A DETAILED STRUCTURAL STUDY OF THE NORTHERN PORTION OF THE STRONTIAN GRANITIC COMPLEX

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A DETAILED STRUCTURAL STUDY OF THE NORTHERN PORTION OF THE STRONTIAN GRANITIC COMPLEX.

Being a THESIS submitted

By

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To The University of St.Andrews

In Application for the

Degree of Ph. D.

D E C L A R A T I O N

I hereby declare that the following Thesis is based on the results of my own investigations, that this Thesis is of my own composition, and that it has not previously been presented for a higher degree.

The research was carried out in the field and in the Department of Geology, University of St. Andrews.

C A R E E R

I matriculated at the University of St.Andrews in October, 1943, and followed a course in Pure Science until October, 1945, when I left the University to commence my period of National Service. I graduated B.Sc. (Wartime) in June, 1946. I returned to the University in October, 1948, and continued my course in Pure Science until I obtained First Class Honours in Geology in June, 1951. In July, 1951 I commenced an investigation into the structures of the Strontian Granitic Complex. The results of this research have been utilised in the production of the following Thesis.

During Sessions 1951-1953 I held a scholarship from the Department of Scientific and Industrial Research.

C E R T I F I C A T E

I certify that Martin Munro has spent nine terms at research work in the Department of Geology, University of St. Andrews, that he has fulfilled the conditions of Ordinance No. 16 (St. Andrews), and that he is qualified to submit the accompanying Thesis in application for the degree of Ph.D.

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SYNOPSIS

Previous work on the Strontian complex has been substaniated by the present investigation, and the knowledge of the structures in the rocks of the complex, and in the adjoining Moine schists and gneisses has been considerably augmented. It has been shown that a planar structure occurs throughout two of the three main units of the complex - the tonalite and the prophyritic granodiorite. A linear structure also occurs in these rocks in a restricted area in the north. These structures largely conform to a simple pattern common to both tonalite and granodiorite. In the northern part of the complex, the granitic veins and the joints both appear to possess distinctive patterns of orientation, which prevail throughout this northern region. These patterns show little similarity to each other, and appear to be largely unrelated to the orientation of the foliation and lineation in the tonalite and granodiorite in this area. The formation of the complex appears to have been attended by considerable shearing and folding in the Moine country rocks which lie within half a mile of the complex. The overall pattern of the structures within the complex and the adjoining areas of country rock, appears to be distinctive, and does not closely resemble the structural pattern within and around other granitic complexes.

It is suggested that the two main units of the complex with a common internal structural pattern have been formed by the more or less simultaneous intrusion of two magmas, and that these magmas were probably emplaced by a process which involved forcible intrusion, and may have been under the control of forces associated with the Caledonian orogeny.

PREFACE.

The study of the structures in granitic complexes has received less attention than the study of the petrology of these rocks, and is still at a comparatively elementary stage. In certain complexes, notably in Germany and the United States, the structures have been studied in considerable detail, field research being backed by experimental work in the laboratory, but many problems remain to be resolved. In several complexes the presence of the same simple structural pattern has been established, but many others show a marked structural individuality, and only limited generalisations can yet be made about the structures in granitic complexes as a whole. In consequence, the examination of the structures of granitic complexes would appear to offer ample scope for research.

An additional factor considerably influenced the decision to undertake the present investigation. Not only are the structures of granitic complexes imperfectly understood, but in many areas they have been virtually ignored, and are largely unrecorded. This is particularly the case in the British Isles. The desire to acquire knowledge in a virtually unexplored field of British geology, was, therefore, an additional stimulus to commence research.

A granitic complex was sought in which no aspect had been fully investigated, which was of reasonable size, and which had obvious structures suggesting that detailed investigation would be rewarding. After a little consideration, it was decided to commence work on the Strontian complex, as, of all alternatives, it seemed to conform most closely to these requirements.

I. INTRODUCTION

(i) Earlier Work on the Strontian Complex.

The complex of granitic rocks at Strontian lies to the west of Loch Linnhe, the sea loch which forms the south-western continuation of the valley of the Great Glen. In the north, the outcrops are roughly five miles distant from the shores of the loch, in the south, part of the complex actually forms the western shore line (Fig.1). The complex is markedly elongated from north to south and is exposed over an area of eighty square miles. It is considered to be Caledonian in age.

The most northerly outcrops occur three miles north of the village of Strontian at the head of Loch Sunart, and from there, exposures extend sixteen miles southward to the south-eastern tip of Morven. The width of the complex is five to six miles in the north, increasing to a maximum of seven to eight miles in central Morven. The visible width decreases in the south, owing to the truncation of outcrops by the western shore of Loch Linnhe.

All the information, which has been given above, was available before the present enquiry was commenced, mainly having been obtained by the Geological Survey in 1931-32, during work on Sheet 52 of the one-inch geological map of Great Britain. Earlier work included that of Scott in 1928, and the Geological Survey investigations described by Bailey and Maufe (1916) and by Lee (1925). The later work of the Geological Survey is of particular importance, for, as a result of this investigation, the nature, extent, and relations of the rocks of the complex, were described clearly for the first time. The preliminary results of the Geological Survey investigation were published in the Summary of

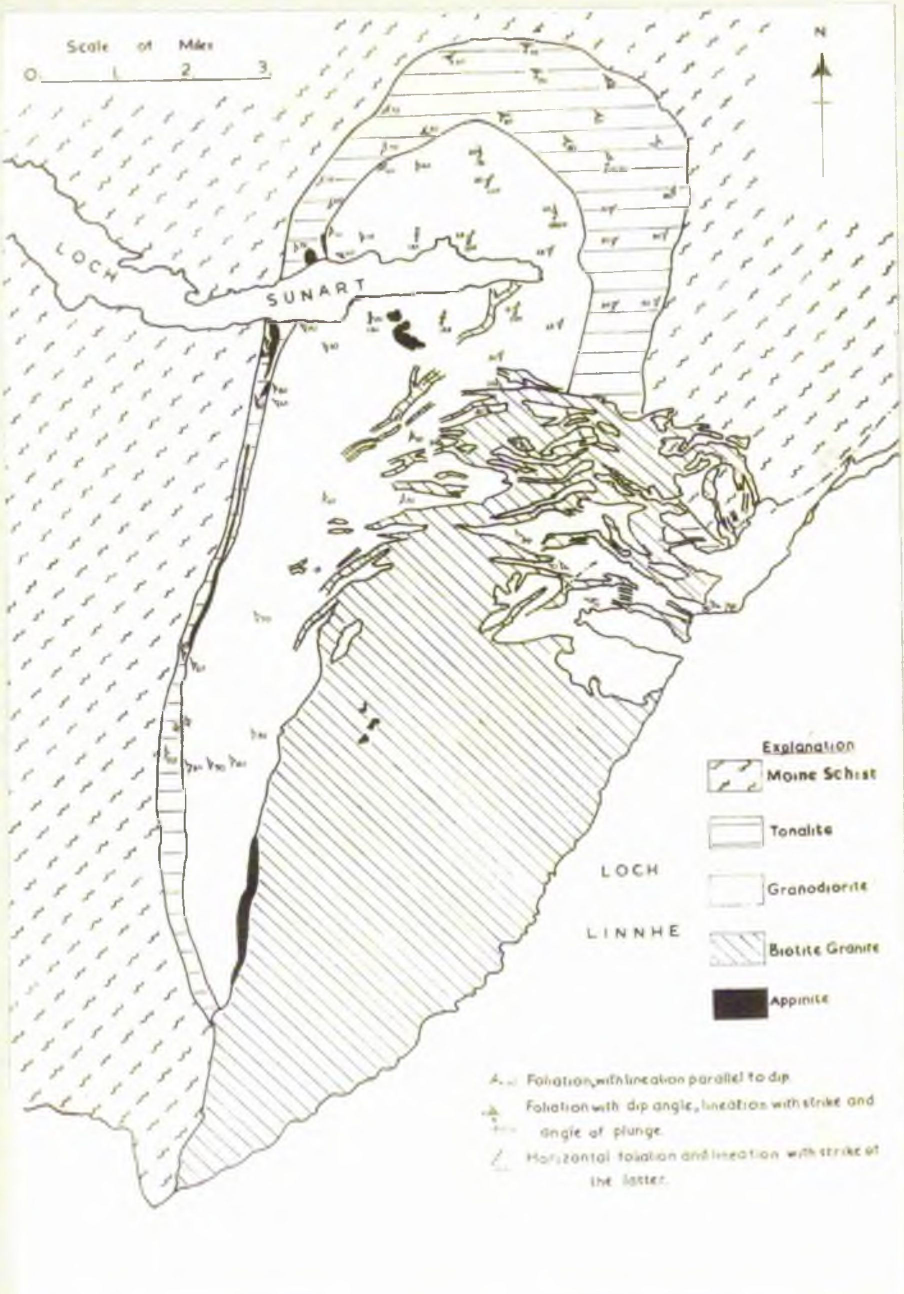


Fig.1.

Map showing the extent and relations of the main rocks in the Strontian complex. The mean trend of the planar and linear structures in the tonalite and granodiorite is also shown. This map is a slightly modified reproduction of the map published in the Regional Memoir of the Geological Survey "The Northern Highlands". The dotted lines indicate faults.

Progress for 1931 (MacGregor and Kennedy, 1932). An incomplete map accompanied this report. This map was completed in the following year, and was published in the Handbook of Regional Geology, "The Northern Highlands" (Phemister, 1948, p.60). This map has formed the basis of all the maps produced in the present investigation, and no major alterations have been made to the boundaries it depicts (Fig.1). The one-inch geological map of the entire area (sheet 52) has not yet been published.

The work of the officers of the Geological Survey shows that three types of rock, together, form the greater part of the Strontian complex - tonalite, porphyritic grandiorite and biotite granite. In the north, these rocks occur in a roughly concentric arrangement, tonalite forming an outer rim enclosing the grandiorite, which in turn largely encloses the outcrops of biotite granite. The biotite granite shows a marked tendency to transgress the contacts between the other rocks, however, and in part extends into the country rock. These northern outcrops of the biotite granite are of a complex discontinuous nature. To the south, outcrops of biotite granite occupy the greater part of the exposed area of the complex. In this area the biotite granite occurs as a large coherent mass, which transgresses the other rock boundaries, and abuts against Moine country rock in the extreme south. As indicated earlier, exposures are incomplete here, being truncated by the shoreline of Loch Linnhe. The concentric arrangement of different types of rock is now no longer apparent.

The officers of the Geological Survey also established the sequence in which the different rocks of the complex had formed.

This sequence is, in order of age, (1) tonalite, (2) porphyritic grandiorite, and (3) biotite granite. At the contacts between the different rocks, it was found that biotite granite everywhere is sharply bounded against all other rock types. The junction between tonalite and country rock is also sharply defined, but the junction between tonalite and grandiorite varies and is sharp in some localities, gradational in others. All of these junctions are nearly vertical, except for the gradational tonalite-granodiorite contact, which seems to be gently inclined.

The Geological Survey report includes descriptions of certain structures within the rocks of the complex. These were of particular interest when a preliminary reviewwas made of the granitic complexes in the Scottish Highlands in which it seemed a detailed structural investigation would be rewarding. In certain granitic complexes elsewhere study of the structures defined by oriented crystals, and of the relations between these structures and the orientation of vein-filled fractures, has shown that all of the structures conform to an overall pattern. In the case of the Strontian complex the descriptions by MacGregor and Kennedy of a planar structure, defined by oriented crystals and inclusions in the outer regions of the tonalite, and of the occurrence of a network of acid veins in the same areas appeared to be particularly significant.

In addition to describing the granite rocks, MacGregor and Kennedy give some indication of the nature of the country rocks and the structures they contain. These rocks are Moine Schists, including psammitic, semi-pelitic and pelitic types, all of which have been altered by regional injection processes to some extent, and locally, injection gneisses and augen gneisses occur. The available evidence suggests that there is no relation between the processes by which these injected rocks were formed, and the processes by which the granitic rocks of the Strontian complex were formed. The grade of regional metamorphism appears to be low, and in addition, no marked thermal aureole is visible near the complex.

As stated earlier, the contact between the Moine country rocks and the rocks of the complex is sharp and relatively regular. In the vicinity of this contact it was found that the regional north-south strike of the foliation in the Moine schists and gneisses is deflected, so that the foliation in these rocks trends parallel to the contact. There is an overall tendency for the margin of the complex to be parallel to the regional strike of the foliation in the country rocks, but the deformation of the latter becomes particularly apparent at any irregularity in the contact, or when the boundary of the complex transgresses the regional structural trend in the country rocks. It was noted that certain distinctive beds can be traced into the vicinity of the complex where they appear to be transgressed, and that in these contact areas the country rocks appear to have been strongly sheared. The dip of the contact was found to be steep on the whole, the direction of inclination being towards the complex. The foliation in the country rocks in the areas adjoining the complex was always found to dip steeply.

These descriptions of deformation in the country rocks adjoining the complex are also of particular interest to the present investigation, as are the descriptions of masses of country rock which lie wholly enclosed within tonalite, or appear to be partially separated from their original surroundings by tongues of tonalite. Inclusions of country rock were found to be abundant near the tonalite Moine country rock contact, but occur throughout the complex.

(ii) Objects and Scope of the Present Investigation

The work of the officers of the Geological Survey has been described in some detail, in order to indicate the full extent of the information which was available before the present investigation was commenced. Some indication of the reasons for undertaking this investigation have been given already, but the main considerations which governed the research can now be more clearly defined.

The primary object of the present investigation was to make a detailed study of the structures within the complex and the surrounding areas, which appeared to be contemporary in origin with the complex itself.

It was hoped that, from the data obtained in this study, it would be possible to deduce how these structures had been formed. If this object could be achieved, then it would be possible to assess the conditions under which the complex of granitic rocks had been formed to some extent, and information of particular significance to the study of thegenesis of these rocks would have been obtained.

Apart from these considerations, it was felt that the investigation would be a useful contribution to the knowledge of the geology of the Scottish Highlands as a whole, and, in particular, might produce evidence which supported the suggestion that the Strontian and Foyers complexes were originally united (Kennedy, 1946). This evidence would be of significance if any further attempts were made to deduce the extent and direction of movement on the Great Glen fault.

The emphasis in the present investigation was almost wholly on field observations, and although all the field characters of the rocks were examined in detail, particular attention was given to a study of the structures. Other aspects, such as the petrography of the rocks, were considered only as ancillary to the main of enquiry. A comprehensive study of all the characters of the rocks of the complex would, of course, enable the data obtained in this investigation to be interpreted much more satisfactorily. As a complete study was beyond the scope of single-handed investigation, however, it was decided to concentrate attention almost entirely on the structures of the rocks. A further factor was the knowledge that although the officers of the Geological Survey were no longer actively engaged on the preparation of the one-inch map of the area, they did intend to complete this map, and to accompany it by a report which would include details of the petrology of the rocks of the complex.

Within the complex, attention was devoted mainly to a study of the structures defined by the oriented crystals and inclusions, and to an examination of the fracture systems. Fractures with a vein-filling received particular attention. In the Moine country rocks, the deformation in the areas adjoining the complex was studied in detail. Structures which can be grouped in these three categories were the main structures which appeared to have been formed more or less contemporaneously with the rocks of the complex.

Before these structures can be interpreted satisfactorily, it is necessary to know how the rocks of the complex have been formed. This, in turn, implies that the study of the structures, while it may supplement a petrological study, and facilitate the comprehension of the full nature of the rock-forming process, is not in itself sufficient to establish how the granitic rocks have been formed. As the present investigation is essentially a field study, the contact relations between the rocks of different type are of particular importance in the interpretation of the structures, for only at these contacts is the field evidence of such a kind that it indicates the probable nature of the rock-forming process. The relations at the tonalite-Moine country rock contact are of greatest significance. The contacts between the rocks of different types were also the subject of a detailed study, therefore, in addition to the study of the structures.

The original approach to the problem was much influenced by the work of H. Cloos and his associates in Germany and the United States, which, to date, forms the most important contribution which has been made to the knowledge of the structures of granitic complexes (see Balk,1948). The discovery of a simple relation between crystal orientation and all other structures, particularly the fracture systems, has been the outstanding result of this work. In the Strontian complex, the original intention was to complete a structural study of the entire complex, based on a search for the relationships described by Cloos.

It was soon found that there was no simple relation between the different structures, and the basis on which the investigation was being conducted had to be revised. It was no longer assumed that certain relations would be likely to occur, and the structures were examined without any direct reference to any previous work in this field. This resulted in a general slowing in the pace of the enquiry, and the original object of examining the whole complex was no longer attainable. Only the northern portion of the complex was examined in detail and attention was confined almost solely to the tonalite and granodiorite. The area of the complex north of Loch Sunart was examined in greatest detail. The area of the complex south of Loch Sunart, which is shown in Fig. 9, was examined rather less intensively, but with sufficient thoroughness to establish clearly the pattern of the structures, and the extent and relations of the rocks. South of this area only reconnaissance mapping was conducted, in no more detail than was necessary to indicate the outline of the structural pattern, and the nature of the rocks. Country rocks were only examined in detail in the areas north of Loch Sunart which are also shown in Fig. 9. In all, about a fifth of the complex was subjected to a detailed study.

It is obvious that the requirements of the present investigation would e satisfied more effectively by means of a study of thestructures throughout the entire area of the complex, than by the incomplete study, the scope of which has been outlined above. However, there were two reasons why the investigation was terminated.

Firstly, it was apparent that a structural study of the entire complex would be a very considerable task - a task of far greater magnitude than was originally envisaged. Secondly, it was felt that sufficient information had been obtained to indicate in how far the fundamental objectives of the investigation could be attained by the specialised approach which had been adopted.

The investigation described in the following page, is, therefore, essentially an incomplete study of the structures in two of the main units of the Strontian complex - the tonalite and the porphyritic granodiorite.

(iii) Methods Employed

Field Methods. Mapping of the northern areas of the complex was carried out on a scale of six inches to the mile. A one-inch map was used in the southern areas. The approximate geological boundaries of the complex were obtained from the Geological Survey map. These boundaries were checked in the field, and modified where necessary. No information was available on the boundaries in the country rock.

In the complex, all the contacts were examined throughout their length in the northern areas; in the south, relations at these contacts were checked at several points. In areas of uniform rock, observations were made at evenly distributed points - at about two hundred yards interval in the areas north of Loch Sunart, at about quarter-mile intervals in the area immediately south of this loch.

In the country rocks north of Loch Sunart, the areas closely adjoining the complex were examined in detail throughout. From these contact areas traverses were made outwards into the country rocks. Where distinctive beds or horizons could be recognized they were followed. South of Loch Sunart, only a few contact areas were examined.

In the field, attention was devoted largely to recording the relations between the different rock types, the variation within these rock types in appearance, texture, etc., and the orientation and nature of any structures. As will be apparent, only samples of the structures were obtained, but it was hoped that sufficient observations had been made to ensure that these samples would be representative. This supposition was later checked in the laboratory to some extent.

Laboratory Methods. These were restricted to the techniques used in the analysis of orientation data. The main technique employed involved the plotting of the data on an equal-area projection, and then the analysis of the scatter diagram so produced by means of a one percent counter, and contouring. Mineral orientation was recorded directly on the field maps. A certain number of petrofabric analyses were carried out, mainly in specimens of rocks of the complex, and in addition, a restricted microscopic examination of the petrography of the granitic rocks was undertaken.

Notation: In order to describe the orientation of the structures concisely, an abbreviated notation is used throughout. The direction of strike of the structure is given first, by means of the compass bearing in degrees, followed by the angle of dip in degrees and the direction of dip. Thus, the orientation of a structure which strikes north-west - south-east and dips at forty degrees to the north-east, is represented by $315^\circ/40$ NE. (Or alternatively by $135^\circ/40^\circ$ NE.).

(iv) Petrography and General Relations.

The previous knowledge of the extent and relations of the main units of the complex has already been described, and it has been found necessary to modify this description only in detail as a result of the observations made in the course of the present enquiry. In the present section, a brief description of the petrography and relations of the rocks of the complex is given, which serves to augment the earlier description, and provides a background for the main part of this research. Detailed description of the contact relations of the tonalite and granodiorite is held over until a later section, in view of the structural significance of the phenomena displayed at these contacts.

The petrographic study of the rocks was undertaken solely to assist the structural analysis, and to augment field observations. The main objects of the microscopic examination of the rocks were to confirm the field identification of minerals, to correlate microscopic texture with the relations visible in the field, and to check that uniformity in appearance indicated uniformity in rock type. In addition, certain rocks, notably the granitic veins, were examined microscopically in an attempt to clarify field relations.

Only the tonalite, the porphyritic granodiorite and the granitic veins were examined in any detail, and then only in the northern areas. The biotite granite, as it lay outwith the area of thorough investigation, was subjected only to a prefunctory examination. The information obtained in this examination supplements and corroborates that obtained by the officers of the Geological Survey. The nomenclature used for the rocks types is that employed in the Geological Survey report (MacGregor and Kennedy, 1932) and is not based on any additional work in the course of this research.

Tonalite.

Petrography of the Normal Rock. The tonalite is typically medium to coarse in grain and grey in colour. The main constituents visible in hand specimen are biotite, hornblende, feldspar and quartz. The feldspar occurs, in part, as subidiomorphic crystals, and the hornblende also tends to develop crystal boundaries. The ferromagnesian minerals normally occur in roughly equal amounts, and taken together, are less abundant than the light-coloured minerals. The constituent crystals of the tonalite are oriented, particularly the crystals or feldspar and hornblende. This orientation is developed with varying degrees of intensity. (Plates 8, 9, 10,12 and 15).

Microscopic examination confirms these observations. The rock can be seen to have a hypidiomorphic granular texture, with hornblende and zoned oligoclase developing crystal margins against biotite, quartz, and orthoclase. The latter mineral occurs in only minor amount.

Variation in Rock Type. The tonalite shows only slight variation throughout its outcrop, the main modification being found in a marginal zone adjoining the contact with the Moine country rocks. The rock is finer in grain in this zone, the feldspars, in particular, showing a reduction in size, and is frequently enriched in ferromagnesian minerals. Biotite is particularly abundant, often to the exclusion of hornblende. Microscopic examination shows that a colourless clinopyroxene is also present in this rock. This mineral is largely replaced by biotite and hornblende, and much of the hornblende in the marginal rocks would appear to have been derived by replacement of pyroxene.

This zone of modified rock may be as much as half a mile in width, but is normally approximately one hundred and fifty yards wide. Locally it is virtually lacking, and normal tonalite may then occur in close vicinity to the outer contact.

Throughout the tonalite, gradationally-bounded fine-grained areas occur, resembling a still finer-grained modification of tonalite than the rock just described. These areas are small, and are often accompanied by irregular biotitic and quartzose streaks. They are particularly common in the contact regions where the country rock is semi-pelitic schist, and similar rock is found as tongues cutting inclusions of Moine schists and gneisses. Small, gradationally-bounded, areas of coarse-grained tonalite also occur, mainly in the inner regions of the complex.

Aggregates of the ferromagnesian constituents of the tonalite are found, normally consisting largely of hornblende, but in the outer contact regions, biotite often predominates in these aggregates. These schlieren are distinctly defined. They are laminar in shape, are no more than a few inches thick, and are usually only a few yards in length. They are oriented parallel to the planar structure in the surrounding rock. (Plate 9).

Prophyritic Granodiorite.

Petrography of the Normal Rock. The prophyritic granodiorite contains large pink phenocrysts of orthoclase, which provide the easiest means of distinguishing between this rock and tonalite in hand specimen. The other main constituents of the granodiorite which are recognisable in hand specimen, are, as in the tonalite, plagioclase, hornblende, biotite and quartz. The granodiorite is coarser in grain than the tonalite on the whole, and has a lower content of ferromagnesian minerals. Hornblende is more abundant than biotite in this rock. As in the tonalite, the hornblende and plagioclase tend to occur as idiomorphic crystals, and, in addition, the orthoclase phenocrysts appear to be idiomorphic in hand specimen. The crystals of these three minerals are always oriented to some extent.

Microscopically, the margins of the orthoclase phenocrysts can be seen to be intergrown with the other minerals, and some interstitial orthoclase is also visible. Otherwise, the mineral relations are as noted in hand specimen. Additional differences between tonalite and granodiorite which are apparent in thin-section are, the higher orthoclase content (now approximately equal to the plagioclase content) the higher content of quartz, and the more albitic nature of the plagioclase in the granodiorite.

Variation in Rock Type. Much of the granodiorite is of uniform appearance, although in the areas south of Loch Sunart, this rock is slightly coarser in grain than in the areas to the north.

Adjoining the tonalite-granodiorite contact the granodiorite is modified, however, and throughout much of the contact region between tonalite and granodiorite, there appears to be a complete gradation from one rock to the other. In progressing from normal granodiorite to tonalite in these regions, the orthoclase phenocrysts become smaller and less numerous, the grain-size of the rock as a whole decreases, and the rock comes more and more to resemble tonalite. Microscopically, no conspicuous features are associated with this contact rock, which appears to be intermediate in composition between tonalite and granodiorite. Inthe restricted area where the tonalite-granodiorite contact appears to be sharp, the granodiorite is only slightly modified in the vicinity of the tonalite, becoming slightly finer in grain, and containing rather fewer orthoclase phenocrysts.

The granodiorite in the vicinity of inclusions of rock of all types, or in the veins which cut these inclusions, is modified locally. Normally the pink orthoclase phenocrysts disappear from the rock within a few feet of an inclusion, and this contact rock then resembles tonalite in appearance. A considerable variation in rock type may be visible, however, and the granodiorite may be locally coarser or finer in grain, or locally enriched in ferromagnesian or feldspathic constituents. In some cases, the veins which cut the inclusions vary along their length, normal granodiorite occurring in the vein at the margin of the inclusion, coarse-grained pegmatite at the centre of the inclusion.

Small fine-grained and coarse-grained areas, with gradational margins, occur in the granodiorite, as in the tonalite. The

Plate 1. Hornblendic schliere in the prophyritic granodiorite near Eilean a'Mhuirich. In the surrounding rock there is a horizontal linear structure parallel to the shaft of the hammer, and a planar structure which dips gently to the left.

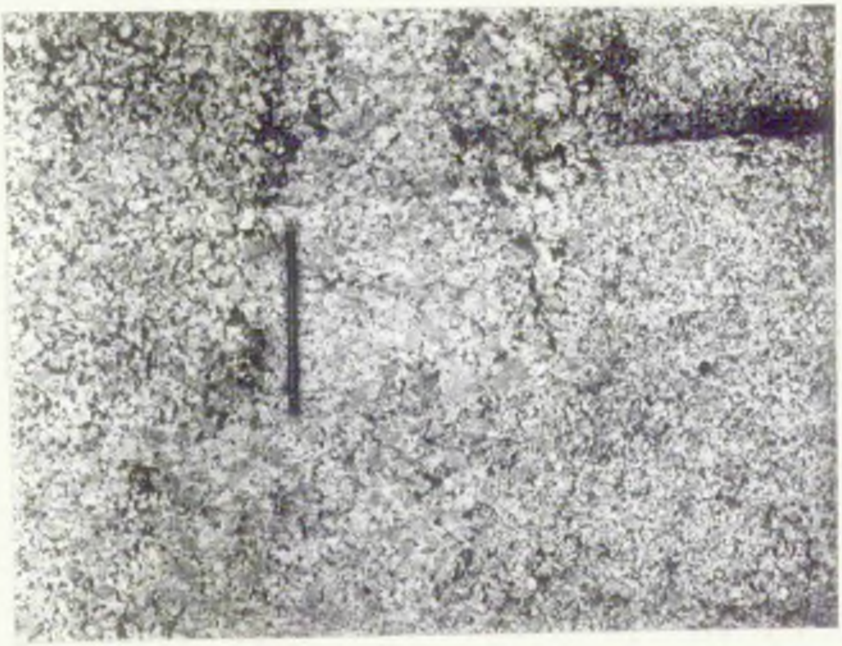


Plate 2. A portion of a coarse-grained, feldspathic schliere near Eilean a'Mhuirich. Normal granodiorite occurs towards the left margin of the illustration, a zone of fine-grained granodiorite towards the right margin.

The former are less abundant than in the tonalite, particularly in the areas south of Loch Sunart. The latter may be as much as ten feet in diameter.

Schlieren occur as in the tonalite. Usually they consist of aggregates of the ferromagnesian minerals, particularly hornblende (plates 1 and 14), but feldspathic schlieren also occur.(plate 2). The latter are thicker, and shorter, than the schlieren of ferromagnesian minerals, and are usually gradationally bounded. A few schlieren are composite in nature, consisting of alternate bands of feldspathic and ferromagnesian constituents.

Biotite Granite.

As described earlier, the biotite granite displays sharp, transgressive contacts against tonalite and granodiorite. This rock was not examined closely either in the field or in the laboratory. It is finer-grained than the two rocks just described, is pale pink in colour, and contains pink feldspar phenocrysts set in a ground-mass consisting largely of biotite, quartz and feldspar. The content of ferromagnesian minerals is low - bitote being the only dark coloured mineral visible in the field. The biotite granite has a higher content of quartz and potash feldspar than the other two rocks. No variation in rock type or texture, was seen in the areas examined. The feldspar phenocrysts and the biotite crystals, may be slightly oriented, but this structure could not be recognised with certainty in the field.

Granitic Veins.

Granitic Veins.

Associated with the main rocks of the complex, is a suite of granitic veins which are largely concentrated in the outer areas of tonalite (plate 14), but are also found cutting all the main units of the complex. These veins vary both in texture and in composition. They were subjected to a detailed field and petrographical study in the hope that some correlation between vein type and vein trend could be established.

Prolonged examination merely showed that it was impossible to recognise distinctive textural and compositional types of vein in the field. Texturally, the veins vary from fine-grained aplites to coarse-grained pegmatites. These textural variations may occur in a single vein, and frequently bands of different grain size occur parallel to the margins of the veins. Mineralogically, the main constituents recognisable in hand specimen are biotite, quartz and feldspar, and variation in biotite content is the most obvious sign of compositional variation in the field. Marked fluctuations in the content of particular minerals can often be seen in individual veins. Moreover, no satisfactory correlation can be made between texture and composition, though biotite-rich veins are often fine-grained. Two extreme types of vein are commonly found together - one, coarse-grained and quartzo-feldspathic, the other, fine-grained and rich in biotite, with no visible quartz. Between these two extremes, it is possible to find veins which seem to represent every possible gradation in grain-size and composition.

Microscopic examination also failed to establish distinctive types of vein. This examination showed that no distinctive minerals or textures, which would have served to identify a particular set of veins, are recognisable. The veins were found to consist essentially of four minerals - biotite, quartz, oligoclase and microcline-microperthite. The relative amount of these minerals was found to vary from vein to vein, and there appears to be a complete gradation from veins, rich in quartz and microcline and poor in oligoclase and biotite, to veins which show a reversal of this mineralogical predominance. The veins, therefore, range in composition from granite to granodiorite.

The only vein which was found to have a distinctive mineralogy and texture was a single vein cutting the granodiorite. This vein is lamprophyric in character, with abundant biotite and hornblende set in an acid groundmass.

Granodiorite Porphyry.

This rock usually occurs as large, sheet or sill-like masses, cutting the tonalite and the granodiorite. It is considered apart from the veins, as it is of distinctive appearance in the field, is of a uniform nature, and tends to form bodies of rock much greater in size than the majority of the veins. Some of the veins cut the granodiorite porphry sheets, others are cut by the bodies of this rock.

Megascopically, it is a fine-grained rock with large feldspar phenocrysts. These phenocrysts measure up to three inches in length, and are considerably larger than those found in the porphyritic granodiorite, or the biotite granite. The

The groundmass is much finer-grained than either the tonalite or the porphyritic granodiorite.

Mineralogically, this rock resembles the porphyritic granodiorite, the phenocrysts being of orthoclase, but it is richer in quartz and orthoclase than the latter.

Associated with the granodiorite porphyry are irregular masses of a fine-grained basic rock which was not examined microscopically.

Inclusions.

Under this heading are described a variety of rocks which occur as small masses enclosed in the main rocks of the complex. no genetic significance is implied in the use of this term.

Basic Lenses. Small, lens-shaped inclusions of basic composition are commonly found throughout the tonalite and granodiorite, and they also occur, though less abundantly, in the biotite granite. These lenses generally have dimensions of the order of one to two feet, but in some cases are many yards in length and breadth. They are of particular interest as they have a similar orientation to the crystals in the enclosing rock. (Plates 5, 8, 10, 11, 12, 13 and 15).

The lenses show some variation in rock type, this variation being visible within a single inclusion on occasions. The most abundant type is a basic, fine-grained, rock with feldspar phenocrysts, but more feldspathic types, resembling tonalite, and more basis types, resembling basic appinite also occur. Frequently, the margins of an inclusion can be seen to be more feldspathic than the core. The inclusions are particularly abundant near appinite masses, but even in these areas, specimens resembling appinite are rare. Boundaries with the enclosing rock may be sharp or gradational, and large feldspar phenocrysts may extend across the junction.

A specimen of the most abundant type was examined microscopically. Zoned andesine, in part as phenocrysts, can be seen to form approximately half the rock, the remainder consisting of roughly equal amounts of biotite and hornblende.

Appinite Masses. These masses occur in all the main rocks of the complex, usually as large bodies with dimensions of up to half-a-mile. They are usually of irregular shape, and may show sharp or gradational boundaries against the enclosing rock. They may contain blocks of schist. The largest masses of appinite occur within the granodiorite immediately south of Loch Sunart. (Plate 6 and Fig.9.)

The appinite varies considerably in nature, but the most common and widespread type, is a rock, finer in grain than tonalite, with feldspar, biotite and hornblende as the most conspicuous constituents. These minerals occur, mainly, as abundant phenocysts in a fine-grained groundmass. The variation in appearance of the appinite is usually due to an increase in the feldspar content, the rock then resembling basic, fine-grained tonalite.

Microscopically, it can be seen that biotite is more abundant than hornblende, and that these minerals are intergrown with zoned andesine, which forms roughly half the rock. A few crystals of quartz and orthoclase occur interstitially.

The difference in appearance between typical appinite, and the rock found most commonly as basic lenses, is due mainly to the occurrence of an abundant, fine-grained, biotitic groundmass in the latter.

Other Basic Inclusions. In the tonalite, masses of a dark, fine-grained rock occur, which usually show a sharp planar contact with the enclosing rock. These inclusions often resemble sills, but close examination shows that they terminate abruptly, and they often appear to be nearly rectangular in shape. They are not of widespread occurrence, and are normally only a few yards in dimensions. A coarse, pegmatitic layer may occur at the contact with tonalite.

In the field, these inclusions were seen to be of a uniform, fine-grained nature, and to contain roughly equal amounts of light and dark constituents. Microscopically, the texture suggests that recrystallisation has occurred, and the constituent minerals can be seen to include orange brown mica, diopsidic pyroxene, plagioclase and a green mineral (probably a chlorite).

Inclusions of Moine Country Rock. Inclusions of every type of rock seen in the area adjoining the complex are visible in the tonalite and granodiorite. They are particularly abundant in the outer areas of tonalite (Plate 7 and Fig.9), and in the complex as a whole they appear to be more abundant in the northern areas. Quartzitic and psammitic types occur most frequently, but pelitic gneisses are particularly abundant in the north-western areas of granodiorite. The inclusions range in size from small blocks, a few inches in length and breadth, to large masses, which may dimensions of as much as three hundred yards. The smaller inclusions, like the basic lenses, are usually oriented parallel to the crystals in the enclosing rock, but larger masses do not appear to be oriented. The inclusions vary greatly in shape, largely as the result of marginal veining by the enclosing rock.

Moine Country Rock.

No detailed petrographical examination was made of these rocks as it was felt that such an examination would be of no great assistance to the main trend of the investigation. Thin sections were cut solely for the purpose of making petrofabric analyses. Such petrographic details as are recorded here, come from a megascopic examination of the country rocks in the areas north of Loch Sunart.

As described earlier, the country rock consists of Moine Schists, mainly psammitic, quartzitic and semi-pelitic types, which locally have been converted into injection gneisses. Relatively uninjected rocks show a foliation parallel to the original bedding, and the grade of regional metamorphism is not high, as only small garnets are visible in rocks of a pelitic nature, and original bedding structures have survived unaltered.

All rocks show signs of injection to a greater or less extent, due to the introduction of quartzo-feldspathic material along the foliation planes. The degree of injection varies within the area and also with the rock type. Semi-pelitic and pelitic rocks seem to be particularly susceptible to injection. With intense injection the rocks are altered to injection gneisses, with the destruction of the original characters of the rock. In these rocks, quartzo-feldspathic material occurs not only as stringers, but also seems to permeate the rock as a whole, this process being accompanied by recrystallisation. Locally, augen gneisses with large lens-like feldspar crystals are found.

II. THE CONTACT RELATIONS AND STRUCTURES OF THE GRANITIC ROCKS.

A. CONTACT RELATIONS.

The significance of the contact relations of the granitic rocks in the interpretation of the structures has already been indicated. These contacts are also of direct structural significance, as the actual contact surfaces may be regarded simply as structures in themselves.

The present chapter consists essentially of a description of the phenomena displayed at two contacts - the tonalite-Moine country rock contact, and the tonalite-granodiorite contact. In addition, the characters of the contact between the tonalite and granodiorite and the included masses of varying type are described.

Tonalite-Moine Country Rock Contact Areas.

The contact between the tonalite and the Moine country rocks is nearly always clearly defined. Much of it is irregular over distances of a few inches, or a few feet, but, when considered on the scale of a six-inch map, the boundary of the complex tends to be smooth and regular. Larger irregularities, extending over several yards, do occur, however, and the occurrence of these irregularities seems to be related to the nature of the country rock. When quartzitic and psammitic rocks occur at the contact, large irregularities are common; when the contact rocks are of a pelitic nature, the contact tends to be smooth in outline.

Examination of these large irregularities shows that in many areas they are due to the occurrence of tongues of tonalite which extend into the Moine country rocks. Frequently these apophyses appear to follow planes of weakness in the country rocks, and in some cases, large masses of country rock appear to have been partially sundered from their original surroundings by these tongues (Plate 4). In the areas where these marginal apophyses of tonalite are visible, large masses of country rock, which are wholly included within the tonalite, are common (Plate 7).

Beyond the main contact between country rocks and tonalite, small outlying areas of tonalite, of up to a hundred yards in length, are often present. These areas tend to be elongated parallel to the prevailing direction of strike of the country rock - and to the nearest contact with the tonalite. Within them, the tonalite is crowded with abundant small schist inclusions. The boundaries of these areas are very irregular.

The outlying tonalite areas, and the large, partially or wholly detached, country rock masses, are absent in the areas where pelitic rocks adjoin the contact with tonalite.

Irregular contacts, and abundant country rock inclusions, are particularly conspicuous in the northern and north-eastern parts of the complex (Fig.9). In these areas, the inclusions may be of considerable size - in one instance occurring as a strip of rock, approximately fifty yards in width, extending for over a mile parallel to the contact.

The contact dips steeply throughout, the direction of dip always being towards the centre of the complex, and never outwards, although vertical contacts may occur. South-east of the Carnoch River the angle of dip of the contact is much less - roughly forty five degrees, as against the normal eighty degrees.

The structure of the country rock is modified considerably near the outer contact of the tonalite - these modifications are discussed in a later chapter.

When the contact between country rock and tonalite is studied closely, it is found that almost invariably, a thin band of very fine-grained rock occurs as a marginal modification of the tonalite (Plate 3). This rock is full of small fragments of country rock. It normally ranges in thickness from a few inches to a few feet. It is narrower against psammitic or quartzitic rocks, broader against pelitic or semi-pelitic rocks. Against the latter, it may be as much as three or four yards in thickness, with an apparent gradation from tonalite into country rock across its width. Apparent gradation into psammitic schists or other rock types may also occur, but the gradation then appears to occur over a distance of only a few inches. Normally the exact point of contact can be located to within half an inch. At the contact with large inclusions of country rock, both in the outer contact areas, and elsewhere in the complex, a similar fine-grained modification of the tonalite occurs.

At its inner margin, this fine-grained, contact rock, normally grades into the main contact modification of the tonalite, which was described in the previous chapter. The

Plate 3.
A contact between tonalite and psammitic schist at the east margin of the complex, one mile south of the Strontian River. The tonalite is appreciably finer-grained than normal for a few inches next to the contact. A straight, parallel-sided, granitic vein transgresses the contact without deviation in trend.

Plate 4.
Marginal stoping of quartzite (Qtz) by tongues of tonalite (T) at the outer contact of the complex, a quarter of a mile south of the locality of the previous illustration.

latter is a much coarser-grained rock, and is of much more widespread occurrence than the rock which has just been described. In a few places this coarser rock can be seen in direct contact with the Moine country rocks, however, flanked by areas where the normal fine-grained contact rock is present. In the vicinity of these abnormal areas, sharp contacts between coarser and finer rock are locally visible. At these sharp contacts, small fragments of the finer rock can sometimes be seen lying in the coarser rock.

It is apparent from the Geological Survey map (Fig.1), that an eastern extension of the complex, which occurs near Loch Linnhe, consists of granodiorite. In this area, granodiorite is in contact with Moine country rock. This contact was not examined, but is apparently faulted in part. Throughout the northern areas, the outer contact of the granodiorite is against tonalite.

Granodiorite-Tonalite Contact Areas.

This contact is rather poorly exposed, and frequently its nature is obscure. Nowhere were normal granodiorite and tonalite seen in actual contact with each other. In the area examined in detail, this contact was usually quite clearly of a gradational nature, but in some places the evidence, whilst rather inconclusive, did suggest that a sharp contact might exist. The contact surface appears to be flat-lying in the east and north, steeply dipping in the west. South of Loch Sunart, the eastern tonalite-granodiorite contact is drawn further to the east than it appears on the Geological Survey map (Figs. 1 and 9).

For a distance of a mile and a half north of Loch Sunart the field relations suggest that the western tonalite-granodiorite contact may be sharply defined. In this area, tonalite, and relatively unmodified granodiorite, can be seen in close proximity to each other (see Fig.9). Unfortunately, in this rather exceptional area, exposures are particularly poor, owing to the near coincidence of lines of faulting with the contact. Weathering is rapid on these fault lines, and the feldspars in the adjoining tonalite and granodiorite become reddened. This reddening obscures the only reliable means of distinguishing tonalite from granodiorite in the field - the presence or absence of the pink orthoclase phenocrysts. The other field characters which distinguish these rocks - the slightly coarser grain, and smaller biotite content of the granodiorite, are by themselves, rather unreliable indicators of rock type. This combination of poor exposures and obliteration of diagnostic features obscures the exact nature of the contact between the two rocks. Tonalite and granodiorite can be seen outcropping within a few yards of each other in some areas, and consequently, if the contact is gradational, then the gradation must occur over this short distance.

North-east of the Allt nan Cailleach (Fig.9), the contact becomes quite clearly gradational, and the extent of the gradational contact zone increases to the east, until it is over a mile wide. In this zone, the rock is intermediate in character between tonalite and granodiorite, and is character-

:ised in the field by the presence of only small, scattered, pink phenocrysts of orthoclase. In the east, small outlying areas of this rock occur, isolated in tonalite. These areas are not clearly defined, and are of approximately fifty yards radius.

South of Loch Sunart the contact between granodiorite and tonalite was found to be gradational at every point at which it was examined, including the outcrops examined in the reconnaissance of the most southerly areas. In the south-east, the gradational zone is extensive, being over a mile wide. In the south-west, it is narrow, with a width of the order of one hundred yards. Within the broad eastern contact zone, small areas occur which are devoid of the pink orthoclase crystals - which, in other words, are indistinguishable from tonalite in the field.

Near the tonalite-granodiorite contact, appinite masses are particularly common. They usually lie wholly within the tonalite, but may occur at the actual contact (Fig.9).

Contacts between Inclusions and the Tonalite and Granodiorite.

As at the main contacts, which have just been described, certain phenomena displayed at the contacts of tonalite and granodiorite with the various included masses, are of particular interest to the present study.

These phenomena are best displayed at the contacts of tonalite and granodiorite with the included masses of Moine country rocks. The inclusions of schist and gneiss vary greatly in shape. Part of this variation is due to the marginal fragmentation and veining of the inclusion, and in extreme cases these processes seem to have acted throughout the whole mass of rock. An aggregate of closely packed, small, or medium sized, inclusions then occurs, separated by irregular thin tongues of tonalite or granodiorite. Some masses are coherent and undivided, but in general, most inclusions of country rock are much veined by a network of tongues of the surrounding rock. Planes of weakness in the inclusion, such as bedding, foliation or shear planes, are usually exploited by these veins (Plate 22).

Similar phenomena are displayed at the contacts of tonalite and granodiorite with the lens-like basic inclusions and appinite masses, though on a more restricted scale. In some cases, large basic lenses appear to have been penetrated by tongues of tonalite and granodiorite, and are now represented by close packed clusters of small, rounded inclusions, separated by thin veins of granitic rock (Plate 5). When the contact between the appinite masses and the enclosing rock is sharply defined, marginal fragmentation, and veining, is of common occurrence, and is partly responsible for the irregular shape of these masses (Plate 6). When the contact between appinite and the enclosing rock is gradational in nature, the boundaries of the appinite tend to be smooth and curving. Some of the veins of tonalite and granodiorite which cut the appinite inclusions, have straight, parallel margins (Plate 6).

Plate 5.

A close-packed cluster of small basic inclusions, separated by thin tongues of granodiorite. This aggregate appears to represent a large basic inclusion which has disintegrated and occurs in the porphyritic granodiorite on the south shore of Loch Sunart, one mile west from the head of the loch.

Plate 6.

The margin of a mass of appinite which occurs in the porphyritic granodiorite on the south shore of Loch Sunart, two miles west from the head of the loch.

B. STRUCTURES.

1. ORIENTATION OF CRYSTALS AND INCLUSIONS.

Oriented elements are found mainly in the tonalite and granodiorite, but they also occur, although less abundantly, in the other rocks of the complex. Examination of orientation was confined almost entirely to the tonalite and granodiorite.

(a) MEGASCOPIC OBSERVATIONS.

(i) General Remarks.

As has been indicated, both tonalite and porphyritic granodiorite possess a structure, due to the orientation of certain of the constituent crystals of the rocks. Small inclusions are also oriented parallel to the crystals, and the small, basic, lens-like inclusions, in particular, often serve to make the crystal orientation more apparent. Both field and microscopic examination are in accord in showing that there are larger, subidiomorphic crystals in the tonalite and granodiorite, which are set in a finer groundmass. In the tonalite these crystals are of plagioclase feldspar and hornblende; in the granodiorite, of orthoclase, plagioclase and hornblende. Invariably it is these larger crystals which are oriented. In addition, biotite crystals are oriented in the tonalite in certain areas. The orientation of the crystals of all minerals is always imperfect, and may be very slight.

The oriented crystals and inclusions define both planar and linear structures, the latter always lying within the former (Plate 12). The planar structure - here called the foliation, is most evident when there is an abundance of oriented crystals

Plate 7.
An inclusion of psammitic schist in the tonalite near the eastern margin of the complex, half a mile north of the River Carnoch. The inclusion is aligned parallel to the foliation in the tonalite. This structure is also shown to some extent by the growth of black lichen on rock rich in ferromagnesian minerals (schlieren). Note the granitic vein on the left.

Plate 8.
Well oriented crystals in the tonalite, a quarter of a mile from the northern margin of the complex. Irregular granitic veins are also visible and a well-flattened basic lens can be seen above the head of the hammer.

of platy habit - for example in the areas of tonalite containing oriented biotite. Normally it is only shown rather imperfectly by the other minerals as they have a tabular or acicular habit. The small basic lenses are usually flattened parallel to the foliation plane, the degree of flattening depending on the intensity of development of the structure. When a planar structure is well developed, these inclusions become laminar (Plates 8 and 10), when weakly developed, the inclusions may be almost circular in section (Plate 11). The basic lenses are the best indicators of the trend of the foliation in the inner regions of the complex, where this structure is rather weakly developed.

The lineation may be shown by any of the large, elongated crystals in the tonalite and granodiorite. Hornblende crystals show this structure particularly well, having an acicular habit, but the plagioclase laths, and the elongated phenocrysts of orthoclase in the granodiorite, may also have a linear orientation. The long axis of elongated inclusions is aligned parallel to the linear structure defined by the crystals (Plate 13). The basic lenses are markedly elongated when the lineation is well developed, and then resemble rather flattened spindles in shape. When the lineation is poorly developed, these inclusions show no sign of elongation in any direction.

Large schlieren, and small aggregates consisting of only a few crystals, are normally aligned parallel to the planar structure defined by the orientation of individual crystals (Plates 9 and 14).

Plate 9.

Similar to plate 8, and obtained in approximately the same locality. Note the biotitic schliere dipping to the left above the head of the hammer.

Plate 10.

A horizontal surface in well-foliated tonalite, a quarter of a mile from the north-western margin of the complex. The foliation is defined by well-flattened basic lenses and by biotite and feldspar crystals oriented parallel to the pencil.

When both a linear and a planar structure are developed, all the oriented elements show both structures to some extent, the shape of these elements determining which structure they show most clearly.

The recording of the mineral orientation was a task which required considerable familiarity with the rocks. Often, the exact nature and attitude of the structures was very obscure, owing to the imperfect orientation of the crystals and inclusions, and to the poor exposures. Mapping was slow, repeated examination of the same outcrops often being necessary.

Whenever possible, an estimate was made of the attitude of the structures defined by the oriented elements and these measurements were recorded on the field maps. Some of the field observations are reproduced in Figs. 2,3 and 4.

Often, only an approximation to the true attitude of the structures could be obtained, but some value was always assigned to the various measureable factors - strike and dip angles, etc. These values are shown on the maps, but being only approximate, some of the variation in the trend of the structures may be more apparent than real. These maps are reproduced, however, to show the type of evidence obtained in the study of the oriented elements in the complex, and to show that the main trend of the structures is clearly apparent. They also serve to indicate the frequency with which observations were made.

Throughout both tonalite and granodiorite the intensity of development of the lineation and foliation is rarely uniform, particularly in the inner regions. One outcrop may show a strong lineation and a weak foliation, and adjacent outcrop may possibly show a reversal of these relations, or both structures may be strong or weak. The foliation is lacking locally. The lineation is lacking over large areas, and even in areas of well-lineated rock, outcrops can be found where no linear structure is apparent. Nowhere were the constituent crystals of the tonalite and granodiorite found to be entirely unoriented.

In broad outline, the structures shown by the tonalite and granodiorite can be treated as a single unit. The foliation forms three sides of a trough-shaped structure in the northern areas, having steep inward dips at the outer contacts, and being flat-lying in the inner regions. This pattern is still evident in the central regions of the complex in the Morven. South of these areas, most of the exposures are of biotite granite, but in the considerable areas of tonalite and granodiorite in the south-west, a new structural pattern is visible. The dip of the foliation is still inwards, but is now uniformly steep, even in areas remote from the contact with the country rocks (see Fig.1).

The lineation is only locally developed in the complex, and seems to be confined to the northern areas (Fig.9). Here it shows a marked tendency to have a nearly constant south-south-west strike, independent of the attitude of the foliation. It plunges gently south, or is horizontal, in the inner regions. The lineation extends to the northern tonalite-country rock contact, and then usually plunges parallel to the dip of the foliation - i.e. with increasing steepness of plunge with approach to this contact, but still in a southerly direction. It is not widely developed in any of the other areas of tonalite adjoining the country rock. There are variations of this general pattern which are discussed below.

(ii) Tonalite.

The tonalite almost invariably contains crystals and inclusions which show a planar orientation with, in addition, a linear orientation in some areas north of Loch Sunart.

At the contact with Moine country rocks, the foliation is well developed, and the tonalite is sometimes almost gneissose in appearance. The foliation decreases in intensity of development with increasing distance from this contact, and generally is rather weakly developed in the inner areas of tonalite (Plate 11). The lineation is as strongly developed as the foliation in the northern contact areas, and although this structure decreases in intensity within the complex, it is usually more clearly defined than the foliation in the inner areas of tonalite.

These relations may be due in part to the relative abundance of elements of shape suitable to define the different structures. Thus, the area with good foliation corresponds to some extent with the area where the tonalite is enriched in biotite. A general tendency for the planar structure to be more evident in the outer areas of tonalite is apparent, however, and the areas of well-foliated rock do not correspond exactly with the areas of biotite-rich rock.

In the outer contact areas, the oriented elements include crystals of biotite and small aggregates of hornblende and biotite crystals in addition to the oriented elements seen elsewhere. The degree of orientation of the biotite decreases with increasing distance from the outer contact, but rock containing oriented biotite may be found as much as two thirds of a mile from this contact. Biotite is never oriented elsewhere as individual crystals, although some of the small aggregates of biotite crystals in the inner tonalite may be oriented. Biotite serves mainly to show the foliation, feldspar the lineation, in the contact areas of tonalite.

The very fine-grained modification of the tonalite in actual contact with the Moine country rock, is usually devoid of structure, except when the contact is gradational. When this is the case, the foliation in the tonalite is invariably parallel to the foliation in the country rock over the gradational zone. The foliation, and, where developed, the lineation, may persist to within a few inches of the outer contact, without decrease in intensity of development.

Locally, there are areas of weakly foliated rock in the main contact zone. In these areas, the orientation of all minerals is more imperfect than normal, the biotite in particular being poorly oriented. The trend of the foliation in these areas is often abnormal. Petrographically they have no distinctive features, and structurally, they are indefinitely bounded. In the gradationally-bounded, coarser and finer grained areas of small size, the crystal orientation is the same as in the normal adjoining rock.

Plate 11.
Basic lenses of rather irregular shape defining the foliation (parallel to the shaft of the hammer) in the tonalite, near the western tonalite-granodiorite contact, on the north shore of Loch Sunart. The foliation is not a strongly developed structure in this area.

Plate 12.
A vertical surface in the tonalite near the northern margin of the complex. A basic lens lies parallel to the exposed surface and has been largely weathered away. The orientation of this inclusion indicates the orientation of the foliation in the tonalite. A faint linear structure, defined by the feldspar, crystals, can be detected in the foliation plane, parallel to the pencil.

The foliation almost invariably is parallel to the general trend of the outer contact, the effect of minor irregularities in this contact being confined to a zone a few feet in width. Within this narrow zone, the foliation is parallel to the actual shape of the contact, but is often rather weakly developed.

The large inclusions of country rock appear to affect the structures in the adjoining areas of tonalite to only a slight extent. The lineation may appear to be slightly intensified in the vicinity of these inclusions, and in the northern areas, the dip of the foliation seems to be modified locally.

In the veins of tonalite which cut these inclusions, a crystal orientation is often apparent. It is usually very imperfect, and always seems to be controlled by the walls of the vein.

Pattern of Crystal Orientation in the Tonalite.

The outline of this pattern has already been given, but the details and modifications visible in the tonalite are described below (Figs.1 and 9).

Foliation. The attitude of the foliation in the outer contact zone of the tonalite seems to be determined by the attitude of the nearest contact with the country rock. Both strike and dip are influenced. The angle of dip of the foliation is steep throughout most of the rock adjoining this contact - usually being 75-85°, and the direction of dip is always inward. South of Loch Sunart, where the eastern contact between tonalite and country rock dips inward at a much smaller angle than normal, the dip of the foliation in the tonalite is also less than normal - averaging 45-60° to the west.

The only other locality in the outer contact zone characterised by a gently dipping foliation occurs at the northern margin of the complex where schist inclusions are abundant. In the vicinity of these inclusions, the foliation dips at approximately 30° to the south. The usual direction of strike is unaltered.

With increasing distance from the outer contact, the tendency for the strike of the foliation to be parallel to the general trend of the contact becomes less perfect. Over large areas the strike of the foliation tends to be constant, and it then changes abruptly, often with alternations between one trend and another in adjacent outcrops, before a particular direction becomes prevalent. In the north, the strike of the foliation is often at right angles to the trend of the regional lineation (115° and 205° respectively) (Fig.2).

The angle of dip of the foliation shows, on the whole, a general gradual decrease with increasing distance from the outer contact. Normally the dip is approximately 45° within a mile of the outer contact, but there are exceptions to this generalisation, and areas with a steeply dipping foliation occur. The comparatively narrow strip of tonalite which occurs in the western part of the complex, has a steep dip (60-70°), throughout its outcrop. The foliation in the tonalite thus defines three sides of a trough-shaped structure. An area where a horizontal foliation prevails, defines the central part of the "trough", but lies mainly within the granodiorite.

An interesting area occurs in the north-west. Here the foliation strikes at right angles to the trend of the lineation, and fluctuates in dip, so as to define a small anticlinal and synclinal structure, which extends for approximately one hundred yards. (Fig.2). The surrounding rock appears to have a relatively uniform structural trend.

Lineation. Near the western contact between tonalite and country rock a linear structure occurs sporadically north of Loch Sunart, but, at best, is only a weakly developed structure in this area. Where it is developed in this area, the lineation follows the direction of dip of the foliation. A linear structure can never be identified with certainty in any of the exposures of tonalite adjoining the western contact with the Moine country rocks, south of Loch Sunart, although the evidence in several outcrops suggests that such a structure may be developed parallel to the dip of the foliation. The exposures of tonalite adjoining the entire eastern contact with the country rocks also seem to be devoid of a clearly defined linear structure.

Lineated tonalite occurs at the northern tonalite-Moine Schist contact, in an area which extends two miles westward from the Strontian River. Southwards, there extends a broad belt of lineated rock. The western margin of this belt runs roughly due south to the tonalite-granodiorite contact near the Allt nan Cailleach. The eastern limits of this area of lineated rock extends south-eastward at a distance of approximately quarter of a mile to half a mile west of the outer contact (Fig.2.). In the south, the width of the belt of unlineated tonalite west of the contact with the Moine Schists increases to over a mile, and lineated tonalite is virtually lacking south of the River Carnoch.

Throughout the area of lineated tonalite which occurs to the north of the granodiorite, the lineation follows the direction of dip of the foliation - i.e. plunges roughly southwards at an angle of approximately 60-70° near the outer contact, 30-40° near the granodiorite. As the trend of the foliation changes, so does that of the lineation. Thus, in the west, where the foliation locally strikes north or north-east, the lineation still conforms to the direction of dip of the foliation, plunging east at an angle of approximately 30-40°. In this area the lineation is sometimes a very strongly developed structure (Plate 13 and Fig.3).

The lineation also tends to follow the direction of dip of the foliation at the eastern, and north-eastern margins of the lineated area, but with increasing distance from the outer contact, a new trend becomes apparent which characterises all the inner regions of the tonalite, east of the Strontian River. In these areas, the lineation tends to strike 205°, independently of the strike of the foliation.

Near the eastern margin of the lineated rock, there are areas where the trend of the lineation is rather confused - one outcrop may show a lineation striking 205°, and an adjacent outcrop a lineation following the direction of dip of the foliation (i.e. the linear structures in adjacent outcrops may be at right angles to each other in this area, in view of the prevailing north-south strike of the foliation). In the inner regions of the tonalite, as the foliation tends to strike north, or north-west, with a westerly dip, and as the lineation lies within the foliation plane, the plunge of the linear structure is usually gently south. The angle of plunge is normally about 30°, but it can vary from 70° to the south, through the horizontal, to a northerly plunge. Occurrences of the latter trend are rare, but in the area where the foliation defines an anticlinal structure, the strike of the lineation is constant, and in consequence, locally plunges north (Fig.2).

In these inner regions, fluctuations in the intensity of the development of the structures, and apparent minor deviations in their trend, are particularly common. Generally, the plunge of the lineation, and its intensity of development become less in the area near the River Carnoch. Both foliation and lineation often have a common 205° strike in this area, the lineation then lying horizontally in the foliation plane.

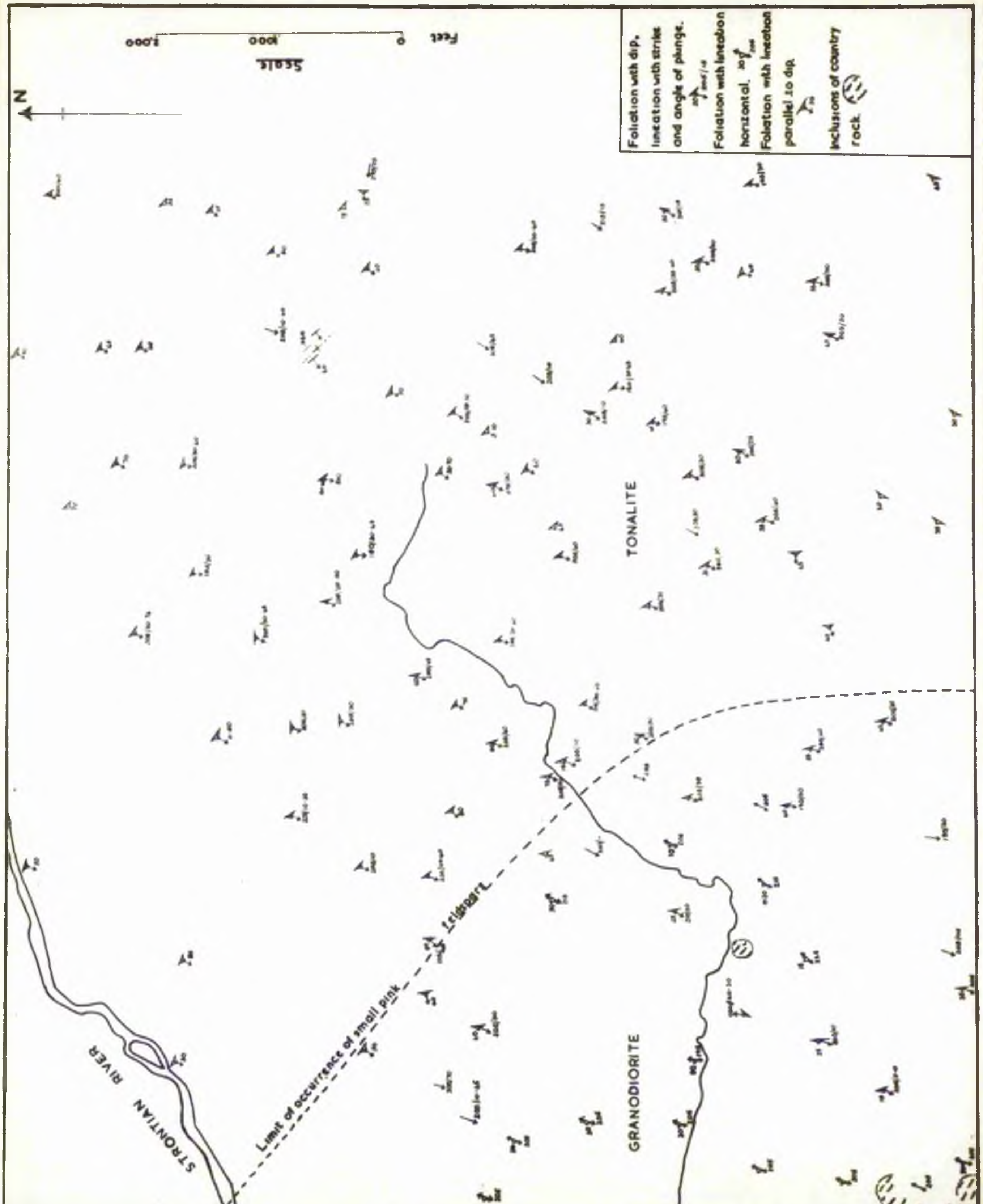


Fig.2.

Reproduction of a portion of a field map showing the orientation of the foliation and the lineation in the tonalite and granodiorite near the gradational north-eastern contact between the two rocks.

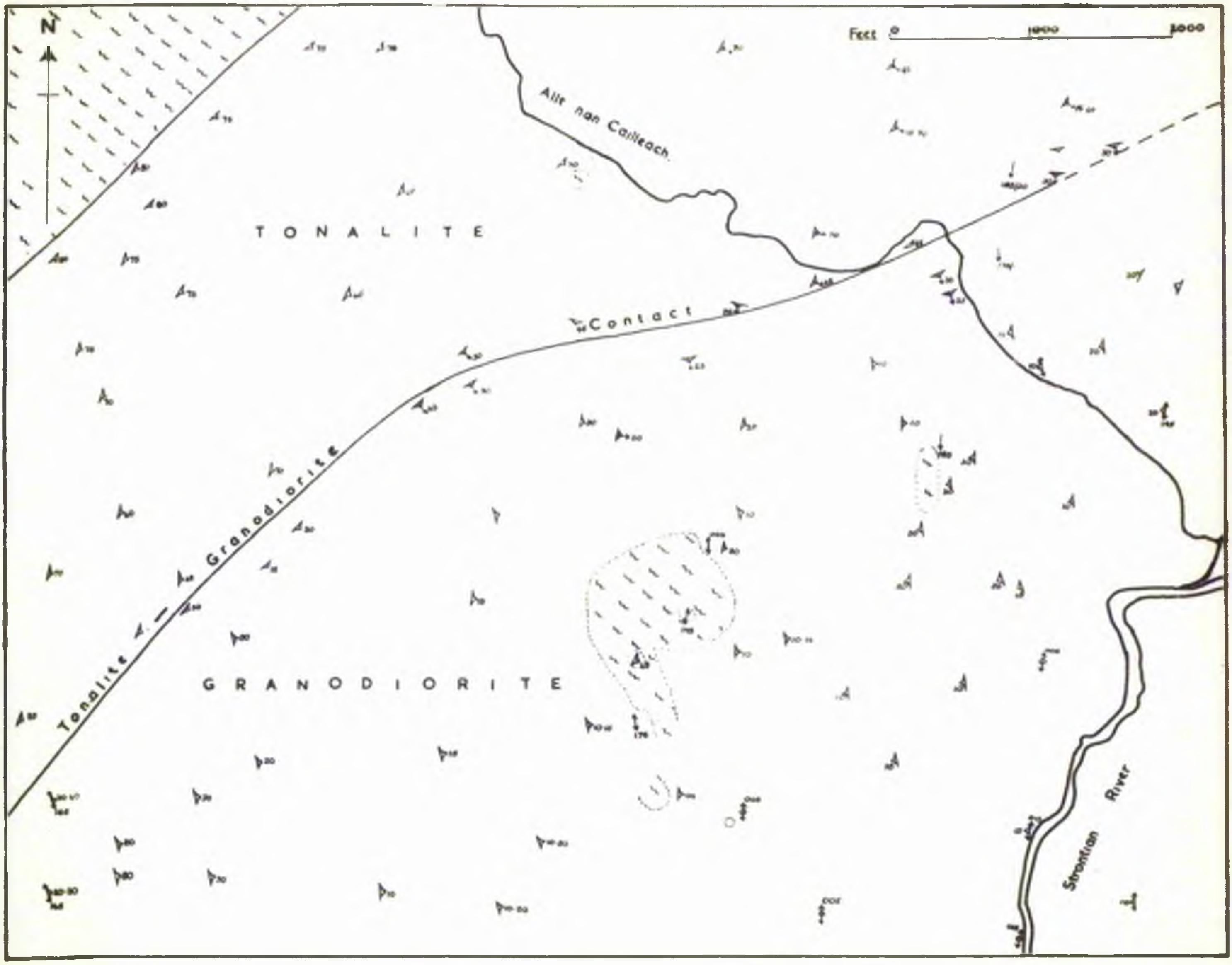


Fig.3.
Reproduction of a portion of a field map showing the orientation of the foliation and lineation in the tonalite and granodiorite near the sharply defined north-western contact between the two rocks.
Explanation as in Fig.2.

(iii) <u>Porphyritic Granodiorite.</u>

In general, in the northern areas of granodiorite which adjoin Loch Sunart, both a planar and a linear orientation of crystals and inclusions is visible, though the lineation is lacking in some areas. To the south only a foliation is consistently developed.

In intensity of development the structures correspond to those in the inner regions of the tonalite. The foliation tends to be the more strongly developed structure, the lineation usually being very weak or absent. South of the areas which were examined in detail, the intensity of development of the foliation increases, and it is always a well-marked structure in the south.

The contact with the tonalite is, on the whole, not a line of structural discontinuity, this being in accord with the petrographic evidence suggesting that much of this contact is gradational. Only in the north and north-west does there appear to be a marked structural break at this contact.

The structures are shown by the same elements as in the tonalite, with the addition of the large phenocrysts of orthoclase. The schlieren, generally, follow the trend of the crystal orientation, but a few ferromagnesian schlieren appear to have an independent orientation. These schlieren are still of a laminar shape. They have no clearly defined orientation pattern, but in the west, many dip steeply east; in the east, many dip steeply west. In one case, an originally straight, parallel-sided, ferromagnesian schliere appears to

Plate 13.
Exposure in the tonalite, near the Allt nan Cailleach, and half a mile from the western margin of the complex. Flattened, deeply weathered, basic lenses indicate the orientation of the foliation and dip away from the observer. A lineation also occurs parallel to the direction of dip of the foliation and is indicated by the elongation of the lenses. This elongation is made apparent in the photograph by the depth of the weathering of the lenses at right angles to the rock surface.

Plate 14.
Large hornblendic schliere in the porphritic granodiorite near Eilean a'Mhuirich. Note the thin layers of granodiorite between the layers rich in crystals of the ferromagnesian minerals. The outline of the schliere indicates the horizontal attitude of the foliation in the granodiorite in this area.

have disintegrated, the fragments, while now lying with a different orientation to that of the original coherent mass, still indicate that earlier orientation by their distribution.

As in the tonalite, the crystals in the small areas of fine-grained and coarse-grained rock have a common pattern of orientation with the crystals in the surrounding rock. Large inclusions of appinite and Moine country rock appear to affect the trend of the orientation structures to only a slight extent. Minor deflections in trend may occur in the vicinity of these inclusions, and a linear structure may be present to the exclusion of a planar structure. There is no intensification of the structures - the reverse being the case, and for several yards in the vicinity of a large inclusion, the crystal orientation in the granodiorite is usually very slight. In the veins cutting inclusions, the crystals may be slightly oriented parallel to the walls of the vein.

<u>Pattern of Crystal Orientation in the Porphyritic Granodiorite.</u>

<u>Central Areas</u>. The structural pattern in the unmodified granodiorite within the contact zone adjoining the tonalite is considered first.

<u>Foliation</u>. In the north, in the area of detailed examination, the foliation outlines much of the central part of the trough-shaped structure, the sides of which were indicated by the foliation pattern in the tonalite. In the eastern part of this area, the foliation tends to strike 205°, and to dip at 15-25° to the west. Much of the central regions is

characterised by a horizontal foliation (Plate 14); further west a gentle easterly dip of 20-30° prevails, increasing in magnitude towards the western contact with tonalite. The strike in the western areas changes through due north, to become north-west in the vicinity of the tonalite - i.e. the foliation strikes at an oblique angle to the western tonalite-granodiorite contact. When the direction of dip is changing through the horizontal from east to west, alternations between opposing dip directions occur in some areas, before a particular direction becomes prevalent. The area, where the foliation is horizontal, lies rather further to the west in the regions north of Loch Sunart, than in the regions to the south. There are a few minor deviations from the trends outlined above, but on the whole, the main trends are remarkably persistent.

To the south, the incomplete examination indicated that, in the central part of the complex, the granodiorite is well foliated throughout. The general trough-shaped section is still suggested to the south for as far as the northern contact of the main mass of biotite granite (Fig.1). Dip angles are generally much steeper there (60-70°), and the central area with horizontal foliation can only be of limited extent. The foliation strikes approximately north-south in the west, in the east it tends to strike between north-west and almost due west.

Further south exposures of granodiorite are confined to areas west of the main mass of biotite granite. The foliation in this region strikes approximately north-south and has a

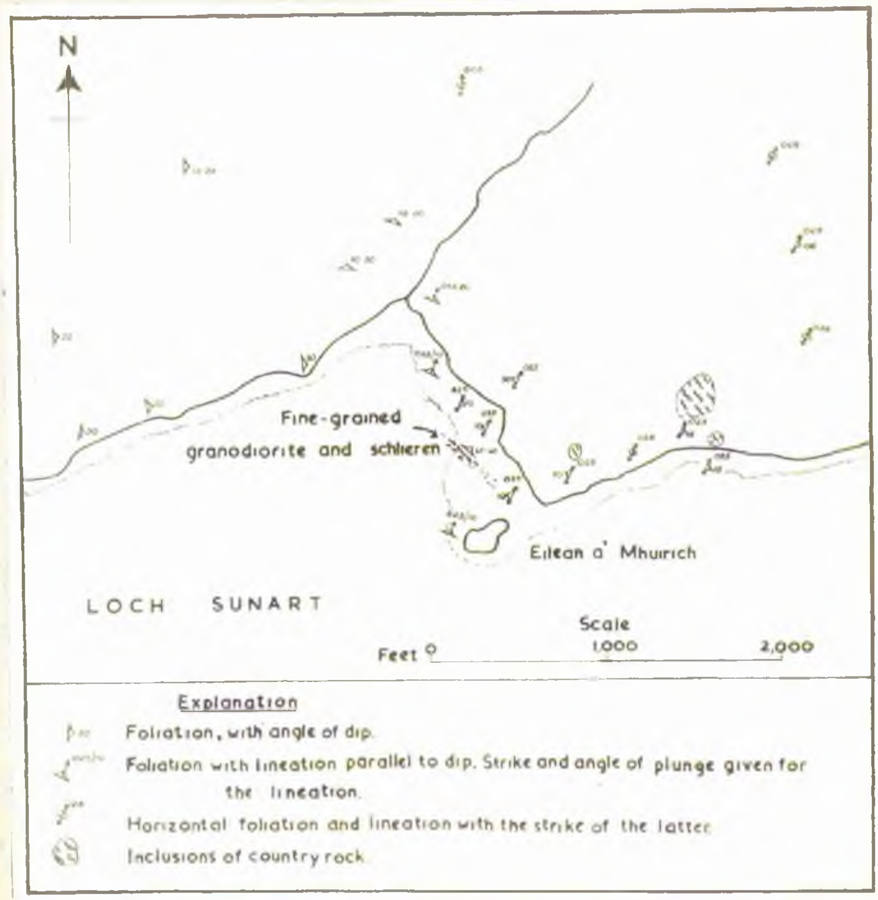


Fig.4.

Reproduction of a portion of a field map showing the orientation of the foliation and lineation in the granodiorite near Eilean a'Mhuirich. The extent of a zone of fine-grained granodiorite is also indicated.

steep easterly dip (70° or more), which does not decrease in magnitude in the inner regions. This region is characterised by a strong foliation with a very uniform intensity of development.

Lineation. In the east and centre of the area of granodiorite adjoining Loch Sunart, a horizontal linear structure is visible. This lineation follows a remarkably constant trend (205°) which corresponds with the prevailing strike of the foliation in the east, and persists in the areas where the foliation is horizontal. In the west, the lineation is also horizontal, but the trend of the structure changes to conform with the more westerly strike of the foliation. The lineation becomes very indistinct within a mile of the western tonalite-granodiorite contact. It also becomes very indistinct south of the areas mapped in detail, extending furthest south in the most central regions.

Local modifications to the general pattern of the foliation and lineation occur in the granodiorite, as in the tonalite. A small area of coarse-grained rock, five yards in diameter, occurs a mile north of Loch Sunart, and immediately west of the Strontian River. In this area, the foliation strikes north-south, and dips at 70° to the west. A faint linear structure following the direction of dip of the foliation is suggested. In contrast, in the surrounding rock the foliation and lineation are nearly horizontal and strike 205°.

A further area of interest adjoins a zone of fine-grained granodiorite with abundant schlieren, near Eilean a'Mhuirich on the north shore of Loch Sunart (Fig.4). This area lies near the region where the dip of the foliation changes from gently west to horizontal. The prevailing trend of the structures in this area is - foliation $205^{\circ}/10^{\circ}$ W ; lineation - horizontal in the foliation plane. For a quarter of a mile north of the island, the foliation sporadically strikes at right angles to its normal trend (i.e. now strikes 115°), and has a gentle northward dip. When this occurs, the strike of the lineation is unaltered and, in consequence, this structure now plunges gently northwards parallel to the dip of the foliation. These deviations from the normal trend occur within areas which are approximately fifty yards in diameter, but which have no distinctive lithological characters.

Contact Areas. The main structural pattern in the porphyritic granodiorite has been outlined and the modification of this pattern in the contact zone adjoining the tonalite can now be considered. The outer limit of this zone tends to be parallel to the trend of the structures in the tonalite - and thus to roughly parallel to the tonalite-country rock contact.

In the east, south of Loch Sunart, there is complete conformity of structure across the gradational zone - the foliation tending to strike 205°, to dip gently west, and to contain a horizontal lineation, as in the adjoining tonalite and granodiorite. North of Loch Sunart, the eastern gradational zone is transitional in structure between the tonalite and granodiorite, though here the structures in these two rocks are not markedly dissimilar. The outlying areas of rock, which resemble the rock in the contact zone, have a common structure with the surrounding tonalite (Fig.2).

To the west, from just east of the Strontian River to the Allt nan Cailleach, the gradational zone becomes much narrower and eventually appears to vanish. In this area, there is some structural discontinuity in the contact zone. In the tonalite and granodiorite on either side of this zone, the linear structure has roughly the same trend - strike approximately north-south, plunge southerly. This structure persists virtually unchanged in trend throughout the contact zone, ignoring any variations in the trend of the foliation although still lying within the foliation plane (Fig.9). The lineation varies in intensity of development, however, and may be wholly lacking, or be a very strongly marked structure. The planar structure, on the other hand, differs in trend on either side of the contact. In the tonalite, it strikes east-west, dipping southwards. In the granodiorite, it strikes roughly north-south and dips west. The latter trend prevails in much of the contact zone, the former only in the vicinity of the tonalite. The change in trend of the foliation often appears to take place across a zone in which a planar structure is lacking. It is noteworthy that the strike of the foliation in the granodiorite, and in much of the contact zone, is nearly at right angles to the horizontal trace of the contact.

At the western contact between tonalite and granodiorite, in the area north of Loch Sunart, it was noted that relations between the two rocks differed from those found elsewhere (page 30). This is also a region where there is a marked structural discontinuity at the contact (Fig.3). The trend of this contact is approximately parallel to the trend of the foliation in the adjoining tonalite, but close examination disloses that the structure in the tonalite is transgressed by the contact. The contact is also transgressive to the general structural pattern in the granodiorite in this area. This pattern consists of a foliation with a north-west, or north-north-west strike, usually at a considerable angle to the contact, with a dip of approximately 20-30° to the east. No lineation is visible.

On the shores of Loch Sunart, and for a short distance to the north the contact trends roughly north-west. In this area the foliation in the granodiorite is slightly intensified near the contact. The strike of the foliation is also slightly deflected, so as to become more nearly conformable to the contact, and the angle of dip is increased (Fig.9). A quarter of a mile north of Loch Sunart, the trend of the contact changes quite abruptly to north-easterly, and this trend continues almost without deviation, to near the Allt nan Cailleach. Associated with this change in the trend of the contact, there appears to be a change in the structural pattern in the adjoining granodiorite.

This structural change is evident in a zone of granodiorite which adjoins the contact, and ranges from ten to fifty yards in thickness. In this zone, the foliation of the granodiorite is usually somewhat intensified, and the strike of this structure is deflected into parallelism with the trend of the contact. Frequently the change in trend occurs abruptly within a few feet. The dip of the foliation is 40-50° to the east, near the contact, and in some areas a lineation parallel to the direction of dip is discernible. These relations are particularly well exposed at the Allt nan Cailleach.

The exposures of the western tonalite-granodiorite contact, which lie south of Loch Sunart, remain to be considered (Fig.9). In the areas immediately south of the loch, while the junction is clearly gradational over a narrow zone, a change in structural trend is apparent at the contact. The contact, as usual, approximately follows the trend of the foliation in the tonalite, as does the foliation in the rock in the contact zone. The foliation in the adjoining granodiorite is, however, at quite a considerable angle to the contact, and seems to be deflected into parallelism only in the immediate vicinity of the tonalite. This deflection is particularly evident in the more northerly exposures. No lineation is recognisable in any of the rocks in this area.

Further south, complete conformity of structure appears to prevail on either side of the contact.

(iv) Other Rocks.

Granodiorite Porphyry. The phenocrysts and fragments of basic fine-grained rock, which are visible in the sheets of granodiorite porphyry, occasionally appear to be slightly oriented in parallelism to the walls of the sheets.

Granitic Veins. In many of the fine-grained, biotite rich veins the crystals of biotite are oriented. These oriented crystals define a planar structure which is invariably parallel to the walls of the vein, and usually transgresses the trend of the structures in the surrounding rock.

Inclusions.

Basic Inclusions. Basic inclusions of all types are usually structureless. In a few instances, a faint foliation, parallel to the plane of flattening, can be discerned in the lens-shaped inclusions. The appinite masses may also be slightly foliated near a gradational contact with tonalite or granodiorite.

Country Rock Inclusions. The structure in the inclusions of Moine schist and gneiss is due to the persistence of bedding and foliation. Shear planes and small scale folds similar to the structures found in the country rocks adjoining the complex, are also of common occurrence. Usually these inclusions show little uniformity of structure, though uniformly foliated quartzite may occur. Normally the structures defined by the foliation are very confused, there being no constant direction of dip or strike, and no constancy in the direction of plunge of the fold axes. Neither the orientation of the shear planes nor the direction of the movements on these structures appears to conform to a clearly defined pattern (Plate 22). The only exceptions to these statements occur in the northern contact areas of tonalite, where the structures in the inclusions tend to be oriented parallel to the adjoining tonalite-country rock contact (Fig.9).

Occasionally when an inclusion is uniformly foliated, it may contain structures which are parallel to the structures in the enclosing tonalite and granodiorite. Normally this correspondence is lacking. Not only are the bulk of the inclusions clearly distinguishable from the enclosing rock because of their distinctive lithology, but they are also structurally distinct.

(b) MICROSCOPIC OBSERVATIONS.

Microscopic examination of crystal orientation was carried out by means of petrofabric analysis, using the standard technique outlined below. Oriented thin-sections were cut from hand specimens which had been oriented in the field. Using a four-axis Universal Stage, the orientation of recognisable crystallographic directions in certain minerals was recorded. These observations were then plotted on an equal-area projection, and finally, using a one-per-cent counter to plot densities, the grouping of the observations was determined by contouring.

Petrofabric analyses were made for three main reasons. Firstly, it was hoped that the data obtained from a microscopic examination of crystal orientation in the tonalite and granodiorite would augment field observations. This would be of most value in areas where the visible orientation was very imperfect, and where megascopic measurement of the attitude of the structures defined by the crystal orientation, was

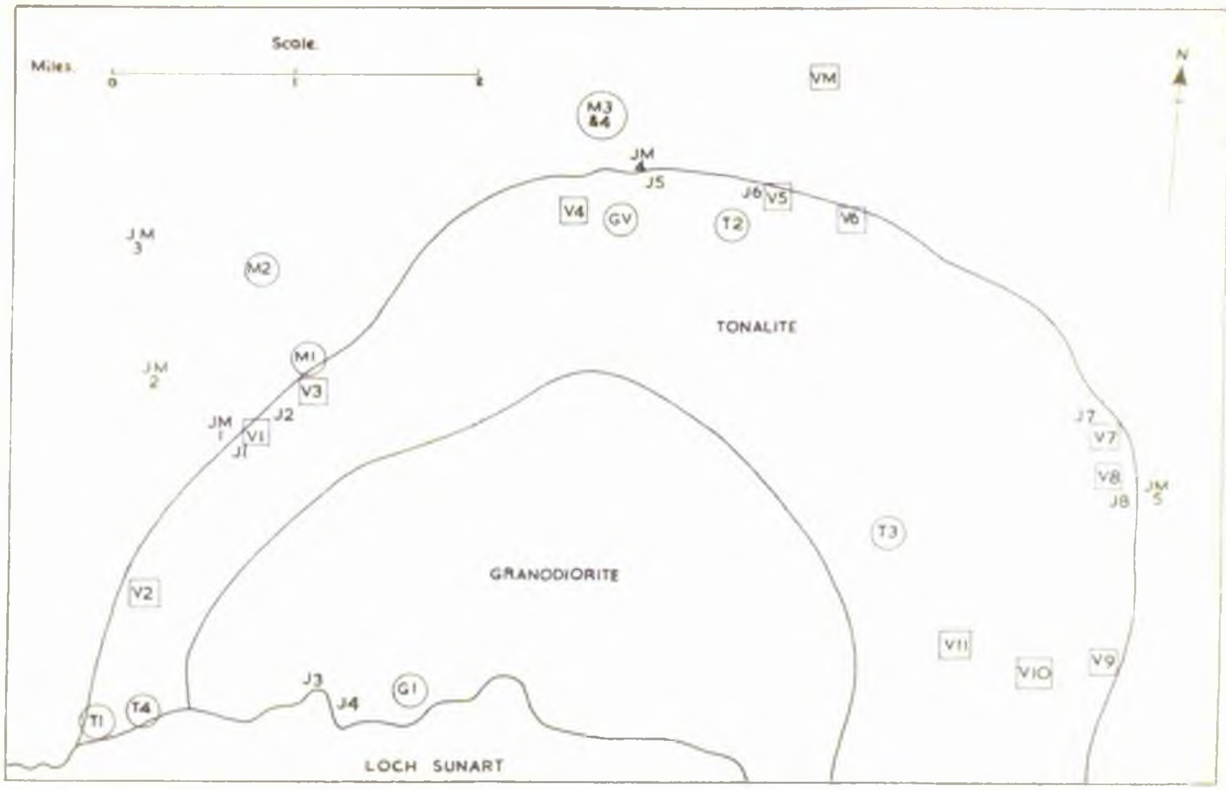


Fig.5.

Outline map showing the localities from which hand specimens were obtained for petrofabric analysis (Fig.6), and the localities in which readings were obtained for the preparation of the joint and vein orientation frequency diagrams. Only the sources of the observations for the diagrams which are reproduced in Figs. 7 and 8 are shown.

Hand Specimens (In Circles)

T1-T4	Tonalite.
G1.	Granodiorite.
GV.	Granitic Vein.
M1-M2	Pelitic schist.
M.3-M.4	Psammitic schist.

Vein Diagrams (in Squares)

V1-V11 in Tonalite.
VM in Injection Gneiss.

Joint Diagrams.

J1-J8 in Tonalite and Granodiorite.
JM1-JM5 in Moine schist and gneiss.

difficult. Secondly, it was hoped that some information would be obtained on the orientation of minerals in the tonalite and granodiorite, quartz and biotite in particular, which were not visibly oriented in the field. Lastly, in order to make a comparison between the structural characters of the rocks of the complex and the surrounding country rocks, the orientation of certain minerals was examined in the country rocks. This examination of the country rocks, was also intended to supplement field observations.

Crystal orientation was also studied in a granitic vein, for the purpose of comparing this orientation with that of the surrounding tonalite, and in order to confirm megascopic observations.

Within the complex, the orientation of the crystals of biotite, plagioclase feldspar and quartz was examined in four specimens of tonalite, and in one of granodiorite. The orientation of the hornblende crystals was examined in the granodiorite specimen, and in one of the tonalite specimens. In addition, the orientation of the quartz and biotite crystals in the granitic vein was examined.

In the Moine country rocks, the quartz and biotite orientation in three rocks, and the biotite orientation in a fourth, was investigated.

The localities from which these specimens were collected are indicated in Fig.5.

<u>Tonalite and Granodiorite</u>.

Two major difficulties were encountered in these rocks.

Firstly, they were so coarse-grained that a single thin section contained insufficient crystals for the satisfactory analysis of crystal orientation. To overcome this difficulty, several sections, cut in three mutually perpendicular directions, were employed in each analysis. As many as six sections were used in some instances.

The second, and more serious difficulty, was encountered in the measurement of some of the crystallographic directions at high angles of tilt on the Universal Stage. This applied in particular to the study of the orientation of the hornblende and plagioclase feldspar crystals and to a lesser extent to that of the biotite crystals. It was hoped that the use of several thin-sections, cut mutually perpendicular to each other, would also overcome this difficulty. The results of the analyses indicate that this was only achieved in part.

In none of the analyses, were crystals of different size found to show a difference in orientation.

Quartz Orientation. The orientation of the optic axes was found in the quartz crystals. Between one hundred and fifty, and three hundred measurements were made in each rock.

The four petrofabric diagrams for the tonalite specimens are alike in showing no apparent preferred orientation of the quartz crystals. In none of these diagrams is there any apparent relation between the orientation of the quartz crystals and the megascopic determinations of crystal orientation. Fig.6a from specimen T1 is a typical example of these diagrams.

The diagram prepared from the granodiorite specimen suggests that the quartz crystals in this rock may have a preferred orientation. In this diagram the plot of the optic axes forms a girdle, the axis of which is nearly parallel to the direction of dip of the megasopic foliation (Fig.6b). As this girdle is diffuse and rather ill-defined the significance of this orientation pattern is dubious.

Biotite Orientation. The poles of the (001) cleavages of the biotite crystals were plotted. In each section the orientation of the cleavage in the vast magority of the crystals was recorded, although inevery case a very small number of crystals were oriented with their cleavages so nearly parallel to the plane of the section that their orientation could not be measured. This difficulty was largely overcome by the use of several sections, cut in mutually perpendicular directions. In each rock the orientation of the cleavage planes of between two and three hundred crystals was recorded.

In two specimens from the outer contact zone of the tonalite (T1 and T2), the field observations of the biotite orientation are confirmed by the microscopic examination. In T1 the cleavage planes of most of the biotite crystals are oriented approximately parallel to the plane of the megascopic foliation. Partial girdles are suggested in the diagram, due to biotite crystals having a common direction, but not a common plane of orientation. These girdles are indistinct however, and again confirm megasopic observation, as no distinct lineation was visible in the field (Fig.6c).

In the other contact specimen - T2, the foliation observed in the field was less intense than in the previous specimen, and this is corroborated in the petrofabric diagram, as fewer biotite crystals appear to be oriented with their cleavage parallel to the megascopic foliation in this rock. The megascopic lineation in this rock is indicated in the petrofabric diagram by a girdle, due to flakes of biotite oriented with a common linear direction - the axis of the girdle. The orientation of this axis corresponds with that of the megascopic lineation - parallel to the direction of dip of the foliation (Fig.6d).

The other tonalite specimen (T3), and the specimen of granodiorite, were collected from areas where the biotite was apparently unoriented. The petrofabric analyses also indicate that the biotite crystals appear to have no preferred orientation in these rocks (Fig.6e).

Plagioclase Feldspar Orientation. Crystals of this mineral seem invariably to be twinned. The composition plane, in the majority of cases, appears to be parallel to (010), though twinning occurs on more than one law. The poles of these (010) composition planes were plotted in the petrofabric analyses, the nature of the composition plane being checked by the Rittmann "zone method". In addition, the "a" axes of the crystals were plotted, being located by the intersection of the (010) composition plane with the cleavage parallel to (001). In each specimen the poles of between one hundred and fifty, and two hundred composition planes were plotted. Approximately one hundred and twenty "a" axes were also plotted in the specimen of granodiorite, and in three of the specimens of tonalite.

In T1, the orientation of the composition planes corresponds with the biotite orientation, defining only a planar structure with clarity, (Fig.6f). "a" axes were not examined in this rock. In T2, the orientation of the composition planes of the feldspar once more corresponds with the orientation of the biotite, and also with the megascopic observations. A planar structure is defined, though rather less clearly than in T1, and a linear structure also, trending roughly parallel to the dip of this planar structure (Fig.6g). The orientation of the "a" axes does not indicate that they tend to be aligned in any particular direction.

In the other rocks, both tonalite and granodiorite, the difficulties arising at high angles of tilt on the Universal Stage were encountered. In these rocks, the orientation of the feldspar is less perfect than in the contact rocks. In the latter, by relating the direction in which the thin-sections were cut to the visible crystal orientation, the orientation of the bulk of the feldspar crystals could be determined. With less perfect orientation, this is no longer possible. It was found, that the concentrations in the petrofabric diagrams are clearly related to the orientation of the planes of the thin-sections - few composition planes being recognised at angles of tilt of more than 30-40°. The results of the study of the orientation of the plagioclase crystals in these rocks are felt to be quite untrustworthy. The concentrations show no marked correspondence to the orientation of the megascopic structures.

Hornblende Orientation. This mineral, being absent or scarce in the outer contact zone of the tonalite, could not be examined in the specimens collected from this zone. In the specimens of tonalite in which petrofabric analyses were made and in the granodiorite specimen, the poles of the (110) cleavages were plotted. The orientation of the "c" axis of the crystals was also recorded whenever possible, by plotting the intersection of the (110)cleavages.

As with the feldspars, it was found that the crystallographic directions which were being investigated, were not discernible at high angles of tilt on the Universal Stage. No marked resemblance to the megascopic orientation pattern was found, the concentrations in the diagrams being apparently related to the orientation of the planes of the thin-sections (Fig.6h).

Granitic Vein.

The vein chosen for petrofabric analysis was fine-grained, with abundant biotite, visibly oriented parallel to the wall of the vein. The vein transgressed the foliation of the surrounding rock.

The poles of the (001) cleavage in two hundred and fifty crystals of biotite were plotted. The diagram produced shows a rather ragged girdle, with an axis roughly parallel to the dip of the vein. The main concentration in this girdle corresponds with the pole of the planar margin of the vein, while the girdle is thin at points ninety degrees removed from this maximum. The main maximum does not even correspond approximately with the plot of the pole of the foliation in the surrounding tonalite. (Fig.6j and Fig.6d show the approximate orientation of the biotite in the surrounding tonalite.)

The orientation of the optic axes of one hundred and sixty five quartz crystals was plotted. No very distinctive pattern of orientation is apparent, possibly because of the rather small number of readings. There are two large diffuse maxima, corresponding roughly with the intersection of the strike line of the vein with the margin of the diagram (Fig.6i).

Moine Country Rocks.

The examination of the mineral orientation in the country rocks was undertaken, as has been stated, solely to provide a comparison with the mineral orientation in the rocks of the complex. No attempt was made to discover the regional pattern of mineral orientation in the country rocks, and the specimens for the petrofabric analyses were chosen from rocks closely adjoining the contact with the complex. The orientation of only two minerals was examined - one (quartz) was not visibly oriented in the field, the other (biotite) did show a megascopic orientation.

One specimen (M1), was a pelitic schist collected fifteen yards from the tonalite-country rock contact. Another (M2) was collected from outcrops of similar rock, half a mile north-west. The two other specimens (M3 and M4) came from different limbs of a small fold in psammitic schists, a quarter of a mile from the tonalite contact. Only one thin-section was used in the preparation of each petrofabric diagram.

Quartz Orientation. This was examined in M1, M3 and M4. The orientation of between two hundred and fifty, and three hundred optic axes wasrecorded in each case. There is little resemblance between the three diagrams, and two (M1 and M3) show no apparent preferred orientation (Fig.6k). In M4, there appears to be a concentration, due to quartz crystals being oriented with their "c" axes roughly normal to the foliation plane in the parent rock - and also, in this instance, to the fold axial plane (Fig.6l). The concentration is somewhat diffuse, is of low density, and its centre does not exactly coincide with the poles of the foliation and fold axial planes. As the two specimens (M3 and M4) were collected no more than six feet apart, and as the quartz crystals in M3 show no distinct orientation, this apparent orientation must be treated with some reserve.

Biotite Orientation. The poles of two hundred basal cleavages of biotite crystals were plotted in each of the four diagrams. A megascopic foliation due to oriented biotite crystals was visible in each case, but no linear structure due to crystal orientation was apparent.

In M1, the diagram shows a girdle with a single main concentration. This concentration corresponds with the pole of the megascopic foliation plane. The axis of the girdle corresponds roughly with the direction of dip of this structure (Fig.6m).

In the other three diagrams a girdle containing two or more main maxima is also present. The main concentrations coincide approximately with the pole of the megascopic foliation plane in each diagram. The correspondence is not exact, however, and the main concentration may be displaced twenty to thirty degrees from the plot of the pole of the foliation plane. The axis of the girdle corresponds roughly with the direction of dip of the megascopic foliation in two cases (M3 and M4) (Fig.6o). In the other (M2) it lies approximately in the foliation plane, but at a considerable angle to the direction of dip of the foliation (Fig.6n). This girdle seems to be related to the orientation of the thin-section used in the petrofabric analysis even although the orientation of every visible biotite crystal was recorded, except for a few which lay with their cleavages nearly parallel to the plane of the section. The concentrations in this girdle are, however, of low value.

In all four diagrams, there is a tendency for a concentration to occur in the north-west quadrant, despite the variable foliation in the four specimens. In the folded psammitic rocks, from which M3 and M4 were collected, this concentration corresponds approximately with the pole of the fold axial plane. No correlation can be made between the positions of the concentrations in these diagrams and the attitude of the nearest contact with the tonalite.

There is no marked similarity between the quartz and biotite diagrams, either as a whole, or in the same rock.

In summary, it can be stated that the petrofabric analyses support the field observations of crystal orientation in all

Fig. 6 Petrofabric Diagrams.

Locality.

The localities from which the specimens were obtained for the preparation of the diagrams are shown in Fig. 5.

Foliation and Lineation.

In Figs. 6a-g the orientation of the megascopic foliation in the surrounding tonalite or granodiorite is shown, and where a lineation is visible, the orientation of this structure is also indicated.

In Fig. 6k-o the orientation of the megascopic foliation in the surrounding Moine schists and gneisses is indicated.

Quartz Diagrams. "c" axes plotted.
Biotite Diagrams. Poles of (001) cleavages plotted.
Plagioclase Feldspar Diagrams. Poles of (010) twin planes plotted.
Hornblende Diagram. Poles of (110) cleavages plotted.

Contours.

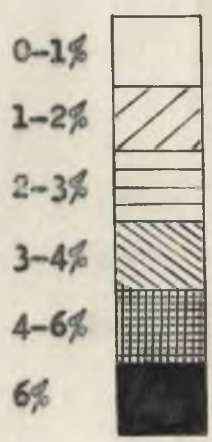


Fig. 6a. Quartz T2.
315 Readings.

Fig. 6b. Quartz G1.
300 Readings.

Fig. 6c. Biotite T1.
200 Readings.

Fig. 6d. Biotite T2.
250 Readings.

Fig. 6e. Biotite G1.
294 Readings.

Fig. 6f. Plagioclase Feldspar. T1.
137 Readings.

Fig. 6g. Plagioclase Feldspar T2.
175 Readings.

Fig. 6h. Hornblende T3.
254 Readings.
Trace of the planes of the three thin sections used in preparing this diagram are shown.

Fig. 6i. Quartz GV.
165 Readings.
Trace of the planar margin of the vein is shown. P is the pole of this surface.

Fig. 6j. Biotite GV.
250 Readings.
Trace of the planar margin of the vein is shown. P is the pole of this surface.

Fig. 6k. Quartz M3.
250 Readings.

Fig. 6l. Quartz M4.
300 Readings.
The dotted line indicates the orientation of the axial plane of the fold in the bed of psammitics.

Fig. 6m. Biotite M1.
200 Readings.

Fig. 6n. Biotite M2.
200 Readings.

Fig. 6o. Biotite M4.
200 Readings.

rocks, in as far as the deficiencies in the technique allow. Comparison of the orientation of quartz and biotite in the outer tonalite, and the orientation of the same minerals in the Moine country rocks, discloses no new features, quartz appearing to be unoriented in both types of rock, biotite being largely oriented parallel to the visible foliation planes.

2. OTHER INTERNAL STRUCTURES.

Certain structures in the tonalite and granodiorite are described separately, as they cannot be grouped satisfactorily with either the orientation structures, or the fracture systems.

Tonalitic Veins.

These veins resemble biotite-rich tonalite in appearance, but are much finer-grained than normal tonalite. They appear to have an even higher content of biotite than the biotite-rich modification of tonalite frequently seen in the outer contact regions, the biotite occurring partly as large rounded clots and aggregates.

Tonalitic veins are restricted to the outer contact zone of the tonalite, and are never abundant. The biotite crystals always show a planar orientation parallel to the walls of the vein, and some of the veins contain inclusions, which appear to consist of disoriented blocks of the surrounding tonalite (Plate 15). The foliation in these enclosed masses is normally related neither to the foliation of the surrounding rock, nor to the foliation within the vein itself. The margins, and also the foliation of the veins, may parallel the foliation in the surrounding rock, or transgress it. The margins of the veins are usually clean-cut, and are often irregular. In some cases, the margins are ill-defined, however, and the veins then appear to grade into the surrounding tonalite, or into biotitic schlieren oriented parallel to the foliation in the tonalite. The veins show no tendency to be oriented in any particular direction.

These veins are cut by the normal granitic veins, which are so abundant in the outer regions of the tonalite.

Zones of Fine-grained Granodiorite.

In the granodiorite, zones of fine-grained rock occur, which resemble elongated strips of fine-grained granodiorite, though in some cases, no pink orthoclase crystals are visible in these zones. The zones may be sharply or gradationally bounded, and the opposite margins of the same zone may differ in nature. The width of the zones is normally no more than a few feet, although they may be as much as fifty yards wide. They appear to be impersistent parallel to their length. In many cases, it is difficult to estimate the width and extent of a zone of fine-grained rock, however, as it may grade into the surrounding rock over a distance of several yards.

Normally the zone of fine-grained rock is foliated parallel to its length, and this structure may conform to that in the surrounding rock, or transgress it.

Near Eilean a'Mhuirich, a zone of fine-grained granodiorite occurs which strikes at right angles to the prevailing trend of the foliation and lineation in the normal granodiorite in this area - 205° (Fig.4). This zone can be traced for nearly three hundred yards, but appears to be impersistent. It varies in width, in some places is no more than a few feet wide, in others is fully thirty yards wide. The northern margin of this zone is sharply defined, the southern margin is gradational over many yards. Both within the fine-grained rock, and in the adjoining granodiorite, schlieren of all types appear to be more abundant than normal (Plate 2).

The rock in the fine-grained zone is foliated, this structure striking 105°, parallel to the length of the zone. The dip of the foliation varies from the vertical to gently north. A linear structure parallel to the direction of dip of the foliation can be discerned in some outcrops. The structures in the normal granodiorite immediately adjoining the zone of fine-grained rock are parallel to the structures within this zone, and do not conform to the normal trend of the structures in this area. The orientation of the structures in the normal granodiorite changes gradually over a few yards in the vicinity of the fine-grained rock, from the prevailing trend (foliation 205° / 30° W; lineation-horizontal), to the trend seen within the fine-grained rock (foliation - 105° /90-10° N; lineation - parallel to the dip of the foliation). It is noteworthy that elsewhere in this area, local fluctuations in structural trend occur (see page 48).

Structures Resembling Shear Planes.

In both tonalite and granodiorite structures consisting of bands of fine-grained rock, between a quarter and half an inch in width, occur. These structures may extend over distances of several yards. They usually appear to be impersistent, and sometimes can be seen to grade into the surrounding rock. The margins of these bands are ill-defined and may be straight or sinuous. The fine-grained rock in these bands, mineralogically, resembles the surrounding tonalite or granodiorite, and is usually foliated parallel to the margins of the band. This foliation transgresses the structures in the surrounding rock. At opposite margins of the bands, the structures of the surrounding rock can sometimes be seen to be deflected in opposite directions.

These structures are most abundant in the outer areas of tonalite and occur sparsely throughout the granodiorite. In one instance, near the tonalite-country rock contact, a small area of tonalite is bounded by these structures. The foliation in this block of tonalite, was seen to differ in trend from that prevailing in the surrounding rock. Insufficient numbers of these structures are exposed to indicate whether they follow any particular trend.

3. FRACTURE SYSTEMS.

(i) General Remarks.

The object of the study of the fracture systems was to discover the general characters and orientation pattern of the fractures which had been formed during the period of genesis of the complex itself. As a preliminary step, it was necessary to establish which of the many fractures in the rocks of the complex were contemporary in origin with these rocks.

Plate 15.

A tonalitic vein in the tonalite near the northern margin of the complex. The vein branches near the hammer and contains small blocks of disoriented tonalite (e.g. immediately to the left of the hammer). The surrounding tonalite is foliated parallel to the rock face (note the flat basic lens), and lineated parallel to the shaft of the hammer (oriented biotite and feldspar crystals defining this structure can just be detected).

Plate 16.

An exposure, near the River Carnoch, half a mile from the eastern margin of the complex, showing the many cross-cutting granitic veins typical of the outer regions of the tonalite.

It seemed apparent that the fractures with a granitic vein-filling had formed shortly after the rocks they cut, presumably as a phase of the same process, but there were numerous other fractures, which were devoid of this filling, and which showed no sign of being related in any way to the formation of the complex. The difficulty experienced in determining which of these barren fractures (the joints) were of genetic significance, was one of the major problems encountered in the study of the fracture system. The characters of the vein-filled fractures were studied first, in view of the obvious significance of these structures. The information obtained in this study provided a basis for the consideration of the joints.

In the study of both joints and veins, an attempt was made to discover if there was any relation between the orientation of these features, and the orientation of the foliation and lineation in the rock which they cut. As described earlier, the search for this relationship dominated the early stages of the investigation, in view of the work of the Cloos school. As no obvious relationship could be discovered, however, later work on the fracture systems treated these structures as a separate problem, without direct reference to the crystal orientation structures.

Attention was largely confined to a study of the fractures in the tonalite and granodiorite in the portion of the complex north of Loch Sunart. Restricted examination of the fractures in the Moine country rocks adjoining the northern areas was also carried out. For convenience, the fracture systems in the granitic rocks and the country rocks are described together.

Methods. In the field, the dip, strike, regularity and persistence of both joints and veins were noted. In the case of the veins, the nature of the vein-filling, and its thickness were also recorded. As the veins cut each other, and are not all of the same age, it is possible to distinguish the trend of earlier and later fractures, and also the amount and direction of movement on the fractures, at any of the vein intersections.

The study of both veins and joints ultimately resolved itself into a study of the orientation of these fractures. The technique employed was similar to that used in petrofabric analysis - the pole of the fracture plane was plotted on an equal area net, and the frequency with which the fractures had a particular orientation was determined by use of a one-per-cent counter and contouring. Large numbers of readings were needed for the preparation of these orientation-frequency diagrams.

In any exposure of tonalite, granodiorite, or Moine country rock, numerous joints, and frequently many veins also, are visible (e.g. Joints - Plates 4 and 13, Veins - Plate 16). Veins are never as numerous as joints, and are only abundant in the areas of tonalite adjoining the country rock. Some of the exposures in the inner parts of the complex are devoid of veins.

In view of the number of joints and veins, it was obviously impossible to record the characters of every fracture in large areas of rock and a sampling technique had to be employed. Originally, sampling was at random, a selection of the joints and veins in a small area being examined. Normally, these areas were approximately one hundred yards in diameter, and the characters of thirty to forty joints, and fifteen to twenty veins were noted in each area. The areas lay on traverses across the complex, and in the contact areas. The outer regions of the tonalite received particular attention.

Considerable difficulty was experienced in interpreting the observations from each area, and in an attempt to overcome this obstacle, the observations from several adjacent areas were combined in order to provide a larger sample for consideration. Approximately two hundred and fifty joint observations, and one hundred and fifty vein observations were considered in each case. The average dimensions of the total area, from which these readings were derived, measured eight hundred by two hundred yards in the case of the joints, twelve hundred by two hundred yards in the case of the veins. Large samples of vein readings could only be obtained from the outer contact regions of the tonalite.

Despite the use of these larger samples, difficulty was still experienced in interpreting and correlating the observations. Additional observations, based on a more rigorous sampling technique, were made, therefore, in order to check and augment the earlier measurements, and to serve as standards for comparison. Within small areas, which were under a hundred yards in diameter, the characters of every joint and vein were recorded. On an average, observations of the characters of over one hundred and fifty joints were made in each area, and in some cases, as many as one hundred readings of the characters of veins. These areas were scattered throughout the part of the complex already examined, and in addition a certain number lay on traverses in the country rocks, extending for over a mile from the complex. The characters of the fractures in the country rock were not studied by any other method, unlike the fractures in the rocks of the complex.

The distribution of the areas from which some of the observations were derived is shown in Fig.5.

Owing to the absence of large quarries in the Strontian district, it was impossible to determine whether the rocks possessed "rift", "grain" and "hardway" planes (Balk, 1948,p.34).

(ii) Vein-filled Fractures.

The objects of the field examination were to determine if any of the veins were of a distinctive type, and to discover if there was any relation between vein type and vein orientation. The characters by which it was sought to distinguish different types of vein were the width, regularity and persistence of the veins, and also the nature of the rock forming the vein.

The width of the veins ranges from three or four feet to a fraction of an inch. Such a variation can occur in a single vein. Frequently the veins show abrupt changes in the direction of strike, and in the angle of dip, or are very sinuous and irregular - often branching and anastomosing. Many veins are short and impersistent (Plate 16). A few veins are straight, parallel-sided, of uniform thickness and persistent over long distances. Such veins are relatively more abundant in the inner regions of the tonalite and granodiorite.

The failure of the attempt to distinguish veins of different petrographic type has already been described, and the attempt to distinguish different types of vein by means of the other characters proved no more successful. Variation in any one character of the veins could never be correlated with variation in another, and veins with a particular orientation appear to have no other outstanding characteristic.

Study of the contacts at vein intersections, indicates that in some areas, as many as four or five successive periods of vein formation have occurred (Plate 17). The contacts between one vein and another are usually sharply transgressive, but in some instances no distinct boundary is visible, and the veins appear to be contemporary. It proved to be impossible to correlate the relative age of the veins with any other character.

At the vein intersections, it is often apparent that movements have taken place, the earlier of the two veins being displaced at the margins of the later. An attempt was made to correlate the amount and direction of movement, with the other characters of the veins. An attempt was also made to correlate all the movements in different parts of the complex, as it was felt that they might show a certain uniformity over large areas of the complex. Once more no recognisable pattern could be established, although the movements at several hundred vein intersections were considered.

With the failure of all other lines of investigation, the study of the veins resolved itself into a study of the orientation of the fractures which had been filled by vein-forming material.

Study of the Orientation of the Fractures with a Vein-Filling.

The veins are only abundant in the outer regions of the tonalite, and in consequence, orientation frequency diagrams could only be prepared from the observations in these areas, as nowhere else were sufficient readings available.

Tonalite and Granodiorite.

It became evident, in the early stages of the investigation, that the orientation of the veins conformed to no clear pattern, although certain trends were common in certain areas. It was not until the observations from several areas had been combined, in the form of an orientation-frequency diagram, that a certain underlying pattern in the orientation of these fractures became apparent. Eight diagrams were prepared initially by combining the readings from many small areas. Three further diagrams were produced from the readings in the areas where the orientation of every fracture was recorded.

The areas, from which the observations were derived for the eight original diagrams, are so distributed that a complete coverage was achieved in the outer regions of tonalite, and in a traverse from the eastern tonalite-granodiorite contact to the eastern tonalite-country rock contact (Fig.5). The three later diagrams were produced from observations which had been made in areas which lie in the northern, eastern and western portions of the outer contact zone of the tonalite.

Examination of the diagrams (Fig.7a-k) shows that in each several maxima are visible. These maxima may be due to concentrations of as high a value as 23%, and frequently one, or even two, maxima of 10% or more, are visible. At least one concentration with a value of 5-7% is present in every diagram. The veins, therefore, show a pronounced tendency to be oriented in certain directions. Other lesser maxima are also present. Frequently two or three concentrations of 3-4% are visible, and when lower concentrations are considered as many as six maxima may be identified. The significance of these lower concentrations is questionable.

Comparison of the eight diagrams derived from the large areas (Figs.7b,c,d,f,g,i,j,k) shows that the strongest maxima tend to lie on the periphery of the diagrams, except in the north-west. It is perhaps worthy of note, that in the two areas where the main concentration is not peripheral, it is of less than 10% (Figs.7c-d). In the east and south-east, the different diagrams show a marked similarity which is apparent both in the diagrams from the contact areas, and in those from areas well within the tonalite. In these eastern areas, many vertical fractures with a west-north-west strike occur, and there is a partial girdle in the south-east portion of the diagram, due to the occurrence of veins with a north-east strike, and low to moderate dip to the north-west (Figs.7g,i,j and k).

In the northern areas the girdle tends to lie in the eastern part of the diagram, and the peripheral concentration is due to vertical veins with an east-west strike. The resemblance to the eastern diagrams is less in the north-east than in the north-west (Figs.7d and f). In the west, the diagrams once more resemble those from the eastern areas. The peripheral concentration is now due to vertical veins with a north-east strike, however, and is more diffuse, suggesting the partial development of a horizontal girdle. A partial girdle once more lies in the south-east portion of the diagrams (Figs.7 b and c).

The three diagrams derived from the compact areas (Figs.7 a,c and h) are considered separately, partly because they were based on a different approach from that employed in the preparation of the other diagrams, and partly because they were intended to augment the earlier observations. When they are compared with the earlier diagrams, no strong anomalies are apparent, and there is always considerable similarity between the diagrams of different type, which have been derived from more or less the same area. Variations in the intensity and in the positions of the maximum concentrations are evident, but there seems to be an underlying similarity in the distribution of the observations in both types of diagram.

These features of the later diagrams, and the overall similarity in the eight earlier diagrams, suggest that the vein orientation conforms to a broad overall pattern. Were this the case, local fluctuations and concentrations would be expected to be of importance in studies of small areas, but when larger areas were considered, the diagrams would be expected to show greater uniformity.

The validity of the comparisons, which have been made above, could be questioned on the grounds that the diagrams are not strictly comparable. In addition, the sampling methods employed have not been rigorously tested, in order to ensure that a truly representative sample was being considered. The similarity in the diagrams, and the strong concentrations they display, suggests however, that a correct representation of the more important trends has been obtained. The outline of the pattern seems to be distinct, although the true concentrations may differ in value.

The regional pattern of the vein orientation is probably suggested more strongly in the "master" diagram, in which the positions of the fifty two maximum concentrations, from the eleven orientation diagrams, are plotted (Fig.7m). Distinction was made between the maxima of different value and the maxima from different localities in plotting this diagram. No concentration of maxima from a particular area is apparent. Whilst distorting the pattern of orientation, by focussing attention on maximum, rather than on overall distribution, this diagram clearly illustrates the tendency for the main maxima to occur on the periphery, and for the other maxima to lie in a girdle in the south-east portion of the diagram.

The orientation of the vein-filled fractures in only a portion of the tonalite has been considered, and the orientation of these fractures in the remainder of the northern exposures of the tonalite and granodiorite has not been discussed. Examin-sation of the orientation of these fractures could only be by study of individual readings, no satisfactory method of group

Fig. 7. Vein Orientation Frequency Diagrams.

Locality.

The localities from which the readings were obtained for the preparation of Figs. 7a-1 are shown in Fig. 5. Large area diagrams are based on the readings from random sampling in a large area, small area diagrams are based on the readings made in small areas where the orientation of every fracture was recorded.

Maxima.

With Figs. 7a-1 the strike and dip of the granitic veins which are sufficiently numerous to define maxima of over 4% in the diagram is indicated.

Foliation and Lineation.

In Figs. 7a-1 the mean orientation of the foliation in the rocks in the area from which the readings were obtained is indicated. The mean orientation of the lineation is also shown where this structure is developed.

Contours.

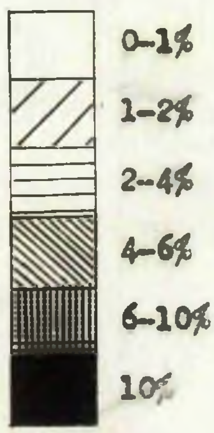


Fig.7a. (V1-Small Area).
Maxima. 165°/40° W (10%)
055°/80° SE (4%)
015°/75° W (4%)
100 Readings.

Fig.7b. (V2-Large Area).
Maxima. 065°/90° (6.5%)
095°/80° N (6.5%)
010°/25° W (5%)
151 Readings.

Fig. 7c. (V3-Large Area).
Maxima. 165°/55°W (9.5%)
055°/90° (8%)
158 Readings.

Fig. 7d. (V4-Large Area).
Maxima. 080°/40°N (7.5%)
040°/40°NW (5%)
147 Readings.

Fig. 7f. (V6-Large Area).
Maxima. 100°/90° (15.5%)
136 Readings.

Fig. 7g. (V7-Large Area)
Maxima. 115°/90° (16%)
105°/40° N (5%)
142 Readings.

Fig. 7h. (V8-Small Area).
Maxima. 130°/85°W (23%)
100 Readings.

Fig. 7i. (V9-Large Area).
Maxima. 130°/85°S (11.5%)
120°/40°N (4%)
163 Readings.

Size of Maxima.	No. of Maxima.
3%	13
3-5%	19
5-10%	11
10%	9

Fig. 7. Distribution of

Fig
Max

99

Fig
Max

15

analysis being possible, in view of the small number of observations which were available. In both tonalite and granodiorite, the vast majority of these veins were found to strike between 255° and 325°. The dip of these fractures ranges from 30° north, to 30° south. Most dip at angles of greater than 60°. No other tendencies are visible.

Relation to the Crystal Orientation of the Tonalite and Granodiorite.

The study of the relation between the orientation of the vein-filled fractures, and that of the constituent crystals in the enclosing rock, was given particular attention in the early stages of the present investigation. The fractures with a particular relation to the crystal orientation which have been found elsewhere, and which it was sought to identify at Strontian, are cross, longitudinal and diagonal joints - using the terminology of Cloos, quoted by Balk (1948, p.34). A search was also made for marginal fissures and thrusts, and for flat-lying fractures, which could have served as movement planes for normal faults.

The orientation of more than fifteen hundred vein-filled fractures was recorded in the course of the present investigation. Of these, the orientation of roughly three hundred was found to have a simple relation to the orientation of the structures in the enclosing rock. Forty (2-3% of the whole), could be considered as cross fractures; approximately one hundred (5-6%), could be considered as longitudinal fractures. Fractures corresponding in trend to diagonal joints, occurred sixty five times (4%). About seventy five (5%) had the same strike as the foliation and a steep dip - a category not included by Cloos in his terminology. A margin of between five and ten degrees in the angles of dip and strike was allowed in considering whether a fracture could have a certain relationship.

An examination of the flat-lying fractures discloses that none have slickensides parallel to the lineation - the criterion for the recognition of the distinctive type described by Cloos. Normally marginal fissures dip inwards when a contact dips steeply outward. In the Strontian complex, with the inward dip of the outer contact, an outward dip of these fissures might be expected. In the outer areas of tonalite, fractures were found which showed a tendency to strike parallel to the outer contact, and to dip outwards at less than 60°. This tendency is not consistently developed, and when a change in strike of the contact occurs, the trend of the fractures frequently is unaltered. Inward dipping fractures, with a vein-filling, seem just as abundant. Nowhere are signs of marginal thrusting on vein-filled fractures visible - either by visible displacement, or by slickensides. Similar flat-lying fractures, which conform to the trends seen in the contact areas, are also found throughout the rocks of the complex, and are not confined to the contact areas of tonalite.

Comparison was also made between the pattern of fracture orientation, shown in the frequency diagrams, and the crystal orientation. The mean values of the angles defining the orientation of the lineation and foliation in the tonalite were taken in each case. In the diagrams from the compact areas, the orientation of the foliation and lineation actually visible in the outcrops could be used.

The positions of the maxima in the diagrams do not correspond with the positions where maxima should occur in the event of any of the fractures described by Cloos being abundant. No other simple relation of a type not described by Cloos can be discerned in the diagrams.

On five occasions in the eleven diagrams, a concentration of fractures with the same strike as the foliation, and with a steep dip occurs. The dip usually differs from that of the foliation plane. These maxima occur irregularly, and vary considerably in magnitude.

Vein-filled Fractures in the Country Rock.

Granitic veins occur in the country rock, being common close to the contact with the tonalite, and decreasing in number with increasing distance from this contact.

Petrographically these veins resemble the veins found in the rocks of the complex, and in many cases, veins can be seen passing from tonalite into country rock, with no change in trend (Plate 3). There also appears to be a regional system of granitic veins, which occur throughout the Moine schists and gniesses and are not concentrated in the vicinity of the complex. These differ in appearance from the typical granitic veins of the complex, being richer in biotite and coarser in grain on the whole. Many quartz veins, and veins of coarse-grained quartz and feldspar, also occur throughout the country rocks.

The granitic veins, which resemble the veins in the complex, often occur with straight, parallel sides - particularly in the eastern contact areas. Sometimes they can be seen to terminate in a network of anastomosing branches. They are never as abundant in the country rocks, as in the adjoining tonalite. Few were recorded at distances of greater than half a mile from the margin of the complex.

When the orientation of these veins is compared with the orientation of the similar veins in the adjacent tonalite, a marked correspondence is usually visible. Flat-lying veins with an outward dip, in particular, tend to be parallel in both country rock and tonalite. These veins are most common in the western contact areas. Many of the vertical veins in the country rock differ in trend from the similar veins in the tonalite, but this is partly due to the tendency of the granitic veins to follow the foliation planes in the country rock. In the east, vertical veins, which have a similar orientation to the veins in the tonalite, are common in the country rock. With increasing distance from the tonalite contact, the degree of correspondence in the orientation of the veins decreases.

The quartzo-feldspathic and quartz veins, which do not appear to be related to the complex tend to follow the foliation planes in the country rocks, and also tend to be oriented parallel to the axial planes of large folds. They are particularly common in the augen gneiss to the north of the complex, and a sufficient number of observations of the orientation of these veins were made in this area to permit the production of an orientation-frequency diagram. This diagram does not resemble closely any of the vein orientation diagrams produced from the observations in the tonalite (Fig.71).

Granodiorite Porphyry Sheets. The reasons for considering the bodies of this rock separately from the granitic veins have been stated already (pages 20–21). Granodiorite porphyry occurs largely as gently inclined sheets, which may be as much as fifty feet thick, and which usually can be traced with little deviation in trend for several miles. The margins of the sheets are normally sharp, clean-cut surfaces - usually of a planar nature. Abrupt changes in the width of the sheets may occur.

Sheets of granodiorite porphyry are never abundant, and are most common in the north-eastern parts of the complex. They may extend into the country rock. The main trend of the sheets is - north-east strike, dip at 45^{o} to the north-west. As has been noted already (Page 73), this is a trend followed by many of the flat-lying granitic veins. Other trends are visible but are less common.

(iii) Joints in the Tonalite and Granodiorite.

As stated earlier, the difficulty experienced in determining whether any of the joints in the rocks of the complex were related to the formation of the complex constituted one of the major problems encountered in the present investigation.

The most satisfactory method of overcoming this difficulty would be by means of a comparison of the joints in the rocks of the complex with the joints in a large area of the surrounding country rock. By this method, it would be possible to distinguish any peculiarities in the orientation pattern and general characters of the joints in the granitic rocks, which would serve to identify the joints contemporary in origin with the complex. Such a complete study would be a separate research problem, however, and could not be attempted without neglecting the study of the other structures.

In consequence, a less fundamental approach was adopted in the present research. The basis of this approach was a comparison between the orientation of the joints, and the orientation of the structures which appear, quite clearly, to have been formed in association with the complex. These structures are the vein systems, and the foliation and lineation in the tonalite and granodiorite.

As with the veins, the orientation, regularity and persistence of the joint surfaces were noted in the field. An attempt was made to distinguish different types of joint by these characters, and to correlate the different characters of the joints. This proved no more successful than in the case of the veins and the study of the joints - as with the veins - resolved itself into a study of the orientation of these fractures.

<u>Study of the Orientation of Individual Joints.</u>

<u>Comparison of Individual Joint and Vein Trends.</u> The

observations of the orientation of joints and veins recorded in the initial survey of the northern part of the complex, were compared in the laboratory. No comparison was made in the field as in the choice of a random sample from the visible joints and veins, it seemed probable that a sample of any joints and veins with the same orientation would be included.

The entire northern part of the complex was subdivided into three regions for the purpose of this comparison - a northern, an eastern and a western. The Strontian River divides the eastern from the western region, and also the northern region from the eastern, and the Allt nan Cailleach divides the northern from the western region. Within these regions, the observations made in each small area on the initial traverses were studied separately from the observations made in the similar adjoining area. Individual comparison was therefore restricted to observations which had been made within an area approximately one hundred yards in diameter (see page 68). A five degree variation in both strike and dip was allowed in considering whether a particular joint and vein were parallel. The orientation of all joints, approximately parallel to veins, within each of the three large areas, was then compounded by plotting the poles of these fracture surfaces on an equal-area net, and contouring, as before. In the eastern and western areas, approximately two hundred and fifty readings were plotted, in the northern area, about a hundred and thirty (Fig.8a-c).

Each of these frequency diagrams shows considerable concentrations. In the diagram from the eastern areas, there is a single main maximum of 28% ($115^{o}/90^{o}$). In the diagrams from the north and west the main maximum is of 16% ($100^{o}/80^{o}$S and $115^{o}/90^{o}$ respectively), with a subsidiary maximum of 7-9% ($020^{o}/90^{o}$ and $045^{o}/90^{o}$ respectively). There is, therefore, a very marked tendency for the joints, which are parallel to veins, to have certain orientations. No tendency can be discerned for joints to have a preferred orientation in any small portion of one of the three large areas.

There is an overall tendency for these joints to reproduce the pattern of vein orientation. This tendency is mainly confined to the vertical joints but, in addition, there are, in some areas, many joints parallel to relatively few veins, and numerous veins to which relatively few joints are parallel. The best correspondence is in the east, the least in the west.

The outstanding features of these diagrams are considered in more detail at the end of the present chapter.

<u>Relation between Crystal Orientation and Individual Joint Orientation</u>.

The orientation of between four and five thousand joints in the complex was recorded. Of these, the number of possible cross joints is forty five (approximately 1%); of possible longitudinal joints - three hundred (approximately 7%); of possible diagonal joints - five hundred (over 10%). Steeply dipping joints with the same strike as the foliation number approximately three hundred and fifty (7%). A five to ten degree variation in the angles of strike and dip was allowed once more, in considering whether a joint conformed to a certain type. In all, approximately a quarter of the total joints appear to bear a simple relation to the structures in the tonalite and granodiorite.

The distribution of the joints with these significant trends is very haphazard. Joints of a particular type may be abundant in one area, and almost lacking in a closely adjoining set of outcrops.

No recognisable marginal fissures were found, and none of the flat-lying joints show signs of having acted as movement surfaces. Flat-lying joints tend to be rather scarce, and although the orientation of these joints shows a certain uniformity throughout the complex, this cannot be related directly to the attitude of the contact with the country rocks.

Joint Orientation Diagrams.

As with the veins, the pattern of the joint orientation in the complex was not apparent from a consideration of individual readings. In any one outcrop, the joints tend to occur in sets having a common orientation (Plates 4 and 13), but there is considerable variation between adjoining outcrops.

Fourteen diagrams were produced by combining the observations from several adjacent areas on the original traverses. These provided a more or less complete coverage of the northern part of the complex. They were augmented by nine later diagrams, which were produced from observations in small compact areas, where the orientation of every joint was recorded. Seven of these small areas lie within the boundaries of seven of the larger areas. The localities, from which the observations were obtained for the production of some of the diagrams, are shown in Fig.5.

The fourteen original diagrams indicate clearly that vertical joints are abundant, the outstanding feature of these diagrams being a girdle with a vertical axis. Flat-lying joints are relatively scarce in these diagrams. On the girdle several maximum concentrations occur, ranging up to 16% in value. Normally at least one maximum of 10% or more is visible, and there may be two such maxima. As many as seven maxima occur in some diagrams, but as many of these are of small value, they are of questionable significance (Figs.8c,g,h and j are representative).

The nine later diagrams are generally similar to the earlier diagrams (Figs.8d,f,i and k are representative), although flat-lying joints appear to be relatively more abundant in the former. Eight of the twenty three diagrams are reproduced as Figs.8d-k. These diagrams were first used for comparison with the vein orientation, and the orientation of the foliation and lineation in the tonalite and granodiorite.

Comparison of Joint and Vein Orientation Diagrams.

Three of the joint diagrams are strictly comparable to the vein diagrams - being produced from observations made in the same area in each case (Fig.8d with Fig.7a; Fig.8i with Fig.7c; Fig.8k with Fig.7h). The basis for the comparison of the other diagrams is less precise, for although the areas of derivation of the readings are generally similar in the two types of diagram, they are not identical.

As might be expected from the study of the parallelism of individual joints and veins, there are some resemblances, and many dissimilarities between the joint and vein orientation diagrams.

Even in the diagrams produced from the same areas, there is little similarity in appearance. There are usually some joints parallel to all the veins, as was noted before, but maxima may or may not coincide. Major vein maxima may coincide with minor joint maxima. Similarities are most marked in the eastern areas.

Comparison of Joint Orientation Diagrams with Crystal Orientation.

The comparison between the joint orientation diagrams and the orientation of the foliation and lineation was made in a similar manner to that carried out with the veins. Only occasionally does a maximum correspond in position with that required by a concentration of joints of a particular type. Diagonal joints apparently occur most frequently. These correspondences occur haphazardly, and are not uniformly distributed throughout the complex. No other simple relation of a type not described by Cloos, could be discovered.

When the results of the study of individual joint trends are taken into consideration, several anomalous features emerge. In many cases when individual joints with an apparently significant relation to the crystal orientation are abundant, no corresponding maximum appears on the joint orientation diagram. The maximum occurs, but lies in a position somewhat removed from the required position.

General Pattern of Joint Orientation in the Tonalite and Granodiorite.

So far, the discussion of the joint orientation appears to be inconclusive, and no simple relation between the orientation of the joints and the orientation of the other structures is visible. The reasons for the assumption that the true pattern of vein orientation was represented in the vein orientation diagrams, have been given earlier. No consideration has yet been given to the question of whether a correct representation of the pattern of joint orientation in the complex has been obtained. If the joint orientation diagrams give a distorted picture of this pattern, then this distortion might explain the failure to discover a relation between joint orientation and the orientation of the other structures. The discovery of the pattern of joint orientation in the complex, was never in itself, a primary object of the present investigation. At this stage of the investigation, however, it seemed that if some indication of this pattern could be obtained, even although it were only an incomplete picture, the main purposes of the research would be furthered.

The approach to this problem was similar to that employed with the veins. The fourteen initial diagrams do not appear to indicate any clear pattern. All are similar, in that the majority of the plotted points lie near the periphery of the diagrams, forming a girdle with a vertical axis. Maxima occur on this girdle, but vary in position and value from diagram to diagram, in an apparently unsystematic fashion. Resemblances do occur in the size and position of maxima, but these, more often than not, are in diagrams from widely separated areas (e.g. Fig.8e and Fig.8j).

The nine later diagrams, like the similar vein orientation diagrams, were prepared in order to provide a means of checking the homogeniety of the pattern shown in the earlier diagrams. Comparing the later with the earlier diagrams, derived from approximately the same locality, in some cases there appears to be considerable resemblance (Fig.8d and Fig.8e). In others, the resemblance is very slight (Fig.8h and Fig.8i). Maxima may be present in one diagram and absent in the diagram of the other type derived from roughly the same area. There is no strong resemblance between the nine later diagrams themselves.

There seem to be two possible ways of interpreting these relations. Either the original diagrams oversimplify the picture, and the true representation of the pattern of joint orientation is given in the diagrams based on the rigorous method of sampling, or alternatively, the latter are too much influenced by local conditions, such as the presence of fault planes, and the true pattern is more akin to that shown in the earlier diagrams.

Every effort was made to choose areas remote from any visible faults when making the observations for the later diagrams, but the topography in some instances suggested that concealed faults might exist, and in several cases there appears to be a simple relation between the orientation of joints defining a maximum on the diagram and the orientation of a probable fault plane. There is thus evidence which suggests that the second explanation advanced above, may be the correct one. If this is the case, however, it is still necessary to explain the distribution of the maxima in the early diagrams.

Preliminary examination of all twenty three orientation diagrams suggested that certain directions correspond with maxima more frequently than others. The whole problem seemed to be clarified when, following this suggestion of regional uniformity, the hundred and fourteen maxima from the individual diagrams, were plotted on a single "master" orientation diagram. The usual procedure of using an equal-area net and contouring was followed. The value, and locality of occurrence, of the maximum concentrations, were distinguished in plotting.

Marked concentrations of the maxima are apparent (Fig.8q). Five concentrations in all can be distinguished, though some are rather diffuse. One, in particular, is very marked, being due to the occurrence of twenty maxima in an area slightly larger than that enclosed in a one-per-cent counter. In other words, twenty out of the twenty three diagrams, show concentrations of joints with this particular orientation. The concentrations of maxima are due to joints with approximately the following orientations:- Strike/Dip (number of maxima in 1% area.)

$040^\circ/85^\circ S$ (15)

$115^\circ/90^\circ$ (12)

$015^\circ/90^\circ$ (11)

$152^\circ/90^\circ$ (14)

$090^\circ/80^\circ S$ (8)

Further evidence of significance in the study of the orientation pattern of the joints, was acquired when a review was made of the regional distribution and trend of the main faults in the area of the complex. The three most prominent fault trends are - 110°/90°, 035°/90°, and 080°/90°. The correspondence between the first two trends, and two of the main concentrations in the "master" joint diagrams, is notable. Normally in each joint orientation diagram, some relation can be found between the maxima and the faults which traverse the area from which the diagram is derived.

From this evidence, it is suggested that the orientation of the joints in the northern part of the complex conforms to a broad overall pattern and that the "master" joint orientation diagram gives at least an approximate outline of pattern of joint orientation in the northern part of the complex. The individual orientation diagrams suggest that the broad pattern is developed rather unevenly, the diagrams derived from large areas approximating more closely to the true pattern than the small area diagrams.

In the latter, local influences would be expected to affect the pattern to a marked degree and the lack of similarity between all the diagrams could be explained as being due to the influence of faulting. The faults are not uniformly distributed, and where they are abundant it can often be seen that the main joint trends tend to be parallel to the local faults. This relation is most apparent in the small area diagrams, as already noted, but can also be seen in many of the large area diagrams.

The study of joint orientation was taken no further. The methods employed in this study have not been substantiated by a rigorous examination of the sampling technique, and in particular, the exact influence of faulting on the joint orientation pattern requires further investigation. The pattern of orientation does seem to be apparent however, even although it may be distorted to some extent. This incomplete picture was felt to be sufficient for the general purposes of the present investigation.

The question of whether any of the trends, shown in the "master" diagram, can be related to the origin of the complex, remains to be considered. None appears to be capable of relation to the orientation of the foliation and lineation directly, although one of the "master" trends ($115^\circ/90^\circ$), is perpendicular to the strike of the lineation in much of the inner tonalite and granodiorite (205°). A comparison can be made with the vein orientation, utilising the diagrams which show the orientation of joints which are parallel to veins. In the west, the predominant trends common to both joints and veins - $115^\circ/90^\circ$ (16%) and $045^\circ/90^\circ$ (9%), coincide with two of the directions shown in the "master" joint diagram as being predominant trends. In the north, a subsidiary maximum, $155^\circ/90^\circ$ (5.5%), coincides with a "master" trend, and in the east, the single main maximum on the common orientation diagram, $115^\circ/90^\circ$ (28%), again coincides with a "master" trend.

Comparing the "master" trends with individual maxima in in the vein orientation diagrams, while every trend corresponds with at least one maximum, the only trend which is commonly followed is $115^\circ/90^\circ$. Five vein maxima coincide with this trend.

The evidence outlined above, suggests that at least one of the "master" joint trends - $115^\circ/90^\circ$, may be related to the formation of the complex.

Joints and Inclusions.

The large masses of appinite and of Moine country rock which occur as inclusions seem to have a distinctive joint pattern, but this was not confirmed by detailed examination. In both types of rock, joints are more numerous than in the surrounding tonalite and granodiorite, and in Moine country rock inclusions, the joints are as numerous as in the rocks surrounding the complex.

(iv) Faults.

The probable importance of the faults which occur within the complex in the interpretation of the joint orientation diagrams has been indicated. Actual fault planes are rarely visible in the field, but the presence of faults can be detected by means of lines of easy weathering, by the reddening of the joints, and by the occurrence of numerous close-spaced parallel joints. The majority of the fault planes appear to be vertical.

None of the faults are obviously and simply related to the origin of the complex. Fault planes oriented $115^\circ/90^\circ$ occur, as has been noted already, but are not confined solely to the vicinity of the complex, and there is no evidence which suggests that the movement on these faults was directly related to the formation of the complex. The occurrence of faults at the western tonalite-granodiorite contact, north of Loch Sunart (page 30), does not appear to be of fundamental significance. A series of faults, which extend outside the area of the contact, occurs in this area; successive faults, in turn, nearly coinciding with the contact as it changes trend.

(v) Joints in the Country Rock.

The joints in the areas of country rock adjoining the northern portion of the complex, were subjected to an examination which was restricted in scope. The main purpose of this study was to obtain some indication of the pattern of orientation of the joints in the country rock in the vicinity of the complex, so that a comparison could be made with the orientation of the joints in the tonalite and granodiorite. No attempt was made to establish the complete pattern of joint orientation in the country rocks.

The techniques employed were the same as those used in the tonalite and granodiorite, and in all, sixteen orientation-frequency diagrams were prepared. As the observations which were incorporated in the diagrams were always made in very small areas, where the trend of every fracture was noted, additional observations of the dominant trends of the joints were made in adjoining outcrops. These additional readings were intended to provide some indication of the extent to which the development of maxima in the diagrams is controlled by local conditions.

The diagrams, like the similar diagrams from the complex, show a girdle with a vertical axis as the dominant feature (Figs.8l-p are representative). This girdle contains maxima, and is usually incomplete. Frequently, indications of incomplete girdles, with a horizontal or subhorizontal axis, are also visible. Maxima tend to be more numerous in these diagrams than in the comparable diagrams produced from observations within the complex.

The joint diagrams were first examined to discover if any of the maxima could be simply related to the structures of the country rocks. These structures were the foliation, with locally, a lineation in addition. In the diagrams derivedfrom the areas immediately adjoining the contact with tonalite, the attitude of the foliation and lineation in the tonalite was also considered in relation to the maxima.

No significant relations are discernible. Neither can the maxima be simply related to the attitude of the contact with tonalite. In several areas, joints which are roughly perpendicular to this contact are common, but these joints are not distributed uniformly.

In general appearance, diagrams from neighbouring areas are usually similar to some extent (Figs.8l and 8m). The trends, which occur as maxima in the diagrams, are invariably found to persist as the dominant trends in the adjoining outcrops. When two diagrams differ in appearance, it is often found that the diagram derived from an intervening area resembles both to some extent. There is no outstanding peculiarity in the diagrams from the actual contact areas, and, in particular, the diagrams from these areas are not characterised by the strong development of flat-lying joints.

Normally, the orientation diagrams for the joints in the country rock resemble to some extent the similar diagrams derived from the adjoining areas of tonalite (Figs.8k and 8n). The orientation of the joints in the country rocks shows few resemblances to the orientation of the veins in the complex.

The positions of the ninety-five maximum concentrations in the sixteen diagrams were plotted on an equal-area net as before, and this scatter diagram was contoured (Fig.8r). Ten concentrations of maxima appear on this diagram, but several of these are of low value. All the "master" joint trends visible in the complex correspond either with actual concentrations of maxima on this diagram, or with areas where, although no local concentration is defined, several maxima occur on the diagram. The important trends in the complex are of less importance in this diagram.

These features of this diagram suggest that the orientation of the joints in the Moine country rocks conforms to a broad overall pattern, which is similar in certain respects to the pattern of joint orientation in the northern areas of tonalite and granodiorite, although the pattern in the country rocks would appear to be more varied and elaborate than the pattern in the granitic rocks.

Fig. 8. Joint Orientation Frequency Diagrams.

Locality.

For the preparation of Figs. 8a-c, the northern part of the complex was divided into three regions, consisting of an eastern area, which lies to the east of the Strontian River, and a northern and a western area, which lie to the west of the Strontian River, and are divided by the Allt nan Cailleach. Within each area all cases of the parallelism of joints and veins were considered together.

The localities from which the readings were obtained for the preparation of Figs. 8d-p are shown in Fig. 5. Large area diagrams are based on the readings obtained by random sampling in a large area, small area diagrams are based on the readings made in small areas where the orientation of every fracture was recorded.

Maxima.

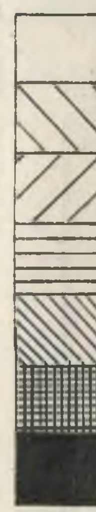
With Figs. 8a-p, the strike and dip of the joints which are sufficiently numerous to define maxima of over 5% on the diagram is stated. With Figs. 8q and 8r, the joint orientations which occur most frequently as maxima on the other diagrams are indicated. The number of maxima which occur on the "master" diagram within the area of a one per cent counter is stated for each concentration.

Foliation and Lineation.

In Figs. 8d-p the mean orientation of the foliation in the rocks in the area from which the readings were obtained is indicated. The mean orientiation of the lineation is also shown where this structure is developed.

Contours.

Figs. 8a-p.	Fig. 8r.	Fig. 8q.
0-1%	0-1%	0-1%
1-2%	1-2%	1-2%
2-4%	2-3%	2-3%
4-6%	3-5%	3-5%
6-10%	5-7%	5-8%
10% +	7% +	8-10%
		10% +



Joints parallel to Veins in the Tonalite and Granodiorite.

Fig. 8a. (Western Area).
Maxima. 115°/90° (16%)
045°/90° (9%)
247 Readings.

Fig. 8b. (Northern Area).
Maxima. 100°/80° S (16%)
020°/90° (7%)
155°/90° (5.5%)
127 Readings.

Fig. 8c. (Eastern Area).
Maxima. 115°/90° (28%)
231 Readings.

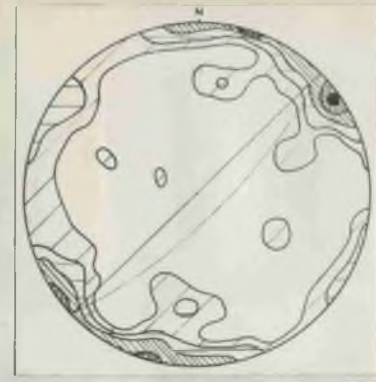


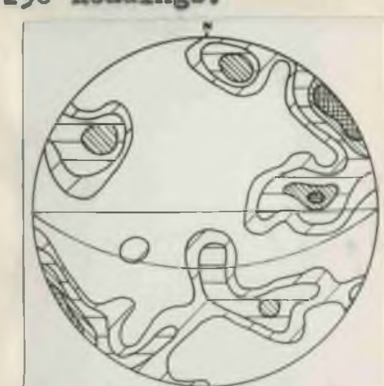
Fig. 8d. (J1-Small Area).
Maxima. 145°/85° SW (11%)
110°/90° (8%)
200 Readings.

Fig. 8g. (J4-Large Area).
Maxima. 115°/90° (12.5%)
010°/90° (6.5%)
269 Readings.

Fig. 8h. (J5-Large Area).
Maxima. 020°/90° (11%)
115°/90° (6%)
075°/25° N (4.5%).
258 Readings.

Fig. 8i. (J6-Small Area).
Maxima. 145°/85° SW (10%)
040°/90° (6%)
150 Readings.

Fig. 8j. (J7-Large Area).
Maxima. 045°/90° (17%)
090°/90° (5.5%)
115°/90° (5.5%)
295 Readings.



These similarities would seem to be due to the occurrence of sets of joints with certain orientations throughout the entire Strontian region. These joints can only have formed during and after the period of formation of the complex.

III. STRUCTURES IN THE COUNTRY ROCKS

(i) General Remarks.

The restricted area within which a detailed examination of the country rocks was carried out is indicated in Fig.9. The object of the study of the country rocks was to discover the manner in which these rocks had been deformed in the areas adjoining the complex. The methods employed in this study were designed to procure samples of this deformation, not to enable a complete geological map to be produced. Traverses were continued into the country rock until signs of deformation, which appeared to be related to the complex, were no longer visible.

The pelitic, semi-pelitic, psammitic and quartzitic Moine Schists occur as beds, which alternate with each other, and which are seldom of more than a few feet in thickness. In some areas, it is apparent that a particular rock type is dominant; in others, rocks of all types appear to be equally abundant. Within the areas of injection gneiss, considerable uniformity prevails, although even in these rocks, bands of rock of differing type occur.

All the country rocks are injected to a greater or less extent, the degree of injection varying with the rock types, and also varying within the area adjoining the complex. Semi-pelitic or pelitic rocks are usually considerably injected, and may be altered to biotitic injection gneisses, when adjoining psammitic rocks are largely unaffected. The main area of injection is to the north and north-east of the complex, and in this region, rocks of all types are altered to injection gneiss. This area is divided from relatively uninjected rocks by a gradational zone which is often only a few yards in width, though it may be much wider if the adjoining rocks are of variable nature. The margins of the injection gneiss tend to occur near boundaries between psammitic and pelitic rocks, but often transgress the structures in adjacent uninjected rocks.

A zone of relatively uninjected rocks, which is usually of a psammitic or quartzitic nature, normally intervenes between the injection gneisses and the tonalite. In the north, this zone is only a few yards in width, or may be lacking. To the east, it increases in extent and becomes fully a mile wide. The width of this zone remains roughly constant throughout the area lying to the east of the complex, and to the north of the River Carnoch. The boundary of the injection gneiss in this area, tends to follow a boundary between psammitic and pelitic rocks, which is approximately parallel to the eastern-tonalite-country rock contact. The psammitic rocks adjoin the complex, and are largely uninjected, the pelitic rocks lie to the east, and are largely altered to injection gneiss. The injection gneiss extends eastwards from this boundary.

To the west of the complex, the rocks in its vicinity are of rather varied nature north of Loch Sunart. No one type of rock predominates over any large area, though quartzitic and semi-pelitic bands of considerable thickness occur. Within a mile of the western contact a large area of injected pelitic schists occurs, bounded on either side by rocks which are mainly

__Plate 17.__ An intersection of granitic veins in the tonalite, near the eastern margin of the complex. A cuts B and C. B cuts C. Note the movement which has occurred at the junction of B and C. The surrounding tonalite is foliated parallel to the pencil.

__Plate 18.__ Strongly sheared and folded psammitic and semi-pelitic schists, two hundred yards from the northern margin of the complex. The contact with the tonalite lies to the right and trends approximately parallel to the shaft of the hammer.

of a psammitic nature, and which, with the pelitic rocks, are involved in a large fold. To the north-east of this fold, the rocks adjoining the north-western contact with the tonalite tend to be of rather varied lithology until the western margin of the injection gneiss is reached. A number of bands, which are predominatly of one rock type, and are of considerable thickness, occurs in this area.

(ii) Tonalite - Country Rock Contact.

The alteration in the rocks adjoining the complex appears to be due largely to shearing and folding. Limited thermal and metasomatic alteration is confined to the immediate vicinity of the junction with the tonalite.

The tonalite-country rock contact has already been described in part, but the characteristics of the country rock at this junction remain to be described.

The actual rock in contact with the tonalite may be of any of the types seen in the areas of country rock adjoining the complex. The western contact rocks are frequently pelitic or semi-pelitic in nature, giving rise to a smooth boundary in the manner already described. In the north-east and east, the psammitic and quartzitic rocks which occur in contact with the tonalite, give rise to an irregular boundary. Part of the northern contact is between tonalite and injection gneiss, and in this area, the junction also tends to be irregular.

The effects of thermal metamorphism are not pronounced in the contact rocks, nor is there any evidence of widespread metasomatic alteration. In some cases, the country rocks appear to have been recrystallised for up to thirty or forty yards from the contact. This is particularly the case when the country rocks are of a pelitic or semi-pelitic nature. Recrystallisation is suggested by a slight coarsening in the grain of the rocks, and by the blurring of the outline of the structures. Biotite and feldspar crystals, in particular, appear to have recrystallised. Complicating factors in determining the amount of recrystallisation are, however, the strong shearing to which the rocks have been subjected, and the almost invariable presence of a certain amount of injected material which has been introduced as part of the process of regional injection. It is evident that any thermal metamorphism to which the rocks have been subjected cannot have been of high grade. The alteration, which has been described above, is of restricted occurrence, being largely confined to the rocks of the types specified. Psammitic and quartzitic rocks frequently show no signs of having been altered in any way by the effects of thermal metamorphism, even when in actual contact with the tonalite.

There is evidence, locally, which suggests that metasomatic alteration has occurred on a limited scale. Quartzitic and psammitic rocks appear to be most susceptible to alteration by this process. In these rocks, a certain amount of material, which has finally crystallised as biotite and feldspar, appears to have been introduced. This phenomenon occurs only sporadically at the tonalite contact, and never extends more than three or four yards into the country rocks. A few quartzo-feldspathic stringers appear to be unsheared in the immediate vicinity of the tonalite, and these may also represent material which has migrated into the country rock from the tonalite.

Another phenomenon occurs, which while giving no evidence of being due to metasomatism, does seem to be due to the introduction of granitic material from the complex into the country rock. Fine veins, usually no more than a quarter of an inch thick, are common in the country rock near the tonalite, and decrease in number with increasing distance from the contact. These veins are granitic in nature, but are not associated with any alteration of the surrounding rock. The occurrence of these veins is controlled by the structural discontinuities in the country rocks - they follow structures such as shear planes, the margins of sheared masses, and bedding planes. (Plates 20 and 21).

When they surround sheared masses, the granitic material seems to form a sparse matrix, containing fragments of sheared rock. Thicker, coarse-grained veinlets also occur, which consist largely of quartz and feldspar. These are of a very irregular nature, and may inject the country rock, locally causing small scale fragmentation. These veins may transgress, or follow the structures in the country rock, and also form a matrix to sheared fragments of country rock in some areas. They differ in mode of occurrence and in appearance, from the quartz-feldspathic stringers associated with the regional injection of the country rocks.

The material which forms both types of veinlet may be identical with that forming the granitic veins, which are so abundant in the outer tonalite. It has been noted that many of the latter extend into the country rock, but these veins are never so numerous in the country rock as in the adjoining tonalite, and the majority obviously terminate in the contact zone. Some can be seen to divide into irregular veinlets before they die out; many tend to follow the foliation planes in the country rock. It seems possible, therefore, that the anastomising veinlets which often permeate the structures in the contact zone of the country rocks, may represent the ultimate limits of many of the granitic veins in the complex. Owing to incomplete exposures, this relation between the different veins could not be directly substantiated.

In the actual contact zone itself, and at greater distance from the complex, there is evidence of widespread deformation which is apparently due to forces associated with the origin of the complex. This deformation is considered as a separate study in the following chapters.

(iii) Shearing.

In the areas of country rock adjoining the complex, evidence that the rocks have been deformed by shearing forces is more widespread than elsewhere.

The contact with tonalite is often accompanied by a parallel zone in which the country rock has been deformed by strong shearing forces. This zone is not invariably developed, but may be up to one hundred yards wide in some areas. (Plate 18).

The areas of strongest shearing tend to lie within a zone which adjoins the complex, and which is approximately half a mile to three quarters of a mile wide. Within this zone, there is a

Plate 19. Uniformly foliated psammitic schists, three quarters of a mile from the western margin of the complex. Contrast with Plate 18.

Plate 20. Sheared psammitic schist, fifty yards from the northern margin of the complex. The schist has been broken into rounded blocks (Ps.) which are set in a granitic matrix (Gr.) The contact with the tonalite lies to the right and trends approximately at right angles to the shaft of the hammer.

general decrease in the occurrence of signs of shearing deformation with increasing distance from the contact with tonalite. (Plate 19). The outer limit of this zone is not sharply defined. Sheared rocks do lie at greater distances from the complex, but are of very localised occurrence. In some instances, these outlying rocks appear to have been deformed by forces unrelated to the complex.

Different rock types can be seen to have reacted to the shearing forces in different ways. Bands of hard rock have broken into small fragments, which are aligned in the softer surrounding rocks, the distribution of the fragments still indicating the original position of the beds. These fragments are angular when shearing has been slight, but with more intense deformation, they become lens-like in shape. (Plate 20). This tendency for a harder band to break into lens-shaped fragments, is well seen when beds of quartzite have alternated with beds of psammitic schist. Psammitic lenses, in turn, occur in a semi-pelitic matrix in many areas. Massive rocks have either been deformed uniformly throughout, as in the case of pelitic rocks in which the foliation has become impersistent and now defines lens-shaped areas, or have remained largely unaltered, as in the case of thick beds of quartzite in which shearing movements have been confined to restricted planes (Plate 21).

The extent of shearing deformation in injection gneiss is difficult to determine. In some areas, rocks with a foliation which trends parallel to the tonalite contact, appear to be unaltered. In other cases, rocks with the foliation striking obliquely to the contact show evidence of shearing movements on clearly defined planes.

The field evidence indicates that the country rocks have not been uniformly affected by shearing forces. Strongly deformed rocks generally occur in restricted areas. Within these areas, rocks of all types have been much deformed. These areas are of very irregular shape and distribution, and cannot be linked in a recognisable pattern. They may be many yards in extent. Between areas where shearing has been intense, considerably larger areas of relatively undeformed rock occur, in which shearing deformation has been largely confined to restricted planes. Study of the distribution of the rock of different types in adjoining areas where deformation has been slight, indicates that lithological boundaries in one area do not persist in the other, and suggests that the country rock may have been divided into large masses, bounded by areas of strong shearing. The dimensions of these masses range up to a hundred yards or more.

The strike of strongly deformed rocks tends to be parallel to the tonalite contact when in the vicinity of that contact, but with increasing distance from the complex, the parallelism becomes less exact. In general, shearing movements mainly appear to have taken place parallel to the direction of the prevailing strike of the country rocks. The direction of movement in the areas of strong deformation is difficult to establish. The absence of signs of horizontal "dragging" and "crowding", and the impersistence of lithological boundaries in the horizontal plane, suggests that the movement has probably been mainly vertical. No linear structure is

Plate 21. Folded psammitic and semi-politic schists, a quarter of a mile from the north-west margin of the complex. The axes of the small folds are approximately vertical. The folds are cut by shear planes which are approximately parallel to the margin of the complex. Thin granitic veins occur on these planes.

Plate 22. An inclusion of psammitic and semi-pelitic schists in the tonalite near the northern margin of the complex. The rocks in the inclusion have been strongly sheared and are cut by irregular tongues of tonalite (T).

visible to support this conclusion (note the results of the petrofabric study however, page 61) and study of vertical rock faces is unrewarding, in view of the tendency for the planes of movement to be oriented parallel to the foliation of the schists and gneisses.

When the strike of the country rocks is oblique to the tonalite contact, localised shear planes are particularly noticeable. These planes appear as thin bands of fine-grained rock, under a quarter of an inch wide which normally extend over many yards, and may be straight or sinuous. The foliation of the surrounding rock is deflected in opposite directions at the opposite margins of these planes. The tendency for small veins of a granitic nature to follow these planes near the tonalite contact, has already been mentioned (Plate 21). In general, the shear planes dip steeply, and only two flat-lying shear planes were observed near the complex.

The orientation of the isolated shear planes was noted in the field, and it was found that within half a mile of the complex they tend to be parallel to the nearest tonalite contact. There are some deviations from parallelism, but, generally, at least three-quarters of the total number of shear planes are oriented approximately parallel to the contact. A few of the shear planes which trend obliquely to the margin of the complex seem to belong to systems which occur throughout the country rock, irrespective of proximity to the complex. The number of cases of parallelism to the tonalite contact would probably be increased if account could be taken of all the shear planes which are parallel the foliation of the country rocks, as such planes tend to be inconspicuous, and probably have been overlooked in many instances.

From the isolated shear planes, unlike the areas of general deformation, it is possible to determine the relative movement on either side of the shear plane, either by the "dragging" of the beds, or by the displacement of distinctive bands. The direction and amount of movement are normally determinable only in the horizontal plane. In the vertical plane, the steep dip of the shear planes is so nearly parallel to that of the foliation in most exposures, that satisfactory observation of movement is impossible. The extent of the horizontal movements on these planes does not appear to have been large.

Examination of the movements indicates that in the northern areas easterly and westerly horizontal movements are equally common. In the western contact areas the north-west block (remote from the complex) has tended to move north-east. In the eastern contact areas, the more remote block has also tended to move to the north. In the north, a few observations were made of vertical movements, which indicate that the northern block (remote from the complex) has moved relatively upwards, seven times, downwards once. The two flat-lying shear planes also occur in the northern contact areas, and on both of these planes the relative movement of the lower block has been outwards from the complex.

(iv) Small-Scale Folding.

The amplitude of the folds under consideration ranges from a few inches to several yards.(Plate 21). Close to the contact between country rock and tonalite, such folds are very abundant, and locally the country rock has a contorted appearance. These areas of intense folding often occur near areas of strong shearing, and, in some instances, small folds appear to lead into shear planes. Small folds may be cut by shear planes, and some sheared fragments are folded. Folds of the size under consideration occur throughout the country rocks, and are not confined solely to the areas adjoining the complex, but very small folds appear to be more common close to the complex than elsewhere.

The fold axial planes, in the areas of country rock immediately adjoining the tonalite contact, are oriented in approximate parallelism to that contact. For example, in an area of a quarter of a mile radius adjoining the western tonalite contact, the orientation of thirty steeply dipping fold axial planes was recorded. All were found to differ in strike by less than ten degrees from the strike of the nearby tonalite contact. The parallelism is less perfect in other areas, partly because the fold axial planes often tend to be oriented at right angles to the nearest tonalite contact (Plate 21); or to be parallel to the foliation of the surrounding rock. Generally, approximate parallelism prevails. This parallelism becomes less noticeable with increasing distance from the tonalite contact, and, as with the shear planes, seems to be largely confined to a zone half a mile wide adjoining the complex. All small folds within this zone have steeply dipping axial planes, and have axes which are either vertical or plunge at angles of greater than 60° to the south. Outside this zone, small scale folding is still visible, and may locally be common. Axial planes in some instances can be related to major structures, and other trends which are apparently unrelated to the complex are discernible. These include a series of folds, in the rocks to the west of the complex, which have sub-horizontal axes.

(v) General Structural Trends in the Country Rocks adjoining the Complex.

The structural trends in the country rocks are indicated by the orientation of the foliation, which follows the original bedding, and also by the distribution of rocks of differing lithology. Complicating factors include the frequent occurrence of areas where the foliation shows little constancy in trend, and the virtual absence of bands of rock of a distinctive nature. Some distinctive horizons were found, however, and, more than any other feature, they provide the key to the structure of the country rocks. Unfortunately, these distinctive bands rarely persist for distances of more than half a mile.

The traverses into the country rock rarely extended more than one and a half miles from the complex. In consequence, only a general indication was obtained of the trend of the structures in the rocks which do not appear to have been disturbed by the formation of the complex.

The country rock actually in contact with tonalite is usually foliated parallel to this contact, and to the foliation in the tonalite. The dip of the foliation in the country rock, in consequence, is usually steeply inwards towards the centre of the complex. In some areas, where shearing has been intense, the foliation of the country rock is, in part, of secondary origin - the direction of shearing now determining the orientation of the visible structure (Plate 18). Fluctuations of thirty degrees or more in the strike of the foliation are common in the country rocks at the contact, however, and in some instances, the foliation of the country rock in contact with tonalite strikes at right angles to the junction. The rocks with these unusual trends are never strongly sheared. Small folds may also be found in the actual contact rocks.

In general, within half a mile of the complex, the foliation of the country rock shows a marked tendency to be oriented parallel to the nearest contact with the rocks of the complex, even in the areas in the north where the contact transgresses the direction of the regional strike in the country rocks. Considerable variations occur, however, and in some areas the foliation is very variable in trend.

In the rocks within half a mile of the complex, large scale structures are normally lacking, but, occasionally large folds can be discerned in the rocks. Large scale structures visible in the rocks remote from the complex, are usually deflected into parallelism with the contact within half a mile of the complex, and cannot be traced further (Fig. 9). The small scale structures are often of a very confused nature, although, as has been indicated, the orientation of the folds appears to be related to the attitude of the nearest contact with the tonalite. In this zone, half a mile in width, lithological boundaries often tend to run parallel to the contact for a few hundred yards, but the lithology usually appears to vary in a direction parallel to the tonalite contact. Thus, in the eastern contact areas, much quartzite adjoins the complex for up to two miles north of the River Carnoch, while to the north, quartzite is largely lacking, and the rocks are dominantly psammite schists. Smaller scale examples of this phenomenon occur elsewhere, particularly in the rocks immediately west of the Strontian River. This is one of the areas where the country rock occurs in large irregular masses of differing lithology, bounded by zones of strong shearing.

The parallelism between the trend of the structures and the margin of the complex, extends much further into the country rocks on the east and west margins of the complex, than in the areas to the north. As the Geological Survey report (MacGregor and Kennedy 1932) indicates that the regional structural trend in the country rocks is north-south, no great significance can be attached to this correspondence. The presence of the injection complex in the north, is an additional factor complicating the structural relationships.

Outside the zone of deformed rock, adjoining the complex, large scale structures prevail. In the country rocks to the west and north-west of the complex, the dominant structure is a large fold, with a vertical axis, and an axial plane which trends roughly parallel to the western margin of the complex. The eastern limb of this fold extends into the western contact region of the complex, and is there considerably deflected and disturbed. Only limited information was obtained on the western continuation of this fold. Within this fold, a major lithological division is visible, as was noted earlier (Page 99) - a belt of considerably injected pelitic rocks, lying between two bands largely composed of psammitic rocks. The boundaries of this division become obscure near the complex. Near the north-west margin of the complex the eastern limb of the fold extends to within a quarter of a mile of the complex, with no deflection in trend. A further pelitic belt of considerable thickness occurs in this area.

North-eastwards from this fold, the western margin of the injection gneiss is visible, but, as has been explained, this margin is not a satisfactory structural horizon. To the north between the western limit of the injection gneiss and the northern continuation of the large fold, the prevailing trend of the foliation is north-east south-west.

Mapping structures within the injection gneiss is a more difficult task than in the other rocks. In uninjected rocks, the foliation and lithology provide a key to the structure, if it is assumed that the foliation originally followed a uniform trend, and that beds or a particular type of rock originally persisted for considerable distances parallel to the strike. In the gneiss such assumptions cannot be made. The production of injection gneiss seems to have been accompanied by the complete recrystallisation of the original rock and, in consequence, the original structures may have been obliterated while the development of a rock of a particular type (e.g. augen gneiss) need not necessarily correspond with an original lithological division. Therefore caution must be exercised in interpreting the structures in the gneiss. Much of the gneiss has a foliation with a very variable trend, although uniformly foliated areas occur and the lithological boundaries and the foliation, do show a tendency to be parallel to the boundary of the complex.

Some of the features of the rocks which occur at the eastern margin of the complex, have been mentioned already. Structures apparently trend parallel to the boundary of the complex throughout most of the area between the complex and the injection gneiss, though at least one fold of considerable magnitude occurs. The lithological discontinuity in this area, which has been mentioned (Page 109) suggests, however, that the apparent structural uniformity may be misleading.

A comparison of the rocks within this zone, adjoining the complex and half a mile in width, with the surrounding rocks , therefore discloses several structural differences. Not only do the rocks adjoining the complex tend to be more strongly sheared and folded, but as a whole, they have more confused structures than the surrounding rocks. Large scale structures are absent and lithological boundaries are impersistent in the vicinity of the complex. Throughout the rocks near the complex there is a tendency for structures of all types to be parallel to the boundary between the rocks of the complex and the country rocks.

Mention may be made here, of the examination of the country rocks south of Loch Sunart. This examination was confined to the rocks in the immediate vicinity of the contact with tonalite. The structures in these rocks show no difference from the structures in the similarly situated rocks north of Loch Sunart. No information was obtained on the structures in the country rock in contact with granodiorite or biotite granite.

IV. EVALUATION AND INTERPRETATION OF THE EVIDENCE

The study of the structures which are visible in a complex of granitic rocks and in the surrounding areas of country rock, and which appear to be contemporary in origin with this complex, should, ideally, be preceded by a detailed petrological examination of the rocks, as otherwise, it is impossible to interpret the structures satisfactorily, and without ambiguity (c.f. page 9). The same structures can be inferred to have been formed in different ways, depending on the particular process by which the rocks of the complex are thought to have been formed, and the structural evidence, by itself, does not enable the nature of this process to be comprehended. In consequence, before a structural interpretation can be made, the mode of formation of the rocks of the complex must be established.

The most satisfactory method of achieving this end, would be, as stated above, by means of a detailed petrological examination of the rocks. In the present instance, as such a detailed examination was not carried out, the nature of the rock-forming process which operated at Strontian, cannot be inferred with as great a degree of certainty as would otherwise be possible. A certain amount of evidence is available, however, which enables some estimate to be made of the probable nature of the process by which the granitic rocks were formed. This evidence is reviewed as a preliminary to the evaluation of the structural data.

1. DISCUSSION OF THE NATURE OF THE ROCK-FORMING PROCESS.

It is generally accepted that granitic complexes, which are distinctly separated from the surrounding rocks, and which occur as coherent units in the earth's crust, have been formed by the introduction of material at that point in the crust. There is considerable difference of opinion, however, concerning the nature, amount and physical state of the introduced material. This controversy resolves itself essentially into a discussion of whether the rocks have been formed by some process of transformation of previously existing rocks, or whether they have been formed by the intrusion of a magma, with the introduction of the new material in a fluid state on a large scale, and the physical displacement of the previously existing rocks.

The authors of the Geological Survey report describe the complex as being of igneous origin (MacGregor and Kennedy, 1932) and the evidence obtained in the present enquiry, while not conclusive, supports this viewpoint more than any other. Most of this evidence is of such a nature, that it does not militate directly against a theory that the rocks have been formed by a process of transformation, and some of the evidence would actually seem to lend positive support to this theory. There are, however, certain phenomena which can be explained much more satisfactorily if it is assumed that the rocks have been formed by magmatic intrusion. The limited petrological examination, and the study of the contacts, provide the information which appears to be of greatest significance in the present context. The critical evidence is listed below.

Once more, attention is confined largely to the tonalite and granodiorite, but brief mention is made of the evidence which indicates the mode of origin of the biotite granite and the granitic veins.

Tonalite.

The observations, which lend direct support to the hypothesis that this rock is of igneous origin, and are difficult to explain on the basis that the rock is of metasomatic origin, are as follows:-

(i) The Moine country rocks and the tonalite are structurally and petrologically distinct.

(ii) The complex seems to have served as a focus for the disruption of the Moine schists and gneisses.

(iii) The outer contact of the tonalite is generally sharp, only being gradational over a limited range when the country rocks are of a type which would appear most likely to be assimilated by a magma.

(iv) The major irregularities in the tonalite-country rock contact could be interpreted as having been produced by magmatic stoping. The rock, which forms the contacts where these irregularities occur, is of a type which would be expected to yield to magmatic pressure by brittle fracture. Smooth contacts, on the other hand, occur against rocks, which from their nature, would be expected to yield to magmatic pressure by plastic deformation.

(v) The occasional occurrence of the coarser of the two contact modifications of the tonalite at the outer contact, and the relations observed at the sharp contacts between these two modifications, suggest that a chilled marginal shell has been fractured, and locally replaced, by a later surge of magma.

(vi) The occasional occurrence of small inclusions in close packed aggregates separated by tongues of tonalite, suggests that large inclusions have been split into fragments as a result of veining by tonalite magma. The sharp, planar contacts between some of the fine-grained basic inclusions in tonalite, also suggests that these inclusions originally were solid bodies in a fluid matrix.

(vii) The petrological examination of the tonalite, in as far as it was completed, supports the hypothesis that this rock is of igneous origin.

In addition, the following evidence, while not directly supporting the hypothesis that the tonalite is of igneous origin, does so indirectly by suggesting that metasomatic origin is unlikely:-

(viii) The Moine country rocks show little evidence of metasomatic alteration in the vicinity of the contact with tonalite.

(ix) If the tonalite has been produced by the metasomatic alteration of rocks similar to the Moine schists and gneisses adjoining the outer contact, then this process must have been capable of altering a very varied assemblage of rocks into a uniform final product.

(x) The process of alteration must have been capable of being nearly fully effective without any appreciable intermediate steps.

(xi) If a metasomatic origin for the tonalite is postulated, then inclusions of Moine schist and gneiss in the tonalite, by analogy with the outer contact, would be expected to have a wide zone of modified tonalite surrounding them.

Porphyritic Granodiorite.

The arguments which support the suggestion that the granodiorite is of igneous origin, are less comprehensive than in the case of the tonalite. Of the points ennumerated above, (vi), (vii) and (xi) would seem to be applicable to the granodiorite. While the gradational nature of much of the tonalite-granodiorite contact might be interpreted as indicating that the granodiorite is metasomatic in origin, the relation at the north-western contact between these two rocks would appear to contradict this view. The structural relations in this region suggest that this was originally a contact between magma and solid rock. (Figs. 8 and 9).

Granitic Veins.

The majority of the granitic veins, which cut all the main units of the complex, quite clearly seem to be of igneous origin. The critical evidence in this case, is that which indicates that dilation has occurred on the fractures now occupied by these veins. This expansion is made evident by the displacement of originally continuous structures on opposite sides of the vein. The sharp contacts of the veins is further evidence supporting the viewpoint that they are of igneous origin.

Biotite Granite.

It seems highly probable that the biotite granite has also formed by the consolidation of a magma. The bodies of this rock display sharp contacts against all types of surrounding rock and do not vary in composition in harmony with the variation in composition of these rocks. The similarity in composition of many of the granitic veins to the biotite granite would also seem to be evidence supporting the hypothesis that the latter is of igneous origin.

On the basis of the evidence which has been outlined above, it is suggested that the three main units of the complex and the granitic veins have consolidated from intruded magma. There are certain arguments which could be put forward against this suggestion, notably the absence of any marked thermal aureole in the country rocks surrounding the complex, but, when considered as a whole, the evidence seems to offer more support to the viewpoint that the rocks are of igneous origin than to any other hypothesis. On the basis of this assumption an attempt can be made to interpret the more purely structural data.

The texture of the granitic rocks, and the geological history of the areas suggests that the rocks are purely intrusive in nature, and have not been accompanied by an extrusive phase.

2. MODE OF INTRUSION OF MAGMA.

The assumption that the rocks of the Strontian complex are of igneous origin, necessitates that further assumptions be made, before a complete explanation of the process of formation of the complex can be presented. Firstly, it must be assumed that magma formed, or was available, at some level in the earth's crust. It is also necessary to assume that this magma moved to the level now exposed at the surface before being finally emplaced in the position now occupied by the rocks of the complex, as there is no evidence to suggest that magma was generated in situ at this level during the formation of the complex. The full nature of the formative process cannot be inferred with certainty from a study of the structures alone, and the evidence obtained in the present enquiry would seem to be of significance only in enabling some estimate to be made of the probable mode of intrusion of magma. Further discussion is therefore largely confined to a consideration of this problem.

The intrusion of magma must be accompanied by the displacement of previously existing rocks, and, with any intrusive rock, discussion of the intrusive mechanism resolves itself largely into a discussion of the means whereby the country rocks have been displaced. Four methods whereby magma could be emplaced are considered, those being the methods which appear to have the widest acceptance in current geological thought. (e.g. King, 1954. Billings 1942 pp.294-5).

They are:-

(i) Intrusion by means of piecemeal stoping.

(ii) Block subsidence of a large portion of the crust permitting intrusion around, and above, the subsiding mass.

(iii) Intrusion into areas of tension produced by orogenic forces. ("Permissive Intrusion" Mayo 1941).

(iv) Forcible intrusion.

The possibility that the intrusive mechanism may be complex in nature, involving two or more of the above processes, is not excluded, but each process is first considered separately.

In view of the different composition of the main components of the Strontian complex, it would seem necessary to postulate that magma of different composition was intruded at different stages in the evolution of the complex. The gradational nature of much of the contact between tonalite and granodiorite, and the parallelism of the orientation of the structures in the gradational zone with the structure in the rocks on either side suggests, however, that the intrusion of tonalite magma and granodiorite magma was roughly contemporary. The wide extent of the gradational contact between these rocks would seem to indicate, that, for the most part, tonalite magma had not completely consolidated when the granodiorite magma was intruded. The relations at the north-west contact between these rocks, suggests, however, that local consolidation of the tonalite magma had occurred before the final intrusion of the granodiorite magma was completed. As a working hypothesis, it is assumed that these rocks have been formed as the products of a single phase of the intrusive activity, which possibly extended over a considerable period of time.

Only the mode of intrusion of the tonalite and granodiorite magma is considered in any detail. Despite the incomplete nature of the study of these rocks, an attempt is made to determine how magma to form the entire mass of tonalite and granodiorite could have been emplaced. The mode of intrusion of the biotite granite magma is considered briefly at the end of this section. The process involved in the formation of the granitic veins appears to be straightforward - the filling of open fissures by granitic magma, following the consolidation of the surrounding rocks, and is not considered further, although the orientation of these fissures is of significance in considering the mechanism of intrusion of the other rocks.

(i) Mode of Intrusion of the Tonalite and Granodiorite Magmas.

The pattern followed in the presentation of the evidence is adopted once more in the present discussion, points which appear to lend support to, or militate against, any of the four hypotheses under consideration, being discussed as they arise.

(a) Contact Relations. The evidence obtained in the study of the contact between the tonalite and the granodiorite is mainly of significance in establishing that these rocks are probably of igneous origin. The relations at this contact have also been discussed above, in order to justify the decision to treat the tonalite and granodiorite as a single unit in the following discussion. Apart from these considerations, some of the evidence exposed at the tonalite-granodiorite contact is of direct significance in the present context.

Many of the observations at the tonalite-country rock contact would seem to indicate that small scale stoping had occurred. It appears unlikely that space for the intrusion of the tonalite and granodiorite magmas could have been created solely by such stoping however, as the evidence suggests this process operated on only a small scale. The masses of country rock, which are partially detached by tongues of tonalite at the outer contact, are of comparatively infrequent occurrence, and while inclusions of country rock are not rare in the tonalite and granodiorite, they never occur in the numbers which would be expected to accompany widespread stoping activity. It could be postulated that stoping ceased a considerable time before consolidation took place, and that all the fragments of country rock had time to settle or ascend in the magma, before it became too viscous to permit such movements. The occurrence of partially detached masses of country rock, and the relation between the trend of the outer contact and the shape of the strip-like inclusion in the north-east of the complex (Page 27), suggests, however, that stoping continued until overtaken by the consolidation of the magma.

In addition to suggesting that the tonalite and granodiorite are roughly contemporary in age, the gradational nature of much of the contact between these two rocks excludes the possibility that space could have been created for the granodiorite magma by means of piecemeal stoping of tonalite. Limited stoping could have occurred at this contact in the north-west, but would seem to be unlikely in view of the lack of supporting evidence.

The mass of tonalite and granodiorite would appear to be funnel-shaped if it is assumed that the attitude of the outer contact of the tonalite does not change with depth. The internal structures suggest, however, that the northern portion of the complex may be trough-shaped, a postulate which is discussed more fully in the next section. Whether the mass of tonalite and granodiorite is assumed to be funnel-shaped or trough-shaped, it is difficult to visualise how intrusion could have been effected by means of large scale subsidence of the country rocks. Cauldron subsidence on an arcuate fracture is clearly excluded, and if subsidence has occurred, then it is necessary to postulate that it has been accompanied by widespread deformation, with complete change of shape of the subsiding mass.

The elongation of the mass of tonalite and granodiorite in the direction of the regional strike of the country rocks, may indicate that intrusion was effected under the control of orogenic forces to some extent.

(b) Foliation and Lineation

The possibility that these structures post-date the formation of the rocks of the complex can be readily dismissed. Evidence of particular significance in this context includes the observations which indicate that the crystals in many of the granitic veins are oriented independently of the crystals in the surrounding rock, and it is difficult to visualise how bodies such as the lens-shaped basic inclusions could be oriented in a solid medium. As these inclusions define the same structures as the crystals in the surrounding rock, it seems necessary to postulate that the crystal orientation was imposed when some of the rock-forming material was in a fluid state, and also, that all of the oriented elements have been aligned in response to the same forces. In the areas where both a planar and a linear structure are developed, both structures must be assumed to have a common mode of origin, as the lineation always lies within the foliation plane.

The possibility that the structures defined by the oriented elements are relict structures has already been considered, and has been excluded by assuming that the rocks of the complex are of igneous origin. In further discussion, the structures are assumed to have been produced after crystallisation had commenced, but before the final consolidation of the magma.

Interpreting the structures on this basis, two possibilities exist. The foliation and lineation could have been produced by the movement of the magma during intrusion. Alternatively, these structures may be the products of the deformation of emplaced magma by forces which operated prior to final consolidation. In the first case, the foliation would be produced by the viscous drag at the walls of the magma chamber, the lineation by the alignment of elongated elements in the direction of flow. In the second case, both structures would result from the distension of the magma, the foliation being produced by forces which acted at right angles to the structure and produced uniform distension, the lineation by forces acting in the foliation plane and producing distension in a particular direction. In some respects, the mechanism by which structures would be produced would then resemble the stretching of the skin of a balloon during inflation, when a portion of the skin is weaker than the remainder and can expand to a greater extent. However, the mechanism by which the structures are formed in a magma need not involve the expansion of the magma chamber as a whole, in a manner similar to the swelling of a balloon during inflation, and expansion may have taken place only in certain directions and been accompanied by contraction in others.

Where only a planar structure is visible, it must be assumed that uniform distension of emplaced magma has occurred, as it is difficult to visualise how this structure could be produced by magmatic flow, unaccompanied by a linear structure. By whatever process the structures are formed, only the final orientation will be preserved, and earlier structures may have been obliterated. The orientation of certain schlieren in the granodiorite suggests that this, indeed, may be the case . (Page 45). The structures must be interpreted with considerable reserve, therefore, as they may be the products of only the final stages of the process whereby magma was employed. As a linear structure is lacking in the greater part of the tonalite and granodiorite, the internal structures in these two rocks would appear to have been produced in response to forces which acted after intrusion had taken place, and only in those areas where both a planar and a linear structure are developed, is the interpretation of these structures controversial. Further discussion is restricted, therefore, to a consideration of the structures in the central and northern portions of the area of tonalite and granodiorite, which adjoins Loch Sunart.

It is probable that planar and linear structures, which are identical in nature, could be produced by either of the processes described above, and only a study of the general configuration and relations of these structures would seem likely to be of assistance in determining their mode of origin. The structures produced by distension would be expected to show marked uniformity in trend, and to be intensified in the vicinity of resistant bodies, such as the Moine country rocks at the outer contact, or the large inclusions of appinite and country rock. Magmatic flow would also seem capable of producing structures which would show considerable uniformity in trend, but abrupt changes in trend and local fluctuations and deviations due to turbulence, would not be unexpected. It would be anticipated also, that structures produced in this manner, would be intensified only in the vicinity of static bodies, not in the vicinity of inclusions which were being transported in the stream of magma. Reviewing the pattern of the structures in the areas of lineated rock, there would seem to be more support for the hypothesis that the structures in these areas have been formed by magmatic flow, than for the hypothesis that these structures have been formed by a process of distension. This leads to the conclusion that the foliation and lineation in the tonalite and granodiorite are probably composite in origin, having been produced mainly by the uniform distension of emplaced magma, but being the products of magmatic flow in a localised area in the north.

The relations at the north-western tonalite-granodiorite contact suggests that in this area, the tonalite behaved as an essentially solid mass when the granodiorite magma was intruded, causing the deflection of the structures in the latter. At the eastern tonalite-granodiorite contact, the relations suggest that the structures in the inner tonalite were formed at the same time, and in the same manner, as the structures in the adjoining granodiorite. If it is assumed that the structures throughout the granodiorite are of the same age, these relations imply that the structures in the outer tonalite were formed before the structures in the inner tonalite and in the granodiorite.

It is possible to distinguish two rather ill-defined areas in the northern part of the complex, in which the structures appear to differ in mode of origin, structural pattern and age, and which are in part separated by a line of recognisable structural discontinuity. (Fig. 9). One area consists of an outer shell of tonalite, characterised by a steeply dipping foliation, with a local lineation following the direction of dip of the foliation. This surrounds an area of granodiorite and tonalite, characterised by a flat-lying foliation, and usually by a sub-horizontal lineation, striking 205°. The boundary of these areas corresponds with the tonalite-granodiorite contact in the west and north, where it is a recognisable line of structural discontinuity, but lies wholly within the tonalite in the east and is ill-defined.

However, despite the differences which have been outlined, it is impossible to divide the northern part of the complex into two distinct areas, within which it can be said that all of the structures appear to differ in age, mode of formation and overall pattern of orientation. While recognising that the structures are locally of a distinctive nature, therefore, and that they are not all of the same age, it seems better to treat the structures in the tonalite and granodiorite as a single unit in further discussion.

Any hypothesis which is put forward to explain the process by which tonalite and granodiorite magmas could havebeen emplaced, must also provide an explanation for the pattern of the foliation and lineation in these rocks. This implies that the intrusive mechanism involved the distension of much of the magma after emplacement had been effected, and also, local flow of magma in a sub-horizontal direction in the northern part of the complex.

It seems probable that the source of the magma lies in the south of the complex. Study of the general configuration of the structures also suggests that the process of emplacement of the tonalite and granodiorite magmas may have occurred in two stages; tonalite magma being intruded first, followed by the intrusion of further tonalite magma and granodiorite magma as a unit. This later intrusion may have taken place into the centre of the mass of magma already emplaced, and have involved the distension of the latter before consolidation was complete.

There are several features which are difficult to explain if intrusion is assumed to have occurred in this way, however, notably the absence in the southern part of the complex of structures which appear to be due to magmatic flow, and the apparently sharp nature of the north-western contact between tonalite and granodiorite. These anomalous features indicate that the emplacement of magma must have been effected by a more complex process than that outlined above.

It is difficult to carry the interpretation of the structures any further, and the available evidence is insufficient for the full comprehension of the process by which the pattern of the structures in the tonalite and granodiorite was produced. It is possible to reach certain conclusions from the study of the foliation and lineation in the tonalite and granodiorite, however, without at the same time, providing a detailed explanation of how these structures were formed. These conclusions are:-

(i) The final emplacement of the tonalite and granodiorite magmas would appear to have been a single process, accompanied, in its later stages at least, by the uniform expansion of the magma chamber. This expansion may have been progressive, and if the marginal regions of the tonalite had consolidated when the core was still expanding, could only be effected by fracture in the outer regions. This possibility is discussed more fully in a later section.

(ii) Movement of magma by flow also seems to have occurred in the northern regions during the final stages of emplacement, but probably occurred at an earlier stage, shortly after the present northern contact between tonalite and country rock was formed. Movement was probably from south to north, and may also have been upwards in the vicinity of the northern contact (cf. pages 41-42).

(iii) The planar structure , irrespective of its mode of origin, probably reflects the attitude of the nearest contact with solid rock. This being the case, the intruded mass of tonalite and granodiorite would seem to be roughly sickle-shaped - with roots in the south, and a tongue-like protuberance to the north.

These conclusions are qualitative, and not quantitative in nature, and it is impossible to estimate the extent of the movements which are thought to have taken place, and, therefore, whether the emplacement of magma was effected solely by means of these movements or not. With this reservation, the results of the study of the foliation and lineation can be related directly to the four hypotheses under review.

It would appear that forcible intrusion of tonalite and granodiorite magmas has occured - though possibly only on a limited scale in the final stage of emplacement, when the magma chamber seems to have expanded as a whole. The uniformity in trend of the foliation and lineation in the northern part of the complex, while not sufficient to justify the interpretation of these structures as being the products of the deformation of magma following intrusion, is such that it suggests intrusion may have been effected by means of a process which was under the control of the orogenic forces to some extent. The inferred shape of the mass also suggests possible external structural control.

(c) Other Internal Structures.

The characteristics of the tonalite veins and zones of fine-grained granodiorite can be best explained on a magmatic basis if it is assumed that thesestructures represent fractures, which formed before the consolidation of the surrounding rock was completed, and which were filled by residual tonalite or granodiorite magma. In this way, the nature of the boundaries and internal structures in most of the tonalite veins and granodiorite zones can be explained. In the neighbourhood of Eilean a' Mhuirich, however, it seems necessary to postulate, in addition, that some deformation of the surrounding rock occurred when the zone of fine-grained granodiorite was formed (pages 65-66). The precise nature of the mechanism whereby this particular zone was formed is obscure.

It seems to be impossible to relate the orientation of these structures to the orientation of any of the other structures in the tonalite and granodiorite. No pattern of orientation which prevails throughout the complex is visible.

These structures would seem to be of significance when related to the conclusion, reached in the previous chapter, that expansion of the magma chamber occurred as part of the process of intrusion, and that this expansion might have been effected by fracture, if marginal consolidation had occurred. The tonalitic veins and zones of fine-grained granodiorite may then represent the fractures produced in a nearly solidified shell by the intrusion of fresh magma in the centre of the complex. The distribution of the tonalite veins would seem to be of particular significance in this context.

The most satisfactory way of interpreting the structures which resemble shear planes, is to assume that they are actual shear planes. It is then possible to explain the occurrence of these structures in a similar manner to the two structures which have just been considered. The distribution of these planes appears to be significant once again, as they are more common in the outer regions of the tonalite than elsewhere.

Study of the three types of structure grouped together in this chapter suggests, therefore, that forcible intrusion of tonalite and granodiorite magmas occurred on at least a limited scale.

(d) Fracture Systems.

The salient features which emerge from the study of the fracture systems, are:-

(i) The fractures which clearly appear to be contemporary in origin with the complex - the vein-filled fractures, are markedly concentrated in the outer regions of the tonalite.

(ii) The vein-filled fractures appear to conform to a pattern of orientation which shows considerable uniformity throughout the northern portion of the complex. The outstanding features of this pattern are the abundance of vertical fractures, particularly the fractures striking roughly east-west, and the abundance of fractures with a north or north-east strike and a moderate westerly dip. (Fig. 7m).

(iii) There appears to be no simple relation between the orientation of the planar and linear structures and the orientation of the fracture systems in the tonalite and granodiorite.

(iv) The pattern of joint orientation, both within the northern part of the complex, and in the surrounding areas of Moine country rocks appears to be a feature which shows considerable uniformity over a large area. It seems probable that this pattern is related to the faulting within the area and is largely unrelated to the formation of the complex. Vertical joints with an east-south-east strike ($115^{\circ}/90^{\circ}$), may be related to the formation of the complex, in part, as these joints are numerous, are commonly found to be parallel to the veins, and trend approximately at right angles to the lineation in the inner tonalite and granodiorite.

Considering these points in turn:-

(i) The concentration of the vein-filled fractures in the marginal regions of the tonalite, would appear to be of significance in view of the discussion in the preceding chapters. The distribution of these fractures would seem to be explicable in the same manner as the occurrence of the tonalitic veins. It seems necessary to assume that a whole series of open fractures was formed at different times, the first being filled by tonalitic magma, the later fractures by successive intrusions of magma of granodioritic on granitic composition. The movements which have occurred on these fractures, are of particular significance to the present discussion, but, as described earlier, it seems to be impossible to discover any definite pattern to which they conform. The extent of these movements is difficult to estimate. While each individual movement is of limited extent, in aggregate they may represent a considerable displacement. Nevertheless, it seems improbable that space for the emplacement of the magma, which has consolidated to form the inner tonalite and granodiorite, could have been created solely by movements on the marginal fractures in the tonalite.

(ii) The pattern of orientation of the vein-filled fractures at Strontian appears to be explicable by none of the accepted theories of fracturing, and whilst possible explanations for this pattern may be put forward, they must remain speculative, in view of the limited knowledge of the mechanism by which such fractures can be produced.

It is difficult to explain the orientation of the vertical and flat-lying fractures by the same mechanism, and as the field relations indicate that the veins are not of the same age, it appears probable that the mechanism whereby these fractures were produced is complex in nature, and that different stresses operated at different times, producing fractures which differ in orientation. Unfortunately, it was impossible to correlate the orientation and the age of the veins.

In view of the evidence which suggests that expansion of the magma chamber has occurred, and that this process has been in part responsible for the formation of the fractures, an attempt can be made to interpret the vein-filled fractures on this basis. The vertical fractures with a vein-filling would seem to vary in trend with the tonalite-country rock contact to some extent, but are usually oblique to this contact (see pages 73-74 and page 78). These fractures could be interpreted as compression fractures, produced by the expansion of the magma chamber, but if this interpretation is correct, then the vein-filled material must have been introduced after the compressive force had relaxed. The evidence providing support for this suggested mechanism is rather inconclusive, therefore, and it is possible to explain the formation of these fractures in other ways. In particular, the possibility that these are cooling fractures cannot be excluded from consideration.

The flat-lying fractures with a vein-filling could have been formed by a horizontal stress acting in a north-west south-east direction, the horizontal stress in a north-east south-west direction being, at the same time, less than this stress, but greater than the vertical stress. Two sets of flat-lying fractures could be produced by these stresses, both striking north-east south-west, but one set dipping gently to the north-west, the other to south-east. (Anderson, 1951, pp.10-11). If the flat-lying veins have been produced by the stresses accompanying the expansion of the magma chamber, therefore, it seems necessary to postulate that these stresses were mainly directed in a horizontal direction, nearly at right angles to the length of the outcrop of the tonalite and granodiorite, and that by some means one of the two sets of fractures which could have formed (the fractures dipping to the south-east) has been suppressed. It would be possible to account for the postulated direction of the greatest horizontal stress if it is assumed that the expansion of the magma chamber took place when the stresses associated with the Caledonian orogeny were still in operation, but there seems to be no obvious explanation for the suppression of the fractures dipping to the south-east.

(iii) In the absence of a simple relation between the orientation of the different structures, the mechanism invoked by Cloos and his associates to explain the formation of the structures in complexes where a definite relation has been found, cannot be utilised to explain the formation of these structures in the Strontian complex.

(iv) Irrespective of the means by which the linear structure in the inner tonalite and granodiorite was produced, it seems probable that this structure indicates the direction of tension when the rocks of the complexes were being formed. On this basis, it would be possible to interpret the set of joints oriented 115°/90°, as tension joints which have been formed over a large area of country, in response to the same stresses which produced the linear structure in the northern part of the complex. This would imply that similar stresses operated both during and after the consolidation of the magma. As noted already, it is possible that orogenic forces influenced the orientation of the linear structure, and the joints in question may have been formed under similar control.

If this interpretation is correct, veins with a similar orientation would be expected to occur, having been formed when vein-forming material was available. Such veins do occur, frequently in large numbers, particularly in the east. (Fig. 7g - k). It is noteworthy also, that veins with approximately the required trend predominate in the central regions of the tonalite and granodiorite. (Pages 75 - 76). To the north and west, in the contact areas, as already indicated (pages 73-74) the most abundant vertical veins change in strike through east to north-east. If these veins have formed on tension fissures, then it must be assumed that the north-north-east direction of tension (025°) was locally deflected in these areas into a direction more nearly at right angles to the outer contact of the tonalite.

It appears, therefore, that the conclusions which can be reached from a study of the fracture systems are restricted in scope, as the mechanism of formation of the fractures is obscure. While the distribution of the vein-filled fractures suggests once more that forcible intrusion has occurred, it is difficult to establish that there is a relation between the orientation of these fractures, and the expansion of the magma chamber which must be presumed to have occurred. It is particularly difficult to explain the vertical veins on this basis, and it seems necessary to assume that orogenic forces were acting when expansion occurred in order to account for the orientation of the flat-lying veins.

The orientation of certain of the vertical joints, and many of the vertical veins, suggests that fractures may have been produced by the same stresses as formed the lineation in the inner tonalite and granodiorite. These also may have been the stresses associated with orogenic movements.

(e) Structures in the Moine Schists and Gneisses.

As stated earlier, if intrusion of magma is assumed to have occurred, then displacement of the previously existing rocks is implied. In consequence, the study of the structures in the country rocks would be expected to be of more value in the determination of the probable mode of intrusion of the magma than the study of any of the structures within the granitic rocks.

The Moine schists and gneisses seem to have been profoundly disturbed within half a mile of the complex. In this zone, the evidence of strong shearing movements seems to suggest that large scale vertical displacement of the country rocks has accompanied the formation of the complex. This movement seems to have occurred largely on planes which are oriented parallel to the boundary of the complex. These movements seem to have been accompanied either by rupture or by plastic flow, depending on the nature of the rocks involved. (Page 103). The distribution of the areas where signs of strong shearing are visible suggests that these movements were greater and more widespread in the immediate vicinity of the complex, and that much of the displacement was piecemeal, with large masses of country rock moving as units.

The country rocks also seem to have been displaced horizontally in the vicinity of the complex by forces directed outward from the margin of the complex. (Fig. 9 and pages 106-8) Study of the structures suggests that these horizontal movements were of limited extent, and did not play an important part in creating space for the rocks of the complex. In particular, if lateral crowding had occurred on a large scale, it would be anticipated that an intense foliation would be developed in the country rocks in the vicinity of the complex, and that this structure would be rigidly oriented parallel to the contact between tonalite and country rock. Sub-horizontal thrust planes, which, in certain circumstances, would be produced by lateral pressure in the vicinity of a granitic complex, are also virtually lacking in the country rocks.

It appears probable, therefore, that space for the intrusion of magma was created mainly by strong vertical forces, accompanied by limited horizontal pressure exerted outward by the magma. The exact mechanism by which the country rocks were displaced cannot be inferred with certainty from the available evidence. Subsidence would appear to be unlikely, in view of the inferred shape of the mass of tonalite and granodiorite, and, therefore, it seems probable that intrusion was effected mainly by means of the vertical uplift of the country rocks. Although much of the evidence, discussed in the preceding chapters, suggests that forcible intrusion occurred, it seems unlikely that the vertical displacement of the country rocks was caused solely by the pressure of the invading magma. As stated earlier (page 118) there is no evidence available which suggests that intrusion took place near the surface. If magmatic pressure were sufficient to lift what must be assumed to be a very considerable load, it would be anticipated that a pressure of similar magnitude would also act horizontally producing far more widespread evidenxe of lateral crowding than is visible. In consequence, it must be presumed that some other agency facilitated the vertical uplift. In view of the other evidence which suggests that the process of intrusion may have been influenced by orogenic forces, it seems logical to consider the possibility that the uplift of the country rocks may have been due, in part, to the action of forces associated with the Caledonian orogeny.

If this hypothesis is to be substantiated, it would be necessary to show that there is a relation between the shape and structures of the complex, and the regional structural pattern of the country rocks. As noted already, the elongation and inferred shape of the mass of tonalite and granodiorite, the orientation of the foliation and lineation, the relation of one of the sets of dominant joints to these structures and the orientation of the flat-lying veins in the northern part of the complex, all suggest that the process of intrusion may have been under the control of oregenic forces.

Apart from this evidence, little information was obtained in the present investigation, which is of value in indicating whether or not the mass of tonalite and granodiorite and the undisturbed countryrocks conform to aregional strutural pattern. The only large scale structure which was recognised in the vicinity of the complex in the area north of Loch Sunart is the large fold visible half a mile west of the complex (Fig.9). As Richey has shown that this fold extends far to the north beyond Loch Shiel (1935, page 65) it cannot be assumed that this structure was produced as part of the deformation attendant on the formation of the complex. The eastern limb of this fold is clearly truncated by the complex, and it is apparent, therefore, that the complex is not conformable to all the large scale structures in the country rocks.

There is little published information on the structures in the country rocks in the vicinity of the complex. It has been suggested that a large isoclinal fold lies to the east of the complex (Bailey and Maufe, 1916, p.85 and Harry, 1954, p.291). If a series of such folds exists, and if the shape of the mass of the tonalite and granodiorite has been inferred correctly, then it is possible that this mass forms a phacolith. Leedal (1952,pp.37-8) has suggested that the Strontian and Cluanie complexes may have been intruded near a line of structural discontinuity. This author suggests that low angles ofdip prevail in the Moine schists and gneisses to the east of this line, steep angles of dip to the west. However, in the vicinity of the Strontian complex, the angles of dip appear to be steep for a considerable distance to the east.

Consideration of all the available information on the structures in the Moine country rocks is inconclusive therefore, and while it seems possible that there may be a relation between the formation of the mass of tonalite and granodiorite and the Caledonian orogeny, this cannot be fully substantiated. In particular, this mass cannot be assumed to be a simple phacolith, for while there is evidence which suggests that the tonalite and granodiorite magmas may have been intruded into the arch or the trough of a fold in the country rocks, there is also a considerable body of evidence which indicates that the complex transgresses and disrupts the structures in the surrounding Moine country rocks.

(f) Concluding Remarks.

Reviewing the entire discussion on the mode of intrusion of the tonalite and granodiorite magmas, it appears that the available evidence is inadequate for the full comprehension of the intrusive mechanism. There is a considerable body of evidence which suggests that the emplacement of magma may have been effected largely by forces associated with the Caledonian orogeney, but it seems desirable to assume that forcible intrusion has occurred on at least a limited scale, in order to explain many of the structures in the tonalite and granodiorite. However, although the evidence is very incomplete, and the limited conclusions which have been reached in the preceding discussion cannot be fully substantiated, an attempt can be made to suggest a mechanism by which it is possible that the tonalite and granodiorite magmas were emplaced. In this way, the discussion can be conveniently summarised, and the field for possible research in the future can be indicated.

It appears that the tonalite and granodiorite magmas may have been intruded into an area which was under considerable horizontal pressure, directed from the north-west and the south-east. If folds of the types described by Bailey, Maufe and Harry exist in the Moine country rocks, then this pressure would seem to have been expressed locally in vertical movements, and if rocks with different physical characteristics reacted to this folding in a different fashion, it is possible that areas near the crests and troughs of these folds were under vertical tension as a result of the folding. In consequence, it is conceivable that the intrusion of magma could have been localised in these areas of tension.

If these inferences are correct, then it is possible that the tonalite and granodiorite magmas may have played a largely passive role during intrusion, rising initially in responses to horizontal pressure, and being finally emplaced in a region of tension produced by these horizontal forces. It must be assumed that the moving magma had sufficient energy to overcome the influence of the regional forces in the vicinity of the complex at this stage in order to explain the deformation in the Moine rocks in the vicinity of the complex, and the pattern of the foliation and lineation in the tonalite and granodiorite. In this way, the distinctive structural pattern of the complex and its immediate surroundings could have been developed, but, evidence such as the shape inferred for the mass of tonalite and granodiorite, and the trend of the planar and linear structures in the inner tonalite and granodiorite, may indicate that the regional control was still effective to some extent. It is also possible that the energy of the moving magma was simply a localised expression of the energy expended in the orogeny. The evidence obtained from the study of the fracture systems, suggests that regional control may have become dominant once more when the magma was static and had consolidated.

It must be presumed that intrusion of the tonalite and granodiorite magmas took place after the Caledonian orogeny had reached its peak, however, and when the regional stresses were waning in intensity. The limited study of the biotite granite suggests that these stresses had ceased to operate when the magma to form this rock was emplaced, as no evidence of external structural control is apparent.

By means of the mechanism outlined above, it would be possible to explain all the phenomena observed in the course of the present investigation. It is suggested, therefore, that the agency which appears to have facilitated the upward expansion of the original chamber into which the tonalite and granodiorite magmas were intruded, may have been a vertical tensional stress produced locally when folding took place in the Moine schist and gneiss during the Caledonian orogeny. This mechanism would be similar to that by which many phacoliths appear to have been formed, but it seems necessary to postulate that, at Strontian, the invading magma had sufficient energy to destroy the large-scale structures in the immediate vicinity of the magma chamber which had been formed when an original weakness in the crust was exploited and enlarged.

The sequence of events during the formation of the rocks of the complex may have been:-

(i) Ascent of magma in the south of the area now occupied by the rocks of the complex, followed by intrusion of some of the tonalite magma into a sub-horizontal region of tension in the country rocks (Arch or trough of a fold, with a sub-horizontal axis?).

(ii) Continuation of the intrusion of magma and the expansion of the original magma chamber, the remainder of the tonalite magma, and much of the granodiorite magma being intruded into the centre of the mass of tonalite magma already emplaced. This second stage must be assumed to have taken place when the marginal tonalite was still plastic, and it is suggested that the marginal foliation and lineation may have been formed at this time.

(iii) Continuation of stage (i), the movements being of a smaller order now, and taking place after the marginal tonalite had solidified at least locally. Marginal tonalitic veins and the foliation and lineation in the central region of the tonalite and granodiorite formed.

(iv) Final small expansional movements, within a wide, solidified margin of tonalite. Zones of fine-grained granodiorite formed in the inner regions, granitic veins and shear planes in the marginal regions of the tonalite.

(v) Intrusion of the biotite granite magma, followed by the formation of the last of the granitic veins.

(ii) Mode of Intrusion of the Biotite Granite Magma.

The mode of intrusion of the biotite granite magma is only considered very briefly, in view of the lack of detailed information on the structures and relations of this rock. It seems probable that intrusion was effected by a process which differs from the process by which tonalite and granodiorite magmas were emplaced. No evidence of widespread stoping was recorded, and there is no evidence which indicates that intrusion of biotite granite magmas was accompanied by deformation of the surrounding rocks. The shape of the masses of biotite granite appears to be largely unrelated to the structures in the country rocks.

These relations suggest that emplacement of magma was not effected by piecemeal stoping, "permissive" intrusion, or forcible intrusion. The vertical contacts between biotite granite and the surrounding rocks would permit the intrusion of the main mass of biotite granite magma to be explained by a process of cauldron subsidence,for if these contact surfaces were originally fracture planes, then the subsidence of a mass of rock bounded by such vertical fractures could have taken place, accompanied by the intrusion of biotite granite magma into the cavity thus created. The irregular, outlying areas of biotite granite could then be interpreted as being produced by magma filling tension fissures, roughly parallel to the fracture which controlled the intrusion of the main mass. Detailed examination of the structures at the opposite margins of these apophyses would be of particular value, if it could be proved thereby that distension on a fracture had accompanied intrusion. However, none of the available evidence lends direct support to the hypothesis that block subsidence preceded the intrusion of the biotite granite magma.

3. STATE OF THE TONALITE AND GRANODIORITE MAGMAS WHEN FINNALY EMPLACED.

As stated earlier, the information obtained in the present enquiry seems to be of significance mainly because it enables some assessment to be made of the probable mode of intrusion of the tonalite and granodiorite magmas. From this evidence an attempt can also be made to infer the physical state of the rock-forming material at the time of intrusion.

While magma may have been intruded originally as a silicate melt, devoid of solid phases, the field and microscopic evidence indicates that the final stages of intrusion took place after crystallisation was well advanced. Whether obtained from field or microscopic examination of the rocks, or from petrofabric analyses, the evidence is consistent in indicating that the oriented crystals appear to be of early formation, and this evidence, indirectly, provided further support for the hypothesis that the rocks of the complex are of igneous origin.

In the marginal areas of tonalite, it would appear that when the final orientation of the crystals, which is now preserved as linear and planar structures, was imposed, the liquid phase consisted essentially of the components which combined later to form quartz and potash feldspar. In the inner regions of the tonalite, biotite, quartz and orthoclase, and in the granodiorite, biotite, quartz and some of the plagioclase and orthoclase, had still to crystallise when the effect of the orienting influences ceased.

It appears probable, therefore, that in the final stages of emplacement of the tonalite and granodiorite magmas, the magmatic material consisted of a comparatively small quantity of liquid, essentially of quartzo-feldspathic composition, which contained a considerable quantity of crystals (probably as much as 70-80% of the whole, in some places). It is possible that there is a relation between the composition of some of the granitic veins, which cut the tonalite and granodiorite, and the composition of this interstitial liquid.

4. COMPARISON WITH OTHER AREAS.

It is possible to make only a very general comparison between the structures in different complexes, as few show much detailed structural similarity, and the majority appear to have individual characteristics which are not found elsewhere. The present section of the discussion is sub-divided into two portions:- (1) a comparison between the structures in the Strontian complex and the structures in other granitic complexes where certain structural similarities are visible, and (2) a comparison between the structures in the Strontian complex and the structures in the other Caledonian granitic complexes of the Scottish Highlands. In both cases attention is mainly confined to comparing the structures in the tonalite and granodiorite with the structures in other granitic complexes.

(i) Comparison on the Basis of General Structural Similarity.

Consideration of the mechanism by which magma was emplaced in each granitic complex, would probably provide the most fundamental basis for a structural comparison, but in the absence of a clear understanding of the intrusive mechanism in the majority of these complexes, it seems preferable to contrast the main features of the structural pattern visible in each complex. The three outstanding structural characteristics of a granitic complex, would seem to be (a) the shape of the complex, (b) the pattern of all the structures within the complex, and (c) the type of deformation in the adjoining country rocks.

(a) It seems probable that the mass of tonalite and granodiorite at Strontian has the form of a harpolith. The paucity of published descriptions suggests that granitic complexes of similar shape are of rare occurrence elsewhere, even when funnel-shaped complexes, which only approximately resemble a harpolith in shape, are taken into account. The term harpolith was defined by H. Cloos from his work on the granitic complexes of eastern Germany, particularly the Hausenberg massif. (Balk, 1948, pp. 74 - 77, and Daly, 1933 p.104). E. Cloos (1932) has described a granodiorite offshoot from the main complex of the Sierra Nevada, which appears to be roughly similar in shape to a harpolith. The form of the Saganaga complex of Minnesota also seems to resemble that of the mass of tonalite and granodiorite at Strontian, although Grout (1935) suggests that this complex was originally intruded as a stock-like mass, which has since been tilted until it is sub-horizontal. Funnel-shaped granitic complexes have been described from Porcher Island, British Columbia (Smith,1947); Loon Lake, Ontario (E.Cloos, 1934); Flamanville, Brittany (Martin, 1953) and from a few other areas.

Although the evidence suggests that the mass of tonalite and granodiorite is not simply related to the major structures in the surrounding Moine country rocks, it has been suggested (page 144) that the mechanism of formation of this mass may be similar to the mechanism by which many phacoliths have been formed. It would seem to be desirable, therefore, to include flat-lying intrusions, such as the Wolf Mountain Phacolith (Stenzel, 1936) and the phacolithic Storm King Granite (Lowe, 1950), in the present comparison, as they are of approximately the same shape as the mass of tonalite and granodiorite at Strontian. Nevertheless, even when these additional examples of "floored" granitic complexes are taken into account, the number of such complexes does not approach that of the batholithic masses which apparently extend downward for an indefinite distance.

(b) When the structural pattern in the tonalite and granodiorite is compared very generally with the structures which have been described in other granitic complexes, it is apparent that this pattern seems to have no exact parallel elsewhere. In certain areas, resemblances to parts of this pattern are visible, but no other complex has been described, which is characterised by planar and linear structures and by fracture systems showing a pronounced overall similarity in development and inter-relations to the structures visible at Strontian. The orientation of the planar structure in granitic complexes usually tends to follow the attitude of the contact with the country rocks, and it is also noteworthy that the linear structure in these complexes almost invariably lies within the planar structure, and usually shows a marked tendency to have a constant orientation. The pattern described by H. Cloos and his co-workers in many granitic complexes (e.g. Balk, 1948, pp.113-116) where the foliation and the lineation define arch or dome-shaped structures, and where the orientation of the structures of all types is simply related throughout the complex as a whole, shows only a general resemblance to the pattern in the Strontian rocks.

From published data it would appear that only the Loon Lake complex (E.Cloos, 1934) possesses a structural pattern which shows a marked resemblance to that seen in the tonalite and granodiorite, and even in this complex, the structures differ from those visible at Strontian in certain respects. Both a planar and a linear structure are developed at Loon Lake, and while the former resembles the structure seen at Strontian in its general relations, the latter differs to some extent, as it invariably follows the direction of dip of the foliation, and is a very widely developed structure in the granitic rocks. The vein-filled fractures, as at Strontian, tend to be oriented in certain directions, but are not simply related to the other structures. No attempt has been made by Cloos to provide a detailed explanation of the structures in this complex.

In some complexes only a planar structure is developed, either marginally, as in the Llano-Burnet Granites (Keppel, 1940), or throughout the whole mass of granitic rocks, as in the Riesengebirge Granite (Balk, 1948, pp.57-60) and the Flamanville Granite (Martin, 1953). To explain the formation of the structures in these complexes a mechanism involving distension and expansion of the magma chamber is often invoked, and in some cases (as in the three examples quoted) it appears to be possible to reconcile the orientation of the fractures in the granitic rocks with this hypothesis. Throughout other granitic complexes, such as the Carnmenellis Granite (Fleet and Hill, 1912, pp.217-8) the Dartmoor Granite (Brammall, 1926) and the Storm King Granite (Lowe, 1950), the structures are thought to have been produced by magnetic flow. A linear structure is generally developed throughout these complexes, and this structure may be accompanied by a planar structure, which may be localised (Storm King) or widespread (Carnmenellis) in its development. These structures may show considerable uniformity in trend, with only local fluctuations and deviations (Storm King) or be generally very variable in trend (Dartmoor). Such variations in orientation are thought to be due to turbulence. When considered as a whole, the combination of linear and planar structures visible in the tonalite and granodiorite at Strontian, does not seem to occur elsewhere. It is noteworthy that in the Hausenberg complex, only a linear structure is developed, and that this structure defines a uniform arch-shaped pattern, ignoring the attitude of the contacts of the granitic rocks. (Balk, 1948, pp.76-77). H.Cloos has interpreted this structural pattern as the product of distension during the intrusion of the granitic magma.

Normally when tension fractures occur in a granitic complex, they are in intimate relation to the linear structure, and do not show the general type of relation to the structure which is suggested at Strontian. Occasionally, some similarities to the relations at Strontian are visible, as in the Storm King Granite (Lowe,1950).

In some complexes there is evidence that marginal solidification has occurred when a fluid core was still in motion, but, as in the Sierra Nevada Batholith (Balk, 1948, p.65), the fractures which have formed are usually simply related to the other structures. In several complexes, such as the Snowbank Stock (Balk and Grout, 1934), early intrusions contain well developed planar and linear structures, while late intrusions are devoid of such structures, and are thus comparable to the tonalite and granodiorite, and to the biotite granite at Strontian respectively.

(c) Several granitic complexes have been described which are surrounded by zones of deformed rock, showing many similarities to the zone of rocks in the vicinity of the Strontian complex. Normally it is found that the structures in the country rock are deflected into parallelism with the boundaries of the complex, and that signs of deformation become more widespread in the vicinity of these contacts. The deformation is often shown by the development of many small folds in the country rocks, and in many areas considerable shearing and stretching of the country rocks has been described. The deformation in the rocks surrounding the Sierra Nevada Batholith (Mayo, 1941, pp.1012-8) and the Saganaga Granite (Grout, 1936), in particular, shows many similarities to the phenomena observed at Strontian. It is also noteworthy that in the vicinity of the Loon Lake complex, the trend of the structures in the country rocks has been deflected into parallelism with the margin of this complex. (E.Cloos, 1934).

In many areas, a vertical linear structure in the country rocks, due either to oriented cyrstals or to stretched boulders in conglomerates, suggests that the vertical displacement of these rocks has accompanied the formation of a granitic complex. In the vicinity of other complexes there is direct evidence, either in the form of doming (Tyrrel, 1928, p.161, and Noble, 1952, p.46) or of sagging (Lowe, 1950), to indicate that vertical displacement of the country rocks has occurred.

In certain other areas it appears that considerable lateral pressure was exerted by a granitic magma when it was intruded. In view of the conclusions reached from the study of the deformation in the Moine country rocks at Strontian (page 139), the evidence of deformation in the rocks in the vicinity of these complexes provides a particularly interesting comparison with the similar evidence at Strontian. In the vicinity of the Flamanville Granite it has been found that both small scale and large scale structures inthe country rocks are conspicuously "wrapped round" the granite, while an intense foliation has been developed in these rocks for several yards in the vicinity of the margin of the granite (Martin, 1953). This foliation ignores original bedding structures, and is not accompanied by a linear structure. Similar phenomena suggesting that strong lateral pressure has accompanied the intrusion of granitic magma have been described in the vicinity of the Snowbank Stock (Balk and Grout, 1934). The evidence in these areas supports the conclusion that no great lateral displacement of the country rocks accompanied the intrusion of the tonalite and granodiorite magmas at Strontian.

It was noted at Strontian that the deformation in the country rocks seemed to occur in localised areas, separated by areas of relatively undeformed rock, suggesting that large masses of the country rocks had moved as units (page 104). The few published descriptions which suggest that similar deformation may have occurred elsewhere include those of the Deadwood-Trojan Stock (Noble, 1952, p.46); the Idaho Batholith (Ross, 1936); and the Mourne Granite (Richey, 1927, p.678); but this appears to be a rather uncommon phenomena.

In summary of this chapter, it can be said that the comparison of the structural pattern in the tonalite and granodiorite at Strontian with the structural pattern in other granitic complexes, tends to reinforce the original impression that most granitic complexes have a distinct structural individuality. It is impossible to state whether or not the difference between the structures at Strontian and the structures in other complexes are of fundamental importance, in the absence of a clear understanding of the mechanism by which the various granitic complexes were formed.

The only complex in which the structures appear to show an overall similarity to the structures within and around the mass of tonalite and granodiorite at Strontian is the Loon Lake complex. Unfortunately, as noted already, the structures in this complex have not been studied in sufficient detail for further comparison to be rewarding.

One of the main conclusions reached in the present investigation was that space for the emplacement of the tonalite and granodiorite magmas was created by the vertical uplift of the country rocks (page 139).

In interpreting the structures in granitic complexes, it is frequently assumed that space for the intrusion of magma has been created largely by means of a mechanism involving the vertical uplift of the country rocks. The type of evidence on which this assumption is based has been indicated above, and the parallelism between the orientation of structures in the country rocks and the margins of a granitic complex, is in many cases ascribed to "dragging" accompanying this uplift and not to outward directed pressure. The upward displacement of the country rocks is thought by many authors, to be due, in part at least, to forcible intrusion. In particular, the mechanism of intrusion invoked by H.Cloos and his associates to explain the structures in many of the complexes they have studied, involves vertical uplift and forcible intrusion. (With reference to the whole of the above paragraph see Balk,1948, pp.112-7, and Noble, 1952).

On many occasions it has been noted that granitic complexes tend to occur in orogenic belts, and that these complexes tend to be elongated parallel to regional tectonic axes. The assumption that there is a relation between the formation of these complexes and orogenic movements appears to be accepted by most geologists. The hypothesis that the intrusion of magma to form some of these complexes is directly controlled by the orogenic forces, and is not due to energy inherent in the magma itself, has received less support. Harker, in his definition of a phacolith (1909, pp.77-78), implied that intrusion could take place under the control of orogenic forces, and this concept has received support from other authors (e.g. Billings, 1952, p.295; Daly, 1933, p.426; Chamberlin and Link, 1927) and, in particular, has been elaborated more recently by Mayo (1941, p.1073). The latter has defined the term "permissive intrusion" to describe intrusion of this type, but the evidence advanced by this author in support of his hypothesis - the deflection of structural trends in certain areas, bears only a general resemblance to the evidence at Strontian which suggests that intrusion may have been controlled by orogenic forces. It is also noteworthy that H. Cloos, who has dominated the study of the structures in granitic complexes with his researches, has suggested (1936) that the intrusion of magma to form many of these complexes may have resulted directly from orogenic activity.

It is possible, therefore, that the mechanism by which magma was implaced at Strontian, may be fundamentally similar to the intrusive mechanism which has operated in many other areas. If this is the case, then local conditions seem to have produced a structural pattern at Strontian which has no parallel elsewhere.

(ii) <u>Comparison with the other Caledonian Granitic Complexes in the Scottish Highlands.</u>

Consideration of the other granitic complexes in the Scottish Highlands, which are of the same age as the Strontian complex, also suggests that the latter is structurally of rather an exceptional type. In the Geological Survey Memoir, "The Granites of Scotland" (Anderson, 1939) twenty-eight granitic complexes are listed, which are stated to be "Newer Granites" of Caledonian age, and which occur in the Grampian and Northern Highlands. Only a few of these complexes show much structural similarity to the Strontian complex.

The shape of the mass of tonalite and granodiorite at Strontian does not seem to be typical of the other Caledonian complexes, in view of the absence of any signs of a "floor" in the majority of the latter. It has been suggested that the Cairngorm granite and the Ratagain complex are laccolithic (Hinxman, 1913, p.63 and Nicholls, 1950, p.334). Leedal's description of the Cluanie complex suggests that this complex is flat-lying and tongue-shaped (1952, p.40) while, if the Ben Loyal syenites are included in the comparison, further examples of complexes which are roughly similar in shape to the mass of tonalite and granodiorite at Strontian can be found (King, 1943, p.149).

Most of the Caledonian complexes appear to be devoid of planar and linear structure defined by oriented cyrstals and inclusions. Pochin-Mould has described a linear structure in the Foyers complex (1946, p.253), and Hinxman (1923, pp.65-66) describes a planar structure in the Moor of Rannoch and Strath Ossian complexes, which is oriented parallel to the outer contact. Planar and linear structures have been described in the Skene complex, and, in addition, the orientation of the fracture systems in this complex appears to be related to the orientation of the other structures. (Cameron, 1945). A planar structure, which may have been produced during igneous intrusion, has been recorded in other Caledonian complexes in the Scottish Highlands (e.g. Lairg and Rogart), but in these complexes there is a considerable body of evidence which suggests that this may be a relict structure. (Read, 1925, pp.22-23 and 1926 pp.148-9).

The country rocks appear to have been extensively deformed in the vicinity of only a few of the Caledonian complexes. The small complex at Ratagain is bordered by a breccia of country rock fragments, and the strike of the country rock is deviated in the vicinity of the contact with the granitic rocks (Nicholls, 1950, p.313). The strike of the country rocks is also deflected in the vicinity of the Moy and Ardclach complexes (Horne, 1923, p.41), the Cluanie complex (Leedal, 1952, p.39) and the Foyers complex (Pechin-Mould, 1946, p.252). The strike of the country rocks is also markedly deflected in the vicinity of the Ben Loyal syenites (King, 1943, p.148).

5. CONCLUDING REMARKS.

As a result of the present research, the earlier work on the Strontian complex has been substantiated, and the knowledge of the structures in the rocks of this complex and the surrounding areas of Moine Schists has been considerably augmented. The previous conclusion that the rocks of the complex are of igneous origin is supported by the new evidence, but although it is possible from a study of the structures to obtain some indication of how magma was emplaced, the precise nature of the intrusive mechanism which has operated at Strontian remains obscure. To some extent magma seems to have been forcibly intruded in order to form the mass of tonalite and granodiorite, but it does not appear to be possible to explain the entire process of emplacement by this means. There is also evidence which suggests that the emplacement of the tonalite and granodiorite magmas may have been effected largely by means of forces associated with the Caledonian orogeny. The biotite granite magma seems to have been intruded in a different fashion - possibly by a mechanism involving cauldron subsidence.

The incomplete nature of the present investigation is partly responsible for the difficulty experienced in interpreting the evidence, and further research on the structures of the Strontian complex would seem to be essential, if a satisfactory structural analysis is to be made. Ideally, the structures and relations of the rocks in the remainder of the complex, and of a large area of the surrounding Moine Schists, would require to be studied, in order that the complex could be seen in its complete structural setting. The methods already used could be employed once more, though possibly on a slightly less intensive scale. As a preliminary to further investigation, it would be desirable to make a detailed petrological examination of the rocks of the complex and the adjoining Moine Schists in order to establish, with as high a degree of certainty as is possible, that the granitic rocks are of igneous origin. It would also be necessary to discover a technique for obtaining a truly representative sample of the variation in the characters of the fracture system. This would probably require to be based on a mathematical analysis of the factors influencing the collection of such a sample. The study of the fractures in the areas already examined in detail could then be completed, and this study extended to include the rest of the complex and the country rocks.

The lack of knowledge of the structures of the other Scottish granitic complexes of Caledonian age is a further factor which renders the interpretation of the structures in the Strontian complex difficult. The existing information suggests that a detailed structural study would be rewarding in comparatively few of these complexes - in particular, the Foyers, Strath Ossian and the Moor of Rannoch complexes. It is notable that several of the complexes in which internal structures have been recorded lie near the Great Glen. No attempt can be made to relate the structures in the Strontian complex with the structures in the Foyers complex until the latter has been studied in detail, but the results of the present investigation suggest that such a study would facilitate the determination of whether or not these two complexes were once united.

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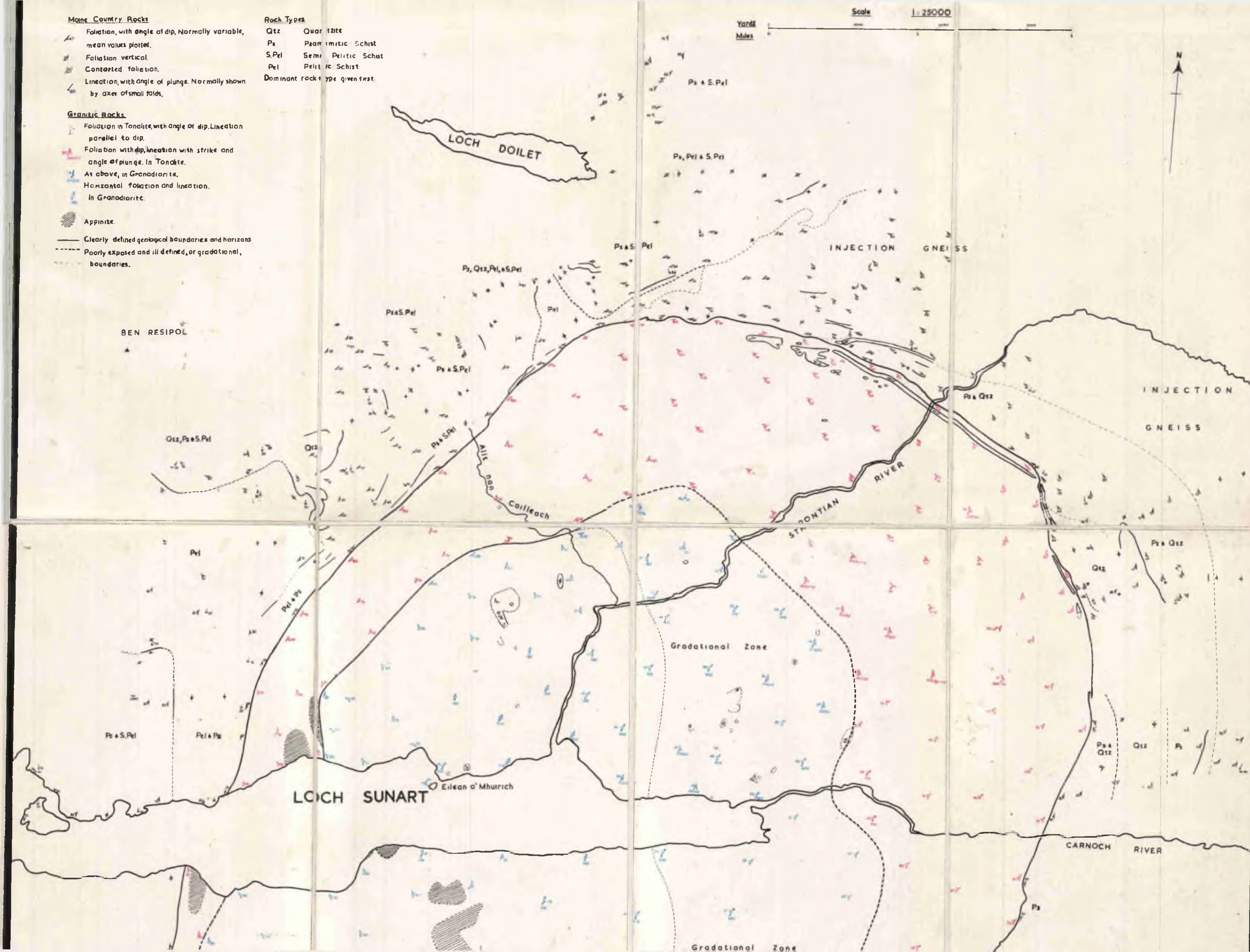
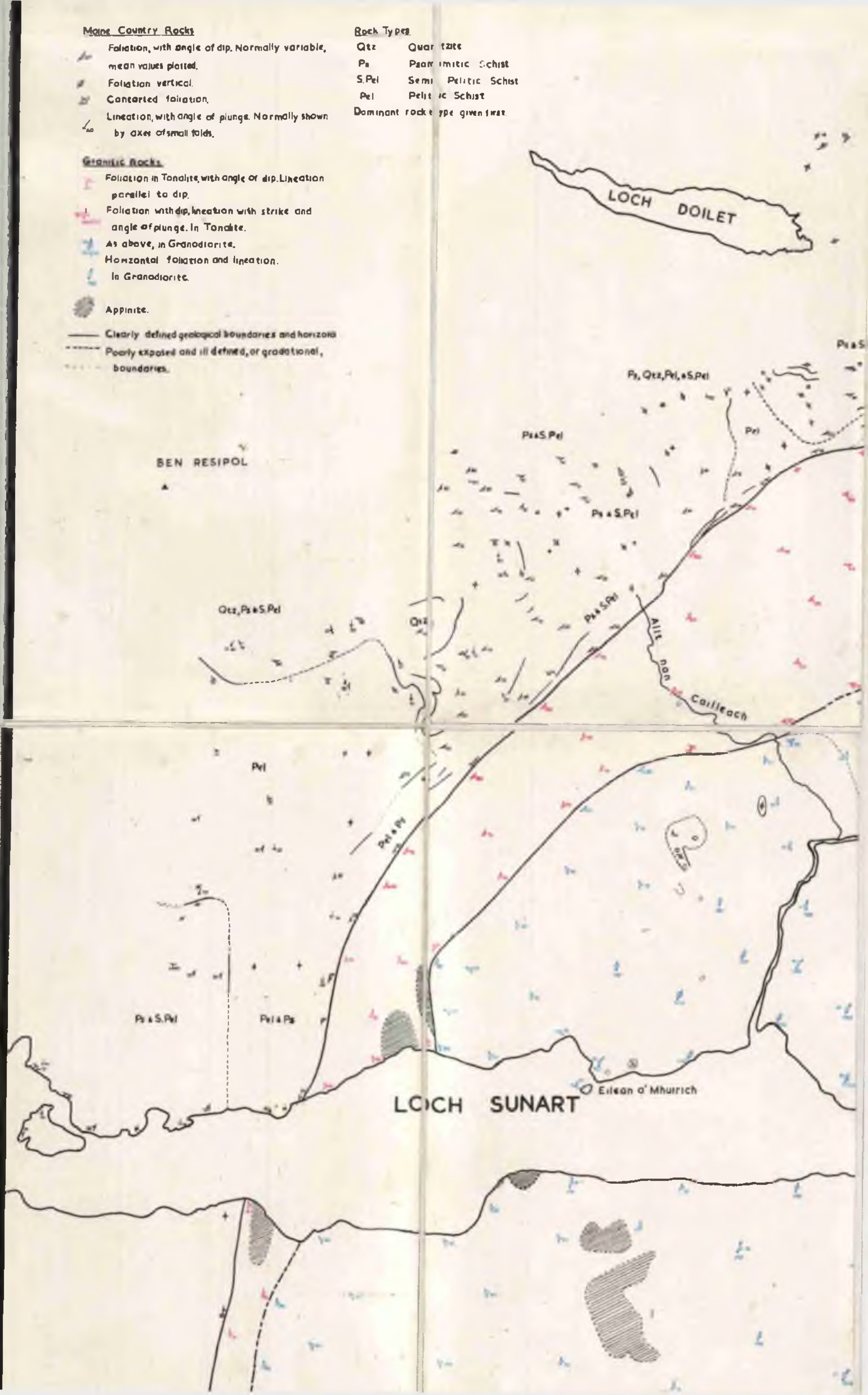
Fig. 9

Structural Map of the Northern Portion of the Strontian Granitic complex and the surrounding areas of the Moine Schist and Gneiss.



Moine Country Rocks
Foliation, with angle of dip. Normally variable, mean values plotted.
Foliation vertical.
Contorted foliation.
Lineation, with angle of plunge. Normally shown by axes of small folds.
Granitic Rocks
Foliation in Tonalite, with angle of dip. Lineation parallel to dip.
Foliation with dip, lineation with strike and angle of plunge. In Tonalite.
As above, in Granodiorite.
Horizontal foliation and lineation. In Granodiorite.
Appinite.
Clearly defined geological boundaries and horizons
Poorly exposed and ill defined, or gradational, boundaries.
Rock Types
Qtz Quartzite
Ps Psammitic Schist
S.Pel Semi Pelitic Schist
Pel Pelitic Schist
Dominant rock type given first
Scale 1:25000
Yards
Miles
N
LOCH DOILET
BEN RESIPOL
INJECTION GNEISS
INJECTION GNEISS
Allt nan Cailleach
STRONTIAN RIVER
Gradational Zone
Gradational Zone
LOCH SUNART
Eilean a' Mhuirich
CARNOCH RIVER
Ps + S.Pel
Ps, Pel + S.Pel
Ps + S. Pel
Ps, Qtz, Pel, + S.Pel
Pel
Ps + S.Pel
Ps + Qtz
Qtz, Ps + S.Pel
Qtz
Pel + Ps
Ps + S.Pel
Pel + Ps
Qtz
Ps + Qtz
Ps + Qtz
Ps


Moine Country Rocks
Foliation, with angle of dip. Normally variable, mean values plotted.
Foliation vertical.
Contorted foliation.
Lineation, with angle of plunge. Normally shown by axes of small folds.
Granitic Rocks
Foliation in Tonalite, with angle of dip. Lineation parallel to dip.
Foliation with dip, lineation with strike and angle of plunge. In Tonalite.
As above, in Granodiorite.
Horizontal foliation and lineation.
In Granodiorite.
Appinite.
Clearly defined geological boundaries and horizons
Poorly exposed and ill defined, or gradational, boundaries.
Rock Types
Qtz Quartzite
Ps Psammitic Schist
S.Pel Semi Pelitic Schist
Pel Pelitic Schist
Dominant rock type given first.
LOCH DOILET
Ps, Qtz, Pel, & S.Pel
Pel
Ps & S.Pel
BEN RESIPOL
Ps & S.Pel
Qtz, Ps & S.Pel
Qtz
Ps & S.Pel
Allt nan Cailleach
Pel
Pel & Ps
Ps & S.Pel
Pel & Ps
Eilean a' Mhuirich
LOCH SUNART

Scale 1:25000
Yards
Miles
N
Ps & S.Pel
Ps, Pel & S.Pel
Pel
INJECTION GNEISS
Ps & Qtz
INJECTION GNEISS
STRONTIAN RIVER
Ps & Qtz
Qtz
Gradational Zone
Ps & Qtz
Qtz
Ps
CARNOCH RIVER
Ps
Gradational Zone