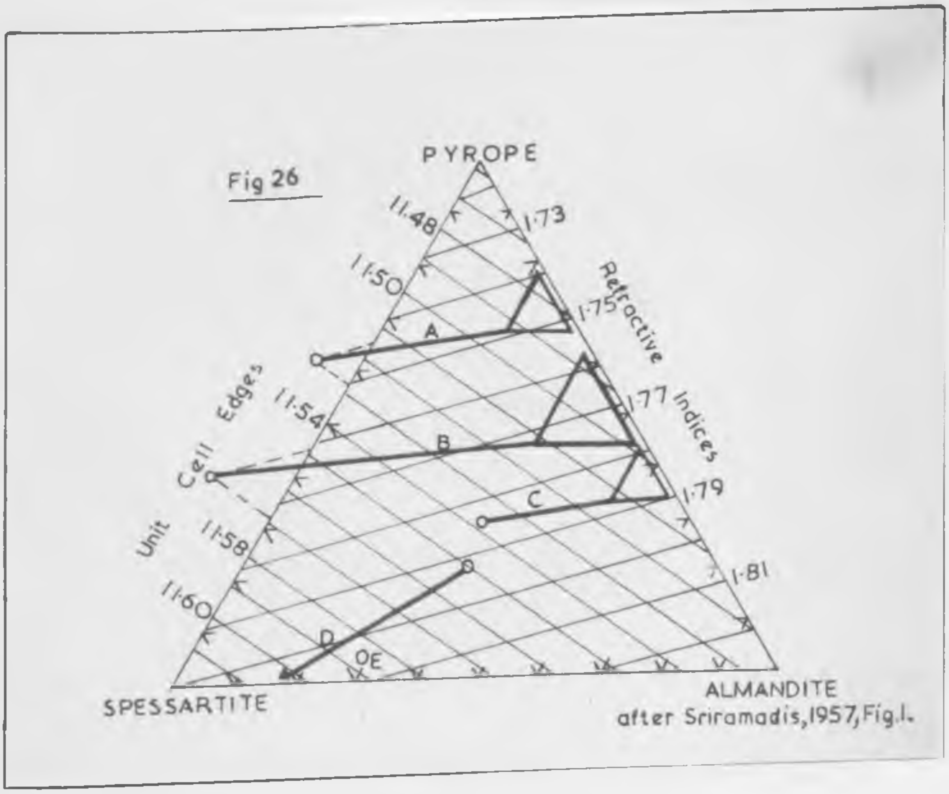
### I. The Composition of Garnets from Buttermere: A Criticism of Diagrams by Sriramadis (1957) for the Correlation of Unit Cell Edges and Refractive Indices with the Chemical Composition of Garnets.

Small yellowish pink garnets have been found in diorite from the top of a laccolith in the Burtness Combe Intrusive Complex (Chapter III). The Xray powder defraction pattern of these garnets corresponds fairly closely to that of an analysed spessartine garnet from Benson, Southern Rhodesia (Hornung, Ph.D. thesis, 1961). A similar pattern is given by artificial spessartine (Yoder and Keith, 1951). The Xray patterns, therefore, indicate that the garnets from Buttermere are spessartine garnets.

The triangular diagram of Sriramadis (1957, Fig. 1) apparently allows the chemical composition of a garnet consisting of a mixture of spessartine, almandine and pyrope to be determined from its unit cell edge and refractive index. The composition of garnet from Buttermere determined from this diagram (Fig. 26) is spessartine 66%, almandine 30% and pyrope 4%.

The accuracy of his diagram has been tested by plotting the compositions of four garnets determined both from their

Variation of unit cell edges and refractive indices with chemical composition in the garnet group Pyrope-Spessartite - Almandite.



after Sriramadis,1957,Fig.I.

LEGEND

△ Composition of garnet determined by chemical analyses.

o Composition of garnet determined from the diagram.

A. Pyrope from Norway, Nixon, 1960.
B. Pyrope from Kao, Nixon, 1960.
C. Pyrope from Kao, Nixon, 1960.
D. Spessartite from Benson, Hornung, 1961.

E. Spessartite from Buttermere.

chemical analyses and their optical properties. There is little correlation between the chemical compositions and optical properties of these garnets. A spessartine from Benson contains only 2.29% of consituents other than pyrope, almandine and spessartine, yet its spessartine content, calculated from its optical properties, is half the actual spessartine content.

The calculated and observed compositions of each of the garnets corresponds to similar values of refractive index. The corresponding values of the unit cell edge, however, are widely different, for example in the spessartine from Benson, the refractive indices of the calculated and observed compositions are 1.793 and 1.803 respectively, while the corresponding unit cell edges are 11.55 and 11.60. It is noticeable that the unit cell edge that is actually observed is always greater than that calculated from the analysed composition of a garnet.

The significance of these differences is uncertain, perhaps a slight impurity of grossularite, andradite or uvarovite distorts the crystal lattice and changes the unit cell edge. The differences make correlation of the chemical composition of a garnet with its unit cell edge and refractive index by means of the above diagram inadvisable.

## 2. The Feldspars of the Main Granophyre.

### A. Orthoclase Microperthite.

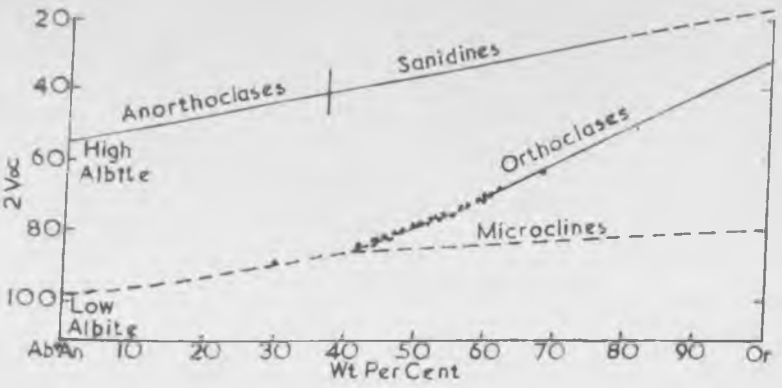
The majority of the feldspar in the Main Granophyre is microperthite. The microperthite occurs in micrographic intergrowth with quartz, in anhedral crystals in the matrices of microgranites, in subhedral prisms and as overgrowths on primary plagioclase phenocrysts.

The perthitic texture can be revealed in the coarsest microperthite by staining with sodium cobaltinitrite. Fine microperthite, however, stains as homogeneous potash feldspar.

In thin section the texture of the feldspar varies from practically homogeneous to distinctly perthitic. The plagioclase occurs in the coarsest microperthite as parallel spindles which show fine albite twin lamellae parallel to their length. This is particularly well seen in microperthite overgrowths on plagioclase phenocrysts where the plagioclase spindles in the microperthite are parallel to the twin lamellae of the primary plagioclase. The most common microperthite has a fine mottled texture in which there are no means of identifying the plagioclase and orthoclase fractions. There is no albite twinning in the plagioclase and the whole feldspar is crowded with dust preventing any differences in refractive indices from being seen.

The 2 V's of several specimens of microperthite from the Main Granophyre have been plotted on part of the graph (Fig. 27). by MacKenzie and Smith (1955, Fig. 1) correlating the optical properties and chemical compositions of alkali feldspars. The microperthites are assumed to be orthoclase microperthite, and are plotted on the graph as such, because their readily observable perthitic texture shows that they are low temperature feldspars. Their 2 V's are in general too high for high temperature feldpars, and too low for

FIG 27



The 2Vs of Microperthites and K-Feldspars of the Main Granophyre.

after MacKenzie & Smith

Photo.16.

Photo.17

microcline microperthites.

This graph shows that the majority of their compositions falls between $Ab+An_{60}\ Or_{40}$ and $Ab+An_{40}\ Or_{60}$.

The phenocrysts in the finest granophyres of the Main Granophyre are commonly composed of a plagioclase core and a micro-perthite rim. The microperthite rims have developed by replacement of the primary plagioclase and in some cases the plagioclase has been entirely replaced, leaving a microperthite phenocryst. The microperthite rims of several phenocrysts in each specimen are perfectly euhedral (Photos. 16 & 17). These euhedral rims are commonly skeletal and their faces appear to have grown in situ at the expense of the surrounding micropegmatite.

The microperthite of some of these euhedral feldspars has lost its microperthitic texture and become a clear grey feldspar. The 2 V's of some of these feldspars are low, in the region of 65 degrees, and a few of them are crossed by very fine striae. Their homogeneous character suggests that these feldspars are cryptoperthites and the fine striae suggests that they may be anorthoclase. The lowest 2 V's of some specimens are lower than those of the normal microperthites but not as low as those of the high temperature feldspars. These feldspars are probably cryptoperthites intermediate in structure between the low and high temperature feldspars.

### B. Plagioclase.

The optical properties of the plagioclase crystals in the Main Granophyre suggest that there are three different plagioclases present; Normal plagioclase with compositions of about $Ab_{95}$ and $Ab_{65}$, and a high temperature form of plagioclase.

The 2 V's of many plagioclase crystals in which the optic sign is negative are very low, between 77 and 69 degrees. This is much lower than the lowest 2 V of low-temperature oligoclase and andesine. Similar values of 2V have been obtained from plagioclase from the Beinn an Dubhaich Granite by Tuttle and Keith (1954) who suggested that the plagioclase was intermediate in character between high and low temperature plagioclases.

## 3. Ferromagnesian Minerals.

### A. The Basic and Hybrid Rocks.

The original ferromagnesian mineral in the basic rocks was a pyroxene which has been almost entirely altered to amphibole or chlorite. Pyroxene is preserved as rare remnants in the cores of amphibole pseudomorphs in a diorite (E 9202) from Burtness, Buttermere. The optical properties of this pyroxene are as follows:-

| | |
|---|---|
| Colour | Colourless. |
| Cleavage | Not observed, possibly due to small size of grains. |
| Relief | High. |
| Birefringence | Moderate. Maximum interference colour observed was first order red. Birefringence is possibly higher as few grains were examined. |

| | |
|---|---|
| Interference Figure | Biaxial positive. The following values of 2 V have been determined 48, 50, 50, 50.5. |

The medium 2 V and lack of colour suggest that this pyroxene is augite.

Titan augite with the following optical properties is abundant in a microdiorite (E 10397) from Buckbarrow in Wasdale:-

| | |
|---|---|
| Colour | Pale pink. |
| Pleochroism | Very weak |
| Cleavage | Two cleavage directions at right angles, not well developed. |
| Relief | High. |
| Birefringence | Moderate. Maximum interference colours are second order greens and yellows. |
| Extinction | $c \wedge z$ 53 degrees. |
| Interference Figure | Biaxial positive. The following values of 2 V have been determined, 46, 46, 43, 44. |

Amphibole occurs as pseudomorphs after augite and is abundant as small fibrous crystals disseminated through almost all specimens. The amphibole crystals rarely have good crystal forms for the fibrous nature of the amphibole gives the crystals ragged fibrous edges. The optical properties of the amphibole are given below:-

| | |
|---|---|
| Colour | Pale green |
| Pleochroism | Pale green to colourless, or occasionally pale brownish green to pale yellow. |

| | |
|---|---|
| Cleavage | Typical amphibole cleavage. |
| Relief | Fairly high. $n_\alpha = 1.625 \pm 0.005$<br>$n_\gamma = 1.655 \pm 0.005$ |
| Birefringence | Fairly high. Maximum interference colours are middle second order colours. |
| Extinction | $c \wedge z$ varies from 20 to 25 degrees. |
| Twinning | Common parallel to (100) |
| Interference Figure | Biaxial negative. 2 V's variable from 72.5 to over 80 degrees. |

The occurrence of the amphibole as a secondary mineral after augite suggests that it is a member of the tremolite-actinolite series. This is supported by the fibrous nature of the amphibole and its pale green colour. Its low refractive index, $n_\gamma = 1.655$, also suggests that it is close to tremolite in composition. The maximum extinction angle is high for tremolite-actinolite, but it is considered that the optical properties of the amphibole are closer to those of tremolite-actinolite than any other amphibole. The mineral is, therefore, referred to as tremolite-actinolite in this work. The variation in 2 V and extinction angle suggests that there may be a variation in composition of the amphibole.

Penninite is by far the most common chlorite present. It is pleochroic from green to pale green, is almost isotropic but shows anomolous Berlin Blue interference colours. Occasionally the penninite has anomalous brown interference colours. The maximum interference colour of the chlorite increases to first order white in a few flakes which may be clinoclore.

A serpentine mineral is abundant in the matrices of sections E 9201 to E 9204 from the Burtness laccolith and is the major mineral in pseudomorphs after feldspar in E 9201 and E 9202. The optical properties of this mineral are given below:-

| | |
|---|---|
| Form | Commonly structureless, but finely fibrous in places. |
| Birefringence | Nil. |
| Relief | Fair. |
| Refractive Index | 1.57 ± 0.01. |

The refractive index and the absence of birefringence suggests that the mineral may be a variety of penninite. The lack of structure, or finely fibrous structure, however, suggests that it is a serpentine. It may be amorphous serpophite or an isotropic antigorite.

### B. Borrowdale Volcanic Series.

Primary pyroxene, from a pyroxene andesite (E 10354) from Little Gowder Crag (G.R. 14031097) has the following optical properties:-

| | |
|---|---|
| Colour | Colourless to very pale pink. |
| Cleavage | Typical pyroxene cleavage |
| Relief | High. |
| Birefringence | Moderate. Maximum interference colours are second orders green and yellows. |
| Interference Figure. | Biaxial positive. The following 2V's have been determined, 56, 56.5, 56.5, 58 degrees. |

# APPENDIX IV.

## PETROGRAPHIC TECHNIQUE.

### I. Staining Feldspars.

The correct identification of potash feldspars has been essential in the study of the hybrid rocks of the Ennerdale Granophyre. In thin sections of the hybrid rocks, plagioclase crystals that have been enriched in potash are commonly very similar to altered plagioclase crystals containing no potash. The only reliable method of identifying potash feldspar in such rocks has been to stain the specimens with sodium cobaltinitrite. The method used for such staining has been a modification on the method described by Bailey and Stevens (1960).

### Procedure.

1. Place an etching vessel on a filter paper on a hot plate at regulo 1, in a fume cupboard.
2. Fill the etching vessel to within ¼inch of the top with 40% hydrofluoric acid solution. The etching vessels used were plastic boxes normally used for packing glass cover-slips.
3. Place a specimen face down over the hydroflouric acid and leave to etch. The etching vessel should be completely covered by the specimen, for if the acid can escape the etch will be uneven.

4. Remove specimen, rinse in water, and immerse it in a saturated sodium cobaltinitrite solution.
5. W-ash specimen, dry, and cover with crystallite and a cover slip.

The times of ten seconds etching and fifteen seconds staining recommended by Bailey and Stevens for thin sections have proved satisfactory. Their recommended times of three minutes etching and one minute staining for polished rock slabs, however, give too thick a precipitate. The best results with polished rock slabs have been obtained with three minutes etching and fifteen seconds staining. The resolution of a stain in which the precipitate is too thick can be improved by gentle rubbing to remove excess precipitate.

## Results

Thin Sections: Staining of thin sections from which the cover slip has been removed is unsatisfactory because of interference by Canada Balsam still covering the section. Washing with xylol to remove this balsam is never completely successful.

The results of staining fresh uncovered sections are usually good. The pale colour and translucency of the precipitate, however, makes it difficult to distinguish accurately between potash feldspar and plagioclase in mixed crystals.

Rock Slabs: The results of staining polished rock slabs are usually excellent. The stain is selective and clearly delimits the potash feldspar. The resolution of the stain can be improved by giving the rock slab a finer polish. The resolution on such well polished slabs is sufficiently good to show fine perthitic and zonary textures in mixed feldspars, but microperthites tend to stain as homogeneous feldspar.

The staining of potash feldspar on polished slabs is believed to be selective enough for the stained specimens to yield meaningful modal analyses when their potash content is counted with a point counter.

Plagioclase: The technique of staining plagioclase by rhodizonate, recommended by Bailey and Stevens, has not been successful. In a few cases the selective staining has worked, but in many cases the rhodizonate stain has not been selective. This may have been due to the porosity of the specimens.

# APPENDIX V.

## HISTORY OF PREVIOUS RESEARCH.

The history of previous research can be conveniently divided into three sections; The Ennerdale Granophyre, the Skiddaw Slates and the Borrowdale Volcanic Series. The early research is of such a generalized nature that all three sections will be described together up to about 1875.

### 1. Early Research.

Research began in the area about 1820 when Jonathan Otley published his 'Concise Description of the English Lake District'. Otley subdivided the Lower Palaeozoic rocks of the Lake District into Lower, Middle and Upper Slates. He gave the first description of the general outcrop of the Ennerdale Granophyre (pp. 156-8) which he believed to be a fine grained variant of the Eskdale Granite. He believed the granitic rocks of the Lake District to be the basement rocks.

Sedgwick (1842, pp. 209-10) recognized the intrusive nature of the granophyre and noted the intense metamorphism of the Skiddaw Slates on Revelin Crag and Herdus in Ennerdale. He attributed the presence of the wedge of Skiddaw Slates on Red Pike to the wedge being "caught up by the syenite, carried to the top of Red Pike and wedged against the green porphyries of High Stile". Otley's Middle Slates were renamed the "Green Slates and Porphery Group" by Sedgwick, who recognized their volcanic origin (pp. 202-5). Sedgwick's work on the Skiddaw

Slates published in numerous papers from 1832 to 1858 was largely concerned with the correlation of the Lower Palaeozoic succession in the Lake District with Palaeozoic successions elsewhere, particularly in Wales.

Phillips (1846, pp. 242-3) suggested that the Ennerdale Granophyre may have been extruded above the Borrowdale Volcanic Series. He gave the mineralogy of the granophyre as "Mostly composed of red feldspar, with some quartz interspersed and a variable admixture of a soft greenish or yellow mineral." Rarely distinct hornblende is observed." In a discussion on the Borrowdale Volcanic Series (pp. 239-44) he postulated a normal volcanic origin for the amygdaloidal lavas and the ashes, but regarded the porphyritic lavas as slates which had been metamorphosed in situ.

This idea was expanded by Marshall (1858, pp. 84-96) who also believed that the porphyritic lavas were the products of selective metamorphism, the interbedded slates remaining unaltered because of their relative infusability. He postulated that syenites and granites were the products of extreme metamorphism being only "altered beds of slate in situ".

In 1863 Harkness published an account of the Skiddaw Slates Series (pp. 113-40) in which he gave a description of the general distribution of the flaggy beds in the slates, and attempted to determine the regional structure. He believed that the Volcanic Series were conformable with the Skiddaw Slate Series (ibid. Fig. 4).

Nicholson (1869a, pp. 105-8; 167-73) considered the junction between the Skiddaw Slates and the Borrowdale Volcanic Series to be an uncomformity. In a later paper (1896b, pp. 435-41) he briefly described the Ennerdale Granophyre, but considering Sedgwick's (1842) detailed description of the outcrop of the granophyre, his inaccuracies are very surprising. His major error was that he did not take into account any outcrop south of Iron Crag, apparently not noticing the areas of granophyre around the Bleng Valley or Nether Wasdale (ibid. Fig.1). He made a comparison between the micrograanites of the Vale of St. Johns and the Ennerdale Granophyre, concluding that the intrusions were probably the roots of vents from which the Borrowdale Volcanic Series were erupted (pp. 440-1.) He failed to recognize any metamorphic effects of the granophyre in the Volcanic Series and so did not realize that the granophyre is younger than the Volcanic Series. He noted (pp. 437) the great width of the metamorphic aureole of the Ennerdale Granophyre in the Skiddaw Slates of Ennerdale, and remarked on the lack of metamorphism in Buttermere. Nicholson (1870a, pp. 559-610) published the results of a survey of the lower part of the Borrowdale Volcanic Series between Ullswater and Keswick. All his sections illustrating this paper clearly show the Volcanic Series uncomformably overlying the Skiddaw Slates. It was in this paper that Nicholson first mentioned the need for a new name to replace Sedgwick's "Green Slate and Porphery Group" (pp. 599). He introduced the name "Borrowdale Series" in a later paper the same year (1870b, pp. 107).

In two short notes (1869, pp. 56; pp. 116) Dakyns suggested that the junction between the Skiddaw Slates and the Borrowdale Volcanic Series was an uncomformity, He reversed this opinion in 1875, when, in a joint note with J.C.Ward (pp. 95), he described the interbedding of Borrowdale Volcanic Series and Skiddaw Slates in Swindale near Shap.

Aveline (1869, pp.382) mentioned Ward's work in the area, and stated that the junction between the Skiddaw Slates and the Borrowdale Volcanic Series was faulted in all places so far examined by the Geological Survey. This statement was modified later in 1872 (pp. 441) when he described an unfaulted comformable junction near Bootle in the Black Combe area. In this later paper Aveline introduced the name "Volcanic Series" for the Borrowdale Volcanic Series.

The Geological Survey were systemmatically surveying the Lake District about 1870, and the Ennerdale Granophyre was covered by the following maps:-

1875. One Inch Quarter Sheet 101 S.E. (Old Series) surveyed by J.C.Ward.

1881. One Inch Quarter Sheet 99 N.E. (Old Series) surveyed by W. T. Aveline, J.C. Ward, and A.C.G. Cameron.

1882. One Inch Quarter Sheet 98 N.W. (Old Series) surveyed by W.T. Aveline, J.C. Ward, C.E. DeRance, G.H. Wollaston, F. Rutley, A.C.G. Cameron and E.J.Herbert

1882. One Inch Quarter Sheet 101 S.W. (Old Series) surveyed by J. C. Ward and A.C. G. Cameron.

These maps gave for the first time a reasonably accurate map of the whole of the Ennerdale Granophyre. They also formed a foundation on which future detailed research could be based.

## 2. More Recent Research.

### A. The Ennerdale Granophyre.

J. C. Ward surveyed the Ennerdale Granophyre for the primary survey of the Geological Survey and the results of his work were published in a series of papers and an official memoir. In 1875 ( p. 584) he estimated that the Ennerdale Granophyre and the Eskdale Granite were formed at the end of the Upper Silurian. By studying the liquid cavities and their enclosed gas bubbles in the quartz of the granophyre, he calculated that the granophyre solidified under a pressure equivalent to that of a load of 35,000 feet of rock. He calculated from geological evidence that the actual load at the time of solidification was 22,000 feet of rock, leaving an excess of internal pressure of 13,000 feet of rock ( p.584.) This excess pressure from below may have acted as a warping agent on the overlying rocks. ( p. 588). In the second part of the same paper (1876, pp. 1-34) Ward developed his theory that the granitic rocks of the Lake District were formed by metamorphism of the country rocks. He collected evidence from various sources, field, microscopical, and chemical examination (pp. 14, 18, 22) to show that the Ennerdale Granophyre originated from the metamorphism of the country rocks in situ. He noted the parallelism between the outcrops of the granophyre contact and the various beds of the Borrowdale Volcanic Series giving a map (p. 15) to illustrate this point. He gave petrographic descriptions of the granophyre and a chemical analysis of a specimen from near Scale Force. Although Ward believed that the granophyre was metamorphic in origin, he recognized the possibility of rheomorphic action leading to the intrusive phenomena ( p.26).

Ward wrote the official memoir (1876 a) describing the Geological Survey Quarter Sheet 101 S.E. (Old Series). The section on the Ennerdale Granophyre is similar to, but less detailed than, that in his paper (1876). The memoir has a full bibliography of early work in the Lake District. He published a summary of his work in the Lake District in 1879 (pp. 49-61; 110-124).

Harker (1886) first introduced the name granophyre for the rock of the intrusion, superceding the older names of sienite, syenite, and syenitic granite ( p. 209). He described a thin section from Buckbarrow and attributed the texture to a mutual crystallization of feldspar and quartz. In 1902 (pp. 487-96) he divided the major intrusions of the Lake District into an older and a younger suite. The Ennerdale Granophyre was put in the older suite, which is closely associated with the Borrowdale Volcanic Series and belongs to the same period of igneous activity, although it is younger than the Volcanic Series. A number of intrusions in this suite are older than the main fold movements of the area. This paper also contains a full bibliography of Lake District petrology. In 1903 (pp. 59-69) Harker gave a list of all chemical analyses then available of Lake District rocks.

Marr (1900, pp. 474-5) suggested that the form of the intrusion was laccolithic, having been 'forced along the lag plane between the Skiddaw Slates and the Volcanic rocks'. He noted the presence of distinct masses of basic rocks associated with the pink granophyre and suggested that the two rock types were derived by magmatic differentiation from a parental magma. In 1906 (pp. lxxxi) he said, "The Ennerdale Granophyre, and perhaps the Eskdale Granite, are apparently of the age of the Borrowdale Group".

Walker (1904, pp. 83-5), describing the Burtness Combe Intrusive Complex, noted that the main mass of diabase was cut by a banded felsite dyke. He recognized the interaction of the diabase and the felsite to produce a quartz diabase. He deduced that fallen blocks of garnetiferous diabase in Combe Gill came from the main mass of diabase and proposed that the Ennerdale Granophyre and the Eskdale Granite came from the same magma, as both show intermediate garnetiferous rocks. He stated, "the felsite was probably first intruded and the diabase came up later," despite the fact that the felsite clearly cuts the diabase.

Rastall published his important paper on the Ennerdale Granophyre in 1906 (pp. 253-72). He gave a petrological description of the intrusion, stressing its variability (cf. Ward, 1867a). He described the basic masses of Seatallan, Mecklin Wood and Bowness Knott attributing their peculiar petrology to hybridization between an earlier basic and a later acidic intrusion (pp. 266; 272). He followed Marr (1900) in suggesting that the intrusion was in the form of a series of laccoliths and that the acid and basic rocks were derived by magmatic differentiation of a parent magma ( p. 268). The areal variation in the granophyre, granitic at the margins, passing to granophyric in the centre, was attributed to 'laccolithic' differentiation after intrusion ( p. 270). Rastall modified Walker's (1904) work on the Burtness Combe Complex by showing that the felsite dyke cutting the diabase was the later intrusion. He attributed the presence of quartz in the diabase to a second intrusion of acid magma into the still molten diabase producing a quartz diabase hybrid ( p. 263). The age of the intrusion was given as most probably pre-Caledonian, i.e. Ordovician ( p. 269). Rastall, with Wilcockson in 1915 (pp. 614-16) gave the charecteristic accessory minerals of the granophyre as pyrrhotite and pale green epidote. Magnetite, brown sphene, apatite, zircon, rutile and ilmenite were much less common. In an acicular hybrid rock all accessory minerals were rare.

Dwerryhouse (1909, p. 58) discussing the relative ages of the Eskdale Granite and the Ennerdale Granophyre as revealed by their mutual contact at the foot of Wastwater, could not produce any direct evidence as the actual contact is covered by screes. He stated however, that the nearest granite to the contact appeared to be of a marginal facies while the nearest granophyre was unaltered. Green (1917, pp. 14-15) believed that the form of the intrusion was laccolithic. He also thought that the intrusion preceded the main fold movements in the area. In a second paper (1919, pp. 175-6) he attributed the low degree of metamorphism around the granophyre to the absence of volatile mineralizers rather than the absence of a significant heat source. The Geological Survey resurveyed the area covered by the Old Series Quarter Sheets 101 S.W. and 99 N.E. The new maps were published in two editions, solid and drift:-

New Series one inch Geological Sheet 18, solid (1929) and drift (1930) surveyed by Eastwood, T.E.E.L. Dixon, S.E. Hollingworth and B. Smith.

New Series one inch Geological Sheet 27, solid and drift (1937) surveyed by Trotter, F.M., S.E. Hollingworth, T. Eastwood and W. C.C. Rose.

Memoirs describing these sheets were published in 1931 and 1937 respectively. Hollingworth and Dixon (in Eastwood et al 1931, pp. 46-55) surveyed the area of Ennerdale Granophyre described in the memoir 28, and revealed several new features of the intrusion. A mass of basic rock on the south side of Ennerdale, below the Crag Fell Iron Mines was described ( p. 47). An east-west tear fault in the depression between Bowness Knott and Brown How was noted and a series of thrust planes on the north side of Herdus discussed ( p. 50). The intrusion was clearly shown to be a stock like mass with vertical sides and a horizontal roof (pp. 47-51), the previous theory considering the mass to be a laccolithic being disproved.

The variations within the granophyre were said to be chiefly marginal. One marginal variation had been traced along the summit ridge of Iron Crag suggesting the close proximity of a horizontal roof which had been removed by denudation ( p. 48). Several minor intrusions associated with the Ennerdale Granophyre were described (pp. 53-5). The intrusion was shown to be later than the regional folding and cleavage but slightly affected by thrusting, therefore a late Caledonian age was suggested ( p. 51).

Hollingworth (in Trotter et al, 1937 pp 41-7) continued the survey of the Ennerdale Granophyre southwards from sheet28 to south of the river Bleng. The geology of the granophyre is complicated at this point, seven sub-divisions being shown on a map of the area ( p. 42). The rock types differentiated in this subdivision were described (pp. 43-5) and a table of the intrusion sequence compiled ( p. 46). Intermediate rocks "believed to have arisen from reactions between this material (fine grained dolerite) and the granophyre are abundant." Hollingworth was uncertain of the place of origin of the intermediate rocks and he wrote, "It is not certain that the mixed types of acidified basic rock and basified granophyre enclosed in the fine grained acid rocks arose from reations occurring after intrusion; they may be due to operations in depth before intrusion of the mixed suite." (p . 44). A belt of normal granophyre was noted along the margin from the river Bleng south-eastwards for half a mile, between the contact and the finer grained rocks of the interior and was thought to be a late marginal intrusion similar to a ring dyke.

In 1956 (Mitchell 1956, p. 446) a pebble of Ennerdale Granophyre was discovered in the conglomerates below the Carboniferous Limestone at Hodbarrow, Millom. This gives an upper limit to the age of the intrusion showing that it is definitely pre-Hercynian.

B. The Skiddaw Slates.

The Geological Survey, on the Old Series Quarter Sheets 101 S.W. and 101 S.E. show the Skiddaw Slates divided into argillaceous and arenaceous divisions. The slates adjacent to the Ennerdale Granophyre are all shown to be argillaceous. The Latterbarrow Sandstone on Lank Rigg south of Ennerdale is the highest horizon in the Skiddaw Slates in this area and occurs within about a hundred yards of the granophyre. The metamorphosed slates within the Skiddaw Slates are indicated on the maps.

Ward (1876a, pp. 6-7) described the metamorphism of the Skiddaw Slates in the Buttermere area and gave a petrographic description of hornfelsed slate from near Scale Force. The ferromagnesian mineral, concentrated in parallel bands, was identified as chlorite. Quartz which frequently formed bands parallel to those of chlorite sometimes contained liquid cavities, Ward gave a chemical analysis of a similar hornfelsed slate from the summit of Red Pike. He gave (pp. 40-43 a fairly detailed description of the areal variation of lithology in the Skiddaw Slates and some indication of their structure. He concluded that there were probably two sets of gritty flaggy beds in the Skiddaw Slate Series and gave the following stratigraphic succession ( p. 47):-

| | |
|---|---|
| VOLCANIC SERIES | 1200 feet |
| TRANSITION SERIES | 6. Interbedded volcanic strata and Skiddaw Slate. |
| | 5. Black Slates of Skiddaw. |
| | 4. Gritty beds of Gatesgarth (Buttermere)<br>Latterbarrow (101 S.W.) Tongue.<br>Beck (Skiddaw) Watch Hill and Great Cockup (101 N.E.) |
| SKIDDAW SLATE SERIES 10,000-12,000 feet. | 3. Dark Slates |
| | 2. Sandstone Series of Grasmoor and Whiteside. |
| | 1. Dark Slates of Kirkstile between Loweswater and Crummock. |

In 1900 (pp. 463-5, Fig. 3) Marr developed his theory that the Borrowdale Volcanic Series and the Skiddaw Slates were separated by a low angled lag fault.

Green (1915, p. 217; 1917, pp. 5-11) said that there was no evidence of faulting along the junction between the Skiddaw Slates and the Borrowdale Volcanic Series, and maintained that the junction was conformable.

Dixon (in Eastwood et al, 1931, p. 25) divided the Skiddaw Slates north of Ennerdale into the following lithological groups:-

d. Mosser Slates and Watch Hill Grits.

c. Loweswater Flags.

b. Kirkstile Slates.

a. Blakefell Mudstones.

Hollingworth, working south of Ennerdale, made the following divisions:-

3. Latterbarrow Sandstone.

2. Mosser Slates.

1. Blakefell Mudstones.

The sequence of rock groups was thought to be:-

4. Latterbarrow Sandstone.

3. Mosser Kirkstile Slates.

2. Blakefell Mudstones.

1. Loweswater Flags.

The Loweswater Flags do not occur in the proximity of the granophyre. The Blakefell Mudstones ( p. 25) were described as pale grey hard slates with a peculiar minutely spotted structure. They were recognized to have been metamorphosed ( p. 38) but were considered to be a distinct stratigraphic unit underlying the Mosser Kirkstile Slates. They were said to extend from Sharp Knott southwards across Ennerdale to just short of the outcrop of the Latterbarrow Sandstone. The Ennerdale Granophyre was shown intruding Blakefell Mudstones on Herdus ( p. 14) and said to intrude them on Crag Fell. The Mosser Kirkstile Slates were described as occupying a narrow band along Gill Beck from Floutern to Ennerdale, and also most of the folded area south of Ennerdale. The Latterbarrow Sandstone ( p. 30) was estimated to be several hundred feet thick and was said to pass up into the Borrowdale Volcanic Series by the incoming of andesitic tuff and fragmental sandstone in the sandy matrix. The structure of the area was discussed (pp. 12-16). The major structural unit was thought to be a triple anticline which passed westwards into a simple one with the main axis trending west south west along the line of Croasdale Beck to Dent. The easterly anticline passed across Herdus and was separated from the central anticline by a sharp syncline of Mosser Kirkstile Slates along Gill Beck. The metamorphic history of the Skiddaw Slates in the Ennerdale area was found to be complex. Three distinct periods of metamorphism were identified (pp. 34-41):-

1. The spotting which is prevalent in the Blakefell Mudstones was attributed to a hidden intrusion, possibly an extension of the Skiddaw or Eskdale Granite. An extension of the Skiddaw Granite was considered most likely as the spotting was confined to the axial region of the Skiddaw Anticline in which, to the north east the granite itself is exposed (pp. 38-39).
2. A general metamorphism of the Skiddaw Slates was noted as the contact with the granophyre was approached. The major effects on the slates appeared to be hornfelsing to biotite hornfels and possibly some andalusite hornfels and metasomatism by silica and alkalis. The altered slates south of Ennerdale were silicified up to one and a half miles from the contact and this silicification,

which appeared to be independant of the granophyre, was difficult to separate from the metamorphic effects of the granophyre (pp. 40-41).

3. The Blakefell Mudstones were affected by a hardening which was independent of both the granophyre and the intrusions causing the spotting of the mudstones ( p. 40).

Hollingworth (in Trotter, et al, 1937) described the Latterbarrow Sandstone which, although it approaches to within about a hundred yards of the granophyre, showed no signs of metamorphism. The sandstone was shown to have been carried north for a mile or more by a low angled thrust (pp. 19-20).

Rose (1954, pp. 403-6) gave a general description of the structure of the Skiddaw Slates. The Blakefell Mudstones were considered to be the rock type of a metamorphic aureole which transgressed the general structure. If this is correct then Dixon (in Eastwood, et al, 1931, p. 35) was incorrect in his supposition that the Blakefell Mudstones form a distinct stratigraphic horizon. Rose stated that the outcrop of Blakefell Mudstones "can be traced from Barrow to Causey Pike in the east through Grasmoor and across Crummock Water to Mellbreak and Blake Fell". This means that Herdus and the fells south of Ennerdale were no longer considered to be formed of Blakefell Mudstones. The argillaceous slates south of Ennerdale must, therefore, have been considered to be all Mosser Kirkstile Slates. The Ennerdale Granophyre is, thus, only in contact with the Mosser Kirkstile Group of the Skiddaw

Slates. Rose's sequence for the Keswick-Buttermere area was:-

| | |
|---|---|
| Mosser Kirkstile Slates | 2,500 feet |
| Loweswater Flags (base not seen) | 4,000 feet |

Mitchell (1956, pp. 414-5) supported the idea that the junction of the Skiddaw Slates and the Borrowdale Volcanic Series was comformable but had been faulted in places by the competent Volcanic Series moving over the incompetent Slates.

## C. The Borrowdale Volcanic Series.

Ward (1876, a.) introduced the modern name of the Volcanic Series of Borrowdale. In this memoir he described in detail the section of volcanic rocks exposed on Falcon Crag in Borrowdale (pp. 13-9) and gave a description of the variation in the lavas and ashes of the whole Lake District. Ward attributed much of the variation to selective metamorphism of individual ash beds, and appears to have mistaken many lavas for highly altered ashes. He gives a general succession ( p. 45).

9. Bedded, mostly fine, flinty ash, of Great End, Esk Pike and Allen Crags.
8. Unbedded, coarse ash, and breccia, of Broad Crag and Long Pike.
7. Bedded, and rough ash of Scafell Pikes, Glaramara and Ullscarf.
6. Partially bedded, fine flinty ash of Base Brown and Rosthwaite Crag.
5. Well bedded ash of Seathwaite.
4. Contemporaneous traps of Watendlath Fell, High Seat and Bleaberry Fell.

3. Breccia and bedded ash of Brund Fell and Watendlath.

2. Contemporaneous traps of Honister, Dale Head, Gate Crag and Falcon Crag.

1. Purple breccia, ash and some contempory trap.

0. Interbedded volcanic strata and Skiddaw Slates.

The Volcanic Series was considered to be about 12,000 feet thick. Ward believed that it was originally interbedded at its base with the Skiddaw Slates, but was now separated from the Slates at nearly all points by faults. The volcanoes from which the Borrowdale Volcanic Series was erupted were considered to have started under the sea and quickly built up to be sub-aerial. Ward gave a summary of his work in the Lake District (1879) which showed that he had a sound knowledge of the structure of the region and recognized the Scafell Syncline and the Langdale Anticline (Sect. 111). His successions were incorrect in places, for his belief that many of the lavas were actually highly metamorphosed ashes, led to an overestimation of the importance of the ashes. This overestimation is seen when section 111 is compared with Hartley's (1932, pp. 15) map of Great Langdale. The following rough correlations can be made:-

| Ward, 1879. | Hartley, 1932. |
|---|---|
| A. Yewdale Breccia. | Felsitic and Basic Tuffs. |
| B. Bedded Volcanic Ash. | |
| C. Volcanic Ash and Breccia. | |
| D. Highly altered Bedded Ash. | Wrengill Andesites. |

| | Ward, 1879 (Cont'd.) | Hartley, 1932 (Cont'd) |
|---|---|---|
| E.<br>F.<br>G. | Highly altered Volcanic Rocks | Bedded Tuffs with lava flows and Langdale Rhyolites. |
| H. | Series of lava flows | Mosedale Andesites. |

Harker and Marr (1891, pp. 246-326) defined and mapped the horizons of the Shap Rhyolites and Andesites in the vicinity of the Shap Granite. Harker (1891a, pp. 145-7) divided the lavas of the Lake District from a chemical and petrographic point of view into:-

1. Basic:

   Hypersthene Basalts of the north outcrop.

2. Intermediate:

   Pyroxene Andesites which make up the bulk of the lavas.

3. Acid:

   Rhyolites, commonest at the top of the sequence.

Marr (1900, pp. 449-930) gave the succession worked out by himself and Harker as:-

1. Shap Rhyolites.
2. Shap Andesites.
3. Scafell Banded Ashes and Breccias - Kentmere - Coniston Slate Belt.
4. Ullswater Basic Lava Group - Eycott Group.
5. Falcon Crag and Bleaberry Fell Group.

He included a group of garnet bearing streaky rocks below the Scafell Banded Ashes and Breccias as possibly intrusive (pp. 476-8). A quarter inch sketch map (Pl. Xiii.) showed the distribution of the various groups. The Ennerdale Granophyre was shown to be in contact along its whole margin with the Ullswater Basic Lava Group. Later Marr (1906, pp. lxvi-cxxvii), influenced by Walker's work (1904), accepted that the garnet bearing streaky rocks below the Scafell Banded Ashes and Breccias were not intrusive and named them "The Styhead Group".

Walker (1904, pp. 89-98) described the garnet bearing streaky rocks of Marr and showed they were a normal stratigraphic unit of the Borrowdale Volcanic Series. He described much of their outcrop, the nearest exposure to the Ennerdale Granophyre being on Yewbarrow.

Green, (1913; 1915; 1917) worked out the following succession and suggested that it was applicable over the whole Lake District:-

i. Rhyolites.
ii. Upper Andesites.
iii. Harrath Tuffs.
iv. Wrengill Andesites.
v. Middle Tuffs.
vi. Lower Andesites.
vii. Mottled Tuffs.

He argued in favour of a much thinner succession than Ward, 1500 feet at a maximum (1915, p. 205), frequently repeated by sharp folding. Mitchell (1929, p. 9; 1934, p. 418) proved Green's theory of the structure and correlation within the eastern part of the Lake District to be wrong (Green, 1915). Green's paper of 1915 was, however, important for in it he explained for the first time the true character of flow breccias ( p. 201). In a later paper (1917, p. 8) Green described the outcrop of the Borrowdale Volcanic Series from Borrowdale westwards to the River Calder. On Plate 1 the Lower Andesites were shown overlying the Skiddaw Slates from Grange to Red Pike where their outcrop swung parallel to the contact of the Ennerdale Granophyre until they were cut off by the Haycock strike fault. The granophyre was thus shown as being intruded along the base of the Lower Andesites. The outcrop of the Middle Tuffs, which formed Haycock and Steeple ran parallel but south of the Lower Andesite outcrop. The Wrengill Andesites outcropped south of the Middle Tuffs. In 1919 (pp. 153-82) Green fully discussed his views on the Borrowdale Volcanic Series. A map (Fig. 25) of the country around Wasdale Head showed the Ennerdale Granophyre intruded into the Lower Andesites which were overlain by a thick tuff band taken to be a much attenuated representative of the Middle Tuffs.

Following Green's work, which was largely a reinterpretation of the official Geological Survey maps, the systematic resurvey of the Borrowdale Volcanic Series began. Hartley (1925) proposed the following succession for the Grasmere and Windermere area:-

| | |
|---|---|
| Rhyolites | 200 feet |
| Upper Andesites | 0-500 feet |
| Felsitic Tuffs | 600 feet |
| Augite Andesites | 300-600 feet |
| Bedded Tuffs with Lava flows | 600 feet. |

In the Langdale area (1932) he found the Upper Andesites had died out and he recognized a thick series of intrusive rhyolites in the Bedded Tuffs. A thick series of andesites called the Mosedale Andesites appeared below the Bedded Tuffs. A similar succession was found in the Thirlmere area (1941).

Mitchell working eastwards from Grasmere to Long Sleddale (1929) recognized a similar succession with several beds below the Bedded Tuffs:-

| Mitchell 1929 | approx. thickness in feet. | Hartley 1925. |
|---|---|---|
| Upper Rhyolites | 0 - 200 | Rhyolites |
| Upper Andesites | 0 - 800 | Upper Andesites |
| Coarse Tuffs | 500 | Felsitic Tuffs |
| Wrengill Andesites | 0 - 300 | Augite Andesites |
| Kentmere Pike Rhyolites | 0 - 150 | |
| Bedded Tuffs | 200 - 800 | Bedded tuffs and Lava Flows. |
| Harter Fell Andesites | up to 500 | |
| Froswick Tuffs | 200 | |
| Nan Bield Andesites. | | |

When Mitchell (1934) continued mapping from Long Sleddale to Shap he found the succession similar to that in his previous area, except the Haweswater Rhyolite occurred below the Nan

Bield Andesite. He then mapped westward from Grasmere and Windermere to Coniston (1940) where he found a similar succession to that in Grasmere. The Upper Rhyolites and Andesites had been cut out by the overlying uncomformity under the Coniston Limestone Series. The pyroclastic rocks had increased enormously in thickness and were subdivided on lithological grounds. Mitchell (1956) surveyed the Dunnerdale Fells where he found that the pyroclastic rocks had again increased in thickness and all beds above the Wrengill Andesite had been cut out by the overlying unconformity. The succession in the Co-niston and Dunnerdale areas was:-

| | Approximate thickness in feet. |
|---|---|
| 1. Yewdale Breccia and Tuffs | 1750 |
| 2. Wrengill Andesites | 0 - 450 |
| 3. Upper Tilberthwaite Tuffs | 1500 |
| 4. Paddy End Rhyolites | 0 - 750 |
| 5. Lower Tilberthwaite Tuffs | 900 |
| 6. White Pike or Dow Grag Andesites | 200 |
| 7. Walna Scar Quarry and Lag Bank Tuffs | |
| 8. Pikes Rhyolite | |
| 9. Caw Tuffs | 800 |
| 10. Lickle Rhyolites | 1600 |
| 11. Dunnerdale Tuffs | 1550 |
| 12. Ulpha Andesites | 550 |
| 13. Duddon Bridge Tuffs | 550 |
| 14 Barrow Andesites. | 1100 |

In the same year Mitchell published an excellent summary of the research on the Borrowdale Volcanic Series in 'The Geological History of the Lake District' (1956 a, pp. 407-63). In this paper he gave a suggested correlation between all work then published (Fig. 3). This correlation was in the main correct, but later work by Firman (1957) proved that it was wrong in some details.

Hollingworth (In Trotter et al, 1937, pp. 21-40) described the Borrowdale Volcanic Series of the Gosforth area giving a map (Fig. 5) of their distribution west of the Ennerdale Granophyre The succession was:-

1. Andesitic and Rhyolitic Lavas (undivided)
2. Rhyolites with subordinate andesites and thin bands of tuff.
3. Andesites with subordinate tuff bands.
4. Mottled Tuffs.

The thicknesses were uncertain, but each group appeared to be several hundred feet thick. The major structure was a double syncline (Fig. 4) striking towards the Scafell syncline in the east. Correlation was difficult because of the presence of the Ennerdale and Eskdale intrusions and the absence of any recent detailed maps of the area immediately to the east of these masses The rhyolites were tentatively correlated with Hartley's (1932) Langdale Rhyolites and the Styhead Group of Marr (1906). Hollingworth briefly discussed the metamorphism of the Volcanic Series adjacent to the Ennerdale Granophyre, the principle changes noted being the formation of pale green tremolitic hornblende, brown biotite and rare pyroxene. The macroscopic effects of the metamorphism were not pronounced and in consequence the outer limit of the metamorphism was not accurately determined. The width of the metamorphic aureole was given as several hundred yards in Worm Gill and Bleng Valley, over half a mile in Bolton Wood and about half a mile in the bottom of Wasdale.

Oliver (1954, pp. 473-83) identified Marr's Styhead Group as partially consisting of welded tuffs and renamed it the Airey's Bridge Group. A sketch map (Fig. 1) showed the distribution of this group in the Scafell area. In later papers (1954a, pp. 407-11, 1961, pp. 377-417) Oliver gave the following succession for the Scafell area:-

1. Esk Pike Hornstones.
2. Lincombe Tarn Formations.
3. Seathwaite Fell Tuffs.
4. Airey's Bridge Group.
5. Birker Fell Andesites.
6. Tuffs of Honister Slate Belt.

The area mapped by Oliver (1961) connected Green's (1917) and Hartley's (1932, 1942) areas following the following carrelations to be made:-

| Green (1917) | Oliver (1954 & 61) | Hartley (1932 & 42) |
|---|---|---|
| Buttermere | Scafell | Langdale & Thirlmere. |
| | Esk Pike Hornstones | |
| | Lincombe Tarn Formations | Felsitic & Basic Tuffs |
| | Seathwaite Fell Tuffs | |
| | ----- Died -- Out --- | Wrengill Andesite |
| Harrath Tuffs | Airey's Bridge Group | Bedded Tuffs and Rhyolite |
| 'Wrengill Andesites | Grey Knotts Andesites | Mosedale Andesites |
| Middle Tuffs | Honister Slate Belt Tuffs | |
| Lower Andesites | | |

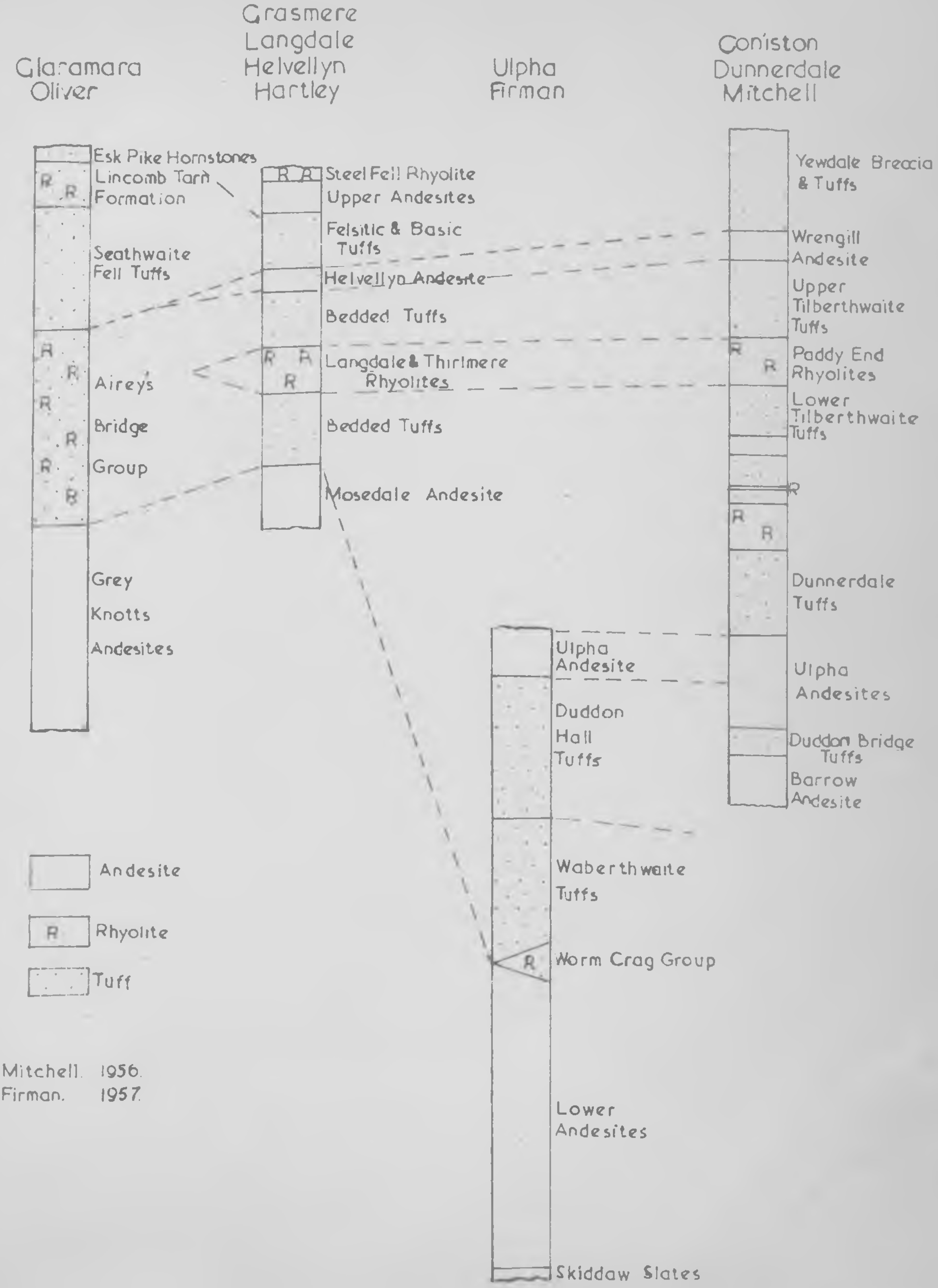
This correlation clearly shows that Green's Wrengill Andesite was misnamed because of a mistaken correlation with the Wrengill Andesite of the eastern part of the Lake District. Oliver (1961, pp. 379) gives the following correlation between Scafell and Eskdale:-

| Oliver (1961) | Firman (1957 |
|---|---|
| Scafell | Eskdale |
| 1. Airey's Bridge Group 3260 - 3410 feet | 1. Wallowbarrow Crag Group. |
| 2. Birker Fell Andesite Group 3500+ feet | 2. Ulpha Andesites |
| | 3. Duddon Hall Tuffs |
| | 4. Waberthwaite Tuffs |
| | 5. Worm Crag Group |
| | 6. Lower Andesites with interbedded tuffs and rhyolite flows. |

This correlation is rather strange considering Firman's (1957) previously published work (see below).

Firman (1957) mapped the area between Wastwater and the Duddon Valley. This work was very important for it connected by direct mapping the work of Mitchell (1956) and Hartley (1932) and Oliver (1954;1961). Sound correlation between the areas mapped by these workers was, therefore, possible. The correlation overleaf is a corrected form of Mitchell's correlation of 1956 incorporating Firman's work.

Recent work by Moseley (1960) in the Ullswater area has proved that the junction between the Skiddaw Slates and the Borrowdale Volcanic Series is faulted in that area.



after G.H.Mitchell. 1956.
& R.J.Firman. 1957.

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THE ENNERDALE GRANOPHYRE.
LEGEND
The Ennerdale Granophyre
Fine Microgranite
Microgranite
Granophyre
Greisen
The Main Granophyre
Minor Felsitic Intrusions
Minor Microdiorite Intrusions
Hybrid Rocks
Zones of the Mecklin Wood Hybrid Outcrop
Discoloured Main Granophyre
O Outer Zone
I Intermediate Zone
D Mecklin Wood Dolerite.
The Borrowdale Volcanic Series
Dacite Group (Rhyolites west of Granophyre)
Grey Crag Tuffs
Andesite Group with interbedded tuffs.
The Skiddaw Slates
Latterbarrow Sandstone
Mosser Kirkstile Slates
Fissile Hornfels
Massive Hornfels
Felsitic Hornfels
Blake Fell Mudstone
Haematitized Slate
Intrusions
Eskdale Granite
Pre Caledonian Intrusions
HP Hole Gill Porphyry
Geological Contacts
Position known within narrow limits
Position inferred
Contact gradational over a wide zone
Contact gradational over a narrow zone
Margin of microgranitic Main Granophyre
Fault
Thrust
Mineralized: Fe. Haematite
Cu Pb. Copper & Lead
60 Dip of Strata
Vertical Strata
Crumpled Strata
SCALE. 2½ Inches = 1 Mile
NORTH
ENNERDALE WATER
CRUMMOCK WATER
BUTTERMERE
WASTWATER
THE SIDE
SCAW
RIVER LIZA
RIVER BLENG
RIVER IRT
Ennerdale Bridge
Buttermere
Iron Crag
Caw Fell
Great Cove
Blakeley Raise
Grike
Crag Fell
Whoap
Latter Barrow
Swarth Fell
Boat How
Stockdale Moor
Hollow Moor
Brown Edge
Seatallan
Middle Fell
Wasdale
Kidbeck How
Latterbarrow
Mecklin Wood
Pillar
Gatesgarth
Hen Comb
Gavel Fell
Mellbreak
Great Borne
Starling Dodd
Little Dodd
Red Pike
High Stile
Haycock
Scoat Fell
Steeple
Pots of Ashness
Caw Gill
Worm Gill
3 06000 mE
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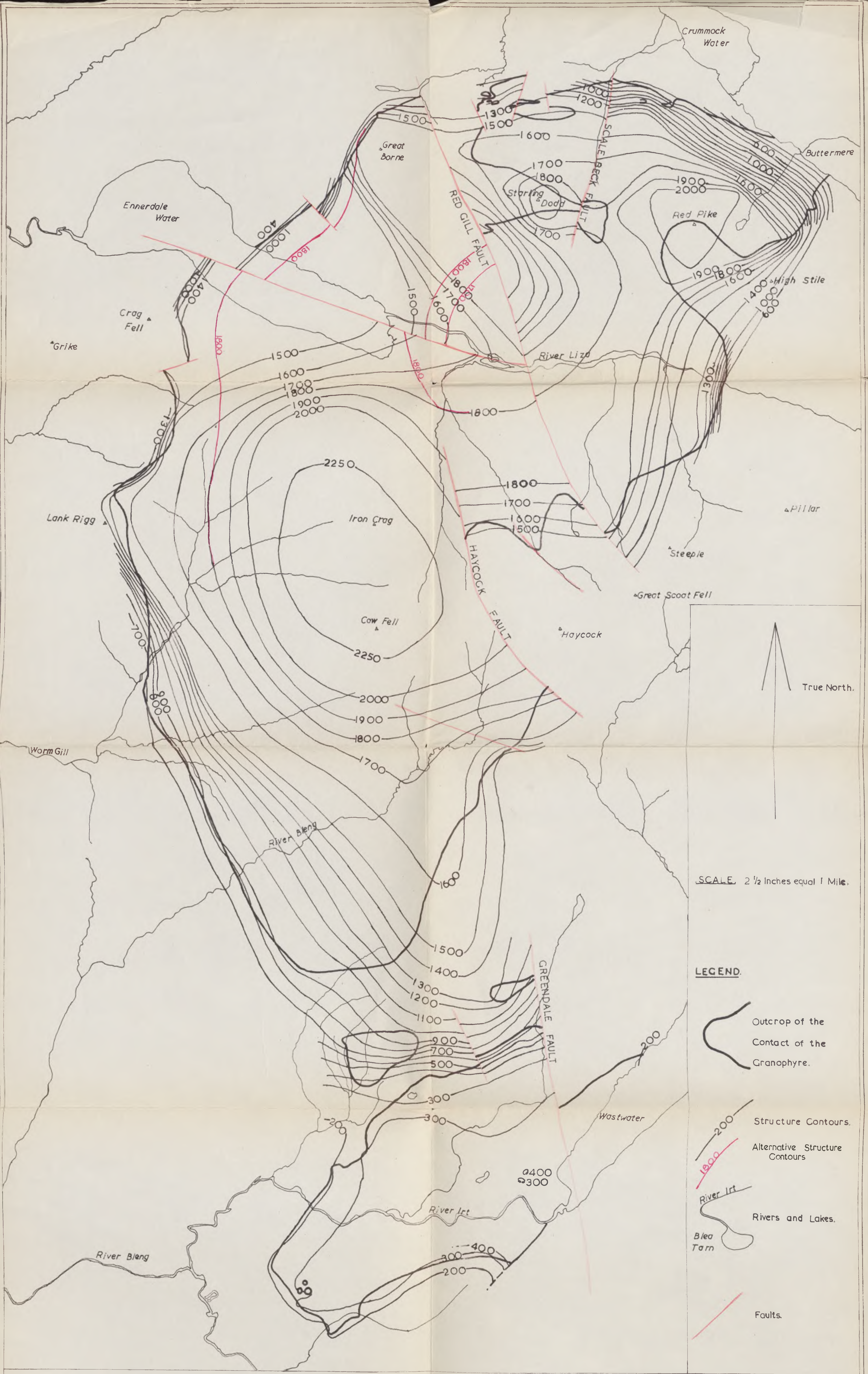

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# STRUCTURE CONTOUR MAP

OF THE SURFACE OF THE

# ENNERDALE GRANOPHYRE