REGIONAL METAMORPHISM AND MIGMATISATION IN DELTING, SHETLAND.

(Thesis presented for the Diploma of Imperial College)

DEREK FLINN.

May 1952.

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CHAPTER 1.

INTRODUCTION

This thesis describes the geology of a part of the largest island in the Shetland archipelago, a group lying about 110 miles N.N.W. of John o Groats and about 220 miles west of Bergan. These islands which may be regarded as a series of hills with a maximumheight of 1200 feet above sea level, rise rather suddenly from the general level of the continental shelf, which to the in this region lies at a depth of 360 feet. The edge of the continental shelf, where the sea bed falls sharply from 600 feet to 3600 feet within 30 miles, is reached 30 miles N.W. of the archipelago.

There is virtually no flat ground in Shetland. Glacial erosion, the deposition of boulder clay, and the formation of the almost universal cover of peat have resulted in a gently rounded topography. This undulating terraine, for the most part covered by heather and poor grass and characteristically treeless, is extremely desolate and uninteresting, but it is bounded by a magnificant coastline. The cliffs are frequently 500 feet high and in one instance rise abruptly to 1300 feet above the sea.

The best exposures are provided by the very indented coastline. The cliffs and the shores of the long inlets or voes, which run as much as 8 miles inland from the open sea, provide many excellent sections, which compensate for the comparative poverty of inland exposures, these being largely confined to the stream beds and to scattered outcrops on the higher ground. The continuous sections exposed in the shores and water courses are in most districts quite sufficient to reveal the geology of the underlying rocks. This is certainly the case in the parish of Delting, the area investigated in this study.

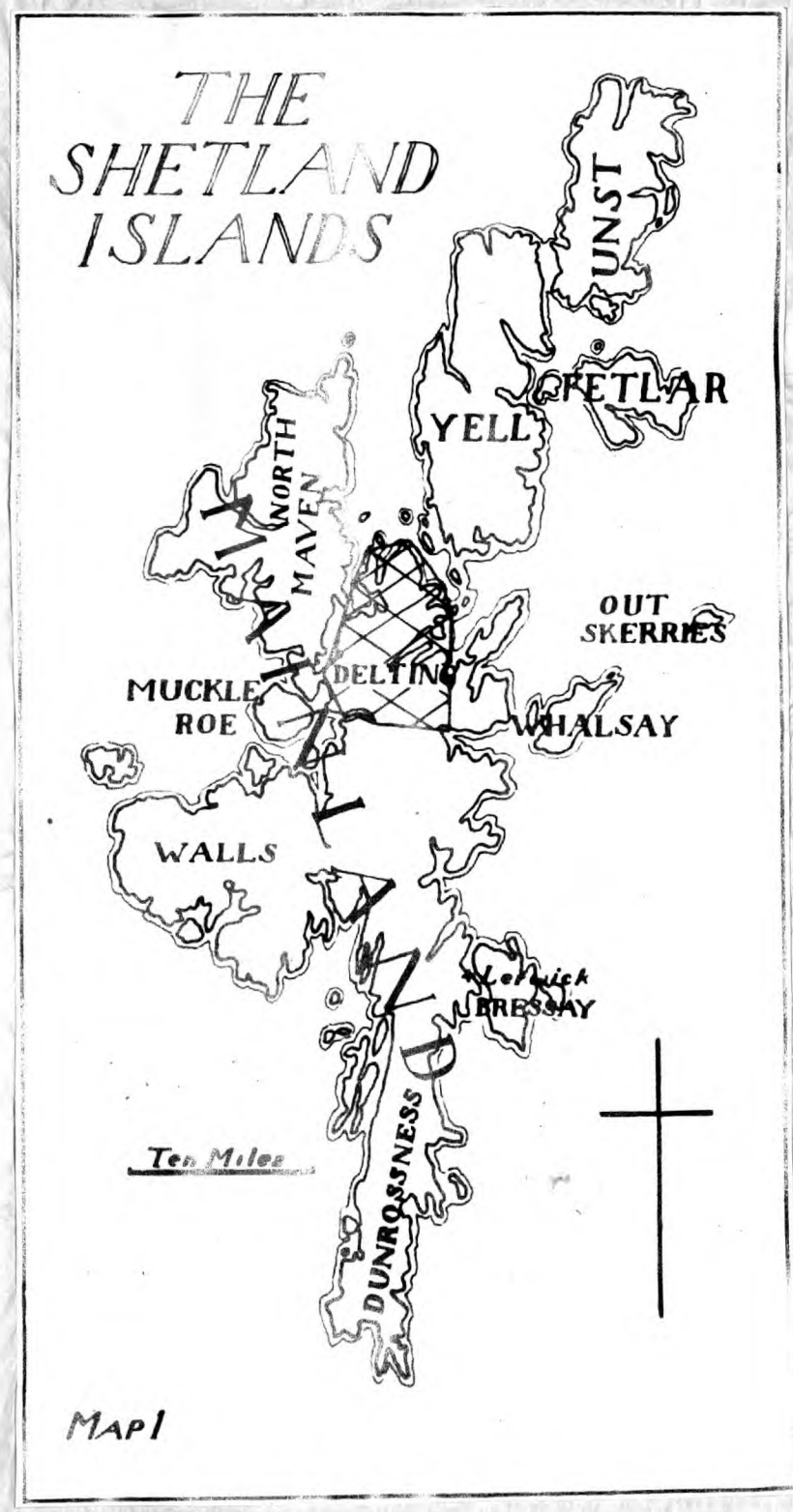
Shetland is inhabited by a scattered population which lives in small townships and in isolated crofts. A very good network of roads has been built to serve these people, so that very few places are more than one hours walking distance from the nearest road.

Shetland has been investigated geologically by a number of private persons and by the officers of the Geological Survey, although no general account of the latter's work has yet been published. Various aspects of Shetland geology were dealt with by Jameson(1800), Hibbert(1822), Heddle (1879, 1880, 1882), Tudor whose map of the whole group remains the best that has been published (1883),Peach and Horne (1879, 1884), Findlay (1929), and by Coles Phillips(1929). These pioneer studies are today largely of historical interest only, but they provide

the frame-work of knowlege on which the more recent work has been carried out by the geologists of the Geological Survey some of whose results appeared in the Summaries of Progress for the years 1929 - 31, and in papers which have been published since by individuals from this team which included G.V. Wilson, H.H. Read, J. Phemister, J. Knox, D. Haldane, T. Robertson, and J.K. Allan. Recent publications include a series on Unst by Read(1933, 1934, 1934, 1934, 1936, 1937), a paper on part of Unst by Fernando (1941) , on dykes in North Maven by Phemister (1950), and on the whole group of islands by G.V. Wilson and J. Knox (1936). A 10 miles to 1 inch map of the whole of Shetland has been published by the Survey as part of the 10 miles to 1 inch geological map of Great Britain (1948). A 1 mile to 1 inch map of Fetlar and maps of various scales of the distribution of various rock types have been published in the Wartime Pamphlets nos,9 and 13 of the Geological Survey and in the Limestones of Scotland Memoir(1949).

It can be established from a study of the publications mentioned above that the islands can be divided geologically into four regions. The most northerly division consists of Unst and Fetlar. The next division to the south is the island of Yell. The Mainland of Shetland and its neighboroughing islands form two distinct units. The westermost of these is made up by North Maven, Muckle Roe, and the Walls peninsular whilst the second region consists of the rest of the Mainland together with Whalsay, Bressay, and the Out Skerries.

(Map 1). This latter region includes the ground covered by this investigation and unlike the other regions, appears to be a single tectonic unit. The Geological Survey whilst working in this region established the following facts. The area is underlain by a series of metamorphosed sedimentary rocks including siliceous and argillaceous schists and gneisses, together with bands of limestone. These rocks strike in a northernly direction throughout most of the area , but in the north half of Delting and Lunnasting the strike swings round to north-east. There is a general increase in the degree of metamorphism of the sedimentary series from east to west. The most easterly rocks are phyllites and grits and include bands of chloritoid schist in the Dunrossness Peninsula. Garnet, staurolite and andalusite are seen only near igneous masses, as for example at Channerwick. Further to the west the rocks become more highly crystalline, and there is a zone of injection or permeation. This zone consists of large sheets and masses of a foliated muscovite microcline oligoclase granite, which as far as can be ascertained does not appear to have much effect on the general metamorphism. Numerous limestones occur among the sedimentary rocks to the west of the injection belt. Biotite and garnet are common minerals. Still farther to the west staurolite-bearing rocks appear, in which the staurolite has been largely replaced by muscovite and quartz. And finally to the west of this the rocks contain fresh staurolite,


THE SHETLAND ISLANDS
UNST
YELL
FETLAR
NORTH MAVEN
OUT SKERRIES
DELTING
MUCKLE ROE
WHALSAY
WALLS
Lerwick
BRESSAY
Ten Miles
DUNROSSNESS

MAP 1

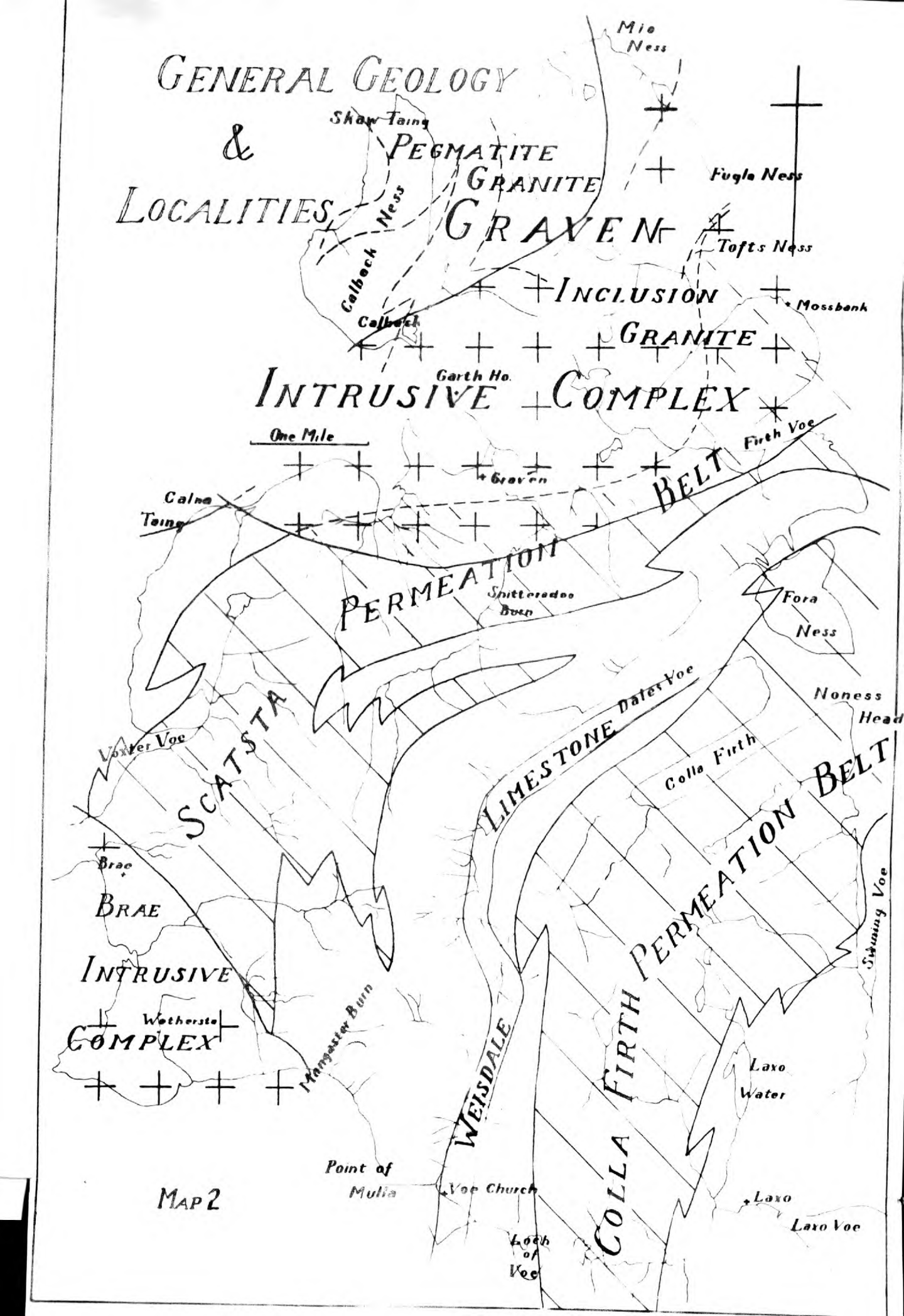
kyanite, and large garnets. This sedimentary series was intruded by basic rocks now hornblendic schists and gneisses, and by a number of granites, aplites and pegmatites. These latter are particularly common in the north part of the parish of Delting, where irregular masses and sheets of acid rock make up one third of the complex, the country rocks of which have undergone considerable injection metamorphism. During this process numerous rocks of mixed parentage were produced, sillimanite and garnet developed in the sedimentary series and garnetiferous amphibolites and hornblende schists underwent extreme injection metamorphism. The boundaries of this injection complex had been mapped previously by Peach and Horne. The Survey officers found further belts of injection or permeation running parallel to the strike for considerable distances and up to 1½ miles wide.

The metamorphic rocks described above, and the metamorphic rocks of the rest of Shetland are unfossiliferous. They are overlain by sediments and volcanic rocks belonging to the Old Red Sandstone. These sediments demonstrate that erosion had laid bare the permeated series by Devonian times. On the other hand the Old Red Sandstone is itself cut by granitic intrusions which might represent the last phases of the plutonic activity which had previously given rise to the permeated and metamorphic rocks. If this is the case the metamorphism is of Caledonian age, if not, then the metamorph-

ism must be Pre-cambrian. But Shetland lies to the east of the strike of the Moine Thrust, and the arrangement of deformed and intruded Old Red Sandstone sediments and volcanic rocks unconformably overlying a metamorphic and migmatitic series is also common to Norway and Scotland. The islands are thus probably part of the Caledonian Mountain chain.

The present study concerns a part of the eastern part of the Mainland; the geology of the whole of which is summarised above. The selected portion is that part of the parish of Delting bounded by Yell Sound to the north, Swining Voe to the east, Sullom Voe to the west, and the townships of Laxo and Voe to the south. This area was mapped for the Geological Survey by D. Haldane.(Map 2).

The present writer spent about 160 days in the field mapping. The mapping was done on airphotos of a scale of 1:10,000. In the course of this mapping 2,000 hand specimens were collected of which 1,000 were sliced. Approximate modes were obtained for the great majority of these sliced rocks, by means of unaided visual estimation. These modes were used in two different ways. First they provided the basis of a simple statistical investigation of the variation in amount of the different minerals, both in relation to other minerals and to the intensity of metamorphism. This was done by plotting the m modal amount of a mineral on a graph either against the modal


GENERAL GEOLOGY
&
LOCALITIES
Mio Ness
Shaw Taing
PEGMATITE
GRANITE
GRAVEN
INCLUSION
GRANITE
INTRUSIVE COMPLEX
Fugla Ness
Tofts Ness
Mossbank
Calback Ness
Calback
Garth Ho.
One Mile
Graven
Firth Voe
BELT
PERMEATION
Calna Taing
Shitteradoo Burn
Fora Ness
Noness Head
Dater Voe
LIMESTONE
Voxter Voe
SCATSTA
Colla Firth
COLLA FIRTH PERMEATION BELT
Brae
BRAE
INTRUSIVE
COMPLEX
Wetherste
Mangaster Burn
Swining Voe
WEISDALE
Laxo Water
Point of Mulla
Voe Church
Loch of Voe
Laxo
Laxo Voe
MAP 2

amount of another mineral in the same rock or against the zone of metamorphism in which the rock occurs. The modes were also used to produce a number of small scale maps showing the geographical distribution of the different minerals and also in some cases of their intensity of their development. These diagrams and maps record much of the factual data from which deductions concerning the geological history of the Delting area are made.

Summary of the Thesis.

No stratigraphic sucession has been established in the varied series of metamorphic rocks which make up so much of Delting, but these may be grouped into four divisions.

In the south-east there is an alternating series of semi-pelitic, calc-silicate and calcareous rocks about 17,000 feet thick. A limestone 1,200 feet across lies to the north and west of this division and can be traced from Voe to the eastern coastline; it was named the Weisdale Limestone by the Survey and forms the second lithological division. To the west and north of this limestone a varied sucession in which pelitic rocks and quartzites are abundant while calcareous rocks are infrequent reaches a thickness of 15,000 feet. The fourth division seen in the extreme north presents a marked contrast to the other parts of the series and consists of a monotonous sequence of semi-pelitic rocks and is perhaps 6,000 feet across.

In general the metamorphic rocksin Shetland have a


FIELD EXPOSURE
DISTRIBUTION
One Mile
MAP

north to south strike but in Delting this regional trend is deflected by a Z-shaped fold many miles across. As a result the steeply dipping rocks which enter the area from the south, running in a northerly direction, trend north-east in the central parts of the region and in the north parts again strike north-south. A deflection of strike similar to this was noted by the officers of the Geological Survey in the Out Skerries 12 miles to the east of Delting. While such a large structural disturbance cannot be elucidated by work in Delting alone a number of smaller structures which may throw light on the regional tectonics have been noted in the district.

The largest of these are folds up to a mile across, which have formed at more than one period. Some appear to date from the time of the regional metamorphism; others ~~whose~~ may have formed at the time of the permeation which is believed to have followed the regional metamorphism. Another set deflect the lineation in the regional metamorphic rocks and are presumably also later than the regional metamorphism. On a smaller scale than many of these structures are several isoclinal folds seen on the north-east coast north of Fugla Ness, which are easily recognisable because of the presence of folded epidiorite bands.

Lineation, shown by the orientation of hornblende crystals occurs in some epidiorites interbanded with the metamorphosed sediments; small drag folds have been noted in limestones and in calc-silicates; mullion structure is developed

in semi-pelitic and siliceous rocks. In certain localities a crinkling is developed on planes of schistosity. More than one set of lineations may occur in the same locality and even on the same surface. While much of the schistosity is parallel to bedding planes, schistosity cutting bedding planes can be seen locally where the contents of a bed have been folded without disturbing the confines of the bed. In the south-east part of the area the rocks are characterised by three intersecting schistosities which produce another type of lineation.

Chapters two and thre deal with the sedimentary rocks and the structure of the area and are followed by a chapter deal dealing with the various metamorphic episodes which have been detected in Delting. The metamorphic history of the district falls into four phases. In the first place there is the widespread regional metamorphism which was followed by a more localised permeation. Around and within such areas, which are referred to as permeation belts, the country rocks have suffered a metamorphism that may be regarded as a contact effect of the permeation process. Thirdly the igneous masses found in the north and west extremities of the area produced aureols of thermally altered rocks. Finally we may distinguish the dislocation metamorphism connected with certain late movements.

The grade of regional metamorphism is lowest in the northern and south-eastern parts of the Delting area and highest in the south-west where kyanite is occasionally found. The relation of the permeation belts to the regional metamorphism is

of some interest. One belt, the Colla Firth belt, lies in the south-east part of the area bounded by rocks of relatively low regional metamorphic grade. The other belt, the Scatsta belt, occupies ground to the west where the grade of regional metamorphism is high, and runs from there in a northeasterly direction to the east coast. The permeated rocks are therefore not confined to areas of higher grade metamorphism as is the case in some other areas outside Shetland.

The large intrusions, principally of acid rocks, are later than the permeation belts, and occur in two areas; in the south-west the Brae Intrusive Complex with a great variety of rock types is exposed along the shore and for a short distance inland. In the north a much larger intrusive complex consisting of dioritic and pegmatitic rocks alternating with country rock screens falls into two divisions; part consists of numerous pegmatite sheets and has been called the Pegmatite Granite, while a larger part made up of a quartz-microcline-diorite rich in small inclusions has been given the field name of the Inclusion Granite. The whole complex is called the Graven Intrusive Complex.

The field relations suggest that the regional metamorphism and the permeation were independent processes, though possibly fairly closely related in time, and were followed at a later date by the igneous intrusions equally independent of the permeation. It is not always easy however at any one locality in the field to distinguish the effects of the regional

metamorphism from the effects of the contact metamorphisms by the permeation and the acid intrusions. Although this is the case, the fact that the intensity of the regional metamorphism varies from place to place quite differently from the way in which the degree of permeation fluctuated, provides a ready method of discriminating between the results of the two processes. This method which consists in establishing the minerals present in large numbers of sliced specimens collected from the entire district, in forming some estimate of the quantity of each mineral developed, and in plotting these results for each lithological type on a series of small scale maps showing the boundaries of the permeated zones and of the acid intrusions, frequently makes it possible to say to what extent a certain mineral is the result of regional metamorphism or of contact alteration around an area of permeation of of igneous intrusion. This technique deals not only with minerals like sillimanite whose origin may never be in doubt , but also with the more common rock forming minerals such as the micas or the felspars, variations in whose abundance might not be apparent during less methodical examination of the specimens. When the development of certain minerals has been correlated with a certain metamorphic event, it is often possible to date this event through an examination of the microscopic appearance of this mineral suite as many other accounts of metamorphic areas have shown.

As a consequence of this approach to the problem much of the fourth chapter consists of accounts of the microscopic appearance of the

appearance of the metamorphic minerals and of estimates of the quantities present. This does not mean that the field appearance of these rocks has been passed over or ~~that~~ its importance underestimated, but that the author feels that this side of the work can be presented in the illustrations and maps without lengthy discussion.

As a matter of convenience the metamorphism of the altered rocks is considered in two sections; in the first the minerals found in the argillaceous and siliceous types are described, while, in the second part, the calcareous rocks, which are in some respects more difficult to interpret, are dealt with. A section dealing with the alteration of the basic masses interealated in the sedimentary sucession follows and the chapter closes with a discussion of the results. In this discussion an attempt is made to consider the movement of material during metamorphism in the light of data collected on the mineral composition of the altered rocks. These data are displayed on a series of graphs showing the varying amounts of aluminous, siliceous and calcareous material.

In the fifth chapter the permeation of parts of h the Delting district is described. In twomain belts, the Colla Firth belt and the Scatsta belt and also in the regions of the Graven Intrusive Complex, metamorphic rocks have been intimately transformed by permeation, but migmatisation involving veining and injection has not occurred. Pelitic , semi-pelitic and to a lesserextent impure quartzites have been affected by permeation while calc-silicaterocks, limestones and epidiorites have

remained more or less unaffected.

The two main belts of permeation are made up of a number of lenticles of strongly permeated rock, separated by narrower areas showing a lower degree of permeation. The majority of the semi-pelitic and pelitic rocks within the belts have been completely transformed, although some partly modified relics of these rocks, together with unmodified bands of epidiorite and calcareous rocks, remain. At the margins of the belts, the lenticles of permeated rock become less numerous and soon non-existant. At a distance from the centres of permeation, the rocks often show quartzo-felspathic streaking or contain ill-defined pegmatites. As permeation becomes more intense, recrystallisation takes place and the differences in composition between the adjacent beds are greatly reduced. The final products of permeation are coarse, slightly banded, granitoid gneisses. The whole change to such rocks may take place in a matter of feet.

In the Colla Firth belt the gneisses produced by permeation are usually fairly uniform. In the Scatsta belt the rocks almost always show a streakiness due to the alternation of quartzo-felspathic and micaceous folia. The stable mineral assemblage of the permeated pelitic and semi-pelitic rocks consists of quartz, muscovite, biotite and plagioclase; microcline is common and garnet, sillimanite, staurolite, and kyanite may be present. It is suggested that there is no marked increase in the felspar content and there is certainly no change in the Ab:An ratio during the permeation.

During the recrystallisation the felspars tend to assume a rounded form at first and later to become rectangular, while the other minerals are accomodated in the irregular spaces between them. In the uniform granitoid gneisses such as characterise the Colla Firth belt the rectangular felspars are evenly distributed. In the Scatsta belt augen or lenticles are very common. On either edge of this belt are narrow bands of very prominant augen rock.

Although the rocks in the permeation belts show no directional structures other than inherited foliation, they are sometimes contorted by flow folds and have probably undergone slight movement during permeation.

The development of microcline is capricious and seems independent of the permeation considered above, since the mineral is common in some regions outside the belts of permeation and is not abundent in the Scatsta belt itself. Its growth was not accompanied by recrystallisation of the matrix and may therefore have taken place at a low temperature.

Of the rocks other than argillaceous types within the permeation zones, the quartzites may be recrystallised and locally felspathised. Some epidiorites, in the most strongly permeated regions, develop thin quartzo-felspathic streaks or blebs of epidotic minerals but are otherwise unaffected. Local potash metasomatism has resulted in the development of biotite.

Pegmatites and aplitic rocks occur as concordant lenticles and as discordant sheets in the Colla Firth belt;

they are much less common in the Scatsta belt.

In the sixth chapter an account is given of the Graven Intrusive Complex. It was formed in three stages, in the first of which the Pegmatite Granite was intruded; this rock type, consisting of many pegmatite sheets most of which are sharply bounded while others have rather hazy contacts, is found principally in the extreme north-west of the complex. Smaller pegmatite bodies have been mapped on the coast within the main dioritic mass and near its southern boundary; single pegmatites occur along the north-east coast at Mossbank and Fugla Ness.

In the second stage, dykes of lamprophyres and related rocks were intruded. Although these have been found to the south of the complex, they increase in quantity within the Graven Intrusive Complex area and clearly form part of it.

In the third stage a rock having the composition of a quartz-microcline-biotite-diorite marked by many small xenoliths was intruded. In the field this rock was known as the Inclusion Granite and the term has been retained. The final episode was the formation of narrow pegmatites and aplites cutting all earlier rocks and frequently only a few inches thick.

The dislocation metamorphism is described in the seventh chapter. It is associated with the development of faults and shatter belts and has produced both mechanical and mineralogical effects. Reddening, shattering, shearing, and the development of chlorite, sericite, and epidote are the most common signs of dislocation metamorphism in Delting. The reactions of different rocks vary with their composition and

with the conditions prevailing at the time the movements took place; repeated movements under varying conditions may have occurred in a single belt.

The last chapter contains a breif review of the geological history of the district together with a discussion of the causes and the significance of some of the events described in the thesis.

CHAPTER 2.

THE SEDIMENTS

The altered sedimentary rocks in the Delting area are a very variable series in which pelites, semi-pelites, impure quartzites, calc-silicates and limestones occur. Every gradation may be seen between pelite and quartzite, and in the calc-silicates between limestone and the pelite, semi-pelite and quartzite rocks. The distribution of all these types is shown in map3, which brings out the predominance of semi-pelites over all the other rocks.

Sedimentary Structures. These metamorphic rocks are seen in the field as sharply defined beds which are usually one or two feet thick but may vary up to six feet thick, as for example at Point of Mulla and on the north shore of Laxo Voe. The beds are mostly homogeneous lithological units and follow one another without any sort of ascertainable lithological order.

When the beds are closely examined certain inhomogeneities appear, the most common of which are the flaggy partings to be seen frequently in semi-pelites and less frequently in impure quartzites. These partings are extremely thin parallel layers of pelitic rock occurring at frequent and regular intervals in the semi-pelite. They rarely join up, never cut each

Diagrammatic Map of the Sediments.

(Exposed & Unaltered by Permeation)

— Pelites

— Semi-pelites

..... Impure Quartzites & Quartzites.

Striped Impure Quartzites.

---- Calc-Silicates

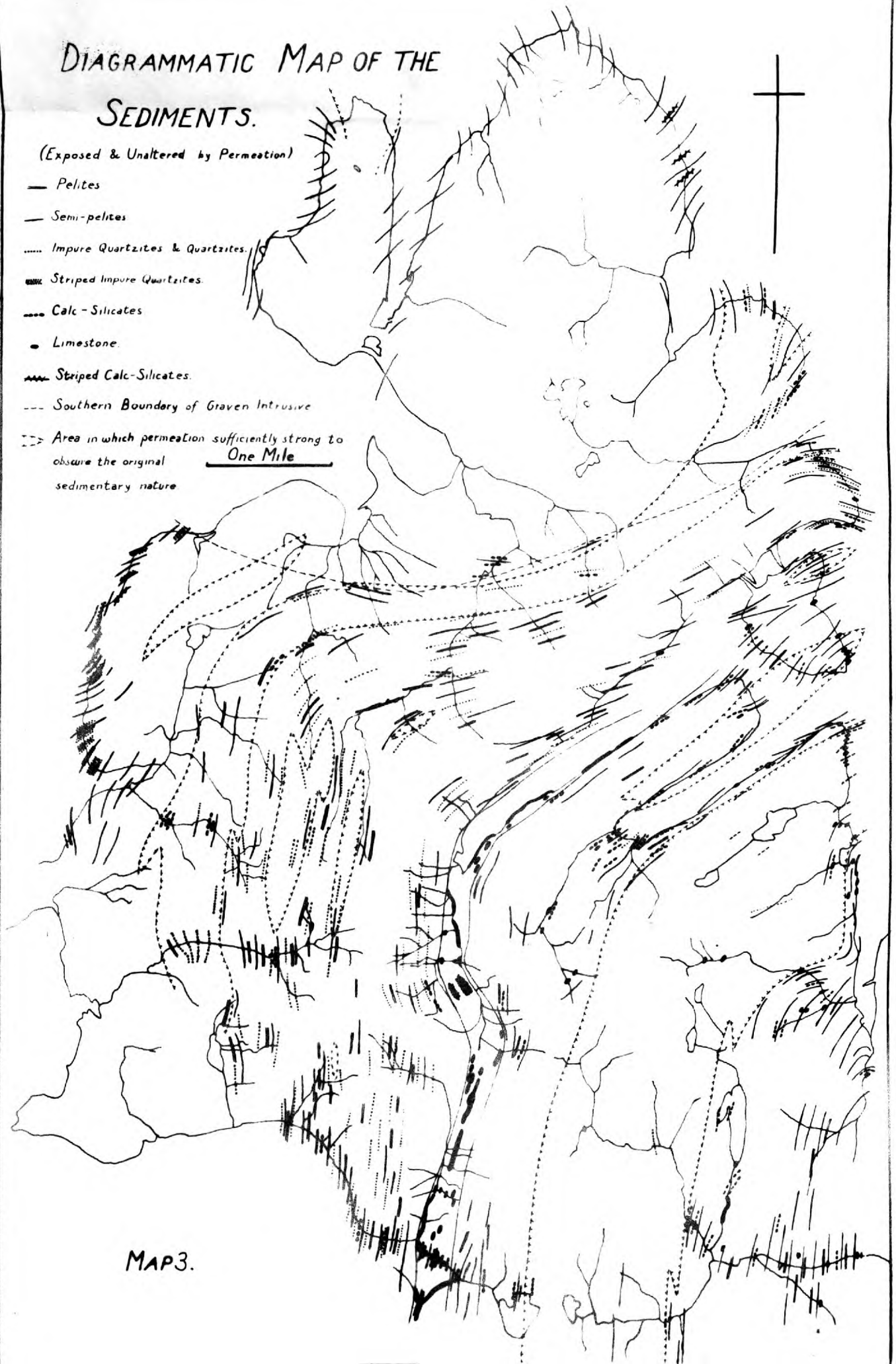
● Limestone.

Striped Calc-Silicates.

--- Southern Boundary of Graven Intrusive

Area in which permeation sufficiently strong to obscure the original sedimentary nature

One Mile



Map 3.

other, and are not current bedded. Frequently they show ~~very s~~ ~~strong~~ very strong folding in a flowing manner, the bedding planes of the beds in which they occur remaining undistorted, (see pps.24-5).

In the Voxter Ness area there are a number of beds showing alternating dark and light bands ⅛" to 1" wide, which are extraordinarly straight and parallel, photo 1. These rocks are here called the Striped Impure Quartzites. The light coloured bands consist of quartz and felspar, the dark bands are of quartz and felspar with a sprinking of biotite flake hese rocks are remarkable for their high content of felspar and almost complete lack of muscovite.

Most of the sedimentary banding, i.e. banding within bedding, seen in the area is associated with calcareous rocks. The calc-silicate beds and the limestones very frequently show composition banding parallel to the bedding. Bands ~~are~~ generally about ⅛" wide of a very slightly calcareous impure quartzite are quite common inside beds of impure quartzites. On the coast between Voxter Voe and Calna Taing and also on the coast to the north of Fugla Ness are a number of beds of calc-silicate rock which show a very fine and very intense striping. These rocks are shown on Map 3 as "Striped Calc-silicates". Under the microscope these rocks are seen to be composed of alternating layers , each a fraction of a millimeter thick, of quartz and of calcareous minerals such as amphibole, pyroxene, and epidote group minerals.

Schists which in the field look as if they were



Photo 1. Striped Impure Quartzites,

Voxter Voe.

half-way between pelites and semi-pelites in composition are sometimes seen in thin-section to be made up of alternating layers of pelite and semi-pelite rock.

All the above structures are interpreted as original sedimentary features. They are invariably parallel to one another. They give no indication of the"way up" because they are never found to form structures of current bedded type; and on the rare occasions when they appear graded, the grading is either too obscure or the bedding is folded in such a complicated manner that the "way up " reading cannot be related to the general structure.

Stratigraphy. The different lithological types occur in a rapidly alternating succession, which can be divided into four major units.

The first unit is composed of all rocks to the east of the Weisdale Limestone, and is some 17,000 feet thick. Semi-pelite is by far the most common rock but there are also many beds of limestone and calc-silicate rock. The second unit is the Weisdale Limestone,which is well over 1,000 feet thick. Most of this thickness is of slightly impure limestone, with occasional thin siliceous bands, but in the neighborhood of Voe there are very large numbers of calc-silicate and even of non-calcareous rocks. The third stratigraphic unit consists of all the rocks to the west of the Weisdale Limestone and to the south-east of Garth House. This unit is about 1[illegible],000 feet thick, and can be distinguished from the first unit in that it contains very considerable numbers of beds of impure quartzite,

a rock type almost absent from the first unit, and of pelite. This unit contains very few calcareous rocks. The fourth major unit is composed of all the rocks to the north-west of Garth House, and is possibly of the order of 6,000 feet thick. This unit differs from the others in that it is almost entirely composed of semi-pelites. None of these four major units contain features which could be made the basis for a further subdivision.

The Weisdale Limestone continues undiminished in thickness for 8 miles to the south of Voe, after which it enters the sea. The reason for its disappearance in the Fora Ness area at the north end of its outcrop is unknown. It gives rise to a deep valley running obliquely across Shetland.

Each of the four stratigraphical units has a characteristic concentration of the different sedimentary types. Therefore if it is assumed that the nature of the sedimentation continues unaltered for as far at 90° to the strike, i.e. in the plane of the bedding, as it does parallel to the strike, then in conjunction with certain structural considerations (pps. 29-30) it can be shown that any repetition of the sucession by folding which may occur in the area is small in comparison with the real thickness represented. The total thickness of the four major units, about 40,000 feet, must therefore be of the same order of size as the true stratigraphic thickness represented in the area.

CHAPTER 3.

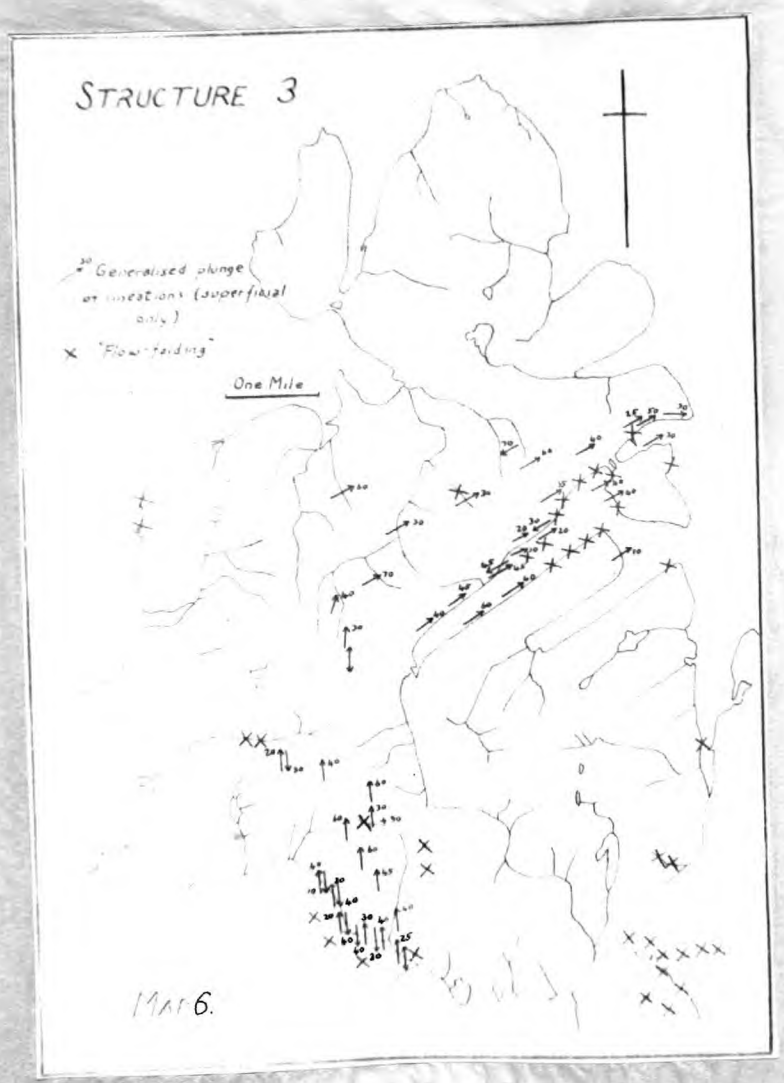
STRUCTURES

The structure of the area has to be considered as a whole because many of the various elements of structure cannot be related to any particular episode or even arranged in chronological order.

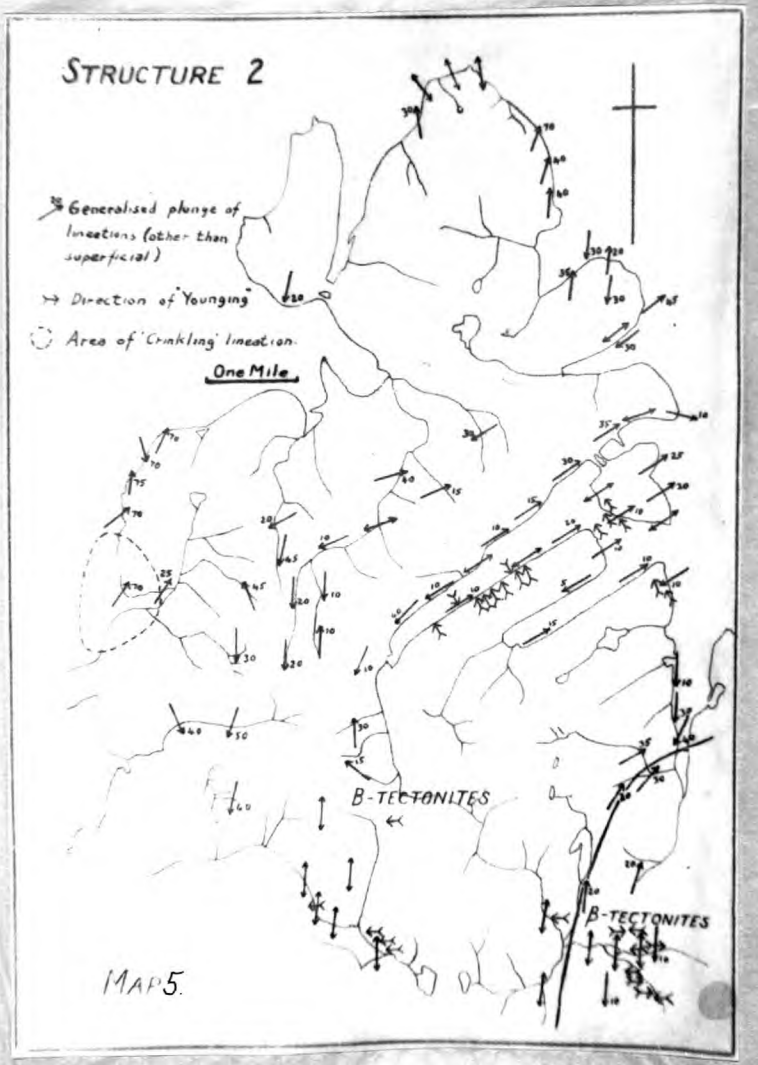
Maps 4,5, and 6 show in a somewhat simplified manner, the structure of the area. For the sake of clarity a number of unimportant complexities have been smoothed out in these maps. In all the maps in this thesis, ornament indicating the schistosity or bedding of rock types has been drawn elongated parallel to the strike. Schistosity and bedding were always found to be parallel

MICRO-STRUCTURES AND STRUCTURES SEEN IN THE HANDSPECIMEN.

Bedding. Bedding is to beseen throughout the area where the rocks are not too thoroughly permeated as separation planes between individual beds and as flaggy partings and composition banding (see above, pps 17-8). These structures are always parallel to the schistosity except in a particular structure described below (pps.24-5). There is no apparent divergence of stratification and schistosity on the regional scale.


STRUCTURE 3
Generalised plunge of lineations (superficial only)
"Flow-folding"
One Mile

MAP 6.


STRUCTURE 2
Generalised plunge of lineations (other than superficial)
Direction of "Younging"
Area of 'Crinkling' lineation
One Mile
B-TECTONITES
B-TECTONITES

MAP 5.

Schistosity. All rocks which developed mica during the regional metamorphism, have probably been at one time schistose. The schistosity has in many cases been wholly or partially destroyed by the permeation and by the contact metamorphisms as is described later. But it is difficult to establish the extent to which the varying degrees of disorder in imperfectly schistose rocks are due to later alterations. The development of the schistosity requires a complete and through going reconstitution of the rock. Only two such episodes are knownin the area; the regional metamorphism and the permeation. It is certain that at the end of the regional metamorphism at the latest the rocks were schistose, probably strongly schistose, everywhere.

Two types of schistosity occur:-

1 - a multi-plane schistose structure characterises the pelitic rocks within the lowest zone of regional metamorphism, near Laxo. A strong schistosity occurs parallel to the bedding but it is crossed obliquely at about 45° by two minor schistosities shown by occasional parallel orientated mica flakes. A few rocks outside this zone approximate to this condition but the subsidiary planes in these cases are not so well developed

2 - a normal single plane schistosity, of varying degrees of perfection, characterises the micaceous rocks of all other zones.

Lineations. The 1,200 lineations mapped were classified into two groups: the fundamental lineations and the superficial lineations.

Fundamental lineations are lineations which can only

arise during a complete reconstitution of a rock, map 5.

1. Z-lineation in epidiorites. The hornblende crystals in the epidiorites show more or less perfectly three main types of preferred orientation. These are:- a/ X,Y,and Z all respectively parallel, b/ X directions all parallel but Y and Z showing no preferred orientation, and c/ Z directions all parallel but X and Y showing no preferred orientation. Type b gives rise to a schistosity and types a and c to a lineation in the rocks. Neither the lineation nor the schistosity are readily seen in the field but the lineation appears in general to be parallel to the other fundamental lineations, and the schistosity appears to be parallelto the general schistosity.

2. Fluting lineation of the semi-pelites and the impure quartzites (mullion structure). This lineation is to be seen at times on the exposed bedding planes of siliceous rocks, map 5,photos 2 and 3. It may be caused by the flow folding (pps.24-5) but is more probably in the nature of a wave form set up at the boundary between semi-pelites and pelites moving at different speeds (Sander, 1948 pps.12-14).

3. Fold axes of intensive drag folding in limestones and calc-silicates, which is brought out in weathered specimens in which the more carbonate-rich bands have been more strongly dissolved.

4. Crinkling lineation. This lineation does not necessarily involve such a complete reconstitution of the rocks during its formation as do the first two. Further more it is confined to a relatively small area, map 5. It is often more of a

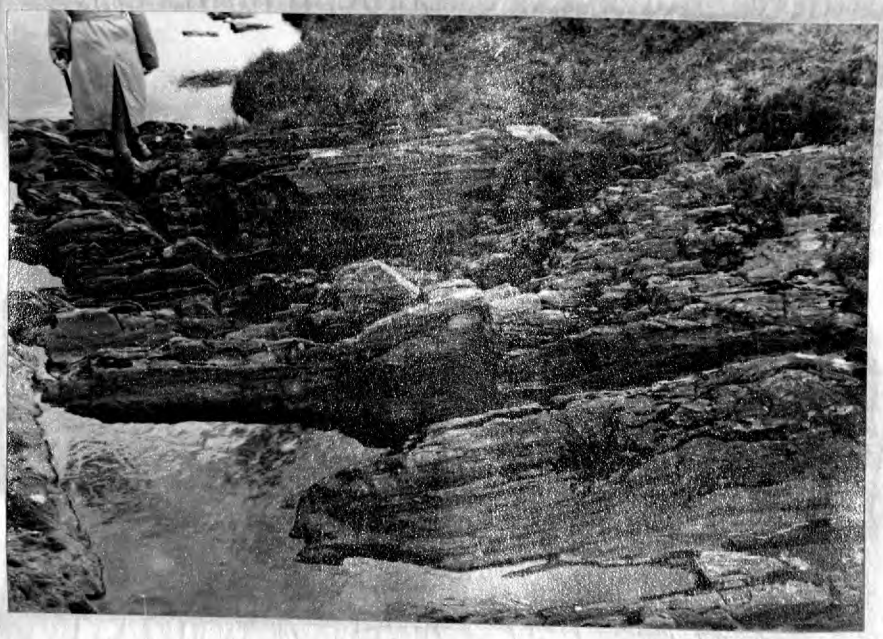


Photo 2. Fluting lineation, Laxo Voe.

Photo 3. Fluting lineation, Point of Mulla.



direction within the rocks than a visible linear structure to be seen on the exposure. It is formed by the intensive folding into small sine-waves at the rate of several to the inch, of strongly flaggy rocks. In contrast to the lineations so far mentioned it is nearly always has a very steep plunge.

5β-lineation. This very definite but not very obvious lineation is the necessary accompanyment of the multi-plane schistosity mentioned above. The lineation is caused by the intersection of the different schistosities.

Superficial lineations are those lineations which are or could be the result of movement unaccompanied by the recrystallisation of the rock, (map 6). The only lineation in the area which comes under this heading occurs in politic rocks, and is the result of folding of the schistosity in a manner identical with that in the crinkling lineation. It is often accompanied by strong linear features on the exposures, photos 4 and 5. It is not uncommon for two such lineations, equally developed, to cross one another on the same schistosity plane. It is even more common for the two crossing lineations to occur on planes separated by an inch or two.

The crinkling lineation would probably be better classified as lying somewhere between the superficial and the fundamental lineations.

Flow-folding. In the flaggy semi-pelite rocks in certain areas (map 6) there can be seen on suitably weathered and oriented surfaces an intensive flow-folding of the flaggy layers within the undistorted confines of the beds themselves. The flaggy

Photo 4. Lineation in pelites, Point of Mulla.



Photo 5.

As photo 4.

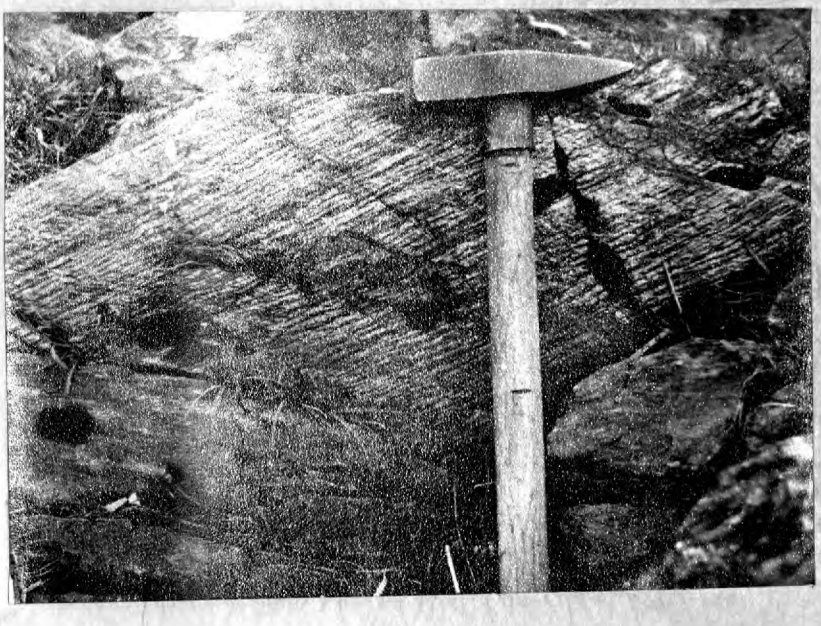
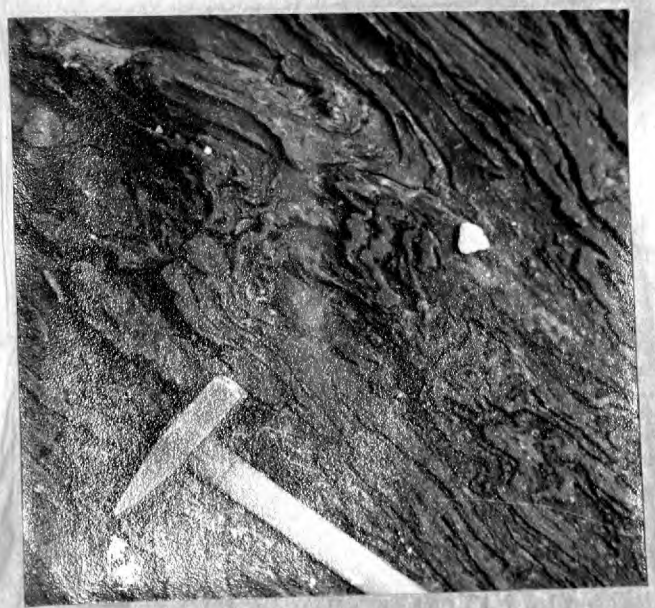
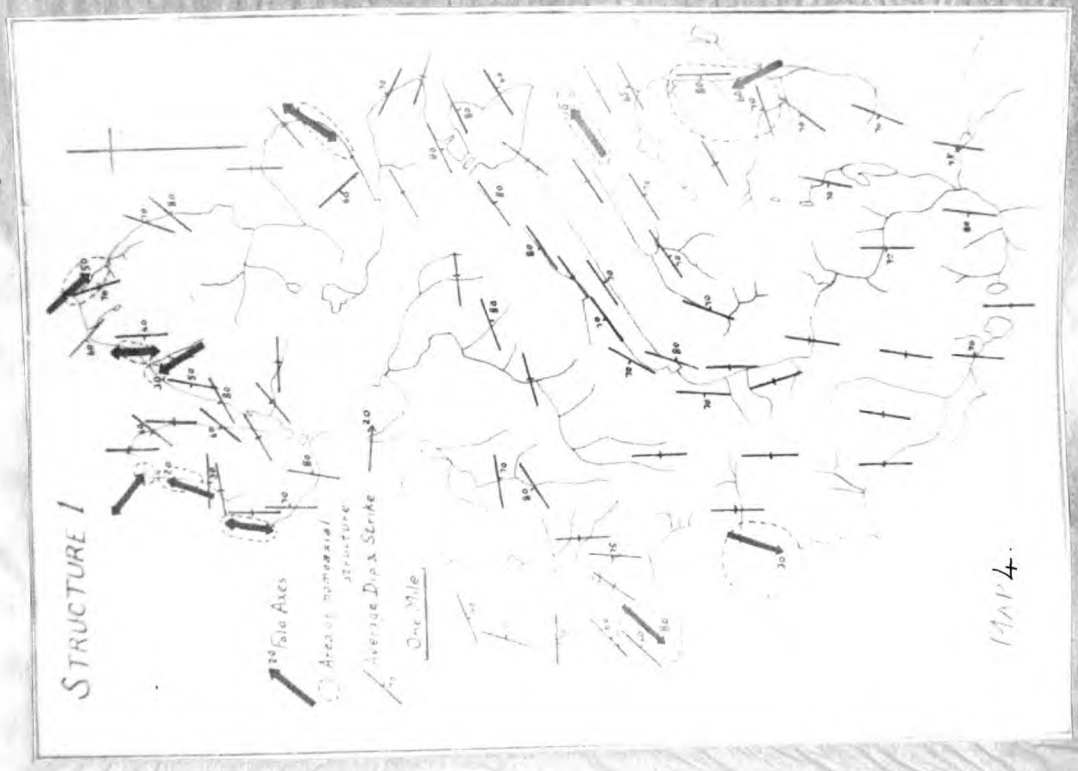


Photo 6. Limestone, Dales Voe.



partings are never broken and never become fused, yet a single loop-like fold can take up almost the entire width of the bed. The style of the folding is much the same as that seen in oil films on water but is more ordered; the axial planes are always parallel to the bedding planes. It is impossible to trace any of the partings very far, or to resolve the structure of the bed for more than a foot or two, due to the faintness of the phenomen as revealed in the field and to the lack of suitably weathered surfaces. The phenomen has no relation to the flow folding of rocks mobilised during permeation or contact metamorphism, where the folding is essentially one of bands of different composition. Here each composition band i.e. each bed of semi-pelite, remains straight edged and undistorted whilst the entire contents of the bed have folded. The axes of folding are generally but not always parallel to the fundamental lineations. Thin-sections from such beds show that the schistosity remains parallel to the bedding and cuts the flaggy layers where they are no longer parallel to the bedding. This schistosity must be later than the flow-folding even if only very slightly later.

Such folding could not be established by a single act of laminage or "einscharige Scherung". But once the flaggy partings had become strongly folded, the penetrative movement causing the mica schistosity would increase, possibly considerably increase, the degree of this folding. The folding and the schistosity were probably formed during the same metamorphism of the rock.



JOINTS

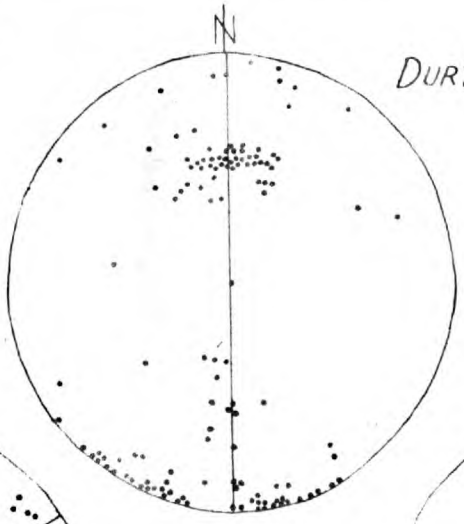
Fig.1.

PLANE TRUE NET.

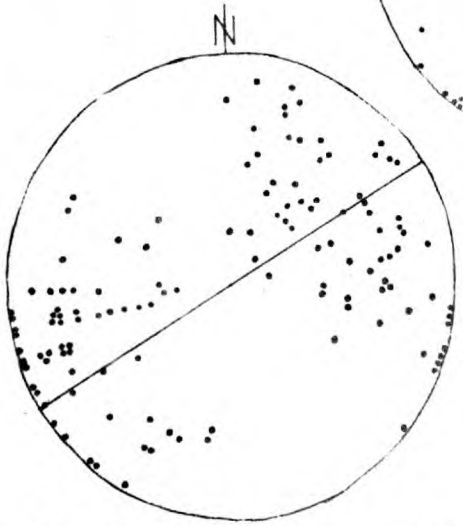
LOWER HEMISPHERE.

• Joint Pole

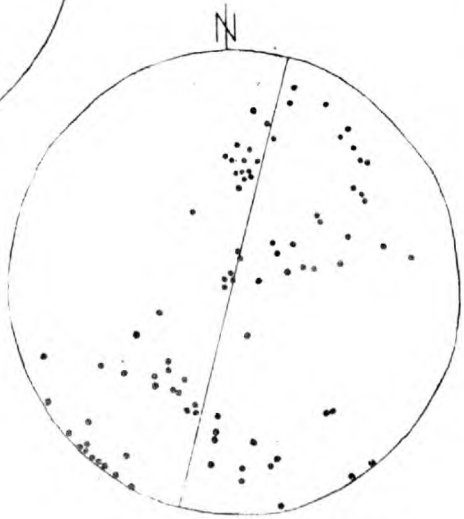
/ Average strike of beds, average dip is vertical.



DURY VOE - NORTH SIDE.



DALES VOE - NORTH SIDE.



POINT OF MULLA AREA.

Joints. Three areas were found where jointing is well developed. Elsewhere the joints have been destroyed by late shattering. The plots of the joints for these areas are shown in fig. 1. In each case there appears to be two concentrations of joints at 90° to each other and to the bedding surfaces. In each of the three cases the joint pole maxima are about 45° to the vertical. Since the fundamental lineations are approximately horizontal in each of the three areas, the pole maxima are at about 45° to the lineation.

SUB-REGIONAL STRUCTURES.

These structures are too large to be comprehended in a single exposure, but are considerably smaller than the regional structures, map 4.

Folds plunging at 90° to the present surface are found by means of stereographic plotting of dips and strikes in the east-west part of the course of the burn flowing north into Voxter Voe, to the west of Mossbank, and between Tofts Ness and Fugla Ness. But the bedding when plotted on a map, shows a very complicated arrangement, which could only be attributed to folding of a very small wave length. No such folding is visible in the areas concerned.

The area to the south of Voxter Voe mentioned above is one of strong dislocation metamorphism. It is believed that the divergent strike is due to movement on the big fault passing through the area dragging the beds out of alignment and rotating shear slices of the rocks.

The structure of the Mossbank area might be due

to the same cause, but with the Tofts Ness area is probably better interpreted as being due to retation of the blocks contained within the Inclusion Granite, while that granite was being intruded or was still plastic.

Folds of three different types all of which plunge at angles of less than 90° have been found. In each type the relation of the fold to the fundamental lineation is different. The big fold on the west side of Swining Voe and the folds on either side of Mio Ness are all on axes widely different from the general direction of the fundamental lineation within the fold. The simplest and best example of this is the Swining fold where the originally horizontal lineation plunges down under the fold and rises up on the other side to become nearly horizontal again. The folds at Mio Ness and at Swining are strongly inhomogeneous in relation to the regional structure.

The fold south of Mossbank, the three fold areas on Calback Ness and the fold on the peninsula just north-west of Graven are not accompanied by lineations, except in the Mossbank area where three widely different lineations occur. In these cases the lineations may have been destroyed by later contact metamorphisms.

A third type of relationship is shown by the folds at Noness Head, north-east of Wethersta, and to the south of Voxter Voe. These folds are parallel to the fundamental lineation. The first two are closely associated with the permeation belts and were probably formed during the perm-

eation. The folding at Voxter Voe seems to be associated with the crinkling lineation and may be due to the same cause.

Three types of folding on the scale of the exposure can conveniently be considered here.

a/ Folding in permeation gneisses, generally with a wave-length of several inches, appearing to have taken place as the result of restricted movement in mobilised or partially mobilised rocks. Examples may be seen in the Mossbank region and on the north shore of Colla Firth, photos 19&20 .

b/ Folding on a scale varying from a wave-length of several inches to several feet can be observed in places in non-permeated areas especially in limestones and calc-silicates, photo 6. These folds generally have axes parallel to the fundamental lineation of the area. If they are interpreted as drag folds and a direction of "younging" is obtained from them, then as seen from map 5 most indicate that the rocks become younger to the west. The occasional folds indicating that the rocks to the east are younger than those to the west may be:-

1 folds on the east limb of a drag fold of a larger scale

2 incorrectly interpreted folds; folds which are badly exposed

3 folds of a later date due to movement of a different sense, for example folding associated with the permeation.

c/ A number of true isoclinal folds occur in the coast section to the north of Fugla Ness. They are obvious because their axes of folding dip 40° to 50° to the north-east. Thus in the cliffs

the epidiorite bands can be seen bent back parallel to themselves. The folding is not so obvious when such bands are not present, but it can still be detected. Along several hundred yards of coast s a number of folds of this type were found. These folds all appear to be small structures.

The question of isoclinal folding is of some importance in the area. In the section on the stratigraphy, pps 19 to 20, it was suggested that 40,000 feet of sediments were represented. It is necessary to consider whether this thickness may not be due to the repetition of a smaller sedimentary thickness by isoclinal folding, especially since the bedding everywhere approaches the vertical. The stratigraphic arguments against isoclinal folding have been given. They are supported by the structural evidence.

Isoclinal folding on a scale so large that only one limb of a single fold is represented in the thesis area may have taken place. As mentioned above, isoclinal folding on a very small scale can be observed in at least one area. But isoclinal folding on any scale intermediate between these two can only have taken place on axes which are now horizontal, since plunging folds would give rise to convergent strikes of bedding and these are not found in the area. Isoclinal folds with horizontal axes are unlikely because the lineations are not horizontal except on the south border of the area.

When the structural evidence is considered in conjunction with the stratigraphical evidence, it can be seen that isoclinal folding must be limited both to a short wave-

length and to few repetitions of any one stratigraphic level at the present surface. Such folding does not appear to be sufficiently well developed to influence the stratigraphy to any noticable extent.

REGIONAL STRUCTURES.

The rocks in the region of Delting are folded about a vertical axis in a simple flexure which has a half wave-length of about 2 miles, map 3. The diversion of strike involved is also found some 12 miles to the east in the Out Skerries. This structure is of major importance in the structure of the whole archipelago.

A few of the structures described above can be related to definite episodes in the history of the rocks, but many cannot. The universal, almost vertical attitude of the beds is due to a structure much larger than the area mapped, and whose nature cannot be predicted from an examination of this relatively small area. Whilst the larger structure is unknown, the significance of many of the smaller structures and their relation in time to the larger structures must remain obscure.

Many of the structures are probably at least as old as the regional metamorphism, and are related to a regional or larger structure. It does not seem possible that

subsequent to the regional metamorphism, the basic structure of the area can have been more than superficially altered. Even in the permeated areas the structure has been preserved in outline if not in detail. Such superficial alterations in t structure would be regional tilting or rotation of the area as a whole, and possibly the large vertical axis fold which twists the strike into an enormous reversed S. A number of structures which fold the fundamental lineation or which fold the schistosity are demonstratably later than the regional metamorphism. But there is no evidence as to how far much later they are, other than that they must have been formed before the dislocation metamorphism.

CHAPTER 4.

METAMORPHISM

Three periods of metamorphism, other than the dislocation metamorphism, are distinguishable in the Delting area. The most wide spread metamorphism is called in this thesis the regional metamorphism, because of its similarity to metamorphisms called regional elsewhere,(Harker, 1939,p.177). The other two metamorphic episodes are both examples of contact metamorphisms (or thermal metamorphisms, Harker, 1939,p.22) one of which was induced near the contacts of intrusive igneous bodies, and the other in the vicinity of belts of permeation, the nature of which will be described later.

Two widely different types of rock are affected; the early basic igneous intrusions and the sediments. The sediments fall into two sets; the pelite-quartzite rocks and the calcareous rocks. These three rock grpups are considered below separately , because of their differences in composition, and in their behaviour during metamorphism. Moreover the behaviour of the calcareous rocks is not so well understood as is the behaviour of the other rocks.

METAMORPHISM OF PELITES, SEMI-PELITES AND QUARTZITES.

Reference to map 3 will show that rocks of pelitic and semi-pelitic composition are fairly well distributed throughout the area. The impure quartzites are more localised.

These rocks are only considered as the three separate types, pelite semi-pelite and impure quartzite, for convenience. In actual fact there is a complete gradation from pelite containing no quartz to quartzite containing no pelitic material. The three types were not accurately defined. Rocks which appear schistose in the handspecimen, and are seen in thin-section to be dominantly composed of micas (and garnet) are called pelites. Rocks in which micas are present in small amount are called impure quartzites, or quartzites if there is no mica present. The rest are called semi-pelites.

METAMORPHIC MINERALS.

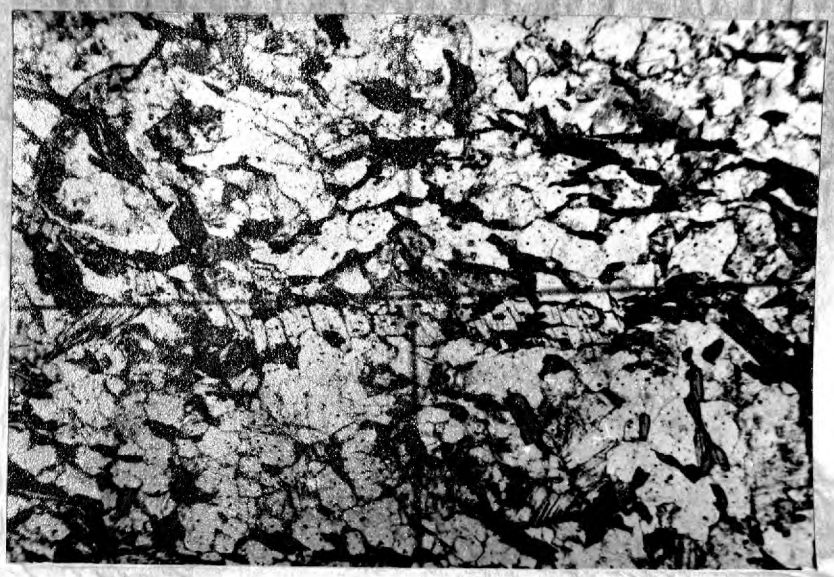
Quartz. The variation in the amount of quartz in the different rocks is largely an original sedimentary feature. Some of this variation may be due to variation in the intensity of metamorphism, because the different minerals developed at different intensities of metamorphism do not contain the same amounts of silica. This latter variation is much smaller than the variation due to the original composition, and is for all practical purposes masked by it. For instance the geographical distribution of the different sedimentary types shows no relation to the intensity of metamorphism.

Muscovite. Two types of muscovite, which are usually disting-

uishable from one another are found in these rocks. A muscovite which is distributed over the whole area is called the regional muscovite, and a muscovite which frequently shows signs of late development is called the late muscovite. The regional muscovite forms flakes, 3-4 times as long as they are broad (length parallel to the cleavage)which are arranged parallel in the rock to form one or more schistosities. They have a similar form and orientation to the biotite, but may cut across the biotite in an oblique manner. The late muscovite flakes form vary from equidimensional to 10 times as broad as long, are frequently very large (3mms in diameter), and are nearly always larger than the regional muscovite flakes. They are completely disorientated and may lie at any angle to the schistosity.

Frequently it is very easy to distinguish between the two white micas, because the late muscovite with its disoriented fabric must have ey crystallised later than and under different movement conditions from the regional muscovite. On the other hand, the distinction cannot be drawn in some instances, possibly due to re-crystallisation of the regional muscovite after the regional metamorphism, or because of late movement during the crystallisation of the late muscovite.

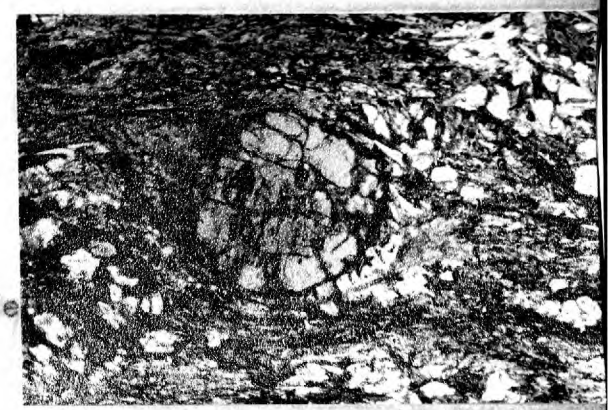
In the Colla Firth region late muscovite often crystallizes across folds which are small enough to be seen in thin-section, and may almost replace rocks showing folding on this scale. This folding is believed to be associated with the



Late muscovite.
X 25.



Late muscovite.
X 60



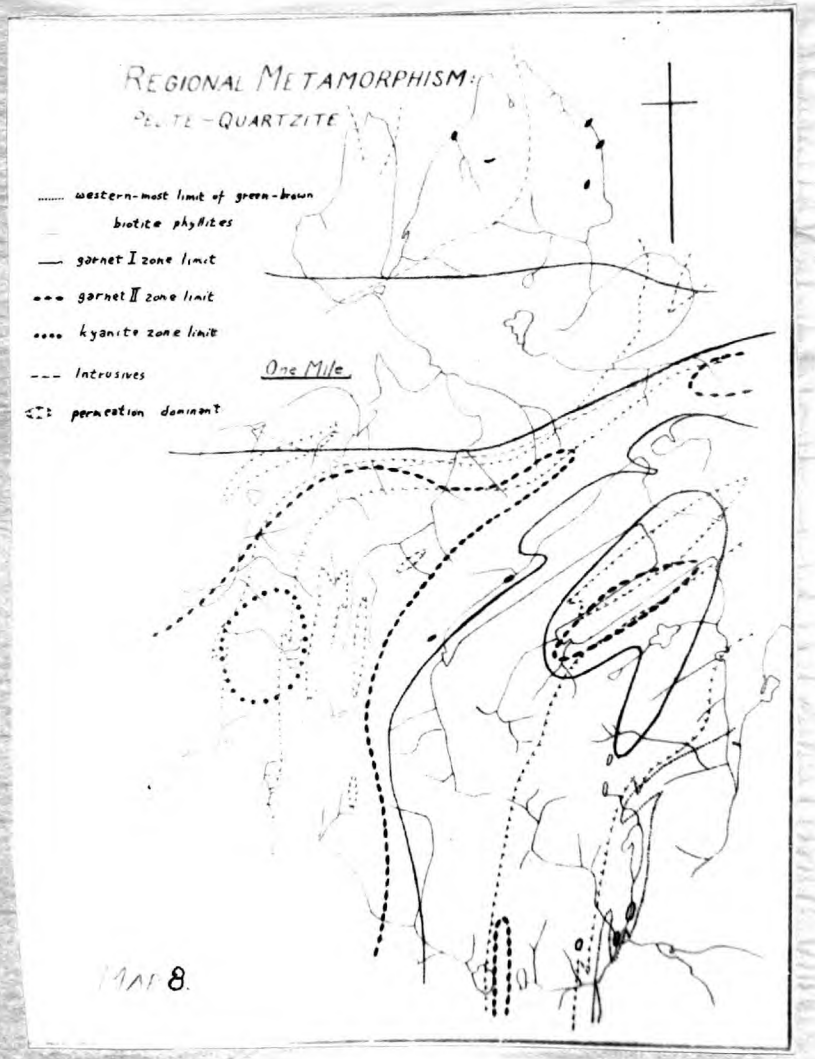
1. Crystallization of sillimanite against garnet.
2. Rotation of garnet.
3. Crystallization of late muscovite.

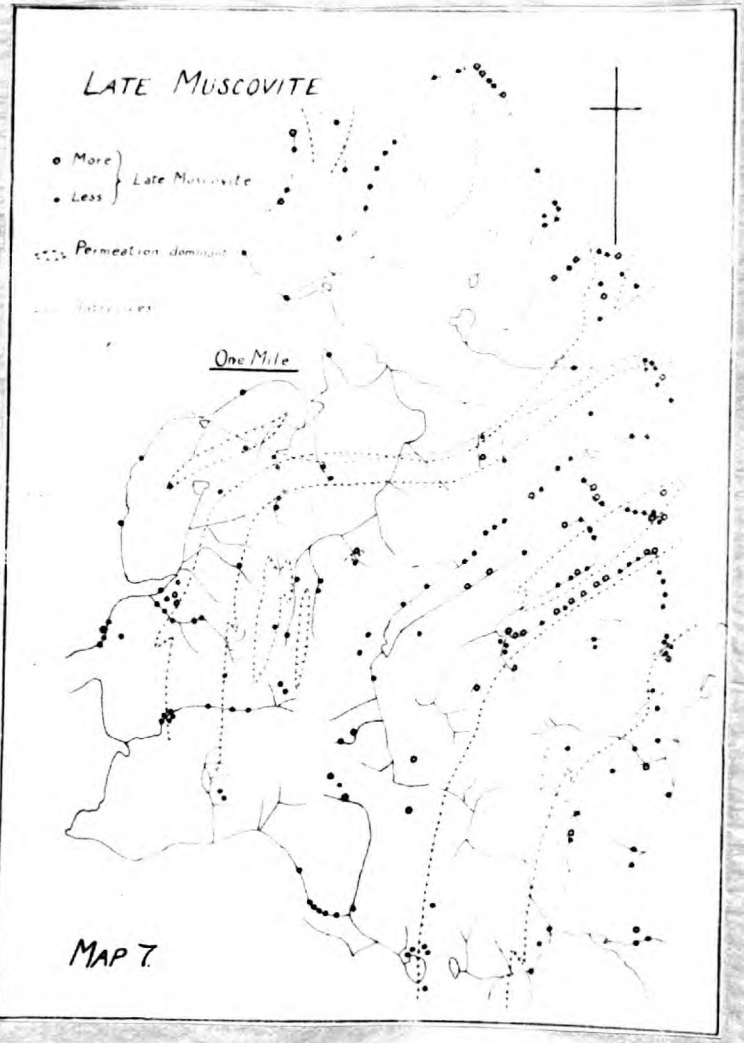
XII.

permeation episode in that area. The late muscovite is therefore more closely related to the permeation than to the regional metamorphism.

Map 7 shows the geographical distribution of all the late muscovite found in the area. The late muscovite is scattered unevenly over the entire area. The highest concentration lies in the Colla Firth area. Several other small concentrations occur. A comparison of the amounts of late muscovite in metamprphic rocks and in permeation rocks shows that although the late muscovite occurs in permeation rocks from all over the area, it does not occur so frequently or so profusely as it does in h the metamorphic rocks; 40% of all sectioned permeation rocks contain late muscovite, whilst 50% of all sectioned pelites, semi-pelites and impure quartzites contain it. The individual amounts of late muscovite in each permeation rock are considerably less on the average than the individual amounts in the metamorphic rocks.

The variation of the regional muscovite concentration in the pelite-quartzite series is considered in some detail at the end of this chapter. Late muscovite occurs in all rocks from pelite to quartzite in composition. It occurs most often and most profusely in pelites. In the latter it can be so well developed that the original rock is preserved only as inclusions in thelate muscovite. Therefore it is probable that the late muscovite is a metasomatic mineral in part; although it grows in the rock due to the addition of material, the amount of material


REGIONAL METAMORPHISM:
PELITE-QUARTZITE
..... western-most limit of green-brown biotite phyllites
— garnet I zone limit
garnet II zone limit
kyanite zone limit
--- Intrusives
permeation dominant
One Mile
MAP 8.

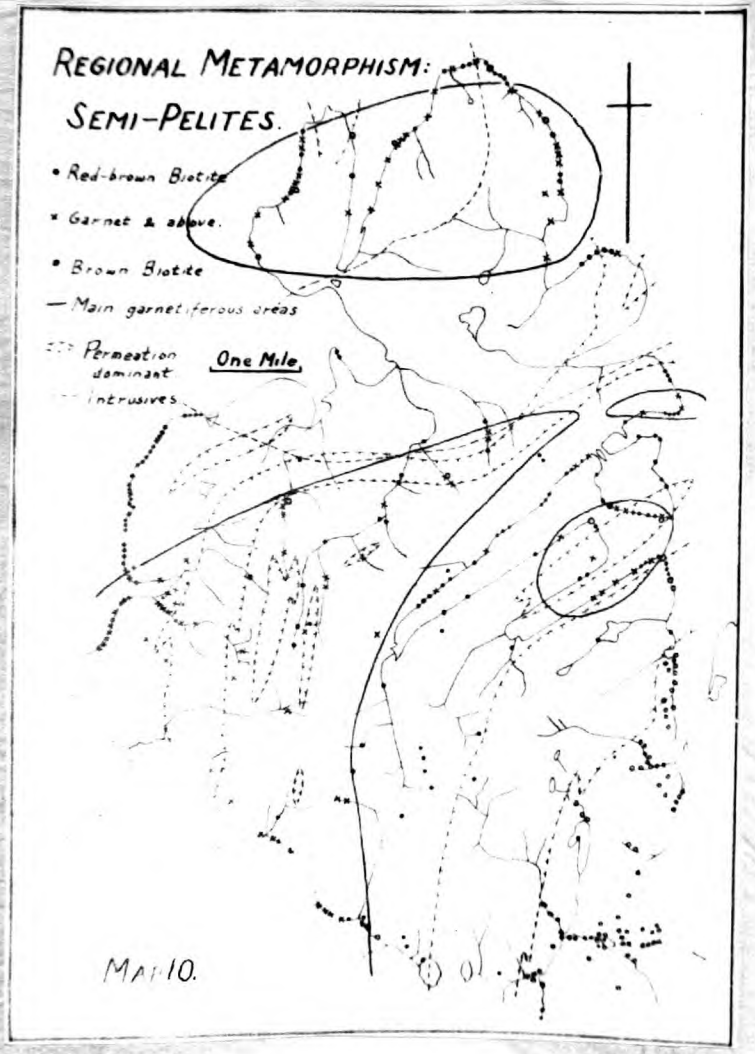

LATE MUSCOVITE
More
Less
Late Muscovite
Permeation dominant
One Mile
MAP 7.

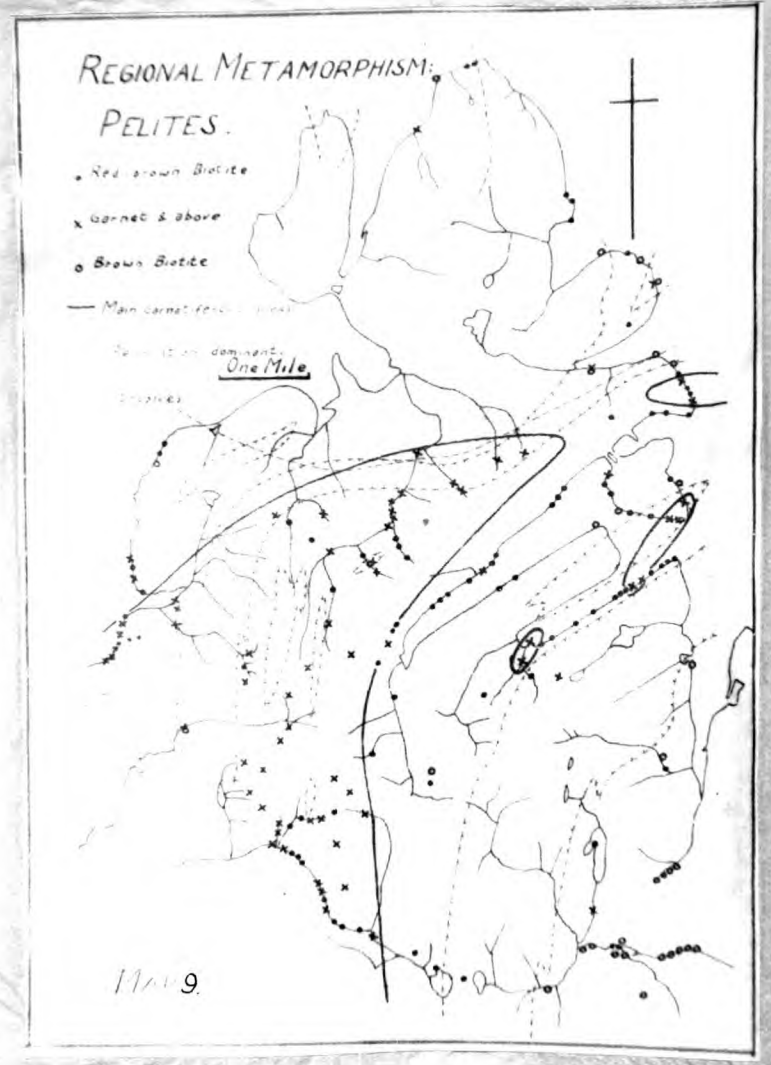
added dependson the original composition of the rock itself.

Biotite. Three types of biotite are recognised. One of these is a red-brown regional metamorphic biotite. Another is a biotite of similar size to the regional metamorphic type, but varying in colour from brown to a slightly greenish-brown. The third type is a green-brown biotite of very small grain size. The distribution of these biotites is shown in maps 8, 9, 10, 11, and 12.

The green-brown biotite is characteristic of a low grade of regional metamorphism. The rocks in which it occurs are phyllites. The red-brown biotite is characteristic of all higher grades of metamorphism. There is a transition from one to the other via the brown biotite. The transition takes place in the general region of the eastern edge of the Colla Firth belt. The brown biotite of this latter region may be of contact metamorphic or regional metamorphic origin. Nearly all the other rocks containing brown biotite are permeation rocks, and the few other metamorphic rocks which contain brown biotite are mostly near permeation areas.

In most of the rocks the biotite together with the regional muscovite forms a reasonably good schistosity parallel to any visible foliation. However a number of metamorphic rocks occur in which the micas do not show prefered orientation. None of the pelites within the Graven Intrusive Complex have parallel orientated micas and some of the semi-pel-ites also show no prefered mica orientation. Semi-pelites and


REGIONAL METAMORPHISM:
SEMI-PELITES.
• Red-brown Biotite
× Garnet & above.
• Brown Biotite
— Main garnetiferous areas
Permeation dominant
Intrusives
One Mile
MAP 10.


REGIONAL METAMORPHISM:
PELITES.
• Red-brown Biotite
× Garnet & above
o Brown Biotite
One Mile
MAP 9.

pelites show more or less complete lack of prefered orientation of micas in the Colla Firth - Fora Ness area and also in the area of the Scatsta permeation belt. The rocks at the extreme edge of the thesis area at Brae show complete disorientation of biotite. All these cases of lack of prefered orientation of the micas are believed to be due to contact metamorphism superimposed on regional metamorphism.

Biotite in rocks of the type considered here varies systematically only in relation to the quartz content. Figs. 7,8,9,12,13,14, show that biotite has a smaller modal variation in rocks of similar quartz content than most other minerals. The biotite content remains relatively unaffected by variations in the amounts of minerals other than qz. This makes biotite extremely useful as a control for testing the variations in the amounts of other metamorphic minerals. Biotite is only used up in reactions to a noticable extent when considerable quantities of sillimanite are formed.

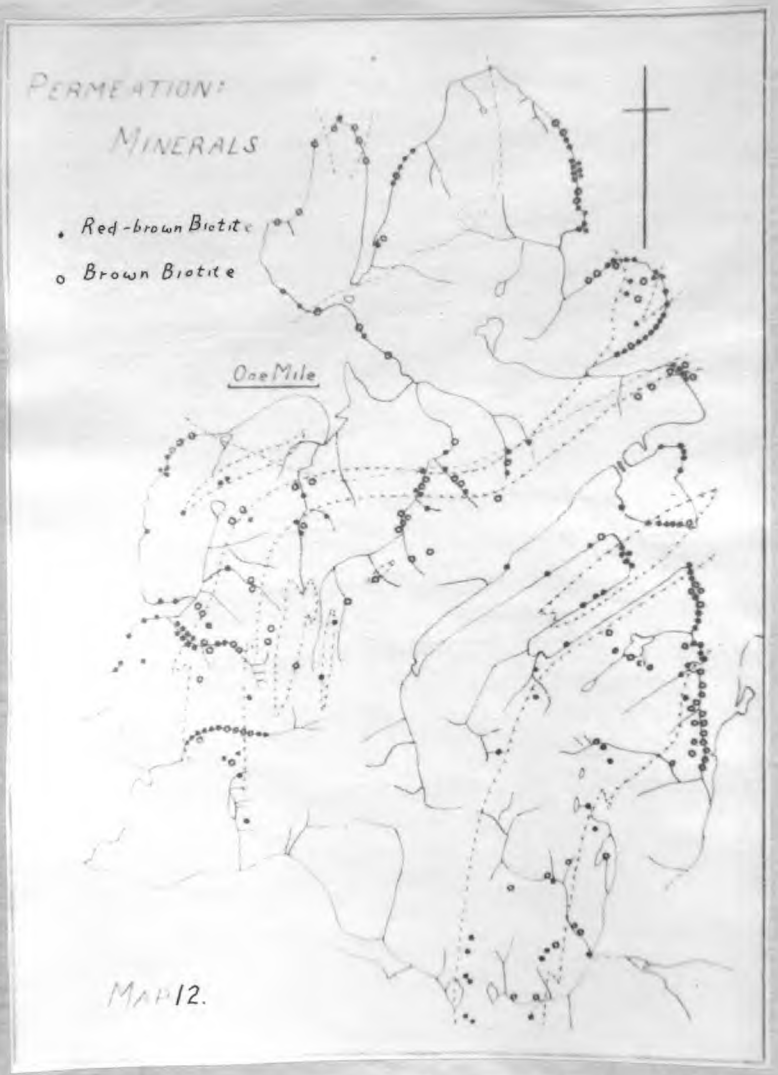
Garnet. Only one type of garnet was recognised. It is similar to the garnet usually found in regionally metamorphosed pelitic to quartzitic rocks. The garnets sometimes contain inclusions of biotite and/or quartz, and are sometimes inclusion free. Some of them have an inclusion rich core in an inclusion free rim. Some are well formed and equidimensional, whilst others are 3-4 times as long as they are broad and follow thin partings of pelite in more quartzitic rock. They show alteration to chlorite aggregates and to fine grained muscovite-biotite

aggregates.

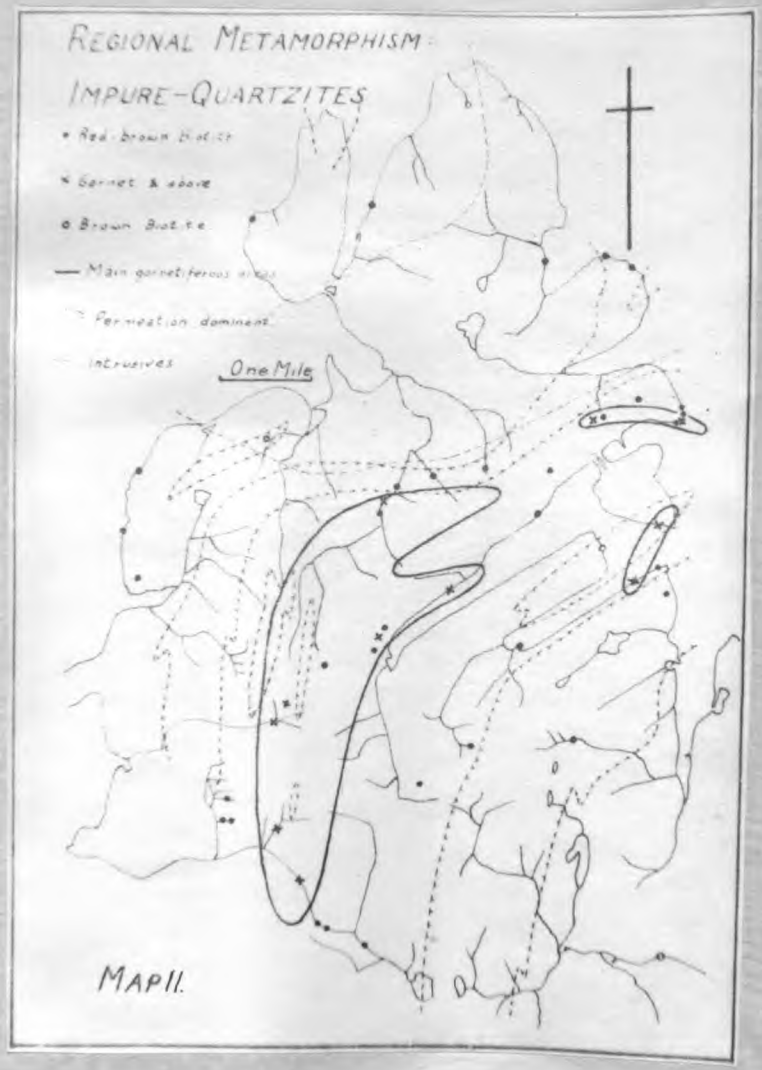
These changes are widespread in the main garnet zone map 8, within the triangle Point of Mulla, Snitteradoo Burn and Voxter Voe, but they are not universal even within that triangle. The changes do not occur elsewhere except as isolated cases. There is no determinable rule of distribution of the different changes. But the change to biotite and muscovite does show some signs of being associated with the permeation. It may be that within the permeation rocks of the Scatsta belt there is a tendency for garnet to breakdown to biotite and muscovite. At the lower temperatures obtaining outside rocks being actually permeated the change is to chlorite.

Occasionally the external form or the inclusions gives evidence that the garnets have been rotated.

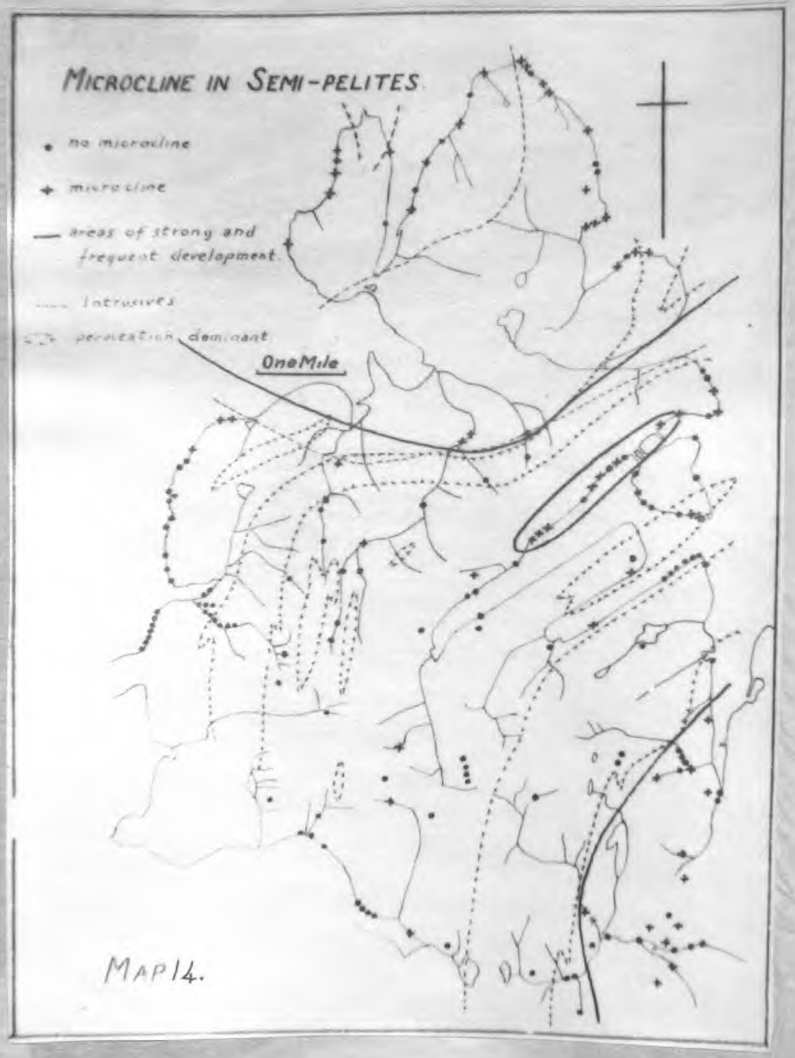
The geographical distribution of the garnets is seen in maps 8, 9, 10, 11, and 13. There is no apparent difference in the distribution in pelites and in semi-pelites. The differences in the distribution of the hand specimens of different rock types are greater than the differences of distribution of garnet within the different rock types. This is illustrated by the fact that 44% of all pelites contain garnet, and 36% of all semi-pelites. But only 20% of all impure quartzites contain garnet. Garnet in impure quartzites is distributed over a smaller area than it is in the other two rock types. This is partly due to the more limited distribution in the


PERMEATION:
MINERALS
• Red-brown Biotite
o Brown Biotite
One Mile

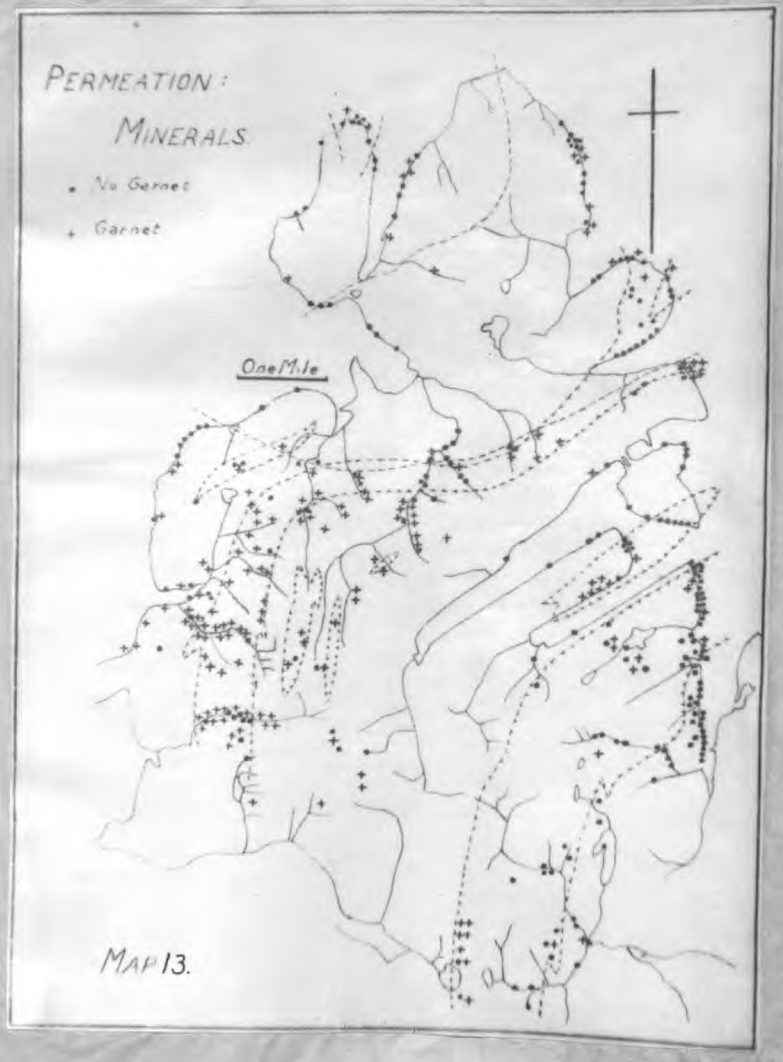
MAP 12.


REGIONAL METAMORPHISM:
IMPURE-QUARTZITES
• Red-brown Biotite
× Garnet & above
o Brown Biotite
— Main garnetiferous area
Permeation dominant
Intrusives
One Mile

MAP II.


MICROCLINE IN SEMI-PELITES
no microcline
microcline
areas of strong and frequent development
Intrusives
permeation dominant
One Mile

MAP 14.


PERMEATION :
MINERALS
No Garnet
Garnet
One Mile

MAP 13.

field of the impure quartzites. It is also due to the fact that with increasing concentration of quartz in the rock, the crystallization of garnet is inhibited. This supression of garnet in quartz rich rocks cannot be easily related to the actual amount of quartz present because impure quartzites very commonly contain flaggy partings and other uneven distributions of the pelitic material. The garnet in the permeated rocks, with the exception of one area near Loch of Voe, shows no relation to the distribution of permeation but conforms very well with the distribution of the garnet in the metamorphic rocks. Thus in this area, garnet in semi-pelites, pelites and in permeated derivatives of these rocks can be considered as having the same geographical distribution. In maps therefore all the garnet information has been combined

When the actual amounts of garnet present in each rock are considered, it is found that there is a complete variation from areas in which much garnet occurs in most of the rocks , via areas in which some garnet occurs in some of the rocks, to areas in which no garnet at all occurs. This gradation makes it difficult to draw a garnet isograd. Contours based on the modal amount of garnet and the number of rocks containing garnet can however be drawn, if a large number of plots are available. In map 8 the inner contour is a line drawn round the area containing all the rocks with more than a certain amount of garnet. The outer contour was drawn outside this round all rocks containing any garnet at all. These

contours are isograds.

Potash-felspar. Potash felspar occurs in 4% of all pelites, in 12% of all impure quartzites and in 33% of all semi-pelites. Potash felspar occurs to some extent in most rock types in the area and appears to be due to many causes. Insufficient potash felspar was found in the pelites and the impure quartzites to be of any use in an investigation of its origin in these rocks. Only potash felspar in the semi-pelites is considered below.

Potash felspar is seen in thin section very frequently as plates twinned in the characteristic microcline fashion. Not all of the felspar shows the twinning to perfection however. Quite often the twinning is very poorly developed and resembles the strain effects shown by quartz. All the potash felspar was identified as microcline

It varies in amount from complete absence to a major constituent. When small quantities are present , the microcline has an intergranular habit. As it increases in amount, it becomes more granular but its low position in the crystalloblastic series is very apparent. Even so it gives the impression of being a relatively late mineral; a mineral which starting to grow in the intergranular surfaces has grown outwards replacing other minerals but still controlled in its form by the old intergranular surfaces.

Plots of microcline against late muscovite show no apparent relationship.

The distribution of microlcline in semi-pelites is shown in map 14. Most of the occurrences are concentrated into three areas. All the rocks containing microcline other than as an accessory mineral occur within these areas. One of these areas is the green-brown biotite zone between Laxo Voe and Swining Voe. A possible origin for this microcline will be mentioned on pps97. Another area is the outcrop of the Graven Intrusive Complex. It is suggested later that this microcline may be related to the crystallization of sillimanite. The third area lies along the north shore of Dales Voe. It will be suggested in the next chapter that some at least of this microcline is due to permeation.

Plagioclase felspar. Plagioclase felspar is a very common constituent of these rocks. Its relation in Ab content and in amount to the bulk composition of the rock in which it occurs will be considered in some detail below, pps96-7. There are relatively few plots shown in figs 28,29 and 30 in comparison to the number of rocks available due to sericitisation (correlated below with dislocation metamorphism) and to the fact that many of the grains do not show Ab twinning. Ab content was determined from the maximum extinction angle of albite twins in the 010 zone - more than 6 readings from each section - in combination with refractive index determinations by comparison with canada balsam and quartz and in cases of doubt by immersion in liquids of known refractive index.

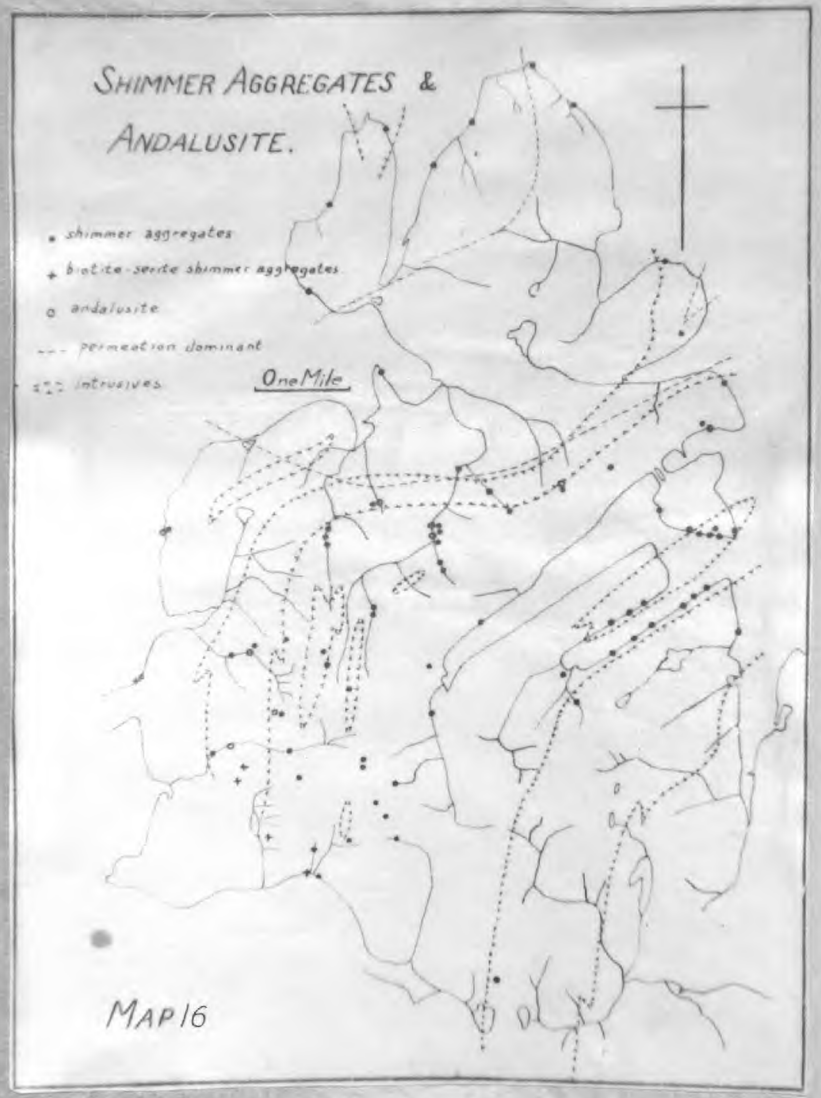
The Ab content shows a very wide range of variation,

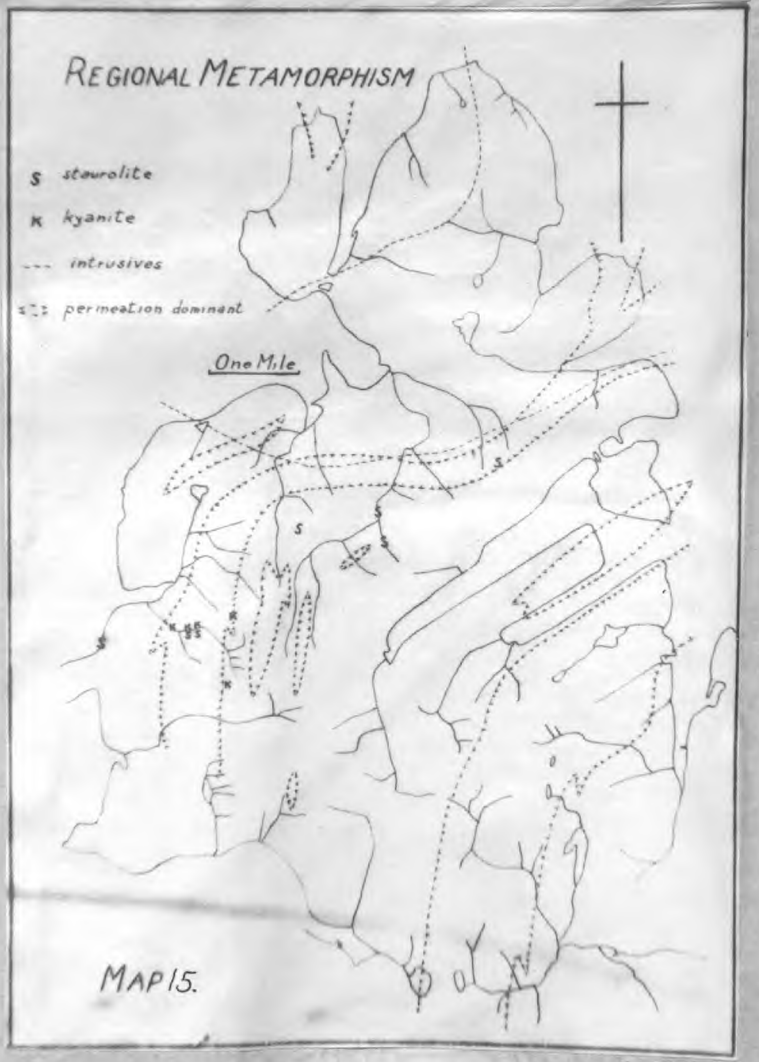
figs. 28,29,and 30, and does not appear to vary with the intensity of the metamorphism. Plots of the Ab content of felspar against the amount of the felspar present do not show a significant distribution. The wide range of Ab content of the felspars in the different rocks is probably related to the composition of the original sediments. Thirty four determinations of felspar in impure quartzites gave an average of Ab86 and varied between Ab60 and Ab100 with one Ab54. One hundred and eight determinations of felspar in semi-pelites gave an average of Ab81 and varied between Ab57 and Ab98. Twenty one determinations of felspar in pelites gave an average of Ab75 and varied between ~~Ab57~~ Ab37 and Ab100. In this latter case the felspars of composition Ab37 occurred as relics inside felspars of composition Ab60, in the rocks on the extreme west of the area just north of Brae. Apart from these the felspars varied between Ab55 and Ab100. If there is any progressive variation in the Ab content with increasing metamorphism in this area such as is described elsewhere, then it is masked by the variation in composition of the felspar itself in rocks showing the same intensity of metamorphism.

Kyanite. Kyanite has been found in 5 rocks; in 2 semi-pelites and in 3 permeated pelites. The geographical distibution of kyanite is shown in map 15.

In three cases the kyanite crystals are surrounded by shimmer aggregate material, though in one of these cases this is only a very narrow rim.

The kyanite in one rock shows itself to have


SHIMMER AGGREGATES &
ANDALUSITE.
• shimmer aggregates
+ biotite-sericite shimmer aggregates
o andalusite
--- permeation dominant
intrusives
One Mile
MAP 16


REGIONAL METAMORPHISM
S staurolite
K kyanite
--- intrusives
permeation dominant
One Mile
MAP 15.

crystallized after the movements which gave rise to the schistosity of the rock, because the individual kyanites contain parallel orientated elongate iron ore grains which outside the kyanite are parallel to the schistosity. The attitude of the iron ore grains to the kyanite lattice varies from grain kyanite to kyanite grain. Furthermore movement in the rocks has rotated some of the grains of kyanite till the iron ore grains are out of alignment with the iron ore grains in the rest of the rock. This latter movement may be associated with the permeation.

Garnets similar to those in the body of the rock are included in the kyanite crystals in one rock.

Staurolite. Staurolite occurs in 17 rocks; in 2 pelites, ~~in 2 semi-pelites~~ and in 5 permeated pelitic rocks. It is rather weakly coloured. It does not show prefered orientation. In three cases the staurolite occurs inside shimmer aggregates. In one rock it forms good crystals. In the other rocks it is present as granules or as aggregates of granules. The geographical distribution is shown in map 15.

Andalusite. Andalusite occurs in 9 rocks; in 2 pelites, in 2 semi-pelites and in 5 permeated pelitic rocks. It shows no prefered orientation. Except in two cases it is surrounded by shimmer aggregate zones, which are generally broad, and against which the andalusite usually has a frayed outline. In one case the andalusite partially surrounds kyanite, both minerals being in the centre of a shimmer aggregate. In two

cases it encloses staurolite crystals, in three cases garnet crystals and in two cases biotite crystals. Its geographical distribution is shown in map 16.

Shimmer Aggregates. These are a common feature of the pelitic and semi-pelitic rocks, and of the permeated rocks. They are almost always pure sericite aggregates; only occasionally are flakes of chlorite to be observed in them. The aggregates vary in shape from good rectangles obviously cross cutting to the schistosity, to long streaks, sometimes folded and sometimes anastomosing. Kyanite , staurolite, and andalusite relics are to be seen in aggregates in different rocks. The latter in particular appear to be breaking down into shimmer aggregates. The aggregates also contain garnet and sillimanite. These latter shown no signs of instability. Fibrous sillimanite can often be found both inside and outside the aggregates, especially in the Colla Firth area, in such a manner that it is obvious that the needles are stable and always have been stable in the presence of shimmer aggregate.

Shimmer aggregates occur in 34% of pelites, in 16% of semi-pelites and not at all in the impure quartzites. This close correlation between the amount of the mineral present and the composition of the parent rock probably indicates that the original mineral was of metamorphic origin. The late muscovite , which is believed to be partially of metasomatic origin, does not show such a close correlation with the composition of the parent rock, and in addition may develop in such

quantities that it forms the bulk of the rock. Shimmer aggregates never develop to such an extent as this.

The distribution of shimmer aggregates is shown in map 16.

It is usually not possible to say with any certainty from what mineral or minerals the shimmer aggregates have developed. But it is believed that they are mostly after andalusite, because:-

1 if the aggregates were after kyanite, then this kyanite would have occurred in rocks both inside and outside the garnet zone. Such a distribution has not so far been described.

2 all gradations between stable andalusite and minute grains of andalusite present in the centres of aggregates occur. Staurolite and Kyanit usually have only narrow rims of shimmer aggregate. In one rock kyanite occurred in the centre of a large shimmer aggregate. But this kyanite was almost completely surrounded by a later growth of andalusite, which had therefore formed the bulk of the aggregate.

3 staurolite and kyanite are occasionally preserved and stable in andalusite which is being attacked by late shimmerisation.

4 the aggregates appear to be the products of later event than the regional metamorphism, because of their occasionally preserved cross cutting outlines and their sharp idiomorphic nature. The contact metamorphism by the permeation would be expected to give rise to the anti-stress andalusite rather than

the stress kyanite.

More is said on this aspect later, pps 60.

Sillimanite. Three types of sillimanite are recognisable on the area. It occurs as coarse crystals, as scattered fibrolite needles and as matted masses of fibrolite, which in this thesis are called fibrolite mats. The distribution of the types is shown in map 17.

The coarse variety is confined to the areas of the Graven and the Brae intrusives. It is seen in thin section as blades or as characteristically diamond shaped cross sections or as large crystals grading outwards into fibrolite rods in parallel growth.

The fibrolite mats have a similar distribution, but they also occur at three places along the west edge of the Colla Firth permeation belt. These fibrolite mats are solid mats of fibrolite, the individual needles of which have in many cases no prefered orientation within the mat. The mat itself is often elongated parallel to the general direction of the schistosity or foliation of the rock. The mats characteristically have a yellowish colour. They are often associated with biotite and may contain biotite relics. It seems that the biotite is used up in the production of these mats.

The fibrolite not forming mats occurs as groups or streaks of separated needles. The individual needles occasionally show a complete lack of prefered orientation, but the

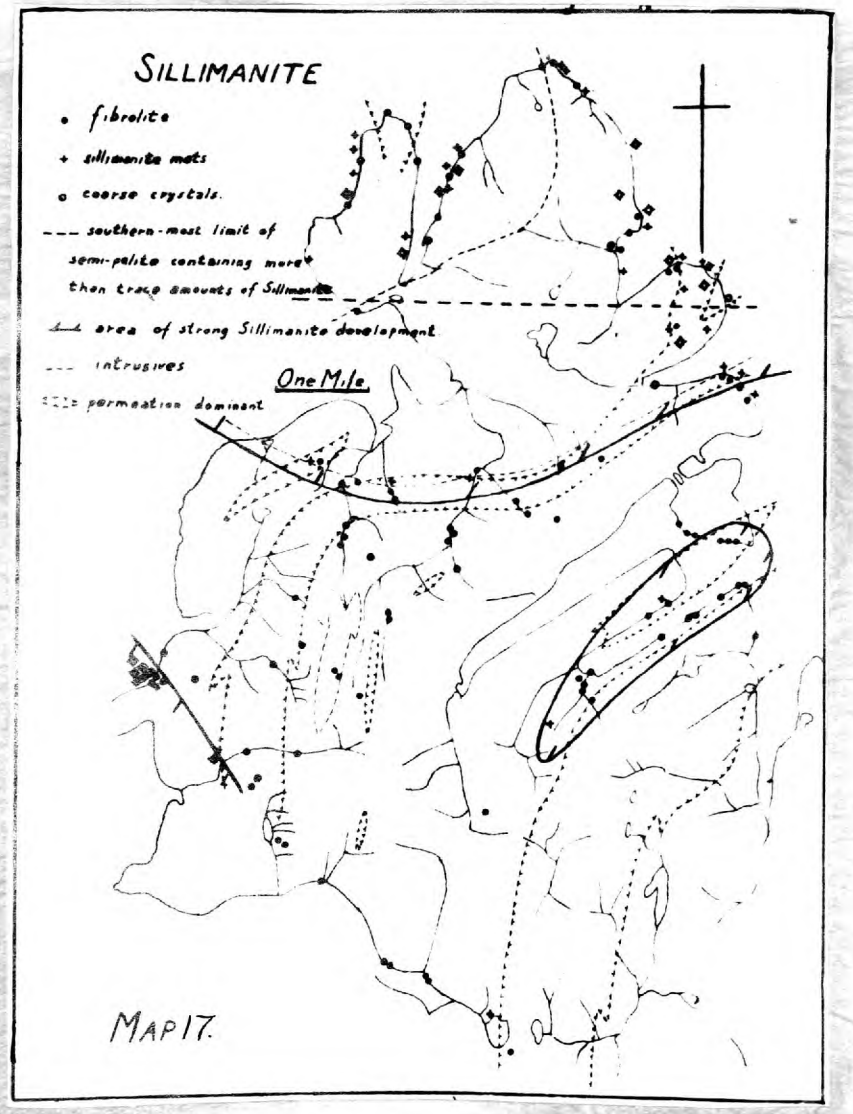


Photo 7.
Polygonal fold.
×13.



characteristic occurrence is as streaks of parallel orientated needles following the schistosity of the rock or some definite though tortuous direction.

There is a complete gradation in aspect from fibrolite needles to fibrolite mats and to coarse crystals. The different varieties of sillimanite probably represent differences in intensity of metamorphism. The fibrolite is a weaker developemnt of sillimanite than are the fibrolite mats. The fibrolite grows in all minerals, but it is most common in the late muscovite. It shows very little association with the biotite. Plots of fibrolite against regional muscovite in pelites and in semi-pelites, figs, 19 and 20, show that whilst most of the fibrolite occurs in rocks in which ~~there~~ regional muscovite is absent, some occurs in rocks in which there is a reasonable amount of regional muscovite. Figs. 10 and 11 show that fibrolite mats and the coarse sillimanite are almost confined to rocks in which there is no regional muscovite and they occur in greater amounts in each rock than does the fibrolite. The above facts suggest that sillimanite is formed from regional muscovite till the muscovite is used up, and then it is produced from biotite. During intense metamorphism the biotite reaction may take place in the presence of muscovite. In other words, the biotite reaction may take place at a higher temperature than does the muscovite reaction. Coarse sillimanite may have a higher temperature of formation than the fibrolite mats, because it has a more restricted field

of occurrence than the latter. Map 17 shows that the coarse sillimanite occurs only within the area of influence of the two intrusive complexes, but not otherwise near the permeation belts. This restriction in geographical distribution may be due either to the contact metamorphism by the permeation being less intense than the contact metamorphism by the intrusives or to some other factor.

Another feature of interest is brought out by map 17. In this map is shown a line to the south of which only very small amounts of sillimanite develop in the semi-pelites. There are very few pelites north of this line, therefore the results of the metamorpgôsm of the pelites under metamorphic conditions which produce large amounts of sillimanite in semi-pelites are not known. (In Galback Ness a solid mass of sillimanite a foot or so across was found). Conditions which produce large amounts of sillimanite in the pelites of Delting produce very little in the semi-pelites. Therefore the development of sillimanite is closely related to the bulk composition of the rock in which it grows. This conclusion suggests that sillimanite may develop from the material already in the rock. It may during its development eject material, e.g. potash, from the rock. Or it is possible that in the area of h the intrusives muscovite+biotite+quartz combine to give sillimanite+microcline, since the area of the intrusives is an area of abnormally high concentration of microcline. But the intrusive rocks themselves are all quite rich in microcline, which

always shows a replacement relation to the plagioclase, pps 142 152 and which may have the same origin as the microcline in the semi-pelites. At the lower intensity of metamorphism at which fibrolite is produced it is possible that the potash goes to sh shimmerise the andalusite.

METAMORPHIC TEXTURES.

The fabric of these rocks is mentioned above under " muscovite" and "biotite". It was also dealt with on pps.22-6. However certain aspects have to be considered here.

As described on pps 23-4 and on map 6 a common feature of certain areas is a crinkle-like lineation in the mica schists. When examined in thin section these folds are seen to be more or less well developed "polygonal folds". At first sight the micas, both muscovite and biotite, appear to be bent into beautiful smooth curves. Closer examination shows however that the degree of strain is slight. The micas are all of such a length and occupy such a position that they do not have to bend. In some examples the polygonal nature of the fold is more obvious, photo 7. Since slight strain of the micas is a feature of the area as a whole, the relatively slight strain in those forming the polygonal folds could be much later than the folds, and be associated with the dislocation metamorphism and with the strain of all the other micas in the area. The strain is far too small to account for the folding.

Therefore this lineation and the microfolding

which causes (ti) are believed to be para-crystalline. The lack of strain shows that it cannot be post-crystalline. The presence of preferential orientation of the micas shows that the folding cannot be pre-crystalline, whilst the fact that re-crystallization elsewhere in the area invariably results in the loss of preferential orientation by the micas indicates that the mica has not grown later mimetically in the fold.

The lineation formed by this folding has a very complicated arrangement in the field, in contrast to the fluting and the β-lineations. The folds could have been formed at any time in the rocks history, after the establishment of the schistosity. The crystallization under whose influence they were formed was therefore later than the crystallization of the B-tectonite fabric, and was probably related to the permeation episode. Out of some 34 rocks which show this lineation only 5 contain late muscovite and three of those were involved in very strong dislocation metamorphism. The relative immunity from this movement of rocks containing late muscovite is perhaps due to the movement occuring after the late muscovite had developed and therefore had strengthened the rocks.

Late movement in the rocks of an intense penetrative character are indicated by streaking out and even folding of shimmer aggregates. As this is most noticable and most intense in the permeated rocks it is most probably due to movement associated with the permeation. But signs of movements associ-

/ iated/

iated with the permeation are not very common and are localised.

INTER-RELATIONS OF THE THREE METAMORPHISMS

There have been three main phases of constructive metamorphism in the area.

The metamorphism which produced the fabrics of the B and β-tectonites was characterised by a wide continuous distribution and by penetrative movements. This is the regional metamorphism and it has destroyed all evidence of previous metamorphisms if any had taken place. Some sedimentary structures have however been preserved. Also there are preserved a number of tectonic structures which may be contemporaneous or earlier. It is very probably the earliest metamorphism.

The Graven and the Brae Intrusive Complexes have metamorphosed their included and surrounding rocks.

The regional metamorphism and the contact metamorphism by the intrusive complexes are obvious in the field. The former is characterised by the tectonites and the latter by the presence of large quantities of sillimanite. On the other hand the contact metamorphism of unpermeated regional metamorphic rocks which are included in or alongside the permeation belts is not readily recognisable in the field, but can be detected in thin sections.

The metamorphisms have different and characteristic geographical distributions. The Inclusion Granite is younger than the Scatsta permeation belt, and the permeation areas in the

in the Calback and Mio Ness areas, since the granite cuts these permeation rocks in an intimate fashion. Each of the minerals described on pps.33-49 has a characteristic distribution and the age relations of some are known. A comparison of all these data makes it possible to relate the minerals to the metamorphisms which produced them, and to arrange the whole into chronological order.

As shown in map 8 green-brown biotite, red-brown biotite garnet, staurolite, and kyanite form more or less concentric zones, which cover the whole area. These minerals are the characteristic minerals of the tectonites and of rocks which may once have been tectonites. Therefore they are regional metamorphic minerals and the zones are zones of regional metamorphism. Some of the zones can be traced through both the permeation belts and through the Graven Intrusive Complex. Some zonal minerals have become involved in changes within the area of the contact metamorphisms. The biotite for instance has changed its colour sometimes and also its orientation sometimes.

The regional metamorphism and the contact metamorphisms cannot be related phenomena, since the zones of regional metamorphism can be traced through both the permeation belts and the contact metamorphic areas. The metamorphisms cannot have happened at the same time; it is impossible to imagine such fundamentally different changes taking place without interference. The effects of permeation die out but do not grade into regional metamorphic effects, they are often superimposed

on the regional metamorphic effects. The first signs of permeation seen in thin section (net-texture, see pps. 112/113) are obviously not regional metamorphic phenomena. They appear to have been superimposed on the regional metamorphism. If the permeation belts had been present before the regional metamorphism than it is unlikely that the relatively fragile net-texture which is to be found so far outside the main development of the permeation would have been preserved in rocks which show evidence of strong penetrative movement. The distribution of the microscopic net-texture beyond the limits of the macroscopic signs of permeation shows that the present belts are not remnants of larger belts being broken down by regional metamorphism later than the permeation. Perfectly regional metamorphic looking inclusions of all sizes can be found in areas of all degrees of permeation. The regional metamorphism could not act on small inclusions completely surrounded by permeation rocks which have preserved a characteristically different texture. As will be desctibed later the calcareous rocks have suffered high grade metamorphism both within the areas of permeation and extending out into regional metamorphic areas. These very sensitive rocks would have been very easily re-metamorphosed to the lower ~~grade~~ regional metamorphic grade, if the regional metamorphism had occurred after the permeation. The permeation and its associated contact metamorphism must have occurred after the regional metamorphism.

The contact metamorphism by the Inclusion

Granite is later than the Scatsta and the Mio Ness and Calback permeation belts. The Inclusion granite cuts lamprophyres. Similar lamprophyres cut the Colla Firth belt. Therefore the Inclusion Granite is probably later than the Colla Firth permeation as well. The Brae Intrusive cannot be dated.

The three metamorphisms are therefore in order of increasing age - contact metamorphism by igneous intrusion, contact metamorphism by permeation, and regional metamorphism. They are placed in that order because so arranged they best explain the facts which are known about them. The age relations of the different permeation belts are more conveniently discussed later.

THE METAMORPHISMS.

Before proceeding to consider the individual metamorphisms it is necessary to consider the theoretical concept of zones of metamorphism. From the technique of zoning metamorphisms by the distribution (presence or absence) of individual minerals has arisen the concept of isograds. Isograds or isothermals are lines of equal temperature of metamorphism (Harker, 1939, p166) by definition. It is reasonable to assume that the line marking the limit of the first development of a mineral, or for that matter a line of equal concentration of a mineral is an isograd, always providing that the stress effects or some other factor have not varied over the area considered. Such assumptions have been made by innumerable workers.

The garnet isograd has been most frequently used. In this thesis area the presence or absence of garnet in 1,000 rocks has been investigated. For the purpose of garnet 900 of these rocks, semi-pelites and pelites, can be considered as isochemical, (see also ~~Tilley~~ Elles and ~~Elles~~ Tilley, 1930, pps 621). The relative amounts of garnet in 350 rocks (including 300 semi-pelites and pelites) have been considered.

It was discovered that there is complete gradation between areas in which most of the rocks of appropriate composition) contain garnet and areas in which none of the rocks contain garnet, but are otherwise the same. Complete gradation was also found between areas in which individual handspecimens of rocks contain much garnet, and areas in which individual handspeciment contain no garnet. As one moves out from areas rich in garnet, so the garnet in each rock gets less on the average and the number of rocks containing garnet get less. Both changes can also be found within a garnet rich area by careful selection of specimens . There is no line at which garnet suddenly appears.

It is possible to contour the garnet occurrence by plotting on a map all garnet modes above or of a certain value, and then drawing a smooth line round them. Such lines appear to be closely related not only to the garnet amount in individual rocks but also to the number of rocks containing garnet in any one area. The contours are therefore probably parallel

to isograds. But they are not parallel to the line at which garnet first appears, which follows a somewhat tortuous course, depending largely on the selection of specimens in the field.

It is obvious that the garnet increase within the rocks and in the number of rocks containing it is a statistical one. The lines at 90° to the contours are lines of statistical increase. The occurrence of garnet in these rocks as revealed by this investigation, is therefore partly controlled by chance. Garnet cannot develop below a certain grade of metamorphism, but above this grade it still does not always occur in rocks of suitable composition. The contours are therefore lines of equal probability of occurrence of garnet. The chance element may be introduced by the method of collection. If the garnets are separated by greater and greater distances of matrix towards the outside of the garnet area, then the chance of collecting specimens with no garnet would increase in the same direction. But in the centre of the garnet area, whilst some rocks are very rich in garnet other rocks are still garnet free. It is probable that chance as well as the metamorphic grade controlled the growth of the garnets.

The chance element in mineral growth is possibly of some importance in metamorphism. It is a factor that is to be expected since the physics of atoms themselves is largely the study of probability. Probability may be a very variable factor The probability of development of garnet increases with the

increasing metamorphic grade. The relatively unpredictable behaviour of staurolite may be simply due to staurolite having a lower probability of occurrence under suitable conditions than does even garnet. On the other hand biotite under suitable conditions appears to have a very high probability of occurrence.

Regional Metamorphism. The minerals crystallizing in this metamorphism are quartz, felspar, muscovite, biotite, garnet, staurolite, and kyanite. The first four minerals show no evidence of their age relations. Garnet sometimes contains identifiable inclusions of quartz and of biotite and is itself sometimes included in staurolite and in kyanite. This may indicate that staurolite and kyanite grew after garnet.

Map 5 shows that the thesis area can be zoned on a mineralogical basis by these minerals. The outer zone is called the green-brown biotite zone. It is characterised by very fine grained phyllitic rocks with β-tectonite fabric. The micas are green-brown biotite and muscovite, both occurring as very small flakes. This zone is represented only in the extreme south-east corner of the thesis area. The rocks to the immediate west of the green-brown biotite zone are of normal grain size and fabric but still contain brown or greenish-brown biotite. It is not clear whether this change is due to the regional metamorphism or to contact metamorphism by the permeation belt.

The next zone to the west of the green-brown biotite

zone is the red-brown biotite zone. It is characterised by the presence of ~~re~~ red-brown biotite, muscovite, quartz and felspar. There are one or two isolated occurrences of garnet. These garnets may represent local developments of the garnet zone, or they may be an unusual contact effect of the permeation.

Within the red-brown biotite zone is the garnet zone The mineral assemblages of this zone are similar to those of the red-brown biotite zone and in addition frequently contain garnet. Two contours have been drawn on the basis of the garnet concentration and distribution. These contours delimit an outer garnet 1 zone and an inner garnet 2 zone. The outer limit of the garnet 1 zone is for all practical purposes the garnet isograd.

Within the garnet 2 zone are a number of occurrences of staurolite. They are too few in number and too widely scattered to be made the basis for a staurolite zone.

Also within the garnet 2 zone is a small area containing 5 known occurrences of kyanite. The rocks of this kyanite zone contain muscovite, biotite, quartz, felspar, garnet, staurolite and kyanite.

The green-brown biotite, red-brown biotite, and garnet zones detailed above appear to apply equally well to rocks of pelitic and of semi-pelitic composition, since no differences were detected in the geographical distribution of the zone minerals, which could not be explained by differences in the collection of specimens.

The distribution of impure quartzites is geographically restricted, map 3. The one occurrence found in the green-brown biotite zone had an assemblage normal for that zone. The same was the case with impure quartzites in the red-brown biotite zone. All occurrences of garnet were within the garnet areas of the other rocks, but it appears that the amount of pelite material in an impure quartzite and more particularly the nature of its distribution within the rock exercises a controlling influence on the crystallization of garnet in impure quartzites, within the garnet zone of the more pelitic rocks. Neither kyanite nor staurolite were found in impure quartzites.

Contact Metamorphism by the Permeation Belts.

Although there are several different types of permeation belt, the only differences observed in the contact effects are of degree. It is therefore convenient to consider the metamorphisms belonging to the different belts concurrently.

All the regional metamorphic minerals which happen to occur in the rocks being contact metamorphosed by the permeation remain qualitatively if not quantitatively stable, except perhaps kyanite and staurolite, the few discovered occurrences of which show some signs of re-crystallization to shimmer aggregates. New mineral types crystallizing under the influence of this metamorphism are believed to be andalusite, shimmer aggregates, sillimanite and late muscovite. These minerals are allocated to this metamorphism partly on the textural (age) relations to other minerals and partly on the evidence of the geographical

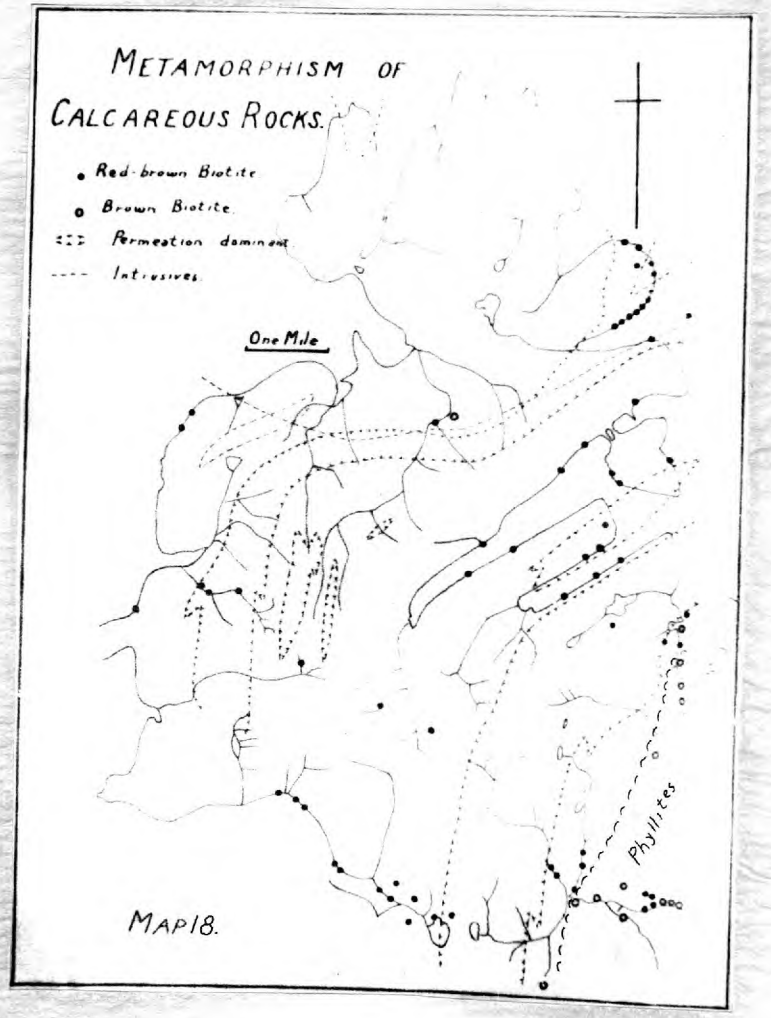
distribution.

The shimmer aggregates are believed to have been derived from andalusite, for reasons given above. The distribution of the shimmer aggregates and the distribution of sillimanite (maps 16 and 17) show a strong resemblance when allowance is made for the very strong development of sillimanite in the areas of the igneous intrusives. Both of these distributions appear to be similar at first sight, to the distribution of minerals allocated to the regional metamorphism, map 8. However as map 17 shows , the sillimanite concentration is greater at Colla Firth than in the Scatsta region, the mineral occurring only in mere traces in the rocks of the latter region. The same consideration applies to map 16 for andalusite. Most of the pelites in the Colla Firth district contain much shimmer aggregate. Many pelites in the Scatsta belt contain no shimmer aggregate, and when it occurs it is on the average less abundant than in the Firth rocks. It is concluded therefore, that the ~~considerations~~ concentrations of these minerals within the individual rocks are related to the permeation belts , whilst the geographical distribution of the minerals is more nearly related to the regional metamorphism.

The distribution of the sillimanite in the Colla Firth area is very similar to the distribution of the shimmer aggregates. In the Scatsta belt, however the sillimanite has a more restricted occurrence. The sillimanite may have there-

forecrystallized (have) at a higher temperature than the mineral replaced by the shimmer aggregates . But it is not possible to decide when the sillimanite crystallized relative to this mineral or to the shimmer aggregates themselves. The shimmerisation may have taken place as a result of reactions giving rise to the sillimanite which would explain the immunity of the sillimanite itself to shimmerization. Or the shimmerisation may have occurred later during the crystallization of the late muscovite when the sillimanite was again immune to potash attack. The andalusite relics occur in the area of low sillimanite and low late muscovite development. The sillimanite portrays the fabric of the rock well. It is not only concentrated in bands parallel to the foliation and the schistosity of the rocks but the individuals are also well orientated. The shimmer aggregates , however, often show cross-cutting attitudes to the schistosity, thus supplying evidence that the original mineral crystallized later than the development of the tectonite fabric, photo 8.

The late muscovite is shown by its distribution to be most strongly concentrated in the Colla Firth - Fora Ness area. It crystallized later than either the sillimanite or the andalusite or the shimmer aggregates. Thus it sometimes encloses and even partially replaces shimmer aggregates. And streaks of orientated sillimanite needles, running parallel to the foliation of the rock right across the section, are



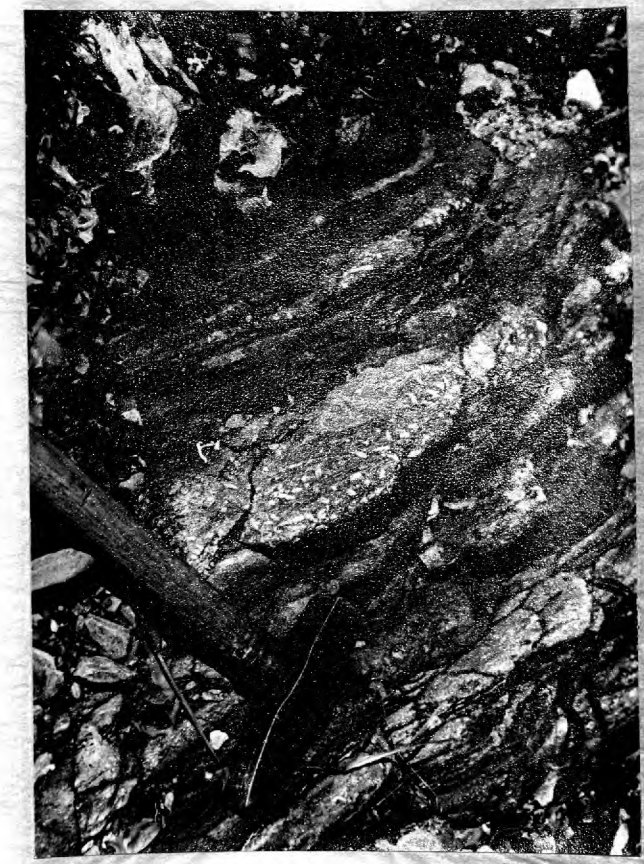


Photo 5. Shimmer aggregates after andalusite, Fora Ness.

undisturbed by large plates of late muscovite, which have grown with their cleavages at all angles to the foliation.

Most of the evidence for this permeation contact metamorphism occurs in pelitic rocks, and the metamorphism itself is most strongly developed in the Colla Firth area. Yet only in two of the pelitic rocks of this area does the sillimanite development compare with that in the semi-pelites of the Graven Intrusive Complex. The intensity of metamorphism by the igneous rocks is therefore considered to be greater than the intensity of metamorphism by the permeation rocks. This may explain the fact that only a few rocks, and those all at Colla Firth, show no prefered orientation of the biotite. On the other hand the movements giving rise to the small folds and contortions of the permeation rocks may have preserved the original orientation.

Contact Metamorphism by the Igneous Complexes.

The Brae Igneous Complex. It is not possible to date this complex at all closely on the evidence available. Its contact with the metamorphic and permeated rocks of the thesis area is very badly exposed. The contact metamorphism is only apparent in the field in one exposure, on the coast just north of Brae. Thin sections show that this metamorphism extends along the entire contact. The emplacement of the complex is later than the regional metamorphism.

The rocks are very rich in sillimanite and garnet on the coast north of Brae for a few yards along the beach.

From map 17 it is seen that the sillimanite development continues along the contact although it decreases in amount to the south. All sectioned rocks from close to the contact contain at least a trace of sillimanite. The high concentration of garnet is not repeated in contact metamorphic rocks elsewhere than at Brae. This garnet probably belongs to the regional metamorphism rather than to the contact metamorphism. The basic labradorite felspar found in some of the rocks from this exposure may be due to contact metamorphism however, as no felspar of this composition was found in any of the regional metamorphic rocks. From map 16 it is seen that this contact metamorphic belt is also characterised by biotite-sericite shimmer aggregates. In these aggregates the biotite varies from normal size to the same size as the sericite and is present in considerably greater proportions. The aggregates have a very indefinite shape. In some occurrences they appear to be associated with chlorite. The biotite in the aggregates is orientated parallel to the biotite in the rest of the rock. These aggregates occur no where else in the thesis area. Their origin is obscure. In the Brae rocks exposures the rocks show no preferred orientation of the micas, elsewhere on this contact zone the rocks have the normal regional metamorphic fabric.

The decrease in intensity of metamorphism along the contact is probably correlated to the decrease in grain size of the intrusive rocks in the same direction. The nearest

exposed intrusive rocks to the contact at Brae are coarse grained plutonic-looking ~~rocks~~. From Wethersta to Mangaster Burn the intrusive rock is relatively fine grained, and is almost doleritic in appearence. This change in grain size of the intrusive rocks takes place suddenly at a contact within the complex.

Graven Intrusive Complex. This complex also shows multiple intrusion, but no differences were observed in the contact effects of the Pegmatite Granite and the Inclusion Granite. Therefore the contact metamorphism is considered as if it were due to a single intrusion.

This metamorphism is chagacterised in the field by an abundence (in places) of sillimanite. All the pelitic rocks examined and some of the semi-pelitic show no preferred orientation of the biotite. The shimmer aggregates scattered through the area may be due to previous events. Most of them are associated with occurrences of permeation.

THE METAMORPHISM OF CALCAREOUS ROCKS.

Map 3 shows that these rocks are not as well distributed over the area as those previously described. Their reactions to metamorphism are more complex than those already dealt with, a circumstance due not only to the fact that two more components have been added to the system, but also to the special nature of one of them - CO_2. The calcareous rocks appear to be very much more sensitive to metamorphic changes than are the pelitic rocks. There is a greater tendency for

the effects of earlier metamorphisms to be obliterated by later metamorphisms. Further more, certain diapthoretic changes have taken place whilst the rocks were cooling down after a phase of constructive metamorphism.

The calcareous rocks show a very wide range of variation in composition. The 270 odd assemblages of which approximate modes were made can be sorted into classes on the basis of their quartz and carbonate content. The assemblages can be divided into those which contain quartz but no carbonate, carbonate but no quartz, neither quartz nor carbonate and both quartz and carbonate. The assemblages are divided fairly equally between these four classes. These classes may be further sub-divided. The quartz and carbonate assemblages may be split into those with more quartz than carbonate and those with less quartz than carbonate. The classes containing quartz only or carbonate only may be less accurately divided on the basis of the quartz or carbonate content of the individual rocks. The assemblages are not equally divided equally among these sub-classes.

The four primary classes into which the calcareous rocks were divided in the above paragraph are best considered as the four parts of a triangular compositional diagram of which pelite, quartzite, and limestone respectively are the components at the three corners. When this is done, assemblages on the borders of a class are seen to be more accurately placed in the triangle than are assemblages falling within a class.

This classification is not meant to be an accurate one. It cannot be accurate without modes and chemical analyses. But it is sufficiently accurate in its present state to show the relation in composition between all the metamorphosed sedimentary rocks found in the thesis area. It can be used to determine the compositional field of stability of a mineral in rocks of the same grade.

This classification and the use of a pelite-quartzite limestone triangle with which it is intimately bound up, is used throughout this thesis as a mental aid for keeping trace of the interrelations of the different isochemical types of metamorphosed sedimentary rocks found in Delting. The complete gradation in composition found between all the sedimentary types makes such a concept essential.

METAMORPHIC MINERALS.

Biotite. The colour of this mineral is rather variable. It is generally lighter in colour than it is in the pelite-quartzite rocks. In some of the limestones it becomes sufficiently pale to be considered as phlogopite.

Biotite occurs in rocks falling in all parts of the pelite-quartzite-limestone triangle. It is also wide spread geographically, map 16. Map 16 shows the close correlation between biotite colour in the calcareous rocks and in the pelitic rocks.

Chlorite. Apart from the normal green chlorite, which is almost

certainly derived from biotite during dislocation metamorphism, another mineral provisionally identified as a chlorite was found in 16 rocks. These rocks are all relatively quartz poor, and may or may not contain carbonate. This mineral may be colourless or faintly green and pleochroic by normal light in thin section. When colourless it may easily be mistaken for muscovite, except that it has a very much smaller bi-refringance; first order yellow is characteristic. The colourless types are uniaxial negative and the green types are uniaxial positive.

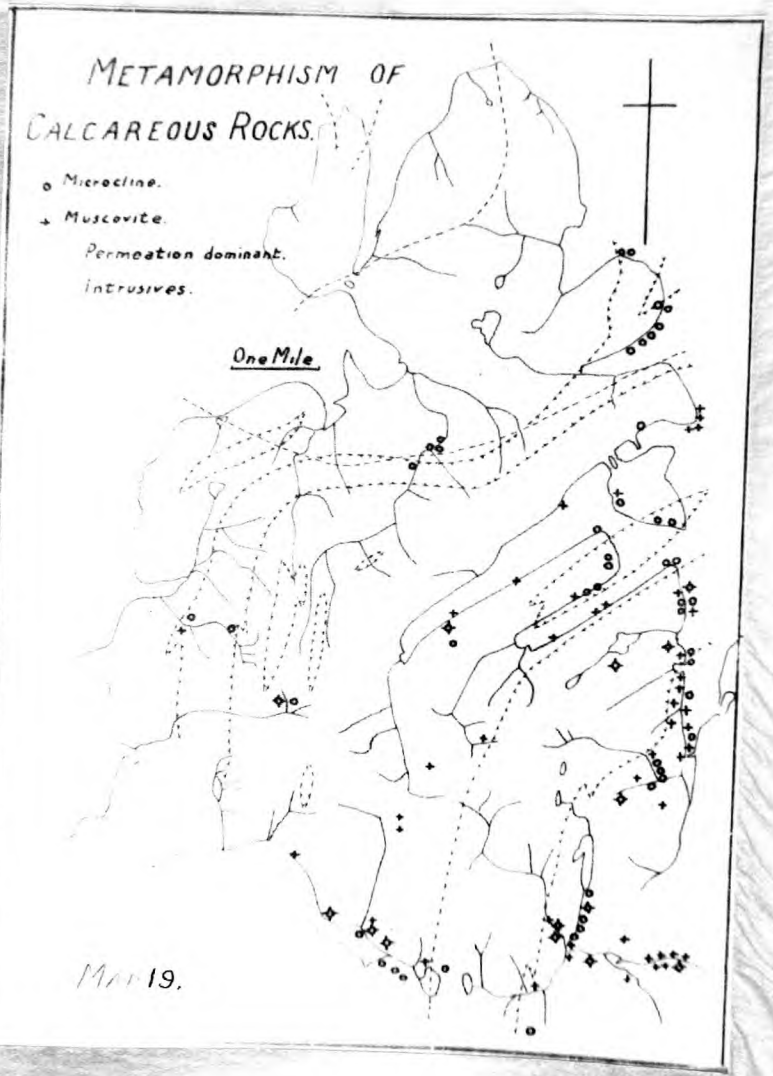
Muscovite and Microcline. Both these minerals are widely distributed over the area and occur in calcareous rocks of all compositions, map 19.

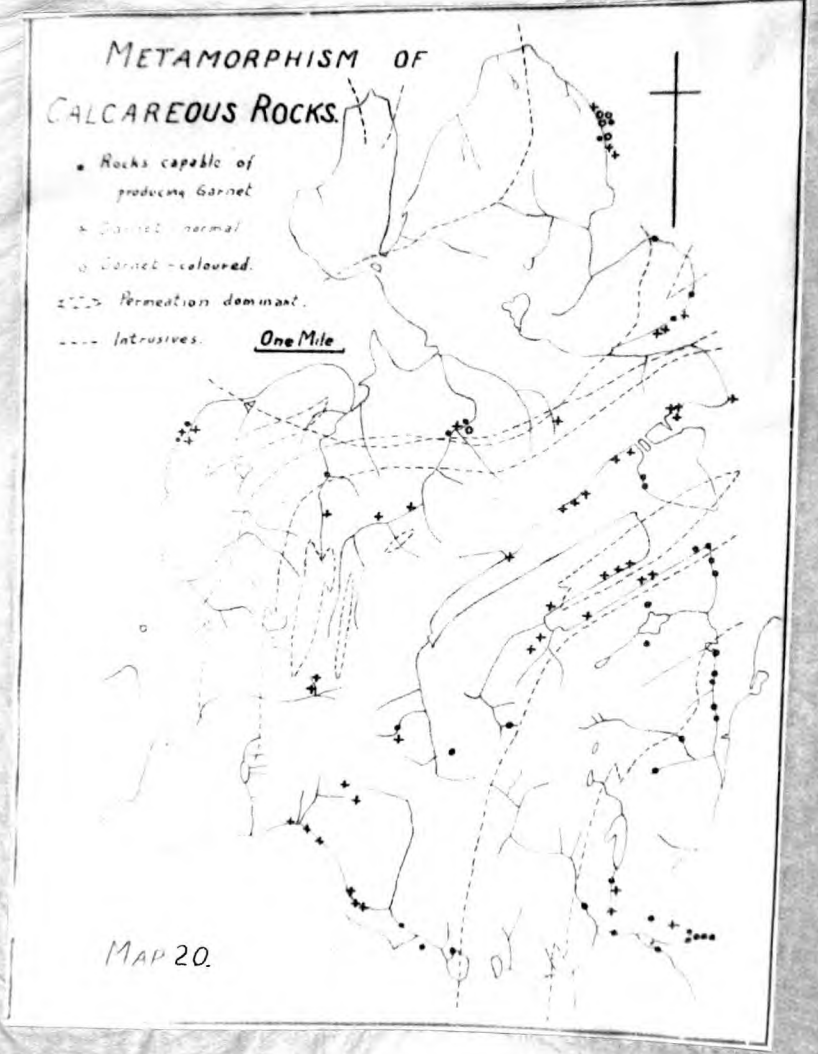
Their most notable feature is the inverse relation which they bear to one another, see fig. 16. This is interpreted as meaning that with increasing metamorphism muscovite changes to microcline. The microcline is mostly developed in pyroxene areas but has a wider distribution than pyroxene. It may therefore form at a lower grade of metamorphism than does the pyroxene.

It should be noted that in the calcium poor calc-silicate rocks microcline frequently shows the replacement relation to plagioclase which it shows in so many of the other rocks of the area.

Plagioclase. Plagioclase has a wide geographical distribution and occurs in calcareous rocks of all compositions.

The felspars show a very wide range of composition.


METAMORPHISM OF
CALCAREOUS ROCKS.
o Microcline.
+ Muscovite.
Permeation dominant.
Intrusives.
One Mile
MAP 19.


METAMORPHISM OF
CALCAREOUS ROCKS.
• Rocks capable of producing Garnet
+ Garnet - normal
o Garnet - coloured.
Permeation dominant.
Intrusives.
One Mile
MAP 20.

They vary from Ab30 to Ab100 but most lie between Ab30 and Ab70. So far as could be determined the albite composition of the felspars did not change with increasing metamorphism, fig. 21. There is evidence, however, fig. 22, that the amount of felspar increases steadily with increasing regional metamorphism; the zones of regional metamorphism being defined by the pelite-quartzite series as described above. But in rocks which contain pyroxene , and have ,as will be shown later, pps 71 , therefore suffered contact metamorphism, the amount of felspar decreases.

Garnet. Two kinds of garnet are seen in the calcareous rocks. The most common kind has a high relief and is a faint pink in thinsection and red in the handspecimen. It is indistinguishable from the garnet in the pelitic rocks. The second garnet has a noticably weaker relief and is a brown colour in thin section and in the handspecimens. The distribution of these two types is shown in map 20.

The low relief garnet is probably calcium rich; a grossularite garnet. It is confined in its distribution to the area of the igneous intrusions. For this reason alone it would be reasonable to assume that it was of relatively late crystallization. In one thin section its late development is obvious. In this rock, in which a very great development of tiny garnets of this type has taken place, the areas of strongest development are seen to be based on partially healed fractures crossing the foliation at 90°.

The red garnet is believed to approximate in composition to the garnet of the pelitic rocks, not only because of its identical aspect, but also because of its association with certain assemblages. The quartz-carbonate content of the assemblages of the 36 rocks containing this garnet show that 32 of them fall on the quartzite side of a line drawn from pelite to 50quartzite:50limestone on the pelite-quartzite-limestone triangle. Three of the exceptional rocks occur in the region of the Graven Intrusive Complex on the north shore of Firth Voe.

In map 20 the plots called "rocks capable of producing garnet" refer to assemblages lying in the part of the pelite-quartzite-limestone triangle which contains most of the garnetiferous rocks. This map shows that this garnet is somewhat more widely distributed than is the garnet of the pelitic rocks. When this fact is taken into account the geographical distribution of the garnet of the calcareous rocks is seen to be very similar to that of the garnet of the pelitic rocks.

But for one occurrence it might be assumed that this garnet forms only during regional metamorphism. The exception occurs in a small area in the green-brown biotite zone, characterised by the development of high grade minerals (of very small grain size) in the calcareous rocks; garnets are developed in one specimen. The bulk of the garnet was developed during the regional metamorphism, whatever may be the explanation of this

exception.

Amphibole. There are two main distinguishable types of amphibole in the calcareous rocks. One has an allotriomorphic outline and is fairly strongly but variably coloured; the Y-direction usually shows green, olive green or brown green. The second amphibole occurs as almost colourless blades or even needles. They cut the previously described amphibole and either cut or form a parallel intergrowth with pyroxene, if this is present. Needles of the amphibole grow along the cleavage intersections in the pyroxene to form the intergrowths. This amphibole is regarded as of later crystallization than both the first and the pyroxene, and is therefore called the late amphibole. The other amphibole, because of its wide distribution, is called the regional amphibole. As with the regional muscovite and the late muscovite it is not always possible to distinguish between the two amphiboles, this being especially the case where only one of them occurs in the rock. It is possible to find a complete gradation in aspect between the two types.

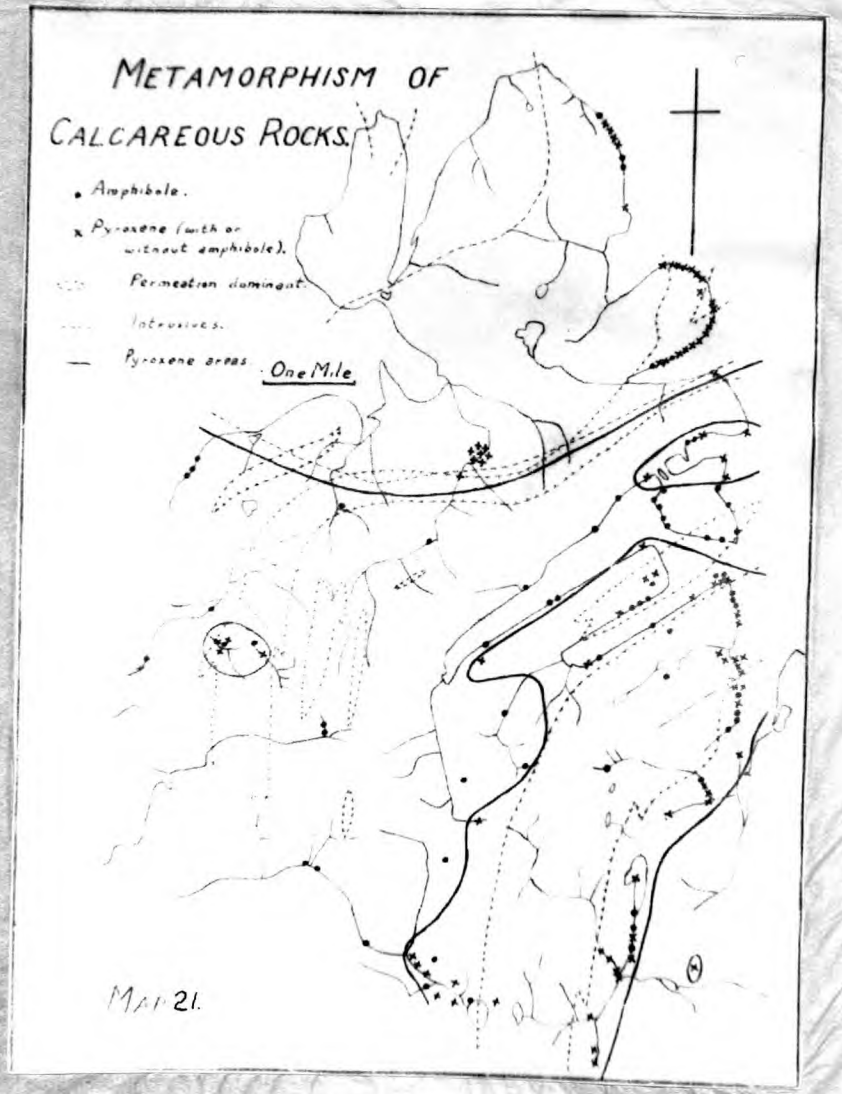
The late amphibole is usually associated with pyroxene. The growth of needles along pyroxene cleavage intersections and the cutting of pyroxene by amphibole blades, make it probable that the late amphibole is crystallizing from pyroxene which has become unstable, possibly due to decrease of temperature after metamorphism. Late amphibole occurs with regional amphibole only in a number of cases, and in one or two instances

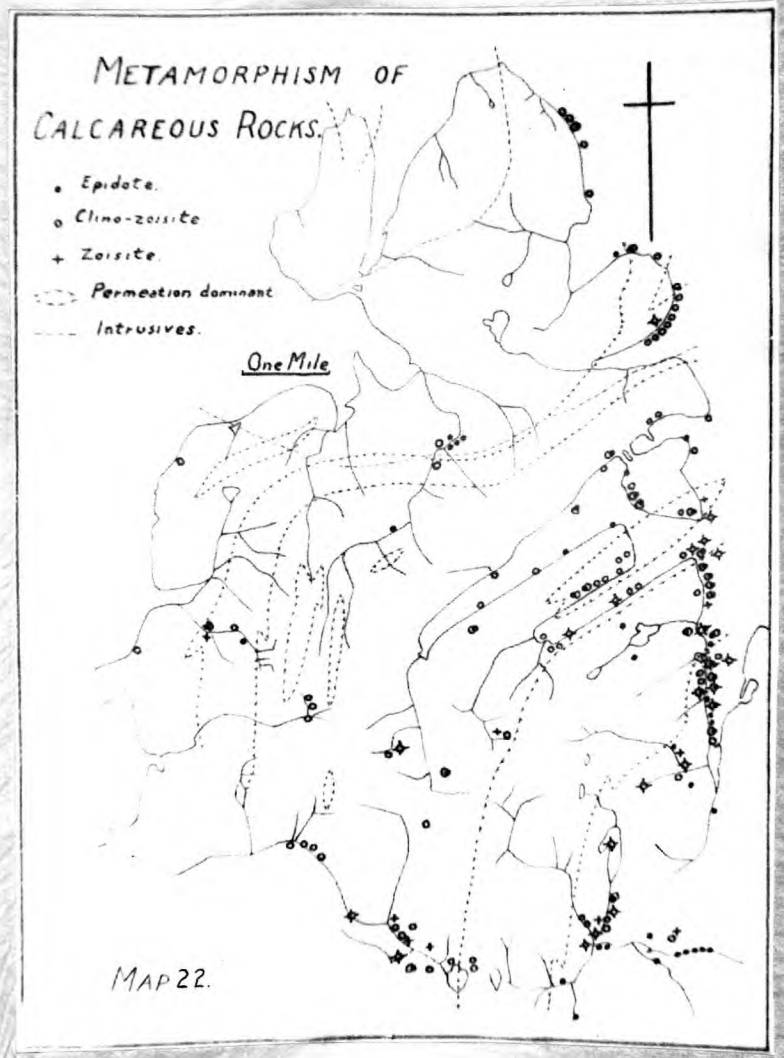
possible late amphibole occurs by itself. It is not clear whether in those cases it is legitimate to assume that pyroxene was once in the rocks and has been completely recrystallised to late amphibole, because the late amphibole may possibly develop from regional amphibole.

Since the late amphibole scarcely ever occurs by itself the distribution of amphibole shown in map 21 is in effect that of regional amphibole. The late amphibole is almost confined to the pyroxene areas.

Pyroxene. The distribution of pyroxene is shown in map 21. The pyroxene area at south of Voxter Voe may be a zone of regional metamorphic pyroxene coincidental with the kyanite zone, or it may be due to the contact effect of the Scatsta permeation belt. Most probably it is due to a combination of both effects (see pps 91) The two areas of pyroxene which coincide with the Colla Firth permeation belt and the subsidiary belts along side it, are obviously a contact effect due to the development of this belt. The pyroxene in the areas of the two igneous complexes is assumed to be due to contact metamorphism by the igneous intrusions

The possibility therefore arises that there may be two generations of pyroxene in the rocks of the Mossbank area. No evidence was found indicating the formation of pyroxene in association with the permeation of this area. If two generations exist they are identical in aspect. But in the Mossbank area it is possible to prove the relatively late age


METAMORPHISM OF
CALCAREOUS ROCKS.
• Amphibole.
x Pyroxene (with or without amphibole).
Permeation dominant.
Intrusives.
Pyroxene areas.
One Mile
MAP 21.


METAMORPHISM OF
CALCAREOUS ROCKS.
• Epidote.
o Clino-zoisite
+ Zoisite.
Permeation dominant
Intrusives.
One Mile
MAP 22.

of some of the pyroxene; in a number of rocks, the pyroxene can be seen to have grown preferentially along old recrystallized fractures and microscopic shears.

The pyroxenes are generally granular crystals with a very pale green colour as seen in thin section. In the peculiar stripy rocks north of Tofts Ness, see p. 16, however, the rather fine grained pyroxenes have a strong green non-pleochroic colour. It should be noted that almost identical rocks, without pyroxene, occur on the coast to the north of Voxter Voe and have strongly and somewhat unusually coloured amphibole.

Pyroxene and Amphibole. It is believed that during contact metamorphism, when a certain temperature was reached amphibole began to crystallize to pyroxene. Comparison of the modal amounts of amphibole and pyroxene show that the two minerals bear an inverse relatioh to oneanother, but since both are often major constituents, this is to be expected. The geographical distribution proves the inverse relationship.

Most calcareous rocks contain pyroxene and/or amphibole. Assemblages which contain neither fall near to the pelite-quartzite and the limestone-quartzite sides of the pelite-quartzite-limestone triangle. That is, these rocks are either very near in composition to members of the pelite-quartzite series but contain some calc-silicate minerals such as zoisite or clino-zoisite, or they are rocks made up mostly of carbonate and quartz. In the first case, before amphibole or

pyroxene can develop in a calc-silicate rock, there must more than a certain amount of calcium. In the second case more than a certain amount of pelitic material must be present before amphibole or pyroxene can develop. In neither case are amphibole or pyroxene necessarily the first calc-silicate minerals to be able to crystallise as the amounts of calcium and of pelite respectively are increased.

Clino-zoisite - epidote minerals. The distribution of these minerals is shown in map 22.

There is a complete gradation in composition between clino-zoisite and epidote, but most of the minerals of this type found in the rocks can be classed as one or the other type.

Epidote. All pistachite and epidote - clino-zoisite type minerals showing a bi-refringance of more than 1st order colours and a +ve 2V were considered to be epidote. The rest were considered to be clino-zoisite.

Epidote appears to have 3 different occurrences in the calcareous rocks. One type of epidote occurs in the green-brown biotite zone. All the assemblages of Calcareous rocks which occur in this zone contain epidote granules as the only calc-silicate mineral. This epidote is believed to be of regional metamorphic origin.

Epidotes in a large number of rocks are shown by ~~their~~ their textural relations to have crystallized late. This is particularly true of coloured epidotes, which may form cross-

cutting veins in the rocks, or they may grow as granules in rocks showing signs of cataclysis. This type of epidote is believed to be of dislocation metamorphism origin. Much of the remaining epidote occurs in or near belts of dislocation metamorphism and although its late age cannot be demonstrated it is very probably also of dislocation metamorphic origin.

The final occurrence of epidote, represented in only a few rocks, is not apparently associated with dislocation nor does it occur in low grade regional metamorphic rocks. This epidote is typically found as granules in felspars. It may have grown during the cooling of the rocks after a phase of metamorphism; it may be due to diapthoretic recrystallization.

It is not believed that epidote occurs in stable assemblages at a higher grade of metamorphism than the green-brown biotite zone, in the rocks of Delting.

Clino-zoisite, as is shown by map 22, has a wide distribution. Most of the clino-zoisite occurring outside the area of the pyroxene development shows signs of secondary development, especially after felspar. It is often found as a growth in the relics of an earlier mineral, which was possibly felspar. Also it is often found as granules in felspar. But several cases occur of clino-zoisite, which show no signs of late crystallization. This evidence suggests that clino-zoisite either does not occur in stable assemblages in regional metamorphic and non-diapthoretic rocks, or that it is stable in such assemblages only over a narrow range of conditions.

Most of the clino-zoisite which does not appear to be of late origin occurs in the pyroxene areas. It is possible th that it may have developed during the metamorphism, which caused the crystallization of the pyroxene.

Zoisite. Map 22 shows that this mineral has a restricted distrb-ution. Most of the occurrences lie along the edges of the Colla Firth pyroxene zone. Two of the three other occurrences are in pyroxene zones. One of the latter cases, that south of Mossbank, is of crystals growing into free space on the face of a joint crack. These crystals probably grew during the contact metamorphism.

The zoisite in the Colla Firth permeation area has a similar distribution to the pyroxene, but it is not so abundent. Thin sections of some of the rocks contain zoisite which is apparently of the same age as the bulk of the minerals. Other rocks, however, have zoisite as skeletal crystals in what was once probably felspar. There is a possibility therefore that zoisite can grow both on the upgrade and on the downgrade.

Zoisite, clino-zoisite and epidote occur in rocks falling in all parts of the pelite-quartzite-limestone triangle except the pelite-quartzite and the quartzite-limestone sides. The distribution and frequency of occurrence of all three as stable phases in stable assemblages is considerably less than is apparent from mere lists of minerals forming the individual rocks. The true stability relations of these minerals are obscured by the great difficulty experienced in determining

which are early and which are late crystallizing members of these types.

Wollastonite occurs in two rocks from near Voe Church and it also forms in calcareous rocks included in the Inclusion Granite on the north side of Firth Voe.

Apatite is found in nearly all calc-silicate rocks.

Pyrite is also common.

Sphene and black Iron Ores. Sphene is a very common constituent, often occurring in relatively large amounts. In some cases it is highly coloured, a kind of reddish brown, and is pleochroic. Sphene is much more common than the ores, which occur mostly in sphene rich rocks. Sphene often forms rims round ore grains and may be derived from them, but no significant distribution of either was determined. This may be due to the fact that no attempt was made to distinguish between ilmenite and magnetite.

METAMORPHIC TEXTURES.

These rocks are mostly granulites (in the Scottish sense). In thin section it is occasionally possible to determine the age relations of certain minerals but for the most part the rocks appear as granular aggregates. The biotite and the muscovite, especially away from the contact metamorphic areas, show quite often parallel orientation, even though they may be scattered through a granular matrix of other minerals, which show no preferential of external form or apparently of internal

structure. This structure schistosity is always parallel to any composition banding visible (except in the green-brown zone). Less commonly the regional amphibole shows preferred orientation. Therefore the regionally metamorphosed calcareous rocks are probably tectonites, although this fact is not always immediately apparent. This fabric was destroyed by the later contact metamorphism. When the late amphibole developed it grew without preferred orientation in the rocks.

METAMORPHISM OF THE CALCAREOUS ROCKS.

The calcareous rocks appear to attain equilibrium more easily than the pelite-quartzite rocks. They are also considerably more complex in behaviour and are consequently less well understood. It was therefore considered best in this thesis to interpret the metamorphism of the calcareous rocks with the aid of the knowledge gained from the pelite-quartzite rocks. It is assumed that the sequence of metamorphisms recorded in the pelite-quartzite rocks has also affected adjoining calc-silicate rocks.

Regional Metamorphism. All assemblages obtained from the areas in which pyroxene is not developed in the rocks, see map 21, were divided into groups based on the zones of peltie-quartzite regional metamorphism shown on map 5.

Green-brown biotite zone - 16 assemblages. The characteristic assemblage is green-brown biotite, muscovite, epidote and plagioclase. Nearly all the rocks contain quartz and about half

contain carbonate. Plagioclase occurs in only about half the assemblages, but due to the fine grain size of the minerals it is not easy to identify it. Only three felspars were determined and they were about Ab60 in composition. Four assemblages showing signs of dislocation metamorphism contain microcline. One assemblage, the only potash free one contains hornblende.

Red-brown Biotite zone - 27 assemblages. The characteristic stable minerals of this zone appear to be hornblende, muscovite, red-brown biotite and felspar. Hornblende is missing from 8 of the assemblages. Six of these assemblages are very rich in quartz and carbonate whilst the other two are very poor in calcareous minerals. Therefore, as mentioned on pps72-73, all 8 assemblages are of a composition which cannot develop amphibole. Muscovite and biotite show the haphazard development usual for these rocks. Plagioclase is more common and more strongly developed than in the green-brown biotite zone. Two felspars of about Ab60 and Ab94 were determined.

Four rocks from this zone contain zoisite, which in three cases can be seen to be forming from felspar. The zoisite probably develops in response to the contact metamorphism by the permeation, the effects of which must extend to a certain extent beyond the limits of the pyroxene areas. Colourless chlorite occasionally occurs in small quantities. Zoisite, clino-zoisite and epidote are all formed but in most cases show evidence of late development. There are three cases of

microcline in small quantities and three instances of garnet.

Garnet 1 zone - 12 assemblages. The essential minerals in this zone are garnet, hornblende, biotite, quartz, carbonate, and plagioclase. Garnet is now more frequent and is better developed -5 cases- than in the red-brown biotite zone. Amphibole occurs in all assemblages, but in two cases may be late amphibole. Biotite occurs occasionally. Felspar is well developed and an Ab55 and a bytownite were determined. Clino-zoisite and epidote occur in about half the assemblages, in most cases but not in all showing signs of late developement.

In passing from the red-brown biotite zone to the garnet 1 zone the only change observed in the calcareous rocks is an increase in the frequency and amount of garnet.

Garnet 2 zone - 12 assemblages. These rocks differ from the previously described rocks only in an increase in the frequency and amount of garnet developed. Four felspars which ranged from Ab36 to Ab92 were determined. Clino-zoisite and epidote occur and as usual they nearly always show signs of late development

Summary. In fig. 34 the approximate compositional fields of stability of the minerals in the different zones of pelite-quartzite regional metamorphism are shown. It is evident that zones of regional metamorphism can be erected for the calcareous rocks. Garnet will provide a zone or zones in the same manner as it does in the pelitic rocks but the zones so delimited will for equal amounts and frequency of development of garnet be of greater geographical area for the calcareous rocks.

The change from the characteristic assemblage

of the green-brown biotite zone to that of the red-brown biotite zone takes place in the general region of the east front of the Colla Firth belt, in the pelite-quartzite rocks. The equivalent change in the calcareous rocks probably takes place also in this region, but all evidence of the change has been destroyed by the development of the pyroxene area of the Colla Firth belt. If this contact metamorphism had not taken place, then it is probable that both the change of colour of the biotite and the change from epidote to hornblende could have been made the basis for isograd lines.

Contact Metamorphism. The development of brown coloured garnet in the areas of the igneous complexes is the only observed difference in effect between the contact metamorphism by the igneous rocks and that by the permeation. For this reason the effects of the two contact metamorphisms can be considered together.

Pyroxene is regarded as the characteristic mineral of the contact metamorphisms. It is probable that at a sufficiently high grade of regional metamorphism pyroxene develops, but if this change occurs in the Delting rocks it is confined to a small area east of Brae, map21. The areas of pyroxene development are therefore regarded as the domains of the contact metamorphisms. But the contact metamprphisms must have produced changes in the calcareous rocks beyond the areas of the pyroxeme development. These areas can be considered as a zone of contact metamorphism of lower grade than the pyroxene zone. This zone lies indiscriminately

across all the above described zones of regional metamorphism, and therefore in some cases the changes in response to contact metamorphism will be diapthoretic and in other cases constructive. Changes observed in the rocks around the pyroxene areas are :- instability in the regional amphibole, the development of late amphibole, the development of late clino-zoisite, epidote, and zoisite, the very strong alteration of the felspar the development of chlorite from biotite.

Signs of re-sorbtion in the hornblende are most probably the result of contact metamorphism, but signs of instability such as the development of chlorite or carbonate in the hornblende are probably due to dislocation metamorphism. All late amphibole is almost certainly the consequence of contact metamorphism. Most late amphibole occurs in the pyroxene areas, where it has obviously developed duringthe cooling, but in the outer zone it may develop at the maximum temperature reached at that point during the contact metamorphism.

The development of clino-zoisite from felspar is a diapthoretic effect of contact metamorphism, but the largest part of the epidote is due to dislocation metamorphism or to low grade regional metamorphism. Zoisite, since it can occur as both skeletal crystals in felspar and as good crystals on its own, and can also occur both with and without pyroxene, is probably formed during the heating up and the / cooling down,/

cooling down, and in both cases it may have a limited field of stability. Zoisite can be regarded as a higher grade mineral than clino-zoisite and therefore than epidote, but it does not continue stable as long as felspar.

The felspars of the contact metamorphic rocks are less sericitised than are the felspars of the non-contact metamorphosed rocks, so that there is no reason to think that the sericitisation of felspar is related to contact metamorphism. But another alteration occasionally found in felspar may be an effect of the contact metamorphism. This is the development of areas of fuzzy material with a high relief, which can occasionally be seen to have a low bi-refringance. It also sometimes resembles skeletal zoisite developing in felspar. This alteration may be an early stage in the development of zoisite in felspar and so an effect of the contact metamorphism.

The above changes are relatively slight. On entering the pyroxene zone, the effects of the contact metamorphism are more obvious. Pyroxene develops in amounts varying from more than 90% of the rock to only a few %. Most of the microcline occurs in the pyroxene areas as does most of the zoisite.

The change amphibole to pyroxene involves loss of aluminium and gain of magnesium. A plot of pyroxene against biotite shows a moderately good inverse relation, fig. 16. A similar plot of pyroxene against microcline shows that microcline is as common in pyroxene rocks as in non-pyroxene rocks, fig.17, and occurs mostly in rocks of the pyroxene

areas. An inverse relation between pyroxene and quartz is shown by quartz-pyroxene plots, fig. 15. Pyroxene is often a major constituent and therefore all other minerals can show an inverse relation to it. Nevertheless, it is possible that the extra magnesium necessary to form pyroxene comes from biotite, the potash of the biotite and the aluminium of the hornblende then forming microcline or leaving the rock.

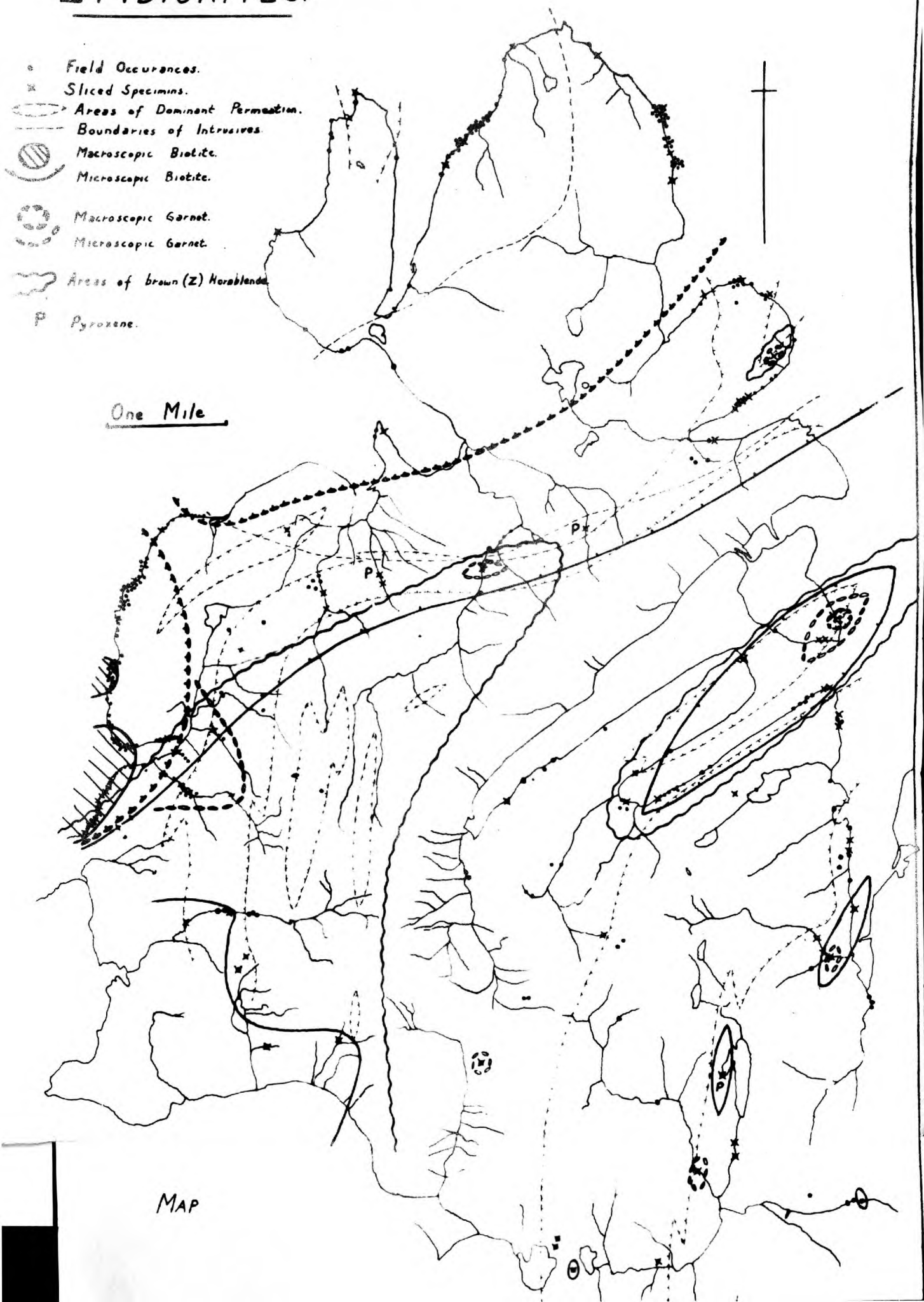
The presence of wollastonite in several places indicates the possibility of the development of a higher grade of contact metamorphism than that characterised by pyroxene. The same consideration might apply to the very localised development of the coloured garnet. But it is possible that the crystallization of these minerals is due to an approach to the conditions under which skarns develop. The occurrences of these minerals are too few and too widely scattered for any conclusion to be drawn from them.

Considerations detailed above show that the contact matamorphic rocks are of two ages; igneous intrusion and permeation. But what is not so obvious from the rocks of the pelite-quartzite series is the great difference between the contact effects of the Scatsta belt and those of the Colla Firth belt. Therefore the metamorphisms by the different permeation belts must be considered separately where ever possible.

METAMORPHISM OF THE EPIDIORITES.

Epidiorites occur in the field as black massive homogeneous rocks forming bands parallel to the general

EPIDIORITES.



schistosity. In thin section they are seen to be made of hornblende and felspar with some quartz and with sphene and black iron ores as very common and often strongly developed accessories.

But in a number of areas and particularly in the north-west of the thesis area the epidiorites have been more or less completely converted to biotite - garnet schists. This change is due in part at least to metasomatism. Fubther more it has not so far been found possible to date the metasomatism. Therefore this problem is considered separately below, pps.[135-139].

METAMORPHIC MINERALS.

Quartz. Quartz occurs in all but 20% of the rocks(94 assemblages considered). It is always a minor constituent but occasionally it exceeds the felspar in amount.

Biotite. Most of the rocks containing biotite occur in the metasomatic area to the north-west of the line from Brae to Firth, but it is also developed in rocks along the edges of the Colla Firth permeation belt. The mica is usually red-brown in colour, exactly like that seen in the regional metamorphic pelitic rocks. A number of the rocks however contain brown biotite, including several in the green-brown biotite zone of the pelitic rocks.

Chlorite. So much of the chlorite can be shown to be derived from biotite, or garnet that in the absence of any other evidence there is no reason to think that any of it has any other origin.

Hornblende is the dominant mineral of the unmetasomatised epidiorites. It is strongly but variably coloured. There are two main types of colouring; in one the Z-direction shows a bluish-green, and in the other a slightly greenish-brown. It is possible to find all gradations between these two colours, and furthermore there are a number of other colours which do not fall under either of these types. The brown hornblende frequently shows rims of blue-green amphibole. In map 23 the distribution of these varieties has been plotted. The distribution of the brown hornblende is as far as one can see from the available specimens similar to that of garnet in the pelite-quartzite rocks. Therefore the colour of the hornblende is probably related to the intensity of the regional metamorphism.

Pyroxene occurs in three rocks. In a rock from Laxo Water the pyroxene develops in one of the small reaction zones which occur in epidiorites in permeation areas, see pps.127. The composition within these small areas of reaction is little different from that of some calcareous rocks so that it is natural to expect pyroxene to develop. The other two cases of pyroxene development are in rocks along the edge of the Graven Intrusive Complex.

Garnet shows the same distribution as biotite, and is considered later.

Felspar is only missing from one of the 94 assemblages and that is a rocks in which all the amphibole has been changed / to biotite. /

to biotite. Felspar can make up nearly half the rock. Most of the felspar is sericitised to some extent but it was possible to determine the composition in 33 assemblages. Seven felspars are between Ab90 and Ab95. The rest are between Ab26 and Ab70. The two most basic felspars, Ab26 and Ab30, occur in rocks at the edge of the Brae Intrusive Complex (where the most basic felspars of the semi-pelites were found, pps 42&63). Some of the most sodic felspars occur in specimens from dislocation belts but more calcic felspars also occur in these belts.

Clino-zoisite and Epidote occur in a third of the rocks. Most of the epidote is obviously of dislocation origin. Much of the clino-zoisite is also of secondary origin. That is, it occurs in and around the reaction areas attributed to permeation, pps . The remaining occurrences of clino-zoisite are all within the permeation areas so that there is no reason for assuming that clino-zoisite is ever of regional metamorphic origin in these rocks.

Sphene and Iron Ores show the same , as yet unexplained relations as they do in the calcareous rocks, but in these rocks the iron ore is more common than the sphene, the reverse being the case in the calcareous rocks. Sphene forms rims round the iron ore sometimes. Sphene occurs in permeated, unpermeated and contact metamorphosed areas. Iron ore also occurs in all these areas. No attempt was made to distinguish between ilmenite and magnetite.

TEXTURES.

The hornblendes of these rocks in more than half of the sliced specimens show preferred orientation, the nature of which is described on pps 23. Rocks with no preferential orientation of the hornblende are frequent in the Graven Intrusive area, and also occur occasionally elsewhere but usually near the permeation areas. Such rocks are considered to have recrystallized under contact metamorphic conditions. Throughout the thesis area there are epidiorites which are tectonites and are considered on that account to be regional metamorphic rocks.

The epidiorites thus stand in contrast to both the pelite-quartzite rocks and the calcareous rocks. The pelite-quartzite rocks show equally the effects of regional metamorphism and of contact metamorphism. In the calcareous rocks the contact effects predominate. But in the epidiorites the regional metamorphic effects dominate. The calcareous rocks and the epidiorites taken together thus show that regional metamorphism was early and universal and that contact metamorphism was late and restricted in distribution.

Another feature of the epidiorites is the occurrence of cracks which have been more or less healed by recrystallization. Either the quartz-felspar element of the fabric has been healed or both that and the hornblende. When the hornblende grows across the fracture it generally grows as colourless or

nearly colourless amphibole in optical continuity with the original hornblende. This recrystallization is possibly associated with the permeation or the contact metamorphism according to the location of the cracked rocks.

METAMORPHISM OF EPIDIORITES.

The regional metamorphism resulted in the development of strongly but variably orientated hornblende in a hornblende, felspar, quartz rock. In the green-brown biotite zone of regional metamorphism, the grain size produced is characteristically smaller than anywhere else in the thesis area. The hornblende is normally one with a Z-direction colour of blue-green. But in the areas corresponding to the garnet 2 zone of the pelite-quartzite series the Z-direction colour is greenish-brown. The grain size and the colour are the only obvious features capable of being used for regional metamorphic zoning.

Permeation besides bringing about a certain amount of felspathisation and reaction and some biotite and garnet development may have also destroyed the preferred orientation of the hornblende.

Contact metamorphism by the Graven Intrusives appears to have destroyed the hornblende fabric in a number of rocks. It may also have caused the crystallization of pyroxene in certain cases.

A DISCUSSION OF METAMORPHISM IN DELTING.

An attempt has been made above to reconstruct from each of the three main rock types or rock series, the pelite-quartzite series, the calc-silicate-limestone series and the epidiorites, the metamorphic history of the area. The three histories so obtained are to some extent different. They differ in that they do not all tell the complete history. For instance it was found necessary to use the pelite-quartzite rocks to a certain extent to interpret the history of the calcareous rocks. There remains the task of combining the three metamorphic histories into a single history.

The regional metamorphism is the earliest metamorphism of which there is evidence in the area in the three series of rocks, and various facts suggest that it was the first metamorphism or was at least more pronounced than any earlier one. As has been described on pps 17-19 various sedimentary structures are preserved in the rocks. These structures are parallel to or are folded on axes parallel to regional metamorphic structures. Any earlier metamorphism would have to have been so slight as to have left the structures relatively undisturbed.

The intensity of the regional metamorphism varied over the thesis area. The distribution of this intensity is shown in map 8.

The permeation took place after the regional metamorphism, and at the level of the present surface of the earth the two phenomena are unrelated, since the permeation belts cut across

the regional metamorphic zones. The evidence on which the statement that "the permeation took place after the regional metamorphism" and not contemporaneously with or earlier than the regional metamorphism, is based , is summarised on pps52-3.

The history of the contact metamorphism by the permeation is made complex by the differing effects of the different permeation belts, by the differing effects of the same permeation belt on the different rock types, and the differing effects within the same permeation belt. Only the Colla Firth permeation belt and the Scatsta permeation belt outside the domain of the contact metamorphisms by the Graven and the Brae Intrusive Complexes, will be considered.

Within the two belts the sillimanite shows a distribution similar to or more restricted than that of the mineral which preceeded the shimmer aggregates. The sillimanite is therefore regarded as of higher grade than this latter mineral. But within the Colla Firth belt both these minerals show a striking relation to the regional metamorphism in distribution. (It is the distribution and intensity of development of these minerals over the whole thesis area, which shows that they are not regional metamorphic minerals, quite apart from textural considerations) In the Scatsta belt these minerals, sillimanite and the predecessor of the shimmer aggregates, are much more widely distributed and less intensively developed.

The above is interpreted as follows. When the

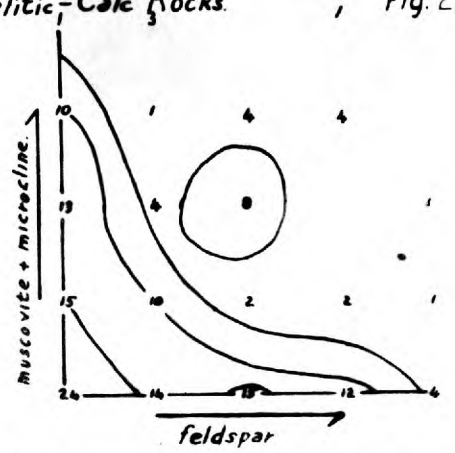
Colla Firth permeation took place the regional metamorphism had finished, but the temperature gradients established during the regional metamorphism had not been eliminated by cooling; areas which had suffered more intense regional metamorphism were still hotter than areas which had suffered less intense regional metamorphism. As a result, when permeation took place, bringing with it or manufacturing in place its own heat, the contact effects were stronger than they were in areas of less strong regional metamorphism. Application of the same arguement to the Scatsta belt shows that there, either the rocks had cooled down more than in the Colla Firth area, i.e. more time had elapsed since the regional metamorphism, or the permeation gave rise to less heat.

It should be noted that typical contact metamorphic effects occur as"outliers" in the rocks at Point of Mulla and to the west of Voe Church. Sillimanite occurs at both places, and the pyroxene area extends far out towards Point of Mulla. These two areas are believedd to be contact aureols of outlying pods of permeation occurring above or below the present surface. In the field the two areas are characterised by a slightly more mobile appearence in the rocks than is usual in the metamorphic rocks. They were identified as areas of weak permeation before the contact metamorphic effects, or in the case of the Voe occurrence, the net-texture in the rocks were observed. The fact that weak permeation produced contact effects, in garnet zone areas, makes it probable that the perm-

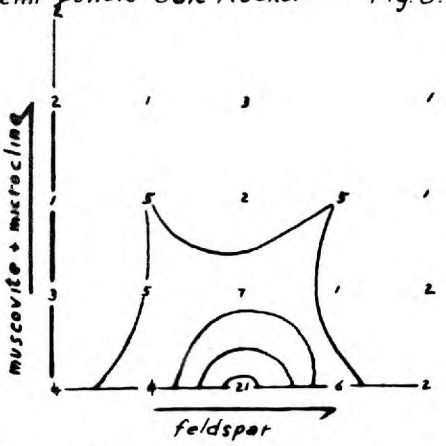
eation belongs in time to that of the Colla Firth belt. Such outlying products of permeation have their counterpart on the east side of the belt in the small area at Laxo.

The distribution of pyroxene is similar to that of the shimmer aggregates and the sillimanite in that it is better developed in the Colla Firth belt than in the Scatsta belt. After using the same arguement as is used above, it is concluded that the metamorphism of the calcareous rocks in the Colla Firth area, and therefore the permeation, was accomplished at a higher temperature than it was in the Scatsta region. But if the ~~calc~~ metamorphism of the calcareous rocks is compared with the metamorphism of the pelite-quartzite rocks then it is seen that the development of the pyroxene is much more widespread in the Colla Firth area than the sillimante and shimmer aggregate minerals, whilst in the Scatsta belt area the pyroxene has a much more restricted distribution than the sillimanite and shimmer aggregates. Therefore in the Colla Firth area the pyroxene appears to be a lower grade mineral than sillimanite, and in the Scatsta area a higher grade mineral. Either the two minerals as seen at present, are the results of different metamorphisms or one of the controlling factors, which appear to so easily influence the metamorphism of calcareous rocks, was different.

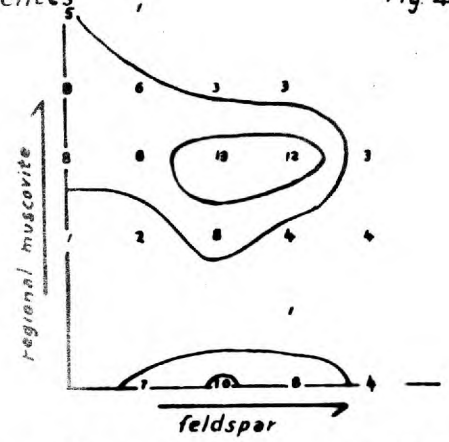
Pelitic-Calc Rocks. Fig. 2.



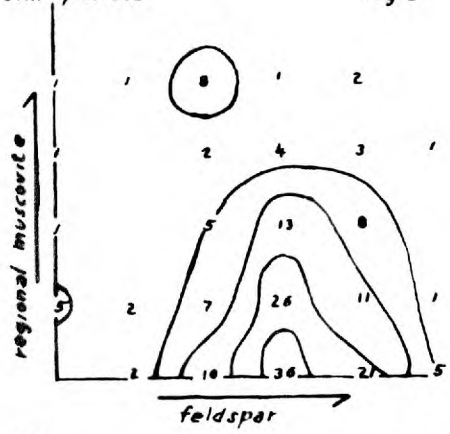
Semi-pelitic Calc Rocks. Fig. 3.



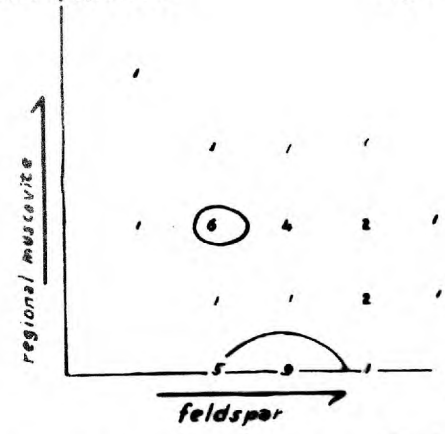
Pelites Fig. 4.



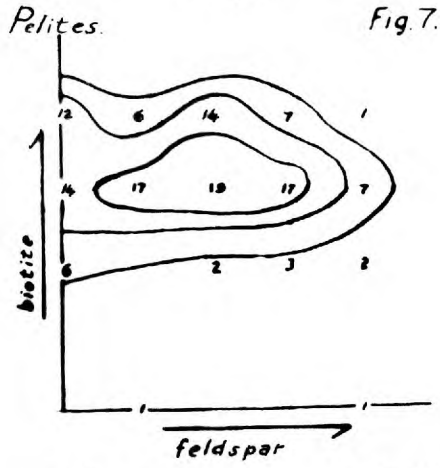
Semi-pelites Fig 5



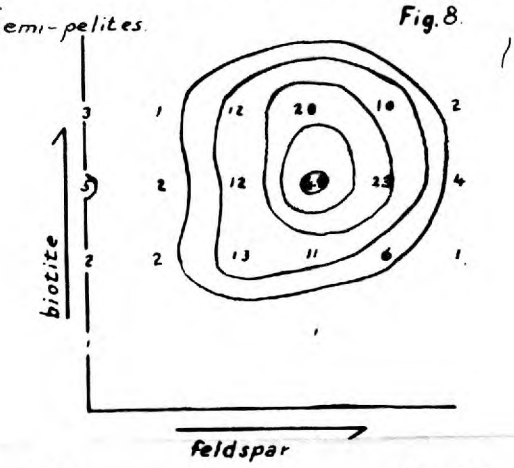
Impure Quartzites Fig. 6.



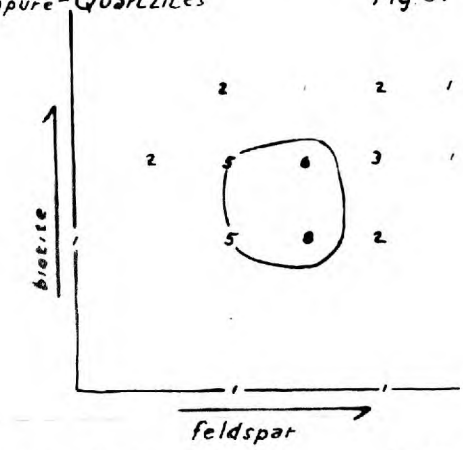
Pelites. Fig. 7.



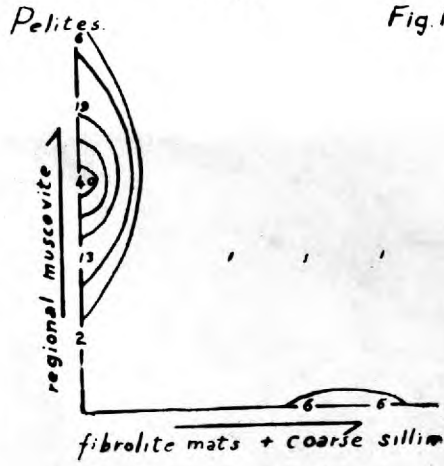
Semi-pelites. Fig. 8.



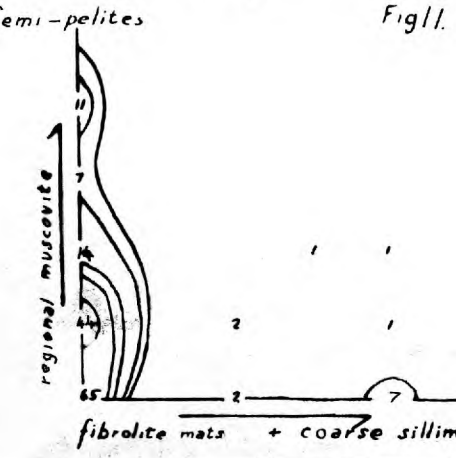
Impure-Quartzites Fig. 9.



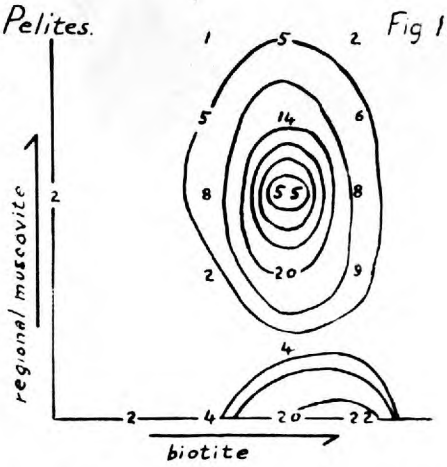
Pelites. Fig. 10



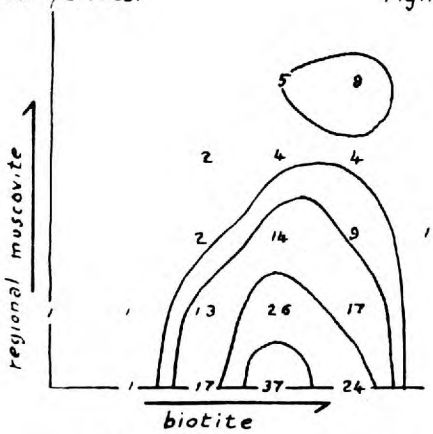
Semi-pelites Fig 11.



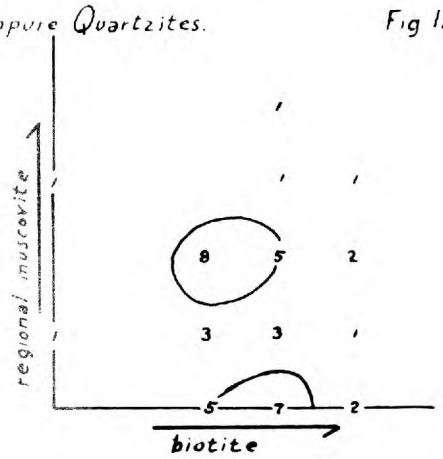
Pelites. Fig 12



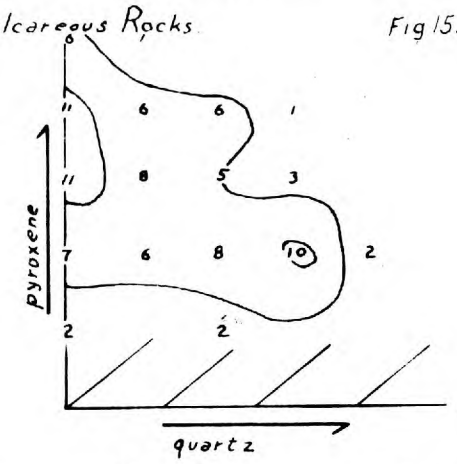
Semi-pelites. Fig. 13.



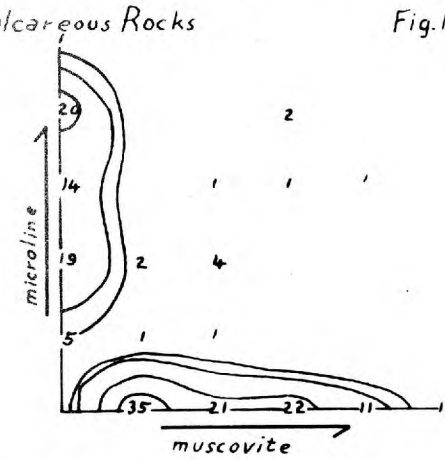
Impure Quartzites. Fig 14.



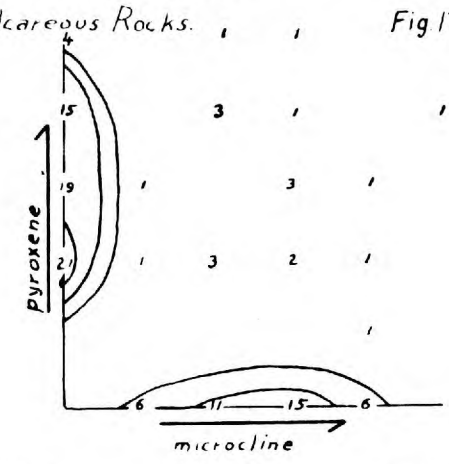
Calcareous Rocks. Fig 15.



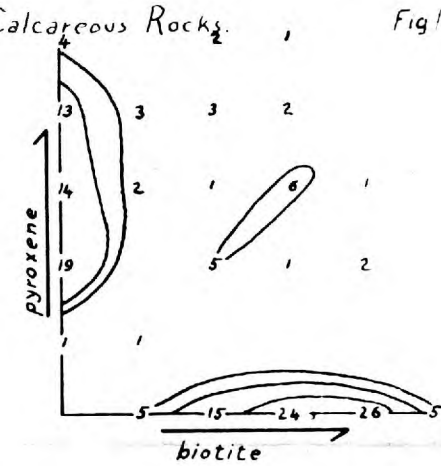
Calcareous Rocks Fig. 16.



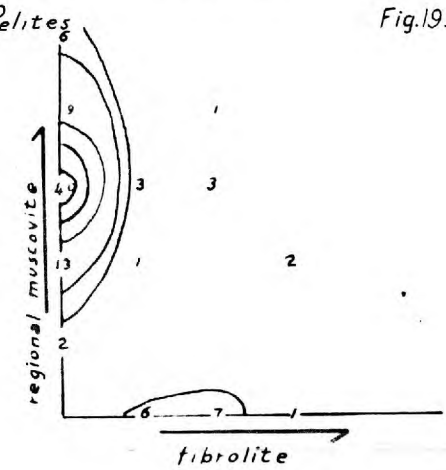
Calcareous Rocks. Fig 17.



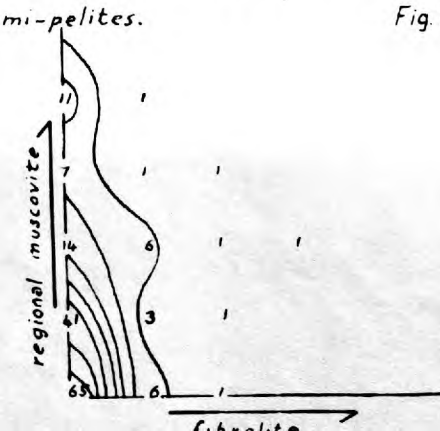
Calcareous Rocks. Fig 18

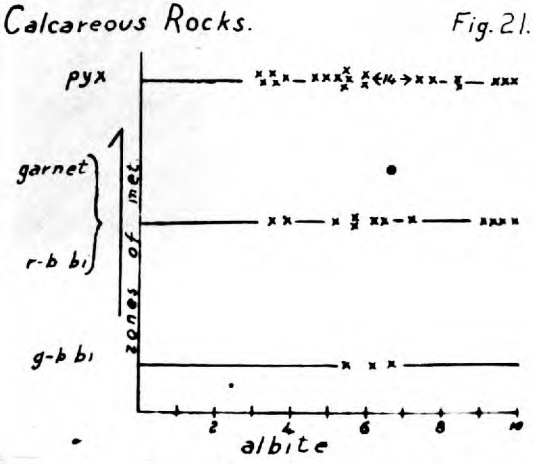


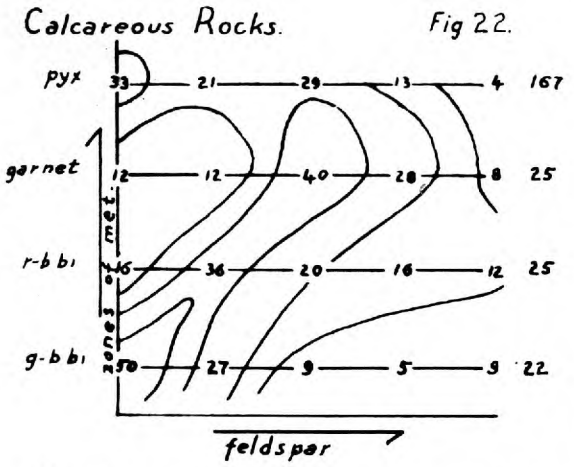
Pelites Fig. 19.



Semi-pelites. Fig. 20.







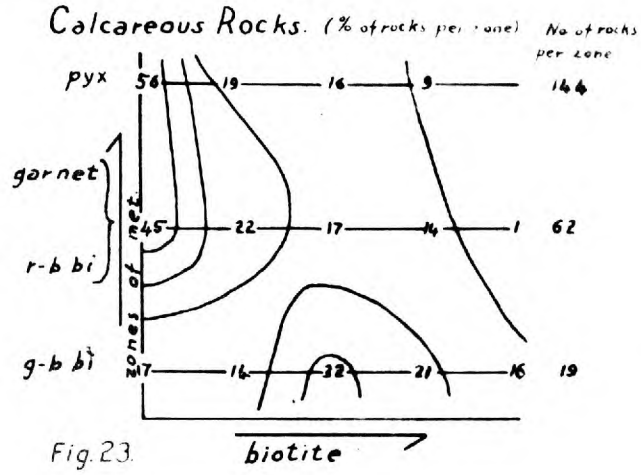


Fig. 23.

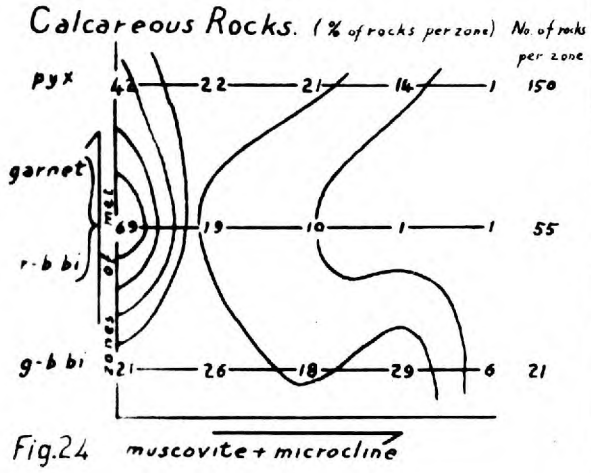


Fig. 24

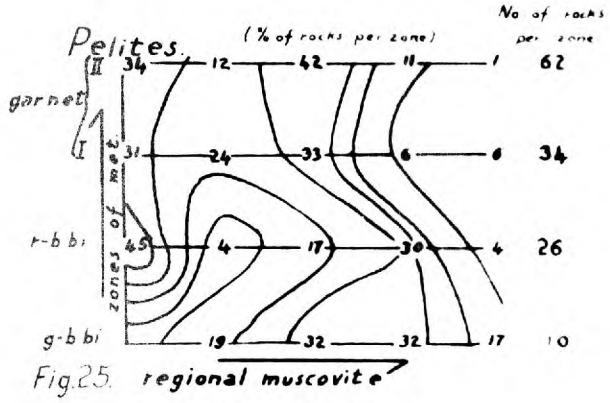


Fig. 25.

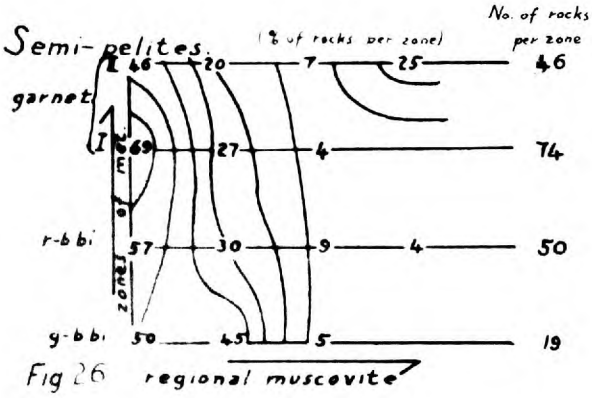


Fig 26

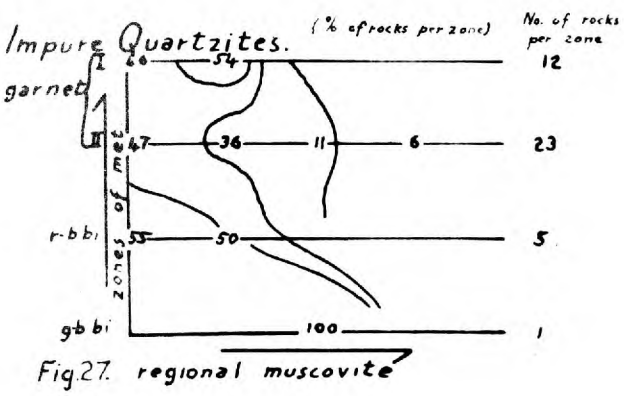


Fig. 27.

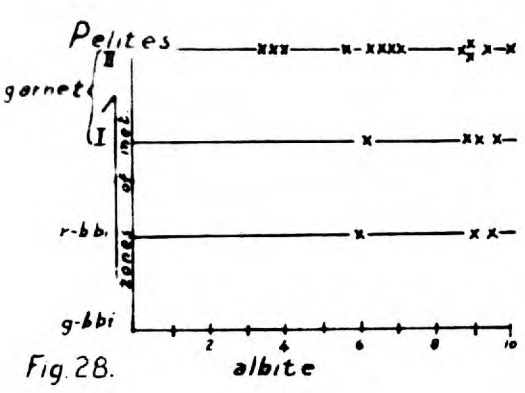


Fig. 28.

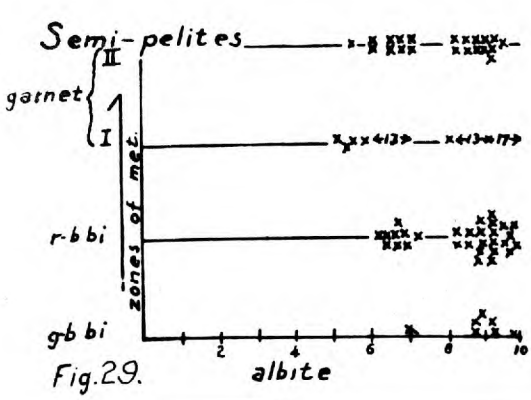


Fig. 29.

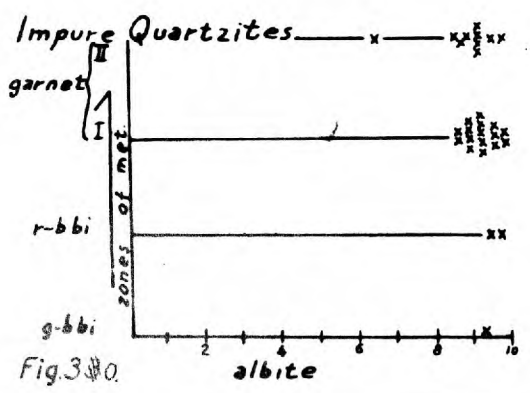


Fig. 30.

Pelites.

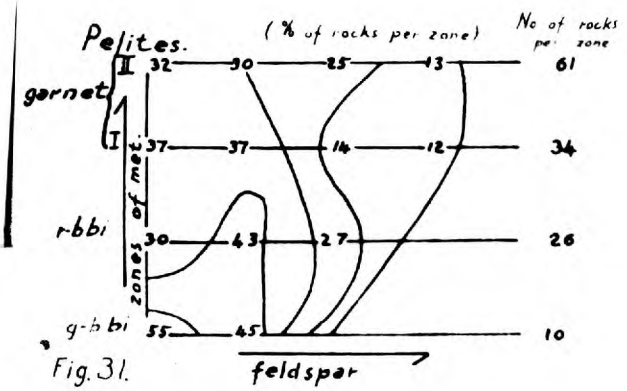


Fig. 31.

Semi-pelites.

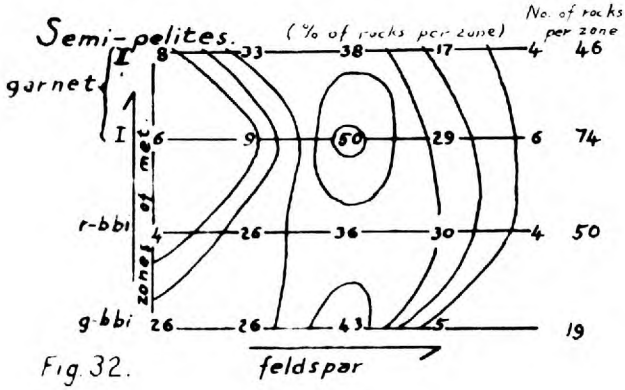


Fig. 32.

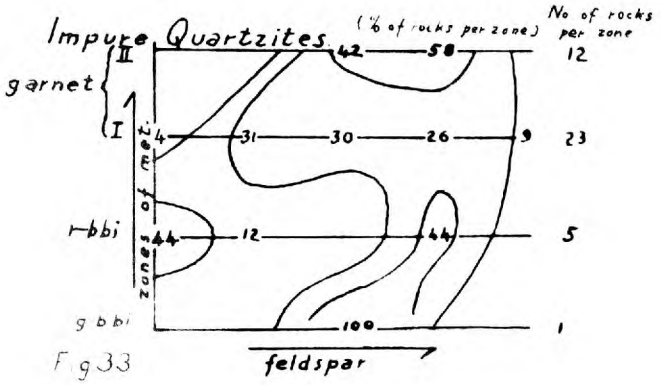
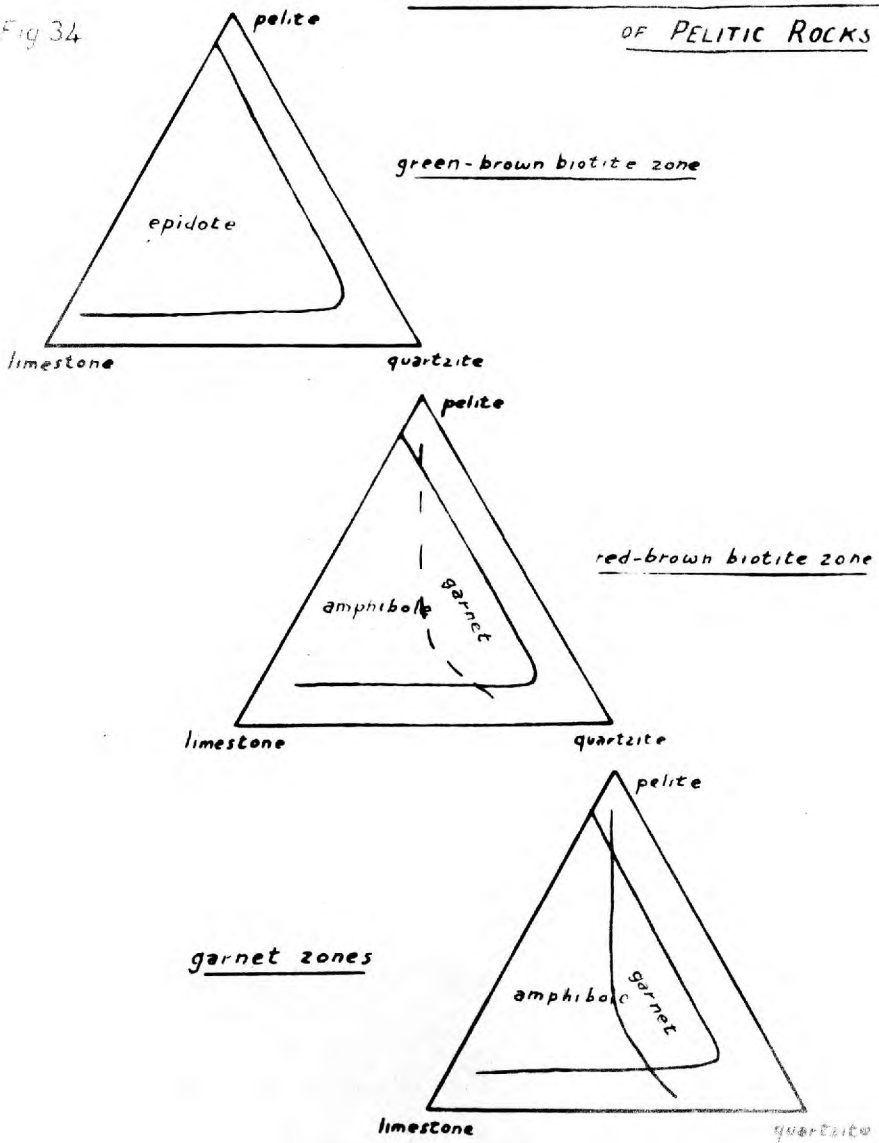


Fig 33

CALCAREOUS ROCKS AND ZONES OF REGIONAL METAMORPHISM

OF PELITIC ROCKS

Fig 34



MIGRATION OF MATERIAL DURING METAMORPHISM.

Although in this thesis the rocks are often written of as sediments, in actual fact they are all metamorphic rocks. The question therefore arises as to how far their sedimentary chemical composition has been preserved during the metamorphism. Further more the conception of a pelite-quartzite-limestone triangle of composition as described above raises the possibility that a correlation may exist between the individual components; that the presence of different amounts of the simple components quartzite and limestone in a rock may alter the nature of the third component, pelite.

The approximate modes of some 700 rocks whose regional metamorphic composition can be estimated wholly or partially were plotted in various ways in an investigation of these problems.

Element Deficiencies. Without accurate modes it is impossible, because of the dilution effect of the other two components, to determine directly the presence of, or lack of minor variations in composition within the pelite component. Larger variations, especially when they lead to the complete absence of an element normally present in the pelite component, can be detected. The actual detection of variations within the pelite component is done indirectly by observing the variations in amount of the different minerals.

A. Continuous Variation - i.e. variation showing a definite

relation to the major components of the pelite-quartzite-limestone triangle.

Calcium. Taken as a whole the rocks show complete gradation from no quartz to 100% quartz. At the same time they show complete gradation from no calcium containing minerals to/calcium containing minerals, and from no $CaCO_3$ to 100% $CaCO_3$. In other words they show the total composition range represented by a triangle with pelite, quartzite and limestone respectively at the three corners. As a first approximation the pelite-quartzite series is a simple dilution of pelite by quartzite. The pelite carbonate range is not so simple. The calcium combines with the pelite to give calc-silicate minerals for the first part of the range, and in general only appears as carbonate when at least a certain proportion of the silicate minerals present contain calcium. In 7 rocks out of 700, carbonate occurs with no other calcium mineral present, and in 8 rocks with only plagioclase as a calcium mineral. Most of these rocks show evidence, in their texture or in the rocks associated with them in the field, of extreme dislocation. All these rocks fall near the carbonate-quartz side of the pelite-quartzite-limestone triangle. This means that either some of the pelite bases have been ejected from the rock during metamorphism or that they were never there. The base chiefly concerned is potash since biotite and muscovite become replaced (volumetrically) by the amphibole-pyroxene miner

and by the clino-zoisite - epidote - zoisite minerals.

It can safely be assumed that the calcium content is largely if not entirely due to the original sedimentary composition. The presence of calcium affects the bases potash and soda, since it combines with the magnesium, iron and aluminium with which these bases are normally combined. The usual solution of this problem offered in the literature, that the original limestone component was dolomitic, is not accepted for this region (see on)

Potash. A noticable feature of these rocks is the scarcity of the regional muscovite in the semi-pelites, compared to its abundance in the pelites. In passing it should be noted that occasional references to such a scarcity in similar rocks can be found in the literature dealing with the Moines.

Using the 360 approximate modes available :-

Muscovite can be plotted against biotite for each of the composition types, pelite semi-pelite and impure quartzite see figs. 12,13,14. From ~~each~~ the figures it can be seen that in each case biotite shows a normal distribution about a positive amount. But whilst the pelite shows a similar distribution for muscovite, fig.4, the semi-pelite, fig.5, shows that most of the semi-pelites contain no muscovite at all.

Muscovite can be plotted a gainst regional metamorphic zones, see figs. 25,26,27. From these diagrams it can be seen

that there is a slight loss of muscovite between the green-brown biotite zone and the next zone above in both cases, but that otherwise the same picture is presented as above.

The relative lack of regional muscovite in semi-pelites as against its relative abundance in the pelites goes back to an earlier stage in the history than regional metamorphism or to a lower grade of metamorphism than is preserved here. Impure quartzite has diagrams of the same type as the semi-pelites.

Sodium. In the pelite quartzite series the % of plagioclase increases from pelite towards the quartzite end of the series, when allowance is made for the dilution by the quartz component. For instance 25% of pelites contain no felspar, 7.5% of semi-pelites, and only 4% of impure quartzites.

In figs. 7,8, and 9 the differences in form of the felspar-biotite plots for semi-pelite, and impure quartzite and for pelite show this variation well.

In figs. 4,5, and 6, the differences in form of the plots of felspar and muscovite show an inverse relation; as felspar increases so muscovite decreases and vice versa.

In figs. 31, 32, and 33 it is shown that the great range in the modal amount of felspar is present from the red-brown biotite zone of regional metamorphism to the the garnet 2 zone, for the pelites, the semi-pelites, and for the impure quartzites. The parts of the plots dealing with

the green-brown biotite zone are not very satisfactory as it is difficult to recognise felspar in the very fine grained rocks of this zone. It is possible that there is a small increase in felspar on passing from the green-brown biotite zone to the red-brown biotite zone.

In the calcareous rocks the behaviour of potash and of sodium is fundamentally different. Both biotite and muscovite + microcline (here considered together because of the above proved relationship, pps 67) show a decrease in amount with increasing metamorphism, figs. 23 and 24. In both cases the loss is almost entirely completed at the boundary of the green-brown biotite zone. The loss of potash is so great and so sudden that it can only be assumed that there is an actual change in the bulk composition of the rocks at this intensity of metamorphism. It is possible that this loss in potash is correlated with the microcline belt in the semipelites near where the change occurs, map 14, p. 41. Neither the biotite nor the muscovite + microcline show a variation in amount in the pelite-quartzite -limestone triangle greater than the systematic variation due to dilution by the limestone and the quartzite components.

So far as it goes, the plot of Ab content of felspars against zones of regional metamorphism, fig. 21, shows the same range in composition for each zone. As with other similar diagrams the width of the range may be due to a number of different effects, such as the compounding in the diagram

of a number of rocks of different composition, figs. 2 and 3. But the information available here is insufficient to analyse such causes. If the amount of felspar in each rock is plotted against the zone of regional metamorphism in which the rock occurs, fig. 22, a steady increase in felspar in the regional metamorphic range is folowed by an decrease in the contact metamorphic zone. This behaviour stands in contrast to the almost constant amount of felspar in the zones other than green-brown biotite in the pelite-quartzite series.

In order to test whether the inverse relation found in the pelite-quartzite series between muscovite and felspar extends into the calcareous rocks, the pelite-quartzite-limestone triangle was divided into two parts, separated by a line drawn from $^1/_3$ of the way from pelite to quartzite, to $^1/_3$ of the way from limestone to quartzite. This gives a pelite-calc-silicate-limestone part and a semi-pelite-calc-silicate-impure quartzite part. The division was made by dividing the calcareous assemblages into two parts; those with less than a certain amount of quartz and those with more. The critical amount of quartz chosen corresponded to that at which in the pelite-quartzite series it became difficult to decide whether the rock was semi-pelite or pelite. The felspar amount was, in each of the two series, plotted against muscovite + microcline. Figs. 2 and 3 are the result. It is seen that the inverse

relation between KAl minerals and NaAl minerals found in the pelite-quartzite series also occurs in the calcareous rocks. Nearly all the rocks falling on the felspar ordinate in the pelite-calc-silicate figure, fig.2, occur in the Mossbank region and in fact are the majority of the calcareous rocks which came under the ~~influ~~ influence of the igneous contact metamorphism. The elimination of this inequality in the data between the two areas leaves an even ~~greater~~ clearer inverse relation between potash and sodium.

Aluminium. Signs of an aluminium deficiency sufficient to outweigh the inaccuracies of the methods used, were indicated by the presence of some 25 rocks lacking all aluminium containing minerals except plagioclase and amphibole. These all fall within the area on the limestone-pelite side of a line from 50 pelite : 50 quartzite to 50 limestone : 50 quartzite in the pelite-quartzite-limestone triangle.

This fact taken in conjunction with other facts given above suggests that the plagioclase felspar lattice has priority on aluminium over all other lattices with common constituents. But whilst it is comparatively easy to show this due to the very great number of variables, both components and phases, involved it is impossible, without the use of more accurately determined data to deduce an order of priority for all lattices or a rule of partitioning of elements between lattices.

B. Discontinuous Variation. Some of the continuous

variations mentioned above are also to a certain extent discontinuous as is shown for example by the variations in amount of the different minerals present in rocks which are regarded as isochemical. The presence of non-essential discontinuous differences in chemical composition is also suggested by the occasional presence of potash mineral free , amphibole-pyroxene free, clino-zoisite group free and plagioclase free assemblages, which, when plotted on the pelite-quartzite-limestone triangle fall in areas normally characterised by the presence of those minerals.

Such occurrences may be due to :-

- inaccurate methods of working,
- chance, i.e. to the fact that minerals seem to have a probality not a certainty of occurrence, pps. 54-7,
- variation from the normal in the original bulk composition, even to the point of complete absence of essential elements. This latter cause seems to be a very real phenomenon. It is more common in the calcareous part of the pelite-quartzite-limestone triangle, than in the non-calcareous part.

CONCLUSIONS.

It is apparent that the metamorphic rocks of this area are not mixtures in all proportions of the three components, pelite, quartzite, and limestone. The complex pelite component varies in composition both predictably and to a much lesser extent, unpredictably in the presence of different amounts

of the two simple components quartzite and limestone.

At first sight the presence of limestone does not appear to upset the relation between the pelite-quartzite components. Large quantities of potash are lost from the rocks when calcium combines with magnesium to give amphibole. But the calcium was already combined with aluminium, which later goes to form felspar and to help form amphibole. There is no reason for considering the original limestone component to have been dolomitic. Therefore the presence of dolomite in the original sediment should not be assumed unless it can be proved or perhaps demonstrated by the presence of magnesium-silicate minerals. The problem of whether this aluminium with which the calcium first combines was excess in relation to the pelite component (supression of potash by the presence of calcium at sedimentation)or whether there was a ~~lack~~ previous ejection of potash from the rock at an even lower intensity of metamorphism,remains unsolved due to lack of lower grade ~~minerals~~ rocks.

The inverse relation between potash and sodium in all rocks, demonstrated above, was possibly an equilibrium relation established durin sedimentation. The term sedimentation is used here in a general sense to include all the time during which the rocks were in contact with the medium in which they were sedimented, i.e. deposition and compaction. The sodium: potash equilibrium could be established through the base exchange properties of the clay minerals, with the quartz concentra-

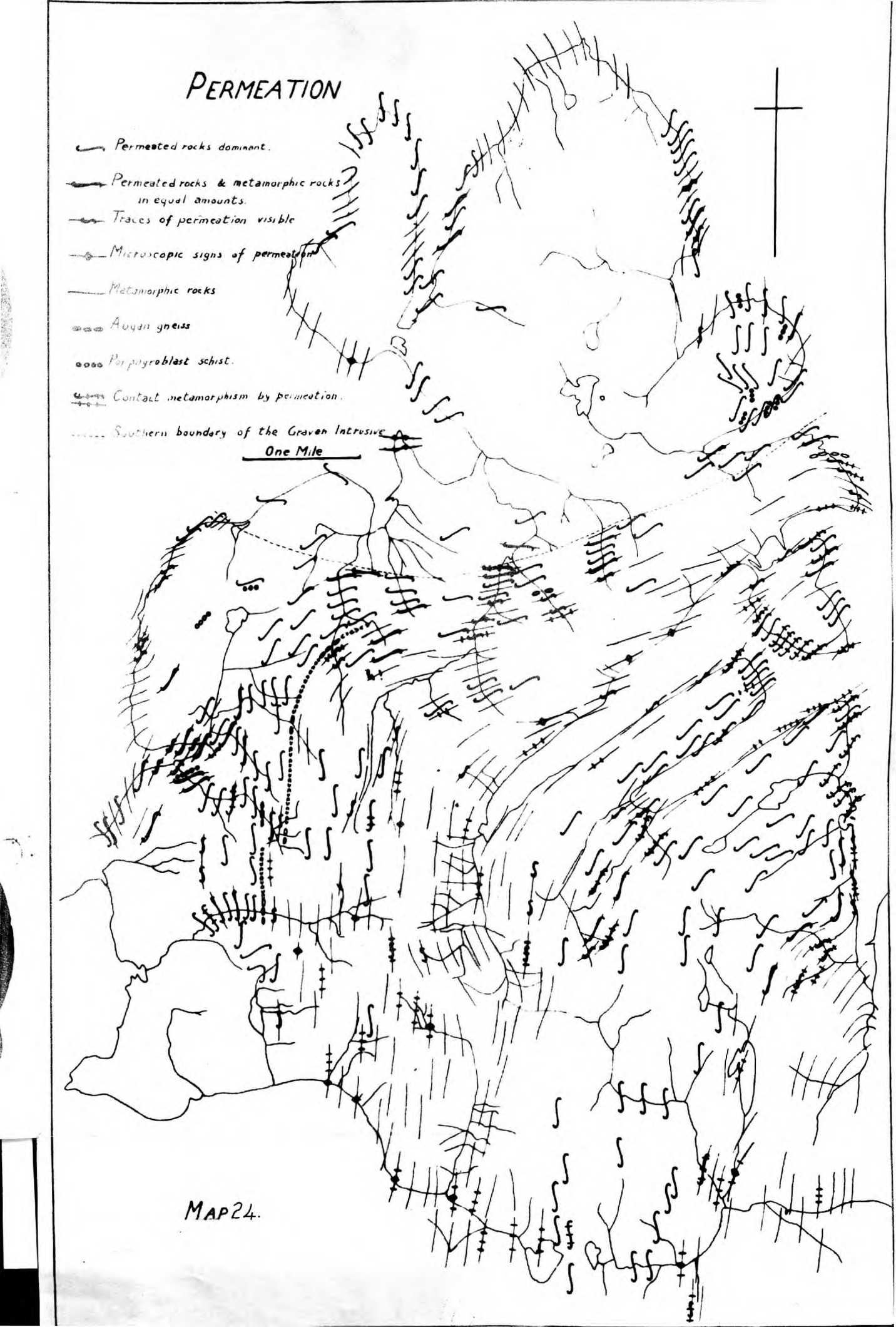
tion or some correlated factor exercising a controlling influence on the potash.

CHAPTER 5.

PERMEATION.

The belts of permeation in Delting are areas in which the rocks have a totally different aspect, both in the field and in thin section, from that shown in the metamorphic areas. The changes are identical with those usually referred to as being due to migmatisation, but in this thesis the term permeation is used in order to emphasise the fact that the change is an intimate and complete alteration of the rock rather than a veining and injection of the rocks producing agmatites, etc

The rocks showing permeation are chiefly pelites, semi-pelites and to a much lesser extent, impure quartzites. Calc-silicate rocks and limestones show no direct signs of permeation, whilst epidiorites show slight signs only. Map 24 shows the distribution of the permeation; there are two main belts, the Colla Firth belt and the Boatsta belt, together with a number of areas of permeation within the Graven Intrusive Complex, which, due to lack of exposure, cannot be shown to have any definite form of outcrop.


PERMEATION
Permeated rocks dominant.
Permeated rocks & metamorphic rocks in equal amounts.
Traces of permeation visible
Microscopic signs of permeation
Metamorphic rocks
Augen gneiss
Porphyroblast schist.
Contact metamorphism by permeation.
Southern boundary of the Graven Intrusive
One Mile
MAP 24.

THE PERMEATION EFFECTS IN THE PELITES AND THE SEMI-PELITES OF THE COLLA FIRTH AND THE SCATSTA PERMEATION BELTS are considered first.

The metamorphic rocks of Delting are well bedded. The bedding is a very obvious feature in the field, photo 9, except where the rocks are extensively shattered by later movements, since it separates the rocks into a series of homogeneous lithological units with an average thickness of a foot. The only inhomogeneity of composition is the flaggy partings of the more siliceous rocks, which are not a very striking feature, composition banding within the beds being almost confined to the calcareous rocks. The grain size of the metamorphic rocks, even of the highest grade metamorphic rocks found outside the permeation areas, is sufficiently fine for the rocks to appear massive and compact in the hand specimen and to make difficult the identification of minerals other than micas.

The Scatsta and Colla Firth belts are both composed of a main belt in which nearly all the rocks capable of being permeated are strongly permeated, with a number of outlying pods of permeation which vary in size from a few feet across to ½ a mile, but which are all very elongate in the direction of strike of the rocks.

The metamorphic rocks can be seen to change quite rapidly into well permeated rocks in the Colla Firth belt during traverses across well exposed areas. The first indication

Photo 9. Bedding in metamorphic rocks, near Voxter Voe.



Photo 10. Onset of migmatisation, half a mile south of Calna Taing.

Scatsta Permeation Belt.



of the proximity of permeation is often given by the occurrence of pegmatites which, instead of being sharp edged lenses of sheets cutting or conformable with the metamorphic rocks, appear to soak into them; the pegmatite has no definite boundary but grades into the metamorphic rocks by ever fewer and ever smaller and more widely separated pegmatite streaks. Another outlying sign of permeation is the occurrence of small areas in which the rocks show the development of quartz-felspar streaking, photos 10, 11, 12, 13. The farther such areas are from the main belt, in general the smaller they are and the weaker the permeation effects are.

The passage from apparently unpermeated metamorphic rocks which to rocks which are strongly permeated generally occurs in no more than a few feet. The first signs of the change are usually quartz-felspar streakings, similar to those mentioned immediately above, which on suitably weathered surfaces can be seen to be accompanied by streaks of re-crystallization to a much coarser texture. Photo 10 shows that these changes are typically related to the lithology. A few feet across the strike from such rocks, it is quite usual to find that the bedding planes have been destroyed, and that the units of different composition which formed the beds have lost their separate entity, photo 14. In such areas the rocks have become massive and granitoid. There is a very considerable increase of grain size; all the minerals can be seen. The compositional differences are evened out until there are no

Onset of migmatisation,
one and a half miles
south of Calna Taing.

Scatsta Permeation Belt.





Photo 11. Onset of migmatisation, Fora Ness.

Colla Firth Permeation Belt.



Photo 12. Onset of migmatisation, north of Fugla Ness.

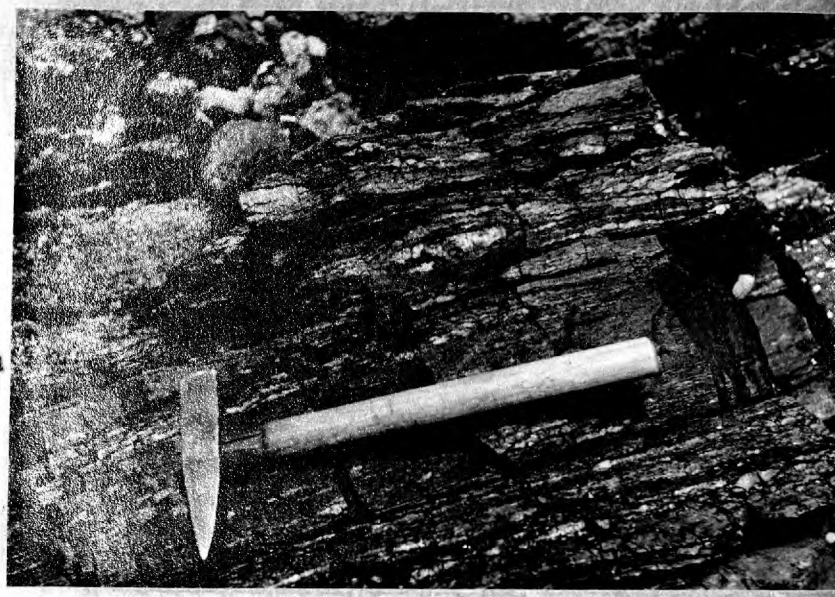


Photo 13. Onset of migmatisation, Colla Firth.

Colla Firth Permeation Belt.



Photo 14. Granitoid permeation rock, north side of Colla Firth.

Colla Firth Permeation Belt.

longer any very pelitic rocks. On the scale of the hand specimen the rocks have been homogenised but on the scale of the exposure and on larger scales the homogenisation is not completed, because, apart from the fact that calcareous rocks and epidiorites remain intact and undisturbed, and recognisable relics of semi-pelites and even pelites are quite common. These inhomogenieties vary from streaks the size of a finger to whole areas of apparently unpermeated rocks, which are the equivalent of the outlying pods of permeation in the metamorphic areas. Mostly these relics occur in situ. That is, if they are bedded or schistose then the bedding or schistosity is parallel to the general bedding and schistosity in the nearby metamorphic rocks, and if they are elongate then the elongation is parallel to the general strike, photos 15 and 16. The rocks have also failed to become completely homogeneous in that the granitoid rock itself varies in composition, as is shown by the colour given to it by the mica content. Exposures which at first sight appear to be quite homogeneous are found on hammering to be a mixture of all shades from dark to light brown due to varying biotite content, which reflects not only variation in the degree of permeation but also probably variation in original material. All these inhomogenieties combine to give a planar structure, which can be mapped throughout the belt and is found to conform to the attitude of the bedding and schistosity of the metamorphic rocks outside the area of permeation, photo 15 and map 24. It should also be noted that the change

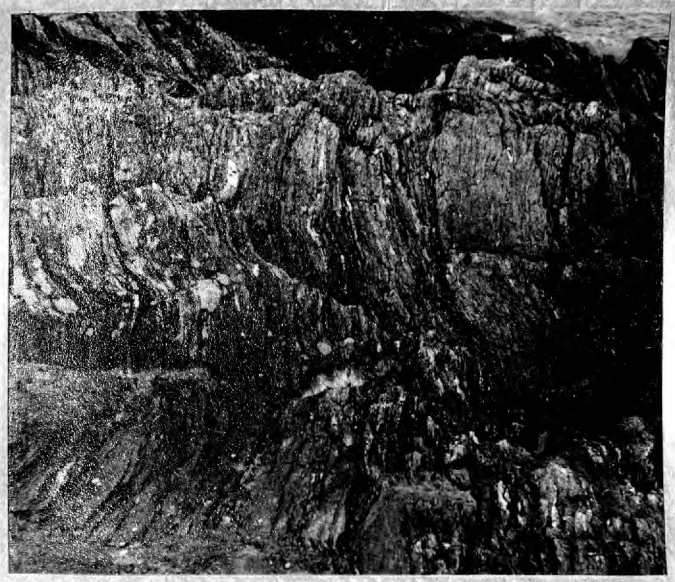


Photo 15. Permeation rocks, Noness Head. Colla Firth Permeation Belt.



Photo 16. Permeation rocks, Noness Head. Colla Firth Permeation Belt.

from metamorphic rock to granitoid rock is in part one of more or less complete loss of preferential orientation of the micas. In one or two small areas in which these inhomogenieties are reduced almost to vanishing point, the rock sometimes contains small sharply bounded disorientated inclusions of epidiorite, calc-silicate and even semi-pelite and pelite. The rocks of such areas can be said to have an igneous appearance.

The general ~~app~~ impression given by the Colla Firth belt is that in a number of lenticular areas which together form a belt lying to the east of the Weisdale Limestone, changes have taken place which result in the rocks becoming more or less completely homogeneous and structurally isotropic. Although within the main part of the belt the changes have failed completely in ~~only a few places~~ a number of places, and have reached completion in only a few places, yet over most of the affected area the rocks have changed a very long way towards a uniform granitoid type.

The general impression gained in the field from the Scatsta belt is very different. The form of the belt is the same, and also in both cases the transition from apparently unpermeated rocks to well permeated rocks may take place within a few feet across the strike. Furthermore the first signs of permeation on approach to a permeated area are the felspar-quartz streakings and recrystallization of the rocks described for the Colla Firth belt, photo 10. But these

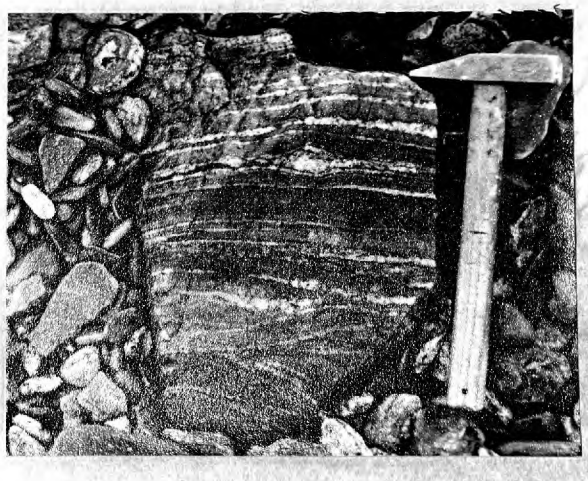
streaky rocks are themselves the characteristic rocks of the Scatsta belt. There is no transition to areas of granitoid rock; there is only a variation in the number of quartz-felspar streaks and eyes. As the number of streaks increases so the mica partings get thinner and thinner and eventually by this process a rock is occasionally produced which is almost identical with the granitoid rocks of the Colla Firth belt. But such rocks are not common and usually they contain many remnants of the mica partings which originally separated the quartz-felspar eyes. Thus the rocks are characteristically schists instead of granulites, and are streaky and gneissoic instead of uniform and homogeneous, photos 17 and 18. The Scatsta belt also differs from the Colla Firth belt in containing a band of very distinctive augen gneiss, which can be traced along the strike from north of Wethersta to the sea just south of Firth Voe. One (or more) bands of a porphyroblast schist often containing felspars as big as a clenched fist are exposed occasionally along a line which can be traced parallel to the strike from Voxter Voe to Mossbank. These rocks are described later, pps 120 - 122.

The two main types of permeated rock as seen in the field, the streaky rocks and the granitoid rocks, occur in both the Colla Firth and in the Scatsta belts but whilst a very large proportion of the permeated rocks in the Scatsta belt are of streaky type or approaching that state,

Photo 17. Streaky permeation rock, one and a half miles south of Calna Taing.
Scatsta Permeation Belt.



Photo 18. Streaky permeation rock, Firth Voe.
Scatsta Permeation Belt.



most of the permeated rocks in the Colla Firth belt are of more or less perfectly developed granitoid type. The two belts from their field aspect, thus appear to be variations on a similar theme. This conclusion is supported by the microscopic evidence.

The rock forming minerals of the two belts are the same. The stable assemblage developed by the permeation is in both cases:- quartz, muscovite, biotite, and plagioclase. Microcline is extensively developed in the permeation rocks, but, since it is believed that this mineral crystallized as one of the last stages of the permeation and only when the rocks had otherwise attained the state in which they are found at present, it is possible to simplify the discussion very considerably by postponing the consideration of microcline till later. Late muscovite, garnet, sillimanite, shimmer aggregates, staurolite and kyanite are found in these rocks, showing the same relations to one another and to the rest of the minerals which they show in the metamorphic rocks, and which have been described in the chapter on metamorphism. Finally the usual signs of dislocation metamorphism, such as chlorite after biotite and sericitisation of felspar are common and these are described below in the chapter on dislocation metamorphism.

Biotite. Some of the biotite is of the same red-brown colour which is so characteristic of the biotite of the metamorphic rocks. Much however is of the brown and

even green-brown variety which has been mentioned above, pps 36, map 12.

Plagioclase Felspar. The composition of the felspars of 59 rocks from the Scatsta belt and 36 from the Colla Firth belt were determined more or less completely by the same methods as were used for the determination of the plagioclase felspars of the metamorphic rocks, p. 41. No significant difference was found between the compositions of the felspars of the two belts. But whilst the felspars of all the metamorphic rock groups showed wide ranges of composition, figs. 31, 30, 29, 28, and 21, all the felspar determinations from the permeated rocks show a narrow range of composition centred on Ab80. Sixty-three percent of the Scatsta rocks and 45% of the Colla Firth rocks have felspars with a maximum extinction angle of albite twins cut normal to (010) of less than 12°, that is, the felspars are between Ab90 and Ab70 in composition. Such felspars were not completely determined (i.e. whether more or less albitic than Ab80) since the labour involved would not be justified by the results. A strong indication of what the results would be of such a determination, is given by the composition of the remaining felspars. The 55% of the Colla Firth rocks whose felspars are not of oligoclase composition (Ab90-Ab70) lie equally distributed between Ab95 & Ab90 and between Ab70 & Ab64 with one Ab58. Most of the 37% scatsta rocks whose felspars are not of oligoclase composition lie between Ab70 & Ab62, the remainder lie between Ab94 & Ab90 with one Ab100. Yet

these felspars are contained in rocks which vary from metamorphic schists with only microscopic traces of permeation to granulitic gneisses; they are not from a carefully selected group of similar and highly permeated gneisses. If these felspar compositions are compared with those of the pelites and semi-pelites plotted in figs. 28 and 29 (pelites and semi-pelites are the ~~pet~~ parent rocks of most of the permeated rocks since they are the most common of the metamorphic rocks) it is seen that the average composition varies only several percent between pelites, semi-pelites, Colla Firth permeation rocks, and Scatsta permeation rocks; only the degree of variation has been altered by the permeation. There is therefore no evidence of a change in the proportion of Ca:Na (Ab:An) in the rocks, during the permeation. It is possible that there may be an increase in the total amount of felspar in the rocks, but such an increase is too small to be detected by the methods of estimating modes used in this thesis.

It has already been mentioned that the permeated rocks have a considerably larger grain size than the metamorphic rocks. One tenth of a millimeter is quite a common average diameter of quartz and felspar grains in semi-pelites of the red-brown biotite zone and the garnet zones. But felspar and even quartz grains of 3mm. diameter are very common in the more strongly permeated rocks, whilst porphyroblastic felspars, when they occur, may grow as large as a clenched fist, although much smaller ones, say of 1cm. diameter, are more

common. The biotite and the muscovite(other than late muscovite are increased in size in proportion.

The increase in grain size is accomplished by considerable changes in texture. The texture of the metamorphic rocks from which these permeated rocks are developed, the pelites and the semi-pelites, is controlled by the micas. In a typical regional metamorphic rock, not affected by later changes such as contact metamorphism, the micas, both biotite and muscovite form a frame work amongst which the quartz and felspar fit in as equally developed partners, that is neither quartz nor felspar tend to develop their form at the expense of the other or of the micas. This texture is shown best by the semi-pelites in which the elongate well formed micas are orientated parallel to one another and scattered through the rock with the gaps between them filled up by the quartz and the felspar. In the semi-pelites there may be so much mica that the quartz and felspar tend to be ~~orientated~~ confined to lenses but this is an extreme case and the described texture may be recognised in most of the non-calcareous rocks metamorphic rocks of Delting.

In the permeated rocks these relations are reversed by two different methods which may be correlated with the two different types of permeated rock, the streaky and the granitoi

The first type of permeation texture is called the net-texture, photo 19a. It occurs in both belts, but more commonly in the Colla Firth belt, and is one of the signs

Photo 19a.

Net-texture.

X 11.

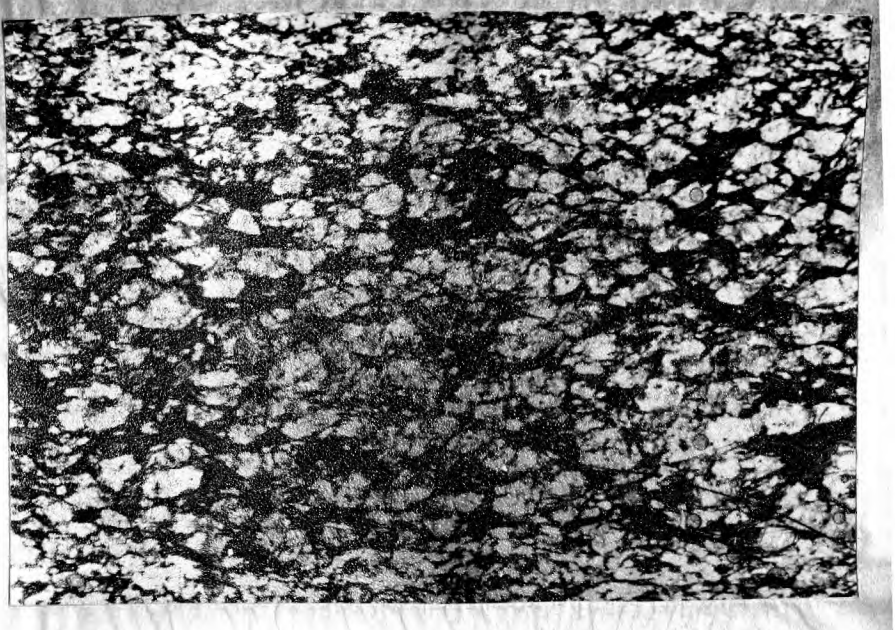
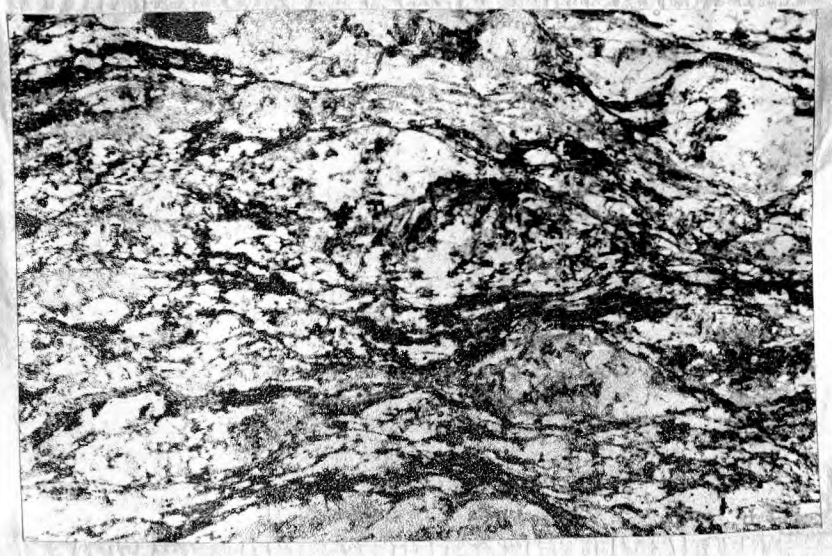


Photo 20a.

Eye-texture.

X 6



of marginal permeation. But it is a texture which can only be identified in thin section under the microscope. It is most fe frequently found in streaks parallel to the schistosity in rocks which in the hand specimen appear metamorphic. Within these streaks recrystallisation takes place before there is an appreciatable increase in grain size. It is rather an alteration of the form of the individual mineral grains. During this recrystallization it is obvious that in contrast to what happened during the regional metamorphism the felspar has been the dominantly crystallizing mineral. It has changed its shape whilst the other minerals have recrystallized passively in order to accomodate themselves to the felspar outline. Quartz occasionally plays a dominant role as well. The resultant effect is of a net, the meshes of which are the felspar and quartz grains and the threads of which are the micas. In the preliminary stages the felspars obtain a rounded equidimensional outline instead of the original amoeboid outline. The micas may react either by retaining their orientation and losing their original sub-rectangular outline, or they may lose this latter and retain their orientation. Generally in the same rock they all do the same thing.

Regional muscovite plays the same role as the biotite when it is present, but in many rocks showing net-texture there is no muscovite. This lack of muscovite and the quite common lack of quartz may be due to metasomatic changes during the development of the net-texture.

The second type of permeation texture is called the eye-texture, photo 20a. It occurs in both belts, but is characteristic of the Scatsta belt. This is also one of the marginal signs of permeation in both belts, and it can be seen in the field. Like the net-texture it requires more than the average amount of mica in order to show its best development. Unlike the net-texture the felspar and quartz instead of re-crystallizing in place grow together in eyes and streaks which open up the schistostiy of the rock. The schistosity is diverted but the individual micas, except those occasionally found in the eyes and some along the edges of the eyes, do not change their crystallographic orientation relative to one another. Within the eyes the felspars, except where they interfer with one another, show dominant crystallization with respect to the quartz. The proportion of quartz to felspar appears to increase from very low outside the permeation belts to very high in a few of the permeation rocks within the belts. The average eyes are probably 50quartz:50felspar. Some of the eyes are single felspar crystals, but the most prominant of these are microcline and will be described later.

Streaks and eyes of quartz and felspar growing in otherwise metamorphic looking rocks of all compositions from pelites to semi-pelites are the most common rocks of the Scatsta belt. As the numbers of streaks increase so the micaceous or metamorphic streaks separating the eyes get thinner

till eventually the rock is composed of streaks and eyes separated by micaceous partings. The number of streaks and eyes per unit volume of the rock varies from very few to so many that the rock is almost a granitoid permeation rock with a schistose look given to it by small relic streaks of the old micaceous partings. These latter rocks are not at all common in the Scatsta belt.

The net-texture described above is also only a preliminary stage in the permeation of the rock. Apparently after the initial development of the net-texture the rock becomes progressively coarser, more quartzitic and less biotitic until it is a typical granitoid permeation rock. To exhibit the typical net appearence the rock must be moderately mica rich. The semi-pelites can re-crystallise in the same way to a granitoid permeation rock without a noticable net-texture stage. The end stage of permeation in the Colla Firth belt appears to be a coarse granitoid permeation gneiss with sub-rectangular felspars contained in a matrix of randomly orientated micas and large quartzes which fill in the gaps between the micas and the felspars.

The permeation acting in these two ways tends to produce eventually rocks similar in aspect and in composition from similar materials. It is possible therefore that whilst the causes of permeation were the same in both cases the conditions under which permeation took place were different. Various reasons for believing that permeation took place at a higher

temperature in the Colla Firth belt are suggested on pps. 90-2. It should also be noted that the development of quartz-felspar eyes and streaks, the typical permeation of the Scatsta belt, is confined more or less to the edges of the Colla Firth belt. It is best developed on the north shore of Coll Firth, where the coast passes obliquely across the south border of the big outlying permeation lens, photos. 19, 20, and 21. It is also very frequent along the shores of Swining Voe, where the edge of the Colla Firth belt lies parallel to the shore. There are never any signs of streaking in the granitoid permeation rocks and even porphyroblastic felspars of large size are uncommon. If these arguements are valid, then it can be said that with increasing ~~intensity~~ temperature, but not necessarily with increasing intensity of permeation, the permeation becomes more penetrating and develops more strongly the power to recrystallize the rocks completely, as ppposed to only recrystallizing small separated streaks of it.

But this throws no light on the reason for, the cause of, or the significance of permeation. The results of permeation are:-

1 considerable increase in grain size.

2 a tendency, very strong in the Coll Firth rocks, to complete loss of preferred orientation of the micas and to loss of all structures in the rocks, i.e. lineations, bedding, composition banding.



Photo 19. Streaky permeation rocks, north side of Colla Firth.
Colla Firth Permeation Belt.

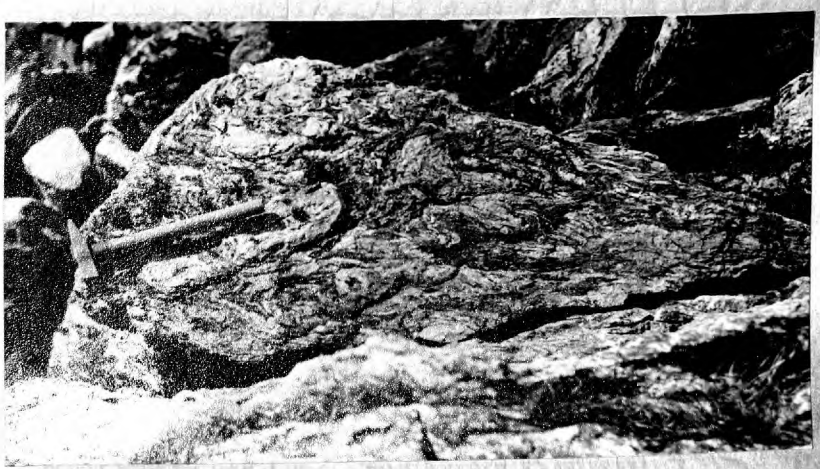


Photo 20. Contorted streaky permeation rocks, north side of Colla Firth.
Colla Firth Permeation Belt.

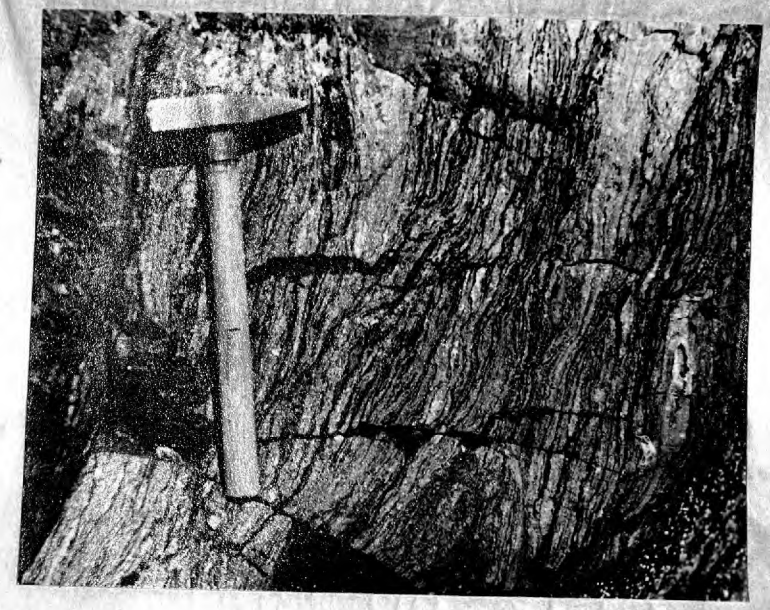


Photo 21. Streaky permeation rock, north side of Colla Firth.
Colla Firth Permeation Belt.



Photo 22. Streaky permeation rock, Mossbank.
Scatsta Permeation Belt.

3 a tendency to standardisation of the composition of the felspars.

4 a tendency to standardisation of the composition of the rocks.

5 a re-crystallization during which the felspar has played a dominant role.

The most important mineral appears to be felspar. Its behaviour is such as to indicate that a felspathisation of the rocks has taken place. But facts quoted above show that the composition of the felspars as a whole remain unchanged. Furthermore the permeation areas may be no more felspathic than the metamorphic areas. But whether the area as a whole has been felspathised or not the changes in the rocks which together are called permeation are ones of homogenisation and especially in the Colla Firth belt are towards isotropism. The apparent isotropism of the more strongly permeated rocks indicates a lack of directed movement in the rocks during the permeation. But the presence of relic micaceous streaks etc., especially those in the rocks of the Scatsta belt may indicate that the permeation had insufficient energy to re-crystallize the rocks completely, rather than that there was movement in the rocks to give the micas their preferred orientation. The two main processes which give rise to this ~~increase~~ change towards homogenisation and isotropism, are the felspar standardisation (or felspathisation ?) and the

recrystallization. These processes may not be as closely related as they appear at first sight, because there is no very close agreement between the felspar composition of the rock and the amount of permeation it has undergone as measured by its appearance in the hand specimen; some of the most strongly permeated rocks are those with felspars of compositions farthest removed from the average.

The rocks appear to re-crystallize towards a structurally isotropic fabric, which indicates crystallization under mechanically static conditions. But there are a number of structural indications of movement in both belts. Some of these are described on pps. 27-8. They consist of a certain amount of folding in the metamorphic rocks alongside the Colla Firth permeation belt and in small drag-foldings in the streaky rocks in both the ~~Saee~~ Colla Firth and the Scatsta areas, photos 19 and 20. Further more in the Mossbank region where the Scatsta permeation appears to reach its greatest intensity, there are signs of an even more intimate mobilisation of the permeated rocks, 22, 23, 24, and 25. Similar signs of mobilisation are found along the north shore of Firth Voe. The movement ~~is in all cases~~ necessary to form these structures is in all cases very small. They could all be the result of a local relatively slight plastic flowage. The movements involved can in no sense be compared with those pperative during the regional metamorphism.

MICROCLINE IN THE COLLA FIRTH AND THE SCATSTA PERMEATION BELTS.

Map25. Microscopic examination of these rocks shows that microcline is an important mineral in many of the rocks described above. It occurs in all amounts from a mere trace to that of a major constituent. But it almost invariably appears to have developed after the state of the rocks described above had been established. The microcline occurs most frequently as tiny shreds and as small elongate grains growing out from the intergranular net apparently by replacement. The outline of these small grains and of the larger grains and even of the porphyroblasts into which they frequently develop, is extremely ragged due to the outgrowth of innumerable pointed and even almost hair-like processes. This form is particularly well shown where the microcline is growing beside plagioclase. It does not appear to be able to replace quartz or the micas so easily and does not usually show a ragged outline against them. Both quartz and the micas are frequently held as inclusions inside the larger microcline grains. Myrmekite is found quite often in the rocks, but it occurs in rocks which do not contain microcline as well as in those which do. Furthermore it is not confined to microcline-plagioclase contacts. Where microcline is in contact with myrmekite it is generally separated from it by a smooth rounded outline , which is convex against the microcline. Thus the

Photo 23. Mobilised permeation rocks, near Mossbank Church. Scatsta Permeation Belt.



Photo 24. As photo 23

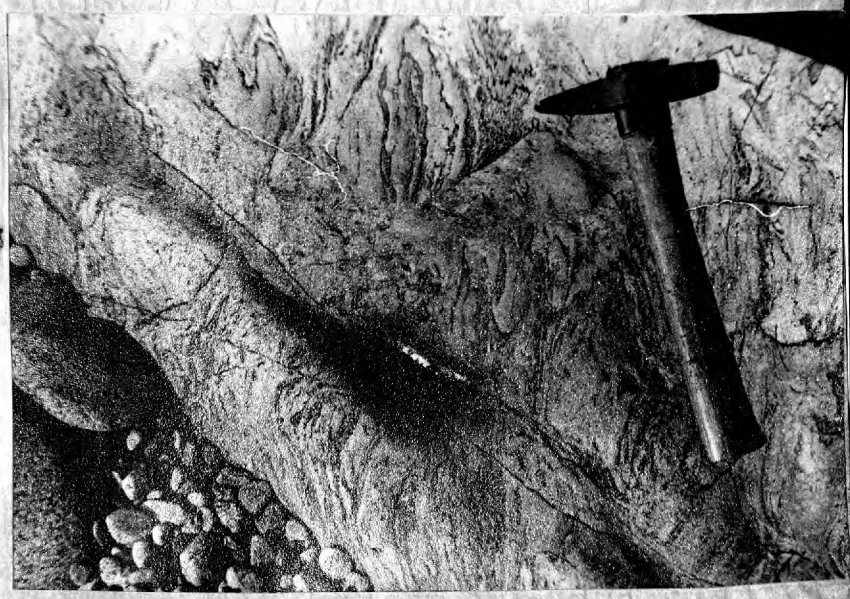
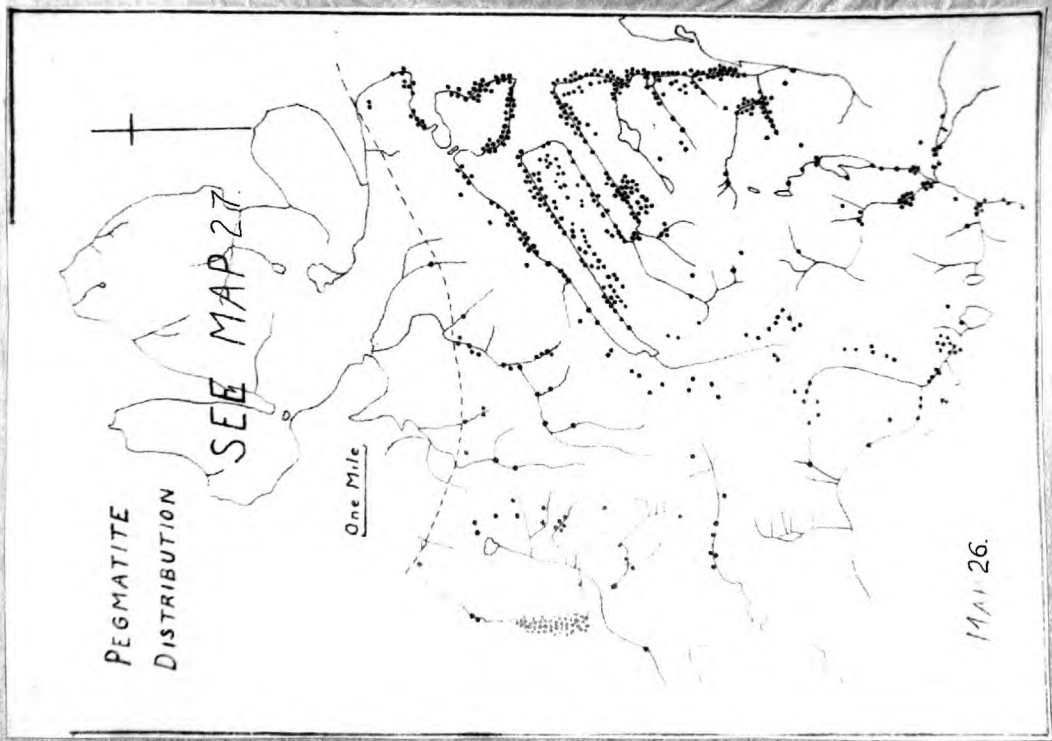


Photo 25. Mobilised permeation rocks,

Mossbank.

Scatsta Permeation





relation of the microcline to the other minerals is the same for the permeation rocks as for most of the metamorphic rocks.

Just as streaks and eyes of quartz and felspar are much less common in the Colla Firth belt than in the Scatsta belt, so are porphyroblasts of felspar. Only in one area are such felspars found in the Colla Firth belt, other than as isolated occurrences. This area is that of a linear series of exposures arranged from north to south and lying immediatally to the east of Loch of Voe. In some of these exposures the rocks seem to have been so permeated that they have lost all traces of their origin; they may be described as granites. Some of these rocks contain porphyroblasts of microcline between ½" and 1" long.

In the Scatsta belt large felspars are much more common in the rocks. Some are of plagioclase, but there are a number of remarkable occurrences of very porphyroblastic rocks in which the microcline is the most noticable mineral. The most remarkable of these rocks is called the Augen Gneiss, see map 24. This rock forms a "bed" not more than 20 feet wide which can be traced with one or two gaps all the way from a hillside just north of Wethersta along the strike to the sea just to the south of the Graven Intrusive Complex boundary on the south shore of Firth Voe. It can be found in all the streams which cross its course and provide exposures. From south of Graven to where it disappears north of Wethersta it forms a topographical feature, in the form of a small

valley or gully which can be recognised both in the field and on air photos. In all exposures this rock has the same extremely characteristic appearance. It is poor in mica compared to the other permeated rocks, and contains very numerous oval to rectangular felspars about ½" long which are orientated parallel to the general schistosity and bedding, and which are seem to have carlsbad twinning. This rock is very similar to the great granite sills in the west face of Tonga in the Valla Field block of Unst (Read, 1934, p.646). In thin section it appears originaly to have been a quartz-plagioclase rock with sparsly distributed tiny biotite flakes which give it a weak schistosity . The plagioclase felspars are large and well formed, that is they are rectangular except where they interfere with one another. In all the sectioned rocks the establishment of this fabric has been followed by a development of microcline so extensively that it is now the chief mineral in the rock. All the felspars are being eaten into and replaced by the microcline, which occurs on all scales from enormous porphyroblasts with the usual ragged edges to tiny veins along the palgioclase edges. As the microcline grows outwards it appears to break up the plagioclase into smaller disorientated grains, and to cause the microcline shreds and grains in its path to recrystallize into crystallographic continuity with itself. The Augen Gneiss band forms the southern most limit of dominant permeation in the main part

of the Scatsta belt. The proportion of permeated rocks to metamorphic rocks drops suddenly to the south-east of the Augen Gneiss although locally small lenses of permeation do occur.

The other porphyroblast rock is called the Porphyroblast Schist. It is found locally along the north side of the main part of the Scatsta Permeation belt, map 24, photos 26, 27, and 28. It occurs just south of Voxter Voe, in two places 1 mile to the south-east of Calna Taing, and in a number of places in the Mossbank region. It may have formed a continuous band like the Augen Gneiss, until the intrusion of the Graven Intrusive Complex, but it is neither so well exposed nor so definite a rock type as the Augen Gneiss. The exposure south of Voxter Voe is of a rather pelitic rock containing numbers of rounded microcline felspars varying from an inch or more in diameter to three or four inches in diameter. The other exposures of Porphyroblast Schist contain felspars very similar to these but sometimes in a matrix which shows also the development of streaky permeation.

When the plagioclase felspars recrystallized in the course of the first described permeation, they did so in an apparently mechanically static environment, but in an environment which appears to have been ionically very mobile, since all the other minerals were forced to re-crystallize in conformity with the felspars. The completeness of this

Photo 26. Porphyroblast Schist, Voxter Voe. Scatsta Permeation Belt.



Photo 27. As photo 26.

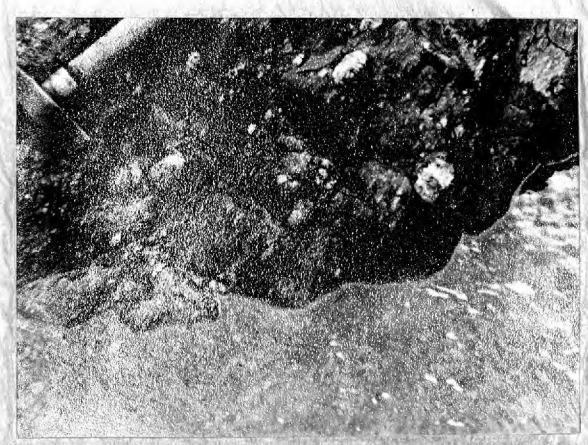


Photo 28. As photo 26.



recrystallization was considerably less in the streaky rocks than in the granitoid rocks. It was suggested that this is to be correlated with a lower temperature of permeation in the streaky rocks than in the granitoid rocks. When the microcline crystallized it was accompanied by no re-crystallization of the other minerals. The microcline grew by replacement in a solid rock under mechanically static conditions, and probably a relatively low ionic mobility. Where the microcline has a good rectangular form it has obtained it by consolidation of its own outline or by complete replacement of an originally rectangular plagioclase. Furthermore the style of the replacement is quite similar to that of the development of orthoclase after plagioclase in rocks exposed on the bed of the ocean,(Mellis, Otto Nature, 1952, p 624) It is quite possible therefore that the development of microcline took place at a lower temperature than the permeation.

Twenty-four of the 99 rocks from the Scatsta belt which were sectioned were found to contain microcline, but 12 of these were samples of Augen Gneiss and of Porphyroblast Schist. Forty of the 64 Colla Firth rocks which were sectioned contained microcline. That is 12% of the normal Scatsta rocks against 60% of the Colla Firth rocks contain microcline. This fact taken in conjunction with the possible low temperature of development of microcline may mean that the potash metasomatism was not directly related to the permeation. It was not for instance

/ the crystallization/

the crystallization from the intergranular film by cooling, of potash previously displaced by a Na permeation, since the Scatsta permeation was not followed by a general potash metasomatism. Furthermore several belts or areas of microcline development in the semi-pelites, were described above, pps 40-1, map 14. Although a number of possible derivations were suggested for this microcline, it is quite possible that, for instance, the belts along the north shore of Dales Voe and along the east edge of the Colla Firth belt, may be ~~belts of potash metasomatism~~ equivalent to the belt of potash metasomatism co-incidental with the Colla Firth belt. The similarity in appearance of the microcline in the metamorphic rocks and in the permeation rocks indicated that it developed in both the metamorphic and the migmatitic rocks under very similar conditions. There appears to be no reason why the potash metasomatism should be confined to, or even occur at all in permeation areas. The establishment of the permeation belts without regard to the intensity of the regional metamorphism, is therefore matched by the still later potash metasomatism which appears to have been established without regard to the belts of permeation or the regional metamorphism.

Reasons were given above, pps 35-6, for supposing that the development of the late muscovite was also an effect of potash metasomatism. Late muscovite occurs less commonly in permeated rocks than in metamorphic rocks and it is much more widely distributed in metamorphic rocks than

is microcline, maps 7, 14, and 25. The late muscovite in these permeated rocks resembles that in the metamorphic rocks, pps. 33-34. It occurs in the same manner in the permeated and in the unpermeated parts of the rocks as well as within the quartz-felspar streaks and eyes. It shows its usual good outline against all other minerals. In several sections it can be seen to have grown across large well formed plagioclases. Therefore the late muscovite developed after the permeation. But its relation to the microcline is obscure; the two minerals appear to avoid one another. In one section where they are in contact the late muscovite is symplekitic at the contact. In another section they both include and cut oneanother. The development of the microcline is almost confined to rocks of semi-pelitic composition whilst the late muscovite is best developed in pelitic rocks. The two processes may or may not be related.

PERMEATION OF OTHER ROCK TYPES IN THE SCATSTA AND THE COLLA FIRTH BELTS.

IMPURE QUARTZITES.

The ~~above~~ descriptions given above apply to the semi-pelites and pelites and their permeated derivatives. But impure quartzites also occur within the permeation areas and are relatively unaffected. The great belt of quartzite traced from Point of Mulla to the sea north of Fora Ness may have been a major factor in the limitation of the advance of migmatisation to the south-east. The occurrence of pods of permeation of more pelitic rocks within the general quartzite area shows

that quartzites did not form a barrier. They have limited the advance of the permeation simply by failing to be permeated themselves. The beds of quartzite within the main development of permeation are frequently unaffected, sometimes re-crystallized to glassy extremely coarse rocks, and finally sometimes have streaks of coarse re-crystallization within which the proportion of felspar has risen to equal to that of the quartz, and at the same time the felspar has tended to develop its own outline.

EPIDIORITES.

The permeation of the epidiorites is somewhat more complex, even when the development of biotite and garnet is left out of consideration (see below) Two direct effects of permeation are found in the epidiorites, one of which is the development of quartz-felspar streaks or eyes in the rock. These streaks and eyes are on a much more reduced scale than the streaking developed in the pelitic rocks. They are developed in only a small proportion of the epidiorites in the permeation areas and the streaks themselves are relatively insignificant and few in number in the individual rocks. The strongest development is perhaps that to be seen in an epidiorite on the extreme north tip of the Mossbank peninsula. This rock is cut by a system of very thin quartz-felspar veins which tend to break up the rock into rectangular fragments. If these veins became strongly developed the rock would be an example of a normal agmatite. Usually however, the quartz-

felspar streaks tend to follow the schistosity of the rocks.

The other effect of the permeation is the development of small eyes or areas of reaction. They are much less common than the quartz-felspar eyes. In thin section they can be seen to be composed not of quartz and felspar but of such minerals as clino-zoisite, epidote, felspar, hornblende, apatite sphene and in one or two cases some pyroxene. Within such areas of reaction the original hornblende-rich felspathic rock has been re-crystallized , and most of the hornblende has disappeared but sometimes odd grains of very pale coloured hornblende occur. The felspar is also recrystallized to a much coarser grain size and generally is extremely sericitised. Most of the space is taken up by clino-zoisite and/or epidote, both of which , and especially the latter may be symplektitic. Very large apatites and sphenes are frequently present. The hornblendes along the edges of the areas are frequently re-crystallized to a lighter colour. These areas of reaction must replace previously existing minerals since there is no sign of the surrounding hornblendes being disturbed.

The metasomatic processes giving rise to these two types of reaction appear to be chemically similar, since the results, felspar and epidote type minerals are chemically similar. The physical conditions, i.e. the temperature, may determine which of the two minerals develops.

Epidiorites showing these types of alterations are restricted in their geographical distribution. They all

occur either within the main belt of dominant permeation in the Scatsta area or within the Colla Firth belt. Thus the epidiorites show the effects of permeation only in the areas of strongest permeation of the pelitic rocks, and even then the effects are very slight.

PEGMATITES.+

Map 26 shows the distribution of pegmatites. Most of these rocks occur as lenses or sheets in the bedding and schistosity of the metamorphic and permeated rocks. Quite often they occur as short fat lenses, in which case they can be seen to have opened up the bedding to make room for themselves, in much the same way that the quartz-felspar streaks in the streaky permeated rocks do. A proportion of pegmatites are, however, cross-cutting sheets. The great majority of the pegmatites are between 1 and 2 feet thick, but several, especially along the shores of Dales Voe are more than 10 feet wide. The term pegmatite has been used here to denote a suite of rocks rather than one particular type of rock, because the rocks vary from aplites to extremely coarse true pegmatites. All however have a characteristic assemblage of minerals in which quartz and felspar are prominant while muscovite is usually present, which mineral assemblage has an indescribable but very characteristic

+ Other than those in the area of the Graven Intrusive Complex.

appearance. Muscovite, biotite, tourmaline, and rarely garnet in that order of decreasing importance are the chief minerals accompanying quartz and felspar but only muscovite is ever of sufficient importance to be considered as a major constituent. A few of these rocks are schistose. Thin section examination shows that the plagioclase felspar is almost invariably between Ab95 and Ab90 in composition . It also shows that the great majority contain microcline, such microcline invariably showing a replacement relation to the plagioclase. The presence of the microcline can sometimes be detected in the field because during the dislocation metamorphism it tends to become reddened; this reddening is not detectable in thin section or accompanied by any apparent breakdown of the felspar.

A number of sheets of rock occur in the region which are perhaps more accurately described as granites or as granitic pegmatites than as pegmatites of aplites. The quartz, muscovite, and felspar are of equal grain size and habit in these rocks, most of which occur in an area along the general strike south of Laxo Water, and most of which are schistose. They are usually wider than the pegmatites, one at Laxo being 17 feet wide. One of these foliated ~~pegmatites~~ granitic rocks was found to be cut by a normal tourmaline pegmatite.

This latter occurrence, taken together with

the following facts:-

1 the presence of innumerable, undeformed pegmatites both cross-cutting and conformable in areas of strong permeation,

2 the occurrence of schistose pegmatites in permeated and unpermeated areas,

3 the occurrence of pegmatites soaking the metamorphic rocks, pps. 104-5, near permeation areas,

all indicate that the pegmatites have probably developed throughout the development of the permeation or at least at a number of different stages during the course of the permeation, though most of them must have been formed before the potash metasomatism.

The abundance of the pegmatites in the Colla Firth belt, map 26, provides yet another distinction between the Colla Firth and the Scatsta belts.

The concentration of pegmatite shown north of Voxter Voe contains considerably more pegmatite than occurs anywhere else south of the Graven Intrusive Complex and is probably therefore unrelated to the Scatsta permeation. The coast line to the north of Voxter Voe contains considerable quantities of pegmatite, mostly occurring as parallel sided regular sheets, parallel to the strike and to one another. These pegmatites contain felspar, quartz and some microcline and muscovite. In the normal metamorphic rocks the sheets vary up to 5or6 feet in width. But in the Striped Impure Quartzites they form innumerable sheets about 1" thick, all

exactly parallel sided and parallel to one another, all in a vertical plane and all cutting obliquely through the schistosity and foliation of the Striped Impure Quartzites at about 5°, photo 1. A thin section of one of these pegmatites shows that it contains felspar of composition about Ab80 and that the felspar is being replaced by microcline which forms numerous small ragged edged grains both in and around the plagioclases. This attack by the microcline extends in an exactly similar manner into the contacted quartzites for several mms. and then dies out rather suddenly.

PERMEATION OF ROCKS WITHIN THE AREA OF THE GRAVEN INTRUSIVE COMPLEX.

The descriptions given above of permeation refer to rocks of the Colla Firth and the Scatsta belts. But within the area of the Graven Intrusive Complex additional examples of permeated rocks may be found. The poor exposures and the presence of later magmatic rocks make it impossible to decide whether these form belts or not. The nature of the permeation in this area is further obscured by the effects of the contact metamorphism by the Graven Intrusive Complex, which , by the crystallization of new minerals such as sillimanite and pyroxene, and by the recrystallization of old textures, has destroyed all evidence of the effects of the permeation on the unpermeated metamorphic rocks. Most of these permeated rocks, apart from the effects of later contact metamorphisms are indistinguishable

from the streaky permeation rocks of the Scatsta belt, and were probably formed under the same conditions as the Scatsta rocks.

But there is another very distihctive type of permeation rock which occurs in the general area of the Graven Intrusive Complex. It is found at its best at Calna Taing, in the west just outside the southern most limit of the Graven Intrusive Complex. It is found again on the coast to the north of Fugla Ness. Rocks which are somewhat similar may be found near to Garth House, and scattered over the Calback Ness region, but this resemblance may very well be fortuitous. In the Calna Taing region the transition from metamorphic rocks to these, the Calna Taing type of permeation rocks, is rather sudden. For some distance to the south of the boundary separating the metamorphic rocks from the Calna Taing rocks, well bedded moderately fine grained homogeneous semi-pelites are the dominant rock type. Then suddenly and without warning , within 12 feet measured across the strike, the change takes place; the rocks ~~are~~ have become massive. The metamorphic rocks were in beds as thick as 3 feet, but in the Calna Taing rocks all signs of bedding are lost and joints become the dominating structure. Otherwise the rocks are apparently unchanged. A few yards farther on, the typical Calna Taing rocks are fully developed, photo 29. They appear to be slightly more coarse tham the original semi-pelites, and they are schistose, the latter feature being emphasised

Photo 29. Calna Taing type permeation rock, Calna Taing.

when horizontal surfaces are viewed, by the development of innumerable tiny eyes. In fact the eyes are more in the nature of rods which plunge steeply within the schistosity. From where this rock is first developed to the Graven Intrusive Complex boundary, a distance of ½ a mile, there is no other type of rock and no variation in this one type which is, for ½ a mile perfectly homogeneous and absolutely invariable. However map 24 shows that the schistosity which dips at 70° to the south-east is sub-parallel to the coast, so that the thickness of rock exposed is much less than ½ a mile. Exactly the same type of rock is exposed on the coast to the north of Fugla Ness, but here it tends to be intercalated with other rock types, and its continuity is also upset by the Inclusion Granite. In thin section these rocks have characteristic features also. They are all of semi-pelitic composition. Felspars in three of the rocks were determined :- two are between Ab90 and Ab 70 and one is Ab67. They are all usually fairly schistose due to parallel orientation of the biotite, (no muscovite of any description was found in any of the sectioned rocks) and to very fine hair-like quartz layers which are visible in the hand specimen with a lens but are not so apparent in thin section. In slices the individual quartz grains can be seen to be very elongate parallel to the schistosity. These rocks differ from the semi-pelites in the frequency with which the felspar shows a good definite shape (as in the permeated rocks) and even forms small eyes. But the average

grain size is little greater than that of many semi-pelites. The rocks thus combine the characteristic features of both the regional metamorphic rocks and the permeation rocks. They apparently have the same fabric as the regional metamorphic rocks, i.e. they are B-tectonites, and they have the same grain size as the regional metamorphic rocks, but they show the characteristic dominating crystallization of the felspar of the permeated rocks. They may therefore be the result of synkinematic permeation, in contrast to all the other permeated rocks which appear to be postkinematically permeated rocks. If this is the case then it is possible that the Calna Taing rocks were formed earlier than the rocks of either of the two main permeation belts.

All 10 rocks of this type which were sectioned contain microcline, which varies in amount, but is frequently the chief mineral in the rocks. The microcline always bears the same relation to the plagioclase as it does in the other permeated rocks, but it is usually far more strongly developed.

BIOTITE AND GARNET IN THE EPIDIORITES.

As is shown in map 23 a large proportion of the epidiorites in the north-west part of the thesis area have been converted to biotite garnet schists. This change is considered here because the phenomen is in part at least one of metasomatism.

The main area of biotite garnet development lies to the north-west of the line from just south of Voxter Voe to just south of Firth Voe, which is drawn on map 23. But both garnet and biotite do occur in epidiorites to the south-east of this line. Biotite and garnet occur in some epidiorites along the edge of the Colla Firth permeation belt. The strongest development is as usual in the Colla Firth - Fora Ness region. The regional metamorphism of this latter area is higher than elsewhere in this permeation belt, but the biotite and garnet development cannot be related to the regional metamorphism on those grounds since both minerals are very poorly developed in the main garnet zone west of the Weisdale Limestone. The biotite and garnet along the edges of the Colla Firth permeation belt are probably therefore related to that permeation. Biotite and garnet do not appear to have developed in epidiorites in association with the Scatsta permeation, unless the local concentration of biotite-epidiorites in the general region of Wethersta is due to this cause. The localisation appears to make this unlikely.



Photo 30. Garnetiferous epidiorite, Fugla Ness.



Photo 31. Garnets on a semi-pelite bedding plane, north side of Voxter Voe.

All the occurrences of biotite and garnet mentioned above are relatively minor affairs, since the minerals are only seen with difficulty in the hand specimen if at all. But to the north-west of the Voxter Voe - Firth Voe line many of the epidiorites have been more or less completely changed to biotite - garnet schists. The complete change is confined to three areas;: the entrance to Voxter Voe, part of the coast north of Voxter Voe, and a place to the north of Fugla Ness, in which latter place only a few epidiorites have undergone the complete change. But even in the Voxter regions many of the rocks have not been completely changed or for that matter have developed both or even either of the minerals.

The garnet is seen in the field to have an extremely erratic occurrence. The garnet crystals vary in size from 1/16" to nearly 1" in diameter, not only in nearby intrusions but even within the same intrusion in a number of cases. Garnet is usually distributed evenly throughout the rocks but where this is not the case , the distribution is without any determinable rule. Especially within the areas where complete biotitisation is common, and occasionally outside them garnets up to 1" in diameter develop across the contacts between epidiorites and the neighbouring semi-pelite beds, which in those areas do not normally develop garnet. In the coast near Voxter it is common to see semi-pelites with their bedding planes covered with garnets which stand out in relief,

where the biotite-garnet schist has been preferentially ~~developed~~ eroded. In areas where macroscopic garnet is poorly developed, it is often restricted to such a mode of occurrence.

Biotite behaves in a more regular manner than does garnet. The end/product of biotitisation is a coarsly crystalline schist with a rich dark brown colour, which generally enables the rock to be distinguished from the pelitic schists, which latter besides never develop garnet to the same extent or size as do the epidiorites. Biotite is not always evenly developed in the individual epidiorite bands. It is frequently confined, as far as can be seen in the field, to a selvage an inch or so thick along the edges of the epidiorites.

In thin section the most noticable feature of these rocks is the biotite fabric. In most rocks, ~~however~~ in which much biotite is developed, that biotite is extremely well orientated. It forms a very good schistosity directly related to the hornblende orientation. When the hornblende can be said to form a schistosity, that schistosity is parallel to the biotite schistosity. But in the rocks in which biotite is best developed, a proportion of the flakes are arranged with their 001 cleavage at 90° to the schistosity. Although/in several of the rocks there is no preferential orientation of the biotite, most of the rocks appear to be unaffected by the contact metamorphism by the Graven Intrusive Complex.

Map 23 shows that with the exception of two cases the garnet lies within a zone of biotite def development. But

the assemblage list shows that on the scale of the thin section it is quite common for garnet to develop without biotite being present and vice versa. It would therefore seem that they are dependant on the same controls but are sometimes if not always independant of one another.

It is possible to say with some certainty that the developemnt of garnet is in no case in response to the regional metamorphism, further more it does not appear to be a bi-product of the processes producing biotite from hornblende, and finally it can be said that in many cases the garnet has grown for much of its history in a rock containing hornblende, although it may now contain within its bounds all the hornblende left in the rock.

For the biotite it can be said that in the great majority of cases it is due to potash metasomatism. A few rocks south of the Voxter Voe - Firth Voe line may contain biotite due to an original potash content (as has been suggested for biotite in epidiorites elsewhere) but most contain so much biotite that this origin is ruled out. The addition of potash was accompanied by addition of water and the almost complete loss of calcium, since in completely biotitised rocks the rather sparsely occurring sphene and felspar are the only calcium minerals left. In such rocks there is a tendency for quartz to increase and for felspar to decrease in amount.

The domain of the main biotite-garnet dev-

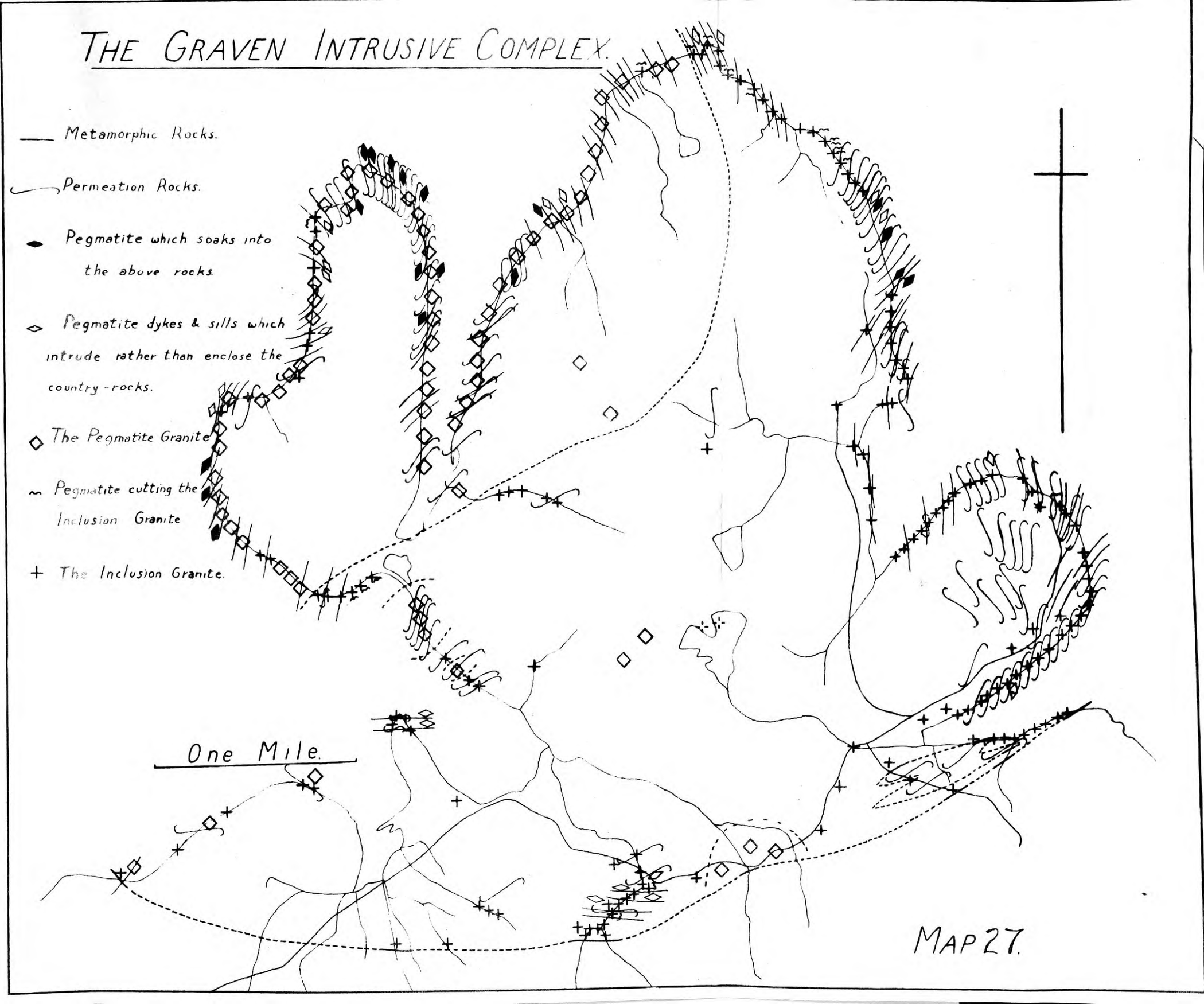
elopment is utterly dissimilar to the domains of any other metamorphism, permeation, or event which has taken place in Delting. It must therefore be unrelated in time to any other known episode in the area, and must be considered an episode in its own right.

CHAPTER 6.

THE GRAVEN INTRUSIVE COMPLEX.

The Graven Intrusive Complex occupies all that part of the thesis area which lies to the north of a line from just north of Calna Taing to the south side of Firth Voe, map 27. It also extends outside the thesis area into various islands and onto the east coast of North Maven. The complex was emplaced in three main stages, each stage being marked by the emplacement of a particular rock type or suite of rocks. The intrusion of the Pegmatite Granite was followed by that of the dyke rocks and finally by that of the Inclusion Granite. The relations of the three rock types to one another are obvious in the field, but just as it was found impossible to delimit the domains of permeation within the Graven Intrusive Complex, so it is impossible to draw boundaries between the two main rock types, the Pegmatite Granite and the Inclusion Granite. The lines which have been drawn on

THE GRAVEN INTRUSIVE COMPLEX.



MAP 27.

map 27 merely separate areas dominantly occupied by the two different types, and are not intended to represent the actual contact between the two or to show the structural relation of the one type to the other. The boundaries can only be guessed at because within the outcrop of the Graven Intrusive Complex there are (except in the Mossbank region) virtually no inland exposures and the otherwise complete coast section fails between the main intrusive boundary north of Calna Taing and Calback.

THE PEGMATITE GRANITE.

The main area of the pegmatite granite lies to the north-west of a line from Calback to Mio Ness. Two small areas of very small similar rocks occur on the coast between Garth House and Calback, whilst to the east of Garth House and also against the south boundary of the complex to the east of Graven are areas in which only coarse pegmatite is visible. A number of pegmatite dykes cut the country rocks, (but not the Inclusion Granite) in the stream just south of Graven, and on the tip of the peninsula just north-west of Graven. Pegmatite is found along the coast between Graven and the main boundary of the complex north of Calna Taing. The exposures in this latter region are so poor that although it can be said that there is pegmatite present, no evidence of its relation to the other rocks can be cited. Pegmatite sheets cutting or conformable with the country rocks and even soaking into them are found at Mio Ness, in the Fugla Ness area, near Mossbank

and on the north shore of Firth Voe.

In the main area of the Pegmatite Granite, enormous quantities of pegmatite are exposed. Probably 50% of all the rocks in this area is pegmatite. A number of different pegmatites appear to be involved. The most plentiful is that which has been called the Pegmatite Granite, which occurs in very large masses. It is a very coarse pegmatite mostly made of felspar with some quartz, and with slight amounts of muscovite and even less of biotite. It is generally possible to detect two felspars. One of these is white, is always present and is generally not very coarsly crystallized. The other felspar is in various shades of pink and it is most frequently present as large blotches, which may either be multi-crystalline aggregates or single crystals. The constituent minerals differ quite considerably in grain size and in amount. Thin section examination shows that the white felspar is plagioclase which has the composition of oligoclase in the four sections examined. The pink felspar is microcline, which is clearly later than the plagioclase and is replacing it.

The Pegmatite Granite is distinguished from the other pegmatites mostly by its mode of occurrence in large masses. Along the coast south of Mio Ness it alternates with h the country rocks, each taking up stretches of coast 10 or even 30 yards long. Even greater stretches of Pegmatite Granite are found on the coasts of Calback Ness, whilst the

the masses of pegmatite east of Garth House and of Graven appear to be typical Pegmatite Granite. When the Pegmatite Granite occurs on this massive scale it is often possible to see that its contact with the country rocks is cross-cutting. But in many places the alternation of the Pegmatite Granite and the country rocks is much more frequent and in fact may take place several times within the width of the coast section. In all such exposures, it can be seen that the country rocks form blocks in the Pegmatite Granite, or that the Pegmatite Granite dykes the country rocks in all directions, the result being the same thing. The Pegmatite Granite sheets are of the same order of thickness as the blocks of country rocks which they separate. If the shape of the smaller exposed blocks is any indication of the shape of the larger blocks, then the latter tend to be equidimensional or at least tend to a largest diameter only several times that of the smallest.

Therefore enormous quantities of pegmatite rock have been intruded into an area of closely frattured rocks, in such a manner that the area has been expanded to at least twice its original ~~volume.~~ extent. It is not possible to say if the intrusion took place in a piecemeal fashion. The pegmatite, within certain limits, is variable, but its surface is so rough that it is rarely possible to trace the variations in the exposures. But in certain favourably weathered places, it can be seen that a number of slightly

different types of pegmatite cut one another. The pegmatite Granite may have been emplaced as a series of dykes, one injected across the other till the area was 50% pegmatite. This method of intrusion could explain the preservation of the structural orientation of the included country rock masses. It is not possible to determine how far these masses have preserved their original orientation relative to the rocks lying to the south of the Graven Intrusive Complex, but, as map 27 shows, the individual blocks have preserved their orientation relative to neighbouring blocks . The only blocks which do not show the general structural orientation are some of those which are only a few feet in diameter. But, as will be explained later, a piecemeal method of intrusion is not necessary to explain the preservation of the structural orientation of included masses in an igneous intrusion.

In places, especially in the Calback Ness area, the style of intrusion of the country rocks by the pegmatite seems to change. In these areas the pegmatite is in sheets generally only a few feet thick, which cut the country rocks in enormous numbers but which are often parallel to each other so that the country rocks instead of being broken up into blocks are cut up into sheets. The general effect is almost identical with that of the pegmatite intrusions of the Voxter region, except that there are no Impure Quartzites present,(pps. 130-131).

Yet another type of pegmatite is that which very slightly soaks into the country rocks instead of being sharply separated from them, as are the previously described types. These pegmatites are best developed in the north part of Calback Ness. Here the pegmatites cut up the country rocks on the same scale as previously but tend to fray out their edges especially where they cut across the strike of the rocks, photos 32, 33, and 34. A pegmatite type which very frequently shows a soaking relation to the country rocks is one which contains very large and very thin sheets of biotite, which give the rock the characteristic appearance of a number of crows foot prints, photos 33 and 35. This pegmatite was also found within large masses of Pegmatite Granite, where in one case at least it appeared to form cross cutting sheets.

The complex nature of the intrusion, the nature of the pegmatites themselves, and the intense dislocation metamorphism which occurs along much of the coast, together make it difficult to separate these different pegmatite types. But they all have in common, together with the pegmatites of the Voxter area, the fact that they occur in prodigious quantities. It is likely that the same conditions prevailed during their intrusion even though that intrusion may have been spread over a period of time. The first pegmatites intruded may have soaked into the country rocks because the latter were still hot. But the later intrusions of pegmatite, which differ little from the first, invariably cut the country rocks sharply

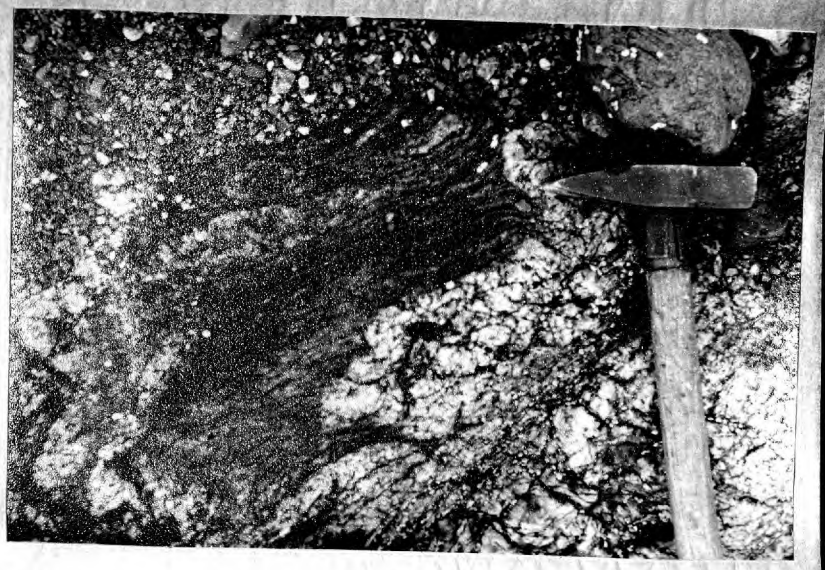


Photo 32. Pegmatite intruding migmatite and fraying it out at the contact, Skaw Taing.



Photo 33. A sharply bounded pegmatite sheet cutting biotite-pegmatite and migmatite Skaw Taing.



Photo 34. Migmatitic rocks frayed out by pegmatite. Skaw Taing.

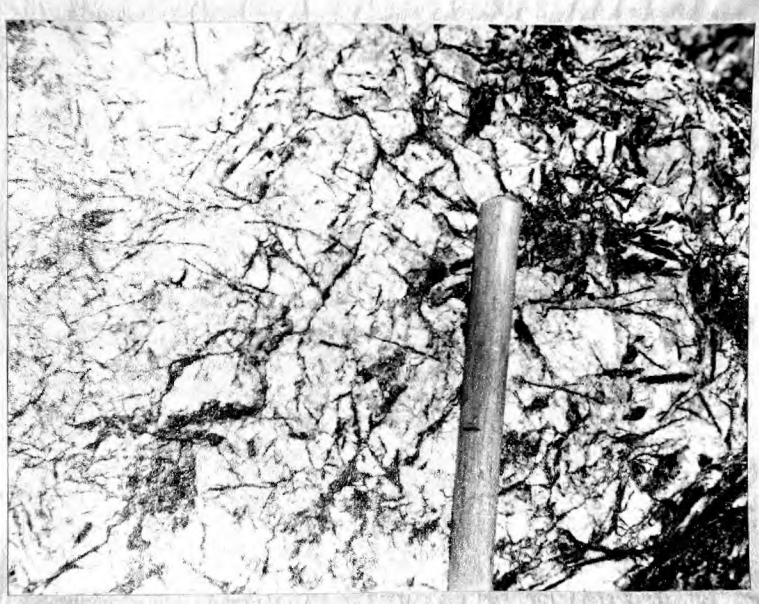


Photo 35. Biotite-pegmatite, near Skaw Taing.

and show no signs or reacting with them.

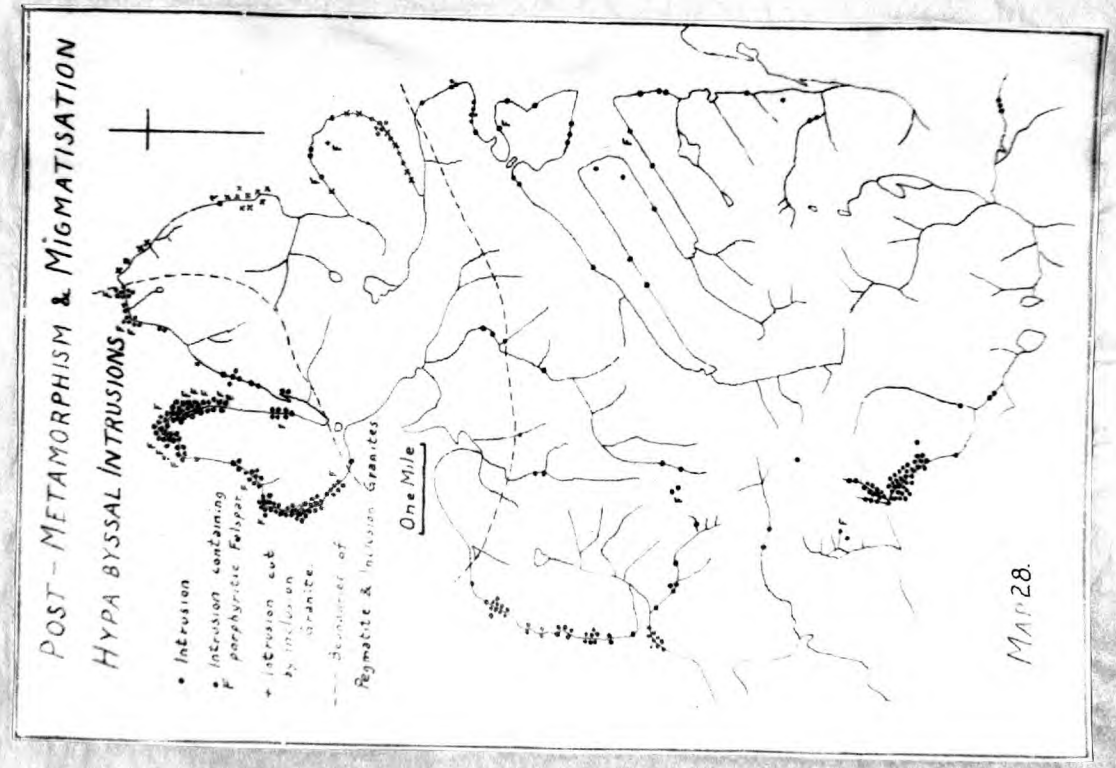
THE DYKE ROCKS.

The next stage in the history of the area is the intrusion of a very considerable number of basic dykes, map 26. The great majority of these dykes are only one or two feet thick, and they probably strike in all directions, although at first sight most appear to strike at 90° to the coast line. But the coast line direction is variable so that this apparent preferential orientation may be due to the fact that dykes striking parallel to the coast have less chance of being exposed, than those striking at 90° to the coast. The dykes are usually vertical and very regular sheets which cut straight through the country rocks and the pegmatites, but which are cut by the Inclusion Granite and are never seen cutting the Inclusion Granite. In a number of cases the dykes themselves are cut by the pegmatite and aplite veins an inch or two thick, even when they are themselves cutting through pegmatite, photo 36. These veins, which also cut the Inclusion Granite, must have been emplaced much later than the Pegmatite Granite.

The dykes occur most profusely in the Calback Ness region which is also an area of very strong dislocation metamorphism. In consequence many of the dykes in this region are so rotted that they have the consistancy of partially consolidated sand. Even so it is possible to see that a number of them are schistose. In some of the rotted rocks the schistosity may be due to a relatively late shearing but in many others it is a

Photo 36. Pegmatite veins cutting a lamprophyre dyke in migmatites, Skaw Taing.





fabric which gives the impression in the field of having been imposed during the crystallization, in the same way that a regional metamorphic fabric does. The schistosity of many of the dykes is parallel to their contacts but in some the schistosity cuts obliquely across the dyke at low angles to the contact.

There are two main classes of dyke rock. One class is composed of lamprophyres and porphyrites. Many of these rocks are very typical lamprophyres, being fine grained dark to light cloured rocks containing randomly orientated phenocrysts of hornblende or biotite or both. Thin sections show that the dark rocks have a matrix of tiny felspars, generally with some quartz and with biotite and/or hornblende grains of similar size. As the proportion or biotite and/or hornblende in the matrix decreases so the rocks become lighter.coloured. A number of the lamprophyres are off-white rocks containing large biotite phenocrysts. The matrix of these rocks is entirely composed of felspar with some quartz. A large number of dyke rocks occur which appear to differ from the lamprophyres only in that they contain largeish rounded felspar phenocrysts as well as the mafic ones. These are the porphyrites. Composite dykes made of these rock types are found in several places. A double lamprophyre, a double porphyrite, a lamprophyre containing fragments of phenocryst-felspar-rich porphyrite, and a dyke with lamprophyre edges and a porphyrite centre which itself contains pegmatite fragments were observed.

Ten rocks, both lamprophyres and porphyrites, which were sectioned provided 8 felspar determinations of both phenocrysts and felspars from the matrix, all of which fell within the andesine range, mostly between Ab60 and Ab70. Thin sections also show that the schistosity of many of the rocks is due to the parallel orientation of the mafic phenocrysts. Both the phenocrysts and the ground mass minerals are perfectly fresh and undisturbed in such rocks thus indicating that the schistosity was imparted to the rocks by movements taking place during the crystallization.

The other group of rocks are all basic dykes. They differ from the lamprophyres primarily in the absence of mafic phenocrysts. They also ~~app~~ appear from their darker colour to be more basic, whilst no macroscopic felspars are visible. Like the lamprophyres they are variable rocks within limits; they are all relatively fine grained but show a wide range of dark shades of green and brown. A thin section of one of these rocks showed that it was made of hornblende with some felspar and it was therefore a micro-diorite. The field relations of these rocks are also the same as those of the lamprophyres but due to the lack of phenocrysts and to the very dark colour it is ~~not~~ not possible to see if they are schistose without the help of thin sections.

Lamprophyres, porphyrites and basic rocks identical with those described from the area of the Graven Intrusive

Complex are found distributed unevenly throughout the area covered by the thesis. But south of the complex they always occur as conformable sheets. Furthermore they are never cut by any other rock types, although they are disturbed by late dislocation metamorphism and occasionally have a schistosity parallel to their contacts.

The petrographic similarity and the similar occurrence of the dyke rocks of the Graven Complex and of the area to the south makes likely that they all belong to the same stage in the history of the area. Probably most of them were intruded after the Pegmatite Granite and before the Inclusion Granite.

The dyke rocks within the Graven Intrusive Complex are closely associated with the dislocation metamorphism. In one case a dyke appears to have been intruded into a shear and then to have been sheared itself. In other cases the dykes cross strong shear zones without shewing offset. The schistosity indicates movement during crystallization, whilst the oblique shearing indicated movement at a late stage in the consolidation of the dykes (Blyth, F.G.H., Q.J.G.S., 1950, p.416). Furthermore the discovery of sheared rocks recrystallized during the contact metamorphism by the Inclusion Granite also points to the conclusion that the dislocation metamorphism in Delting started at least as early as the emplacement of the dyke rocks and was well established by the time the majority of these rocks had been intruded.

THE INCLUSION GRANITE.

Map 27 shows that the distribution of the Inclusion Granite. The main mass lies to the south of a line from Calback to Mio Ness. Several other small masses, which cut both metamorphics and pegmatites, are found along the coasts of Calback Ness, photo 37. The Inclusion Granite is a moderately coarse grained plutonic rock with a magmatic habit and has a rather characteristic in the field, photo 38. It is a felspathic rock, speckled with hornblende and biotite, usually containing some quartz, and with a granular texture. It is called the Inclusinn Granite because it invariably contains many small inclusions; these are of two different types. The least common type are inclusions of metamorphic rocks similar to those which the rock itself intrudes. The more common type are basic inclusions which either have the appearance of recrystallized epidiorite fragments or, and making up the great majority, aggregates of a rich green hornblende which has the characteristic appearance of the hornblende of the zoned balls of Unst, Read, Min/Mag. 1934. Inclusions of all types are generally less than 1" in diameter, and very few are larger than 2" or 3". These inclusions are usually scattered fairly evenly ~~over~~ through the rock, but now and then concentrations of inclusions occur. In one place there is a very close concentration of angular fragments each several inches across, but usually the concentrations are of a mixture of the hornblendic and the epidioritic types, each being little bigger than a thumb nail. The other

Photo 37. Inclusion Granite cutting metamorphic rocks and pegmatites, Calback Ness.



Photo 38. Typical Inclusion Granite,

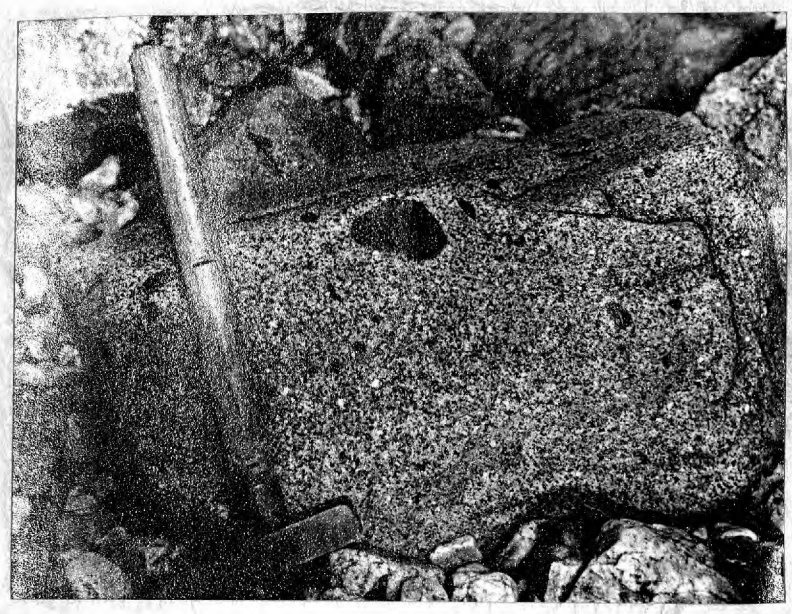


Photo 39. Inclusion Granite cutting migmatites and pegmatite streaked epidiorites, north shore of Firth Voe.



type of inclusion appears to be a slightly finer grained and rather darker version of the Inclusion Granite. It contains inclusions identical with those in the Inclusion Granite proper. Over much of the area the inclusions are roughly equidimensional and the granite as a whole appears to be structurally isotropic. But in a number of localities, for instance near Galback, to the south of Graven, on the south shore of Firth Voe, and both to the west and the ~~east~~ south of Mossbank, small areas of the granite appear to have a roughly schistose structure. The rock looks as if it had been slightly sheared on a vertical plane. The strike of this schistosity is always paralèl to the general stike of the metamorphic rocks and the migmatitic rocks, and it is sometimes accompanied by an elongation and parallel orientation of the inclusions.

Eleven hand specimens of ~~this rock~~ the Inclusion Granite were sliced, and all were found to contain biotite, which varied from brown to greenish-brown and was thus similar to the typical biotites of the permeation rocks. Rocks which are apparently biotite free are common in the field but they may contain microscopic biotite. Eight slices contain olive-green hornblende, but sections of the basic hornblende inclusions show that these are composed of pale slightly blueish green hornblendes and have a narrow rim of olive-green hornblende similar to that in the rock. Both the hornblendes and the biotites are usually well formed. All the sliced specimens

contain quartz although one has only a trace and all have less quartz than placioclase. The composition of the plagioclases was found to vary between Ab70 and Ab97. The felspars themselves are well formed, and have the same appearance as the felspars in a well developed granitoid type of permeation rock. They frequently show a very faint but nevertheless definite zoning. In a number of rocks some of the felspar grains look as if they are being replaced by felspars of similar composition. In one rock a fragment of zoned felspar is truncated by another felspar grain of approximately the same composition; this felspar may have been broken up during the intrusion of the rock. All the sections except one from a group of basic inclusions contain microcline, which varies from a trace mineral to the chief mineral in the rock. As usual, the microcline seems to be replacing the plagioclase. Mostly it forms grains no larger than the general size of the felspars and quartz, but in one case it forms phenocrysts up to 1" long.

The relation of the Inclusion Granite to the metamorphic and migmatitic rocks is exactly that of the Pegmatite Granite to the same rocks, except that the Inclusion Granite is distributed over the area less evenly. All the coast on the south side of Firth Voe from the main contact nearly to the head of the voe, is of Inclusion Granite. A similar long stretch of Inclusion Granite is to be seen between Mio Ness and Fugla Ness. But in many cases the fact

that the country rocks have been broken up into blocks which are now surrounded by Inclusion Granite is clearly demonstrated in the cliffs, photo 39. It is especially clear along the north coast of Firth Voe. Map 27 shows that on the whole the orientation of these rocks has been disturbed very little.

The strikes plotted on map 27 have been smoothed to a certain extent in some places. But whilst locally the blocks may have been somewhat disorientated (pps. 26-7) and whilst it is possible that some of the curves of strike of regional extent may be due to the emplacement of the magma, on the whole a very considerable quantity of magmatic rocks has been intruded in a very intimate fashion with no disturbance on a corresponding scale of the country rocks. It is possible that the Pegmatite Granite may have been intruded as a series of individual sheets. But there is no sign thatthe Inclusion Granite was emplaced in such a manner; there are no internal contacts visible in the granite, and the variations which it shows are themselves very vague.

The Graven Intrusive Complex therefore has a "ghost stratigraphy" which is produced by magmatic intrusion. But it is a rather poor example because there is very little stratigraphy in the rocks and because the almost complete lack of in-land exposures prevents the tracing of permeation areas for example from coast to coast. It is rather an example of a ghost structure.

It was shown above that the dislocation metamorphism was operative during the phase of dyke intrusion. In thin sections of Inclusion Granite there may be seen a number of large felspars which have been broken across and separated slightly. Quartz has crystallized in the cracks and in one particular grain this quartz can be seen to be an extension of and is in crystallographic continuity with one of the quartz grains of the granite. This latter occurrence probably indicates thatmovement took place in the granite when it was almost consolidated, but whilst the quartz was still capable of recrystallizing. These movements may be those which gave rise to the dislocation metamorphism.

The final act in the emplacement of the Graven Intrusive Complex is the intrusion, throughout the entire complex, of the aplite and pegmatite veins which cut the dykes and the Inclusion Granite, map 27, photo 36. These are mostly an inch or two thick, but north of Fugla Ness there is a late aplite one foot thick.

A number of other granite intrusions are found in the complex. A series of vertical sheets, 5 to 10 feet thick, lie immediatally to the south of the main boundary of the complex at Firth Voe, and strike parallel to that contact. They are mostly rich in felspar and poor in biotite. Many granite are found in the Pegmatite Granite area where they form thin sheets, irregular and indefinite, or regular and sharply bounded sheets, and sometimes small masses, all within

/the Pegmatite Granite/

the Pegmatite Granite, as well as in the country rocks. One at least of these sheets is cut by a basic dyke. Those observed in the area of the Inclusion Granite were cutting the metamorphic rocks and not the Inclusion Granite. Most of these granites are composed of equal proportions of biotite, quartz, and felspar and are of finer grain size than the Inclusion Granite. In the general area south of Graven and north of the complexs south boundary are some very hornblendic coarse grained rocks which contain spots of felspar and felspar-quartz.

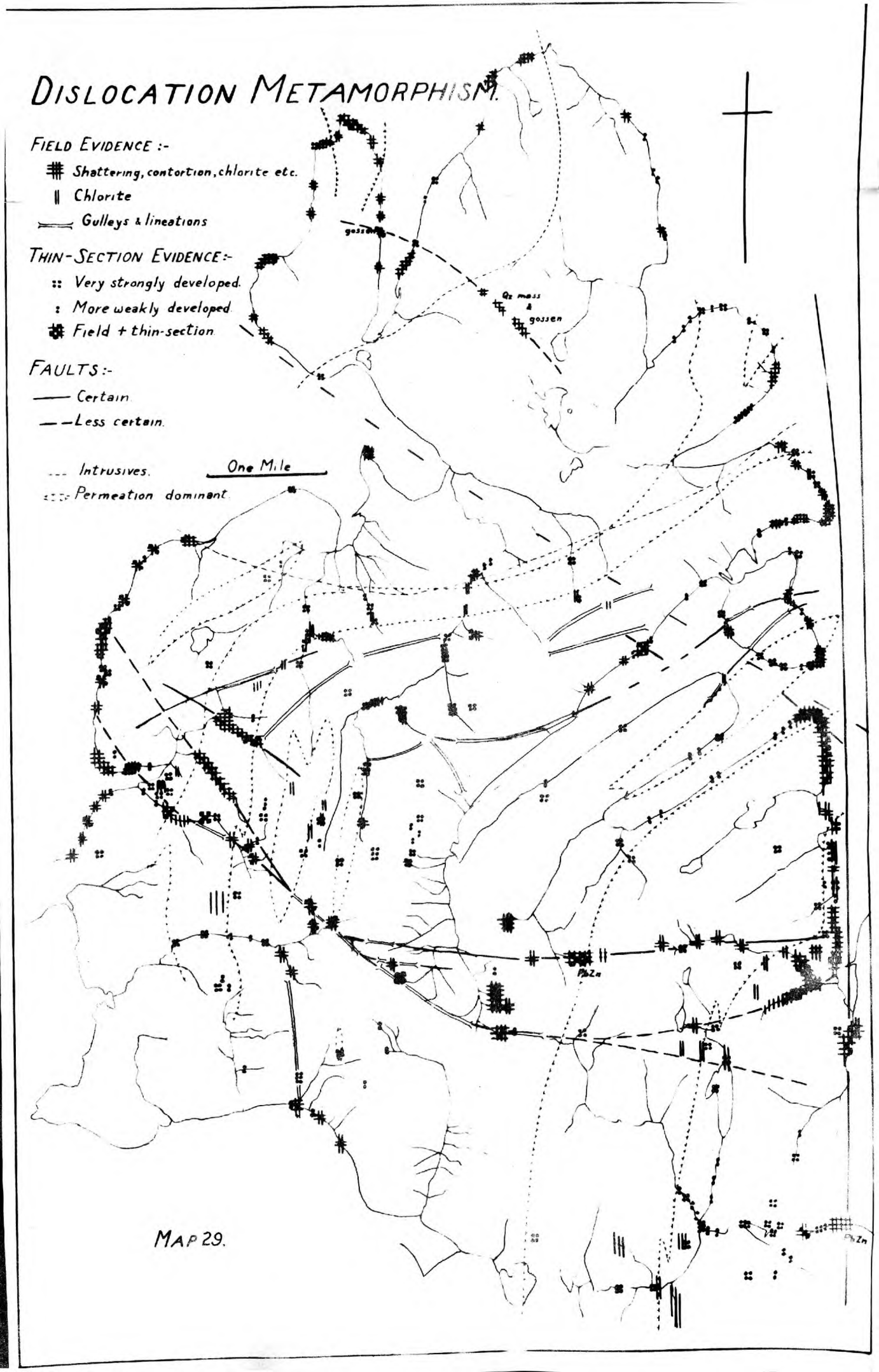
CHAPTER 7.

DISLOCATION METAMORPHISM.

The term dislocation metamorphism is used in this thesis to denote diapthoretic metamorphism associated with faulting and fracturing of the rocks, and thus does not include other types of diapthoretic metamorphisms, such as changes associated with the cooling of the rocks, which are not directly associated with faulting. This latter type of metamorphism has been described above in the chapter on metamorphism.

Dislocation metamorphism changes the rocks structurally and mineralogically. Both these effects can be recognised in the field. The mechanical effects vary over the area. The long stretches of dislocation metamorphism shown on the western coastline, map 29, are areas of intense shattering. The quartzites are broken into innumerable small fragments often without any displacement on the fracture planes. Less brittle rocks are more strongly altered and in fact are often

DISLOCATION METAMORPHISM.



MAP 29.

sheared into an unresolvable mess in these areas. The dislocation metamorphism is often accompanied by reddening of h the rocks some of which may be a general staining of the rock, but some is due to staining of sericitised felspar by a red pigment, possibly hematite, and some to the reddening of microcline. The biotite can often be seen to have changed to chlorite.

On the eastern side of the area the dislocation metamorphism has a different aspect. Shattering is much less common, and is confined to narrow belts crossing the coastline. Reddening is occasionally found but is confined to the felspars. The dislocation metamorphism on this coast is characterised by the development of chlorite, and by the contortion of the rocks near to the vertical shears which frequently cross the coastline. Dislocation effects such as these may also be seen throughout the area.

A number of topographic features termed "gullys or lineations" are marked on map 29. These are fairly prominant features such as cols, small valleys, very elongate boggy patches etc., which may be recognised both on air-photos and on the ground, and which are probably developed on the site of faults. They all cut across the strike of the rocks and so cannot be due to the underlying lithology. Many can be shown to be based on faults by the presence in them of exposures of shattered rock. The others are shown on the map because they are such

prominent features and may by analogy be related to the faulting.

The rocks can be divided into four groups for a detailed consideration of the effects of dislocation metamorphism. These groups are the igneous rocks, the epidiorites, the calcareous rocks, and the pelitic rocks, that is the pelites, the semi-pelites the impure quartzites and the permeated derivatives of these.

In pelitic rocks, the microscopic features which are interpreted as effects of dislocation metamorphism are as follows :- biotite changing to chlorite, sericitisation of felspar, strain effects finally leading to the crushing of the different minerals, development of epidote, zeolites etc.

The development of chlorite from biotite near to late fractures has been frequently described in the literature. It is an extremely common phenomenon in Delting, where it shows all degrees of development. The change is not a mechanical effect, although it is frequently associated with strong strain effects in the different minerals, since perfectly unstrained pseudomorphs of chlorite after biotite associated with unstrained biotite may be found in the same section. The converse case of chlorite-free biotitic rocks in which the biotite shows extreme contortion also occur.

The more or less complete breakdown of plagioclase felspar to sericite mats is very common in Delting. The complete change almost invariably occurs in belts of strong

dislocation metamorphism. The change is also frequently observed in the felspars alongside hair-like fractures in the rocks. For these two reasons, sericitisation is believed to be characteristic of dislocation metamorphism, although like the development of chlorite it is not a mechanical process since badly strained felspars are often seen to be unsericitised, and sericitisation frequently takes place in rocks which show no other signs of dislocation metamorphism.

Strain in crystals, best seen between crossed nicols, is very common. Scarcely one of all the 1,000 thin sections examined shows unstrained quartz. The effects of strain vary from wavy extinction, to the development of bands of equal extinction parallel to the c-axis (described by Eskola, Hietanen, Sander and others), incipient granulation of the individual grains and finally to a grinding up of the quartz to a powder. Strain in mica is somewhat less common and bent felspar twins are still less common.

The straining of the quartz crystals can be considered as an early stage in the process which ends in the intense shearing and shattering of the rocks seen so well in the field. In thin sections of extreme cases the rocks are seen to be ground-up aggregates of quartz, microcline, plagioclase (sericitised) and muscovite shreds. In still more extreme cases quartz, sometimes microcline or carbonate (after plagioclase ?) are the only recognisable minerals left. A number of such rocks

contain broken fragments of vein quartz, which indicate at least two phases of shearing separated by one of crystallization. Finally several rocks with streaks of apparently non-crystalline mylonite were found.

When the reactions of semi-pelites, pelites, and impure quartzites to dislocation metamorphism are compared, certain differences of behaviour are apparent. For instance the percentage of rocks showing very strongly strained quartz is highest in the impure quartzites, less high in the semi-pelites and is least in the pelites, whilst in the case of mica the ratios are reversed. This is to be expected since, whilst in a quartz-rich rock the quartz grains will tend to take up most of the strain by forming a rigid frame-work, in a mica-rich rock the mica flakes will play the same role. On the other hand, complete sericitisation of the felspar is found in a high percentage of impure quartzites as is the development of chlorite; the semi-pelites show a lower percentage and the pelites the lowest percentage. The relative effect on the rocks has to be considered in this indirect way because the belts of dislocation metamorphism are in general too narrow and too poorly exposed for the onset of the dislocation to be properly studied in the field. In Unst Read (1934, p678-681, & 1937, p.195) found that the biotite of the pelites changed to chlorite more readily than that of the more siliceous rocks during the third metamorphism of Unst. However this latter

metamorphism is an altogerher different type of metamorphism which has as an end product the perfectly crystallized phyllonites, whereas in Delting the dislocation metamorphism has as its end-product cataclastic rocks.

The rocks described above provide the bulk of the evidence on dislocation metamorphism, not only because they are the most common rocks of the area but also because they show the effects of dislocation most clearly.

The calcareous rocks show the following changes:- straining of quartz; twinning of carbonate grains, straining of the twinned carbonate grains and finally the destruction of the individual grains to form fuzzy masses; the straining of micas; the development of cracks and veins in the rocks; the development of chlorite after biotite; the occasional breakdown of hornblende to chlorite and to chlorite + carbonate; sericitisation of plagioclase; the development of epidote. It should be noted that some of the rocks in which all the biotite has changed to chlorite contain unsericitised felspars and vice versa. These changes have been commented on in this chapter and in the chapter on metamorphism. The rocks which apparently show the extreme results of dislocation metamorphism contain fuzzy carbonate grains, strained quartz and sometimes small twisted muscovite flakes.

Epidiorites show the following changes:- straining of quartz; sericitisation of plagioclase; development of

biotite after chlorite; development of chlorite after hornblende; cracks; epidote; zeolite veins. Most rocks present some signs of sericitisation of the felspar, so that rocks showing chloritisation of the biotite almost invariably show sericitisation, but otherwise there is no determinable rule. Rocks in which all the biotite has changed to chlorite may reveal only slight traces of sericitisation and complete sericitisation may be accompanied by complete lack of chlorite.

All the signs of dislocation metamorphism described above may be found in the pegmatites and the Inclusion Granite, but strain effects are much more common than mineralogical changes. The felspar twins are quite commonly bent, and quartz grains strained to the point of granulation are also much more common than usual. Stable-looking biotite showing strong signs of strain is more common in these rocks than in the metamorphic and migmatitic rocks, although in a number of places it has been changed to chlorite.

A number of criteria of dislocation metamorphism have been mentioned above. When these are plotted all together on a map, they still fail to give other than a very fragmentary picture of the pattern of the belts of dislocation. This is partly because the exposures are so very incomplete and partly because the belts of dislocation metamorphism vary from a foot or so to one hundred yards wide and form a very complicated pattern. To fully investigate such a pattern as this, an extremely large number of specimens would have to

be collected and examined, and a very much larger proportion of the area would have to be exposed. Moreover the criteria themselves, when compared with one another, frequently fail to agree. Even when the sericitisation of the plagioclase is excepted from consideration, no regular sequence of mineralogical and structural changes can be erected to fit all cases. Frequently with increasing dislocation metamorphism the following processes take place :- ~~strain~~ straining of quartz: straining of mica: sericitisation of felspar starts: chloritisation of biotite and hornblende start: finally, mechanical breakup becomes dominant. These processes may however, take place quite independently of one another. Structural and mineralogical changes although occurring in response to the same underlying causes are not always directly related to one another, neither are the individual mineralogical changes.

This complexity is due to a number of causes. It has already been mentioned that plagioclase felspar may be sericitised as the result of a number of causes other than dislocation metamorphism. It may for example be the product of the last and weakest phase of the potash metasomatism. In fact the manner in which sericitisation is associated with fractures, not only on the regional scale but even on the scale of the thin section may indicate that the fracturing which caused the dislocation metamorphism, also provided channels which were used by the excess potash left in the

intergranular film not only of the igneous rocks but also of the permeated rocks. The metasomatic activity of excess potash in areas not affected by dislocation metamorphism would complicate the geographical distribution of sericite.

The complexity of the dislocation metamorphism is also certainly due in part to repetition of dislocation metamorphism. As will be mentioned below the belts of dislocation metamorphism were laid one on top of the other, the intensity of metamorphism varied from belt to belt, and frequently the same belt was metamorphosed again and again, and each time at a different intensity.

The concept of repeated metamorphism leads directly to the idea that if dislocation metamorphism took place over an extended period of time the different phases may well have occurred under different conditions of P and T. Therefore, not only would the conditions of crystallization have been different but the mineral assemblages towards which the changes tend would have been different. For instance, the change from biotite to chlorite would fail to take place under conditions of even strong dislocation metamorphism, if the rocks were under P and T conditions in which biotite was stable, or if the P and T conditions were too low. The pelites, occurring in the area of the pelite lineation, which show extreme straining of biotite and muscovite without any signs of dislocation metamorphism, such as instability of the minerals or fracturing of the rocks, may have been subjected to movements at temper-

atures too high to allow the development of chlorite, but under conditions which did not allow the recrystallization of the biotite. An example of dislocation metamorphism in which the PT conditions were too low to allow the formation of chlorite may be provided by rocks on the east side of Swining Voe. In this area the minerals in the rocks are all strained, the rocks are in places very intensly sheared, and zeolitic veins and cracks are common. Yet the biotie has remained the normal red-brown type.

There are three, possibly four, major faults in the area, map 29. The Swining Voe fault forms the eastern boundary of the area. It has a very considerable displacement, since it brings rocks very similar to those of the Voxter area into contact with the phyllitic rocks of Laxo. The fault is known to continue as far south as Lerwick. It is accompanied on its west side by a belt of minor faulting and of chlorite development. The reactions of the rocks on the east side of the fault are described immediately above.

The belt of dislocation along the west side of the thesis area may be associated with the fault which passes down the east coast of North Maven through the isthmus west of Brae and on towards the south where it separates the Old Red Sandstone of the Walls peninsula from the metamorphic and migmatitic rocks of the east part of the Mainland. This fault is one of the major features of the structure of

Shetland, and separates areas which are very different both structurally and lithologically. In the Brae region and to the north it is accompanied by very considerable shearing and shattering of the rocks and by reddening.

The third important fault of the area is that which runs in a curve from Voxter in the west to Swining in the east. This fault may produce a certain amount of offset to the west of the Weisdale Limestone. It appears to offset the Augen Gneiss slightly, map 24, and may offset the Porphyroblast Schist even more. Many of the more strongly dislocated rocks from this fault show the sucessive granulation of several generations of quartz.

Topographical features are the only evidence for the fourth fault, which is shown in map 29 by a dashed line running along the coast south of Garth House, across Dales Voe, along the south side of Fora Ness and past Noness Head. On the larger scale map (map 1) it can be traced across the Lunna peninsula, via the isthmus, onto Whalsey. Its course is marked by the termination of a number of headlands.

Some of the proposed faults in the neighbourhood of Fora Ness may explain the disappearance of the Weisdale Limestone, but they are accompanied by no other visible signs of offset.

The faults cannot be dated relative to oneanother. It is known that dislocation metamorphism took place before the

emplacement of the Inclusion Granite, pps 149 and 154, and continued after the emplacement of the Inclusion Granite, which is itself cut by the Swining Voe fault, and by the fault on the west side of the area. Some of the faults of the Delting area are probably members of the set which are seen to block fault the Old Red Sandstone in other parts of Shetland.

CHAPTER 8.

CONCLUSIONS.

The geological history of Delting, as outlined in the thesis, can be considered in relation to the history of the rest of Shetland as it is known at present. This history starts with the deposition of a very thick pile of sediments, which at some early date were intruded by numerous basic sills. The sediments and sills were subsequently regionally metamorphosed and deformed in such a manner that not only were folds possibly of very great wave length formed, but the new rocks were tectonites. The intensity ot the regional metamorphism varied over the area in a manner unrelated to the structure. At some later date than the regional metamorphism, but possibly not very much later, the rocks of certain stratigraphic levels were permeated. The resultant belt-like forms of the permeation rock-masses as seen at the present surface do not appear to be based on any particular favourable stratigraphic level, but are controlled mainly by the structures, and therefore have a

different distribution from the zones of regional metamorphism. At a still later date an injection complex was emplaced in the north part of Delting. First, very large quantities of pegmatite were intruded, this was followed by the injection of very many lamprophyric and basic dykes, which were followed in turn by the intrusion of a quartz-microcline-biotite diorite. The final episode in the history of the rocks of Delting was the dislocation metamorphism related to the faulting. This metamorphism started not later than the phase of dyke injection. In parts of Shetland lying to the south and the south-west of Delting there are many thousands of feet of Old Red Sandstone which are cut by lamprophyres and are faulted. The intrusive complex of north Delting may therefore be of Old Red Sandstone age, and approximately contemporaneous with the other more acid intrusives which cut the Old Red Sandstone.

The history outlined above is very similar to the histories of orogenic belts in many parts of the world. It is very similar, as far as it goes, to the history of the Caledonian mountain chain of Norway and Scotland, and Shetland because it lies between Norway and Scotland, is probably part of the Caledonides.

The most interesting aspect of the history of Delting, and the point in which it differs from most other similar accounts, is that the migmatisation is clearly later than the regional metamorphism. If migmatisation can take

place after the regional metamorphism and can take place in quite low grade regionally metamorphosed areas, then regional metamorphism and the migmatisation are not as closely as has sometimes been assumed. The zones of regional metamorphism cannot have risen through the rocks as a sort of aureole in front of the migmatite front, because the regional metamorphism has stopped and the regional metamorphic rocks have been overrun by the migmatisation without showing any signs of adjusting themselves to the new conditions, as regional metamorphic rocks. In the neighbourhood of the migmatitic rocks the regional metamorphic rocks have been changed to contact metamorphic rocks with a contact metamorphic ~~aureole~~ assemblage. In the light of this fact it is best to regard the zones of regional metamorphism as being zones of depth in the orogenic belt. These zones may be more closely related to some centre of heat well below the migmatite front than to the centre of the earth, but they are not directly related to the migmatite front.

Regional metamorphic rocks appear to have assemblages of minerals in equilibrium with the composition of the individual rocks and with the PTX conditions. Migmatitic rocks or rather the occasional rocks which most nearly represent the ultimate end products of migmatisation appear to approach a single uniform composition which is not related to the composition of the original individual rocks. Furthermore migmatisation is frequently found to have occurred in

a very uneven manner through the rocks, whilst the effects of regional metamorphism generally have a very regular distribution. Something more than a special combination of PTX conditions is necessary to explain these differences.

This factor is generally regarded as taking the form of a migration of material through the rocks. There is no general agreement on either the physical state or the composition of the materials involved, and the Delting area can contribute nothing towards the solution of this problem, since the bulk composition of the migmatised areas appear to have changed very little. The emanations have passed through the rocks, have impressed on them the characteristic features of permeated rocks, but have left the composition of the area relatively unchanged. But elsewhere the emanations, in order to produce very similar rocks, have caused ~~the~~ considerable changes in the composition of the rocks, therefore the composition towards which migmatisation causes the rocks to tend is probably an ideal composition unrelated to the nature or the composition of the emanations.

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ACKNOWLEDGMENTS.

The author wishes to express his gratitude to Prof.H.H. Read, F.R.S., Dr.J. Sutton and Dr.J. Watson for their help and guidance during the preparation of this thesis.

The work was made possible by the grant of a Maintenance Allowance by the Department of Scientific and Industrial Research for which the author also wishes to express his thanks.