THE PLUTONIC ROCKS IN THE VANCOUVER NORTH - COQUITLAM AREA,

IN THE SOUTHERN COAST MOUNTAINS OF BRITISH COLUMBIA

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

UNIVERSITY OF WASHINGTON

1955

Approved by ____________________

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Date ____________________

ABSTRACT

This thesis is essentially a study of the plutonic rocks in a 500 square mile section of the southern Coast Mountains of British Columbia. The purpose of the study was to ascertain the general characteristics of such a large plutonic area, to determine which phenomena are common, and which are rare, and from such data to adopt a theory of the genesis of the plutonic rocks which best accommodates the major characteristics of the region.

The approach to the problem does not follow the usual line, which involves a detailed study of the pre-granitic rocks with the emphasis on contact phenomena. The writer and certain other geologists (Misch. 1949, p.210) feel very strongly that no matter how thoroughly contact phenomena are studied, the only inferences that can be made are applicable to the contact area only. It is frustrating, if, after much painstaking work, it is concluded from a certain contact that granitization has occurred here, that others can maintain that marginal granitization has indeed been well proven, but such granitization is to be expected to accompany large magmatic intrusions, so no important progress has been made. The major problem is not the genesis of certain contacts but the genesis of the core of the plutonic bodies. The writer believes there is sufficient evidence, far from the contacts, in the plutonic rocks themselves, to establish their genesis, and once this has been done the result is applicable to the whole body not merely to a small portion of its outer margin.

In the first part of the thesis the non-granitic rocks are described rather briefly, and in the remainder of the thesis, the plutonic rocks, along with the small inclusions and dykes which are everywhere present, are considered in some detail.

The writer, after the first season's work, found the classifications of plutonic rocks commonly used, to be unsatisfactory for rather detailed mapping of large areas of plutonic rock. Consequently he devised another classification which places the emphasis on the mafic minerals rather than upon the potassium feldspar-plagioclase ratio. This classification brings out some important relationships which tend to be obscured by the commonly accepted classifications.

The microscopic study of the plutonic rocks involved the examination of the characteristics of each of the five major constituent minerals (plagioclase, hornblende, biotite, quartz and potassium feldspar) in each of the rock types. This approach brought out the fact that these minerals have different habits in different rocks. The most irregular-shaped crystals, and those containing the most inclusions were found to be in the hornblende-rich plutonic rocks, especially hornblende diorite, and hornblende quartz diorite; while the better shaped crystals, and those free of inclusions, were noted in the biotite-rich rocks, particularly in biotite granodiorite and biotite granite. This evidence along with other data, substantiates the field data, which led to the conclusion that the plutonic rocks evolved from about the composition of hornblende diorite, through hornblende-biotite quartz diorite, biotite-hornblende grandiorite (and other intermediate types), to biotite granite. Hornblende diorite, the least evolved of common plutonic rocks, is not far removed from the most common pre-granitic rock in the area, a hornblende granulite, into which the diorite frequently grades.

The microscopic study also revealed some interesting phenomena bearing on the significance of plagioclase zoning, the development of twinning in plagioclase, and on the origin of perthite.

The study of the characteristics and distribution of the inclusions in different plutonic rocks showed that they are most abundant in the least evolved plutonic rock, and least abundant in the most advanced rocks. Considerable other data are presented, and it leads to the conclusion that a magmatic genesis could not account for the widespread phenomena observed in the plutonic rocks.

Perhaps the most interesting part of the thesis concerns the dykes. These are described in considerable detail, and a new interpretation of them is made involving the premise that they were intruded while rather than before the plutonic rocks were forming and evolving.

The problem of the genesis of the plutonic rocks has thus been approached along four major and independent lines of investigation.

1. The pre-granitic rocks.
2. The individual minerals and textures of the different plutonic rocks.
3. The inclusions.
4. The dykes.

From the results of the study, it has been concluded that the plutonic rocks are of metamorphic origin, and that the plutonic series is actually a relatively high temperature, retrograde metamorphic sequence.

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INTRODUCTION

This thesis deals primarily with the granitic rocks which comprise most of the mountainous region bordering Fraser River Delta on the north. More precisely, the thesis area is bounded by longitudes west 123°00' and 123°40', and latitudes north 49°15' and 49°30' (Photograph 1).

Although close to a large metropolitan area (Vancouver), the region is singularly lacking in roads and other developments. This results from the use of the area as five watersheds supplying Vancouver and neighbouring communities. Except for certain narrowly defined areas, the whole mountainous region between Howe Sound and Coquitlam Lake is barred to the general public.

The most important routes of access from west to east are Howe Sound, Capilano Valley road, Seymour Valley road, Indian Arm, Coquitlam Lake, and Pitt Lake. Away from these routes the country is typical of the Coast Mountain belt. The valley walls are steep, and the ridgetops cut by numerous deep transverse saddles. Rain forest vegetation, characterized by exuberant underbrush, covers the valley sides and bottoms. Generally, the ridges do not reach true treeline but they are often bare because ice and snow has scoured away any accumulation of soil.

On the whole exposures are numerous within the area. Heavy growths of moss and lichen, however, make surface observations difficult, and often many pieces must be broken off before the general character of even a single outcrop can be determined. The best exposures are found in steep tributaries to the main streams. Good exposures are found also along shorelines, on ridgetops, and in cliff faces.

Photograph 1

Index map of British Columbia, showing location of the thesis area.


BRITISH COLUMBIA 1953
APPROXIMATE SCALE
MILES
LEGEND
PLACES
AIR PORTS
ROADS
RAILROADS
PIPE LINES
PEACE RIVER
GRAND PRAIRIE
EDMONTON
JASPER
MASSETT
QUEEN CHARLOTTE
SANDSPIT
PRINCE RUPERT

The field work on the area was begun on the Vancouver North sheet in 1948 by a Canadian Geological Survey party under Dr. J.E. Armstrong. I joined the party as senior assistant in 1949, and in the following year undertook the mapping of the Coquitlam sheet which borders the Vancouver North sheet on the east. The field work on the thesis area (which combines the Vancouver North and Coquitlam Sheets) was completed in the fall of 1952. Some geological mapping has been done also in areas adjacent to the thesis area. The islands in Howe Sound were mapped by Armstrong in 1950, and about 2,000 square miles of mountainous country east and north of the thesis area were mapped by my party during 1953 and 1954, on a reconnaissance scale of four miles to the inch.

Within the thesis area the scale used was one half mile to the inch for the field work, and half that for final publication.

Generally the field party consisted of three assistants besides myself. Most of the work was done by traversing in pairs along routes designated by the geology and topography. Standard survey instruments and procedures were used, in conjunction with complete air-photo coverage.

PREVIOUS WORK AND ACKNOWLEDGMENTS

Most of the thesis area had not been mapped even on a reconnaissance scale previous to 1949. Some attention had, however, been given to the area west of Indian Arm. In 1908 O.E. LeRoy, working for the Canadian survey, made a general reconnaissance along the shoreline of Howe Sound and several other fjords to the north. Burwash in 1918, made a general reconnaissance map covering a considerable part of the present Vancouver North sheet. His interest, however, was primarily in glaciology and physiography. In the early 'thirties T.C. Phemister, then a professor at the University of British Columbia, mapped in considerable detail Bowen Island, and certain small areas along Burrard Inlet and Howe Sound. Although the area covered by Phemister was small, his petrographic descriptions are excellent, and his observation that some of the dykes in the area are actually older than the granitic rocks which they appear to cut, prompted much closer attention to them than might otherwise have been paid.

Much aid was given me in both the field and laboratory phases of this thesis. I am especially grateful to Dr. J.E. Armstrong whose continued interest and assistance did much to insure the completion of the work, and to Professor P. Misch whose enthusiasm and aid in the laboratory and theoretical aspects of the thesis were essential. Discussions with R.B. Campbell of the Canadian survey during the winter of 1953-54 proved very useful in clarifying some of the features in the thesis area. Very helpful, also, was the criticism of the manuscript given by Professors Goodspeed, Coombs and Mackin, members of the staff at the University of Washington. Finally, I thank the many field assistants whose conscientious work and enjoyable companionship made each season, in spite of the frustrations of weather and topography, very pleasant. These men include

William Heywood	1949, 1950	--- Cowichan, B.C.
Surendra Amin	1949	--- Bombay, India
Ralph Venour	1949	--- Winnipeg, Man.
Gerry Krause	1950, 1951	--- Edmonton, Alta.
Bruce Young	1950	--- Winnipeg, Man.
James Allen	1950	--- Edmonton, Alta.
Kenneth Northcote	1951, 1952	--- Mission, B.C.
Bruce Watson	1951	--- Brandon, Man.
Joseph Chamberlain	1952	--- Vancouver, B.C.
Martin Christie	1952	--- Fanny Bay, B.C.

For certain photographs taken during the season of 1948, I am thankful to Robert Christie, now of the Canadian survey.

Financial backing for all the field work, the making of thin sections, and innumerable other details connected with the work were undertaken by the Geological Survey of Canada. I am especially grateful to Dr. George Hanson, Director, Geological Survey of Canada, without whose aid and cooperation this work could not have been attempted.

PHYSIOGRAPHY

GENERAL CHARACTER OF THE REGION

The region is mountainous with an average relief of about 4,500 feet. The higher peaks reach about 6,000 feet. The relief of most of the Coast Mountain belt is considerably greater than that of the thesis area. (Peaks over 8,000 feet are fairly common to the north and east.)

In many ways the lower elevations found in the mountains north of Vancouver are more of a hindrance than an aid to geological mapping, for the topography is as rugged as in the higher regions, but vegetive cover is thicker, and the outcrops less clean. Sawtooth ridges and other extremely jagged forms, common in much of the Coast Mountains, are found only locally in the thesis area.

The large valleys are characterized by steep walls and flat bottoms, covered with heavy bush and forest, or where logged off, by slash and windfalls. The gradients of these valleys are about 100 feet per mile. The tributary valleys are usually relatively straight and very steep (gradients of 2,000-3,000 feet per mile). Most are V-shaped (Photograph 2).

Cutting the area at fairly regular intervals are six, large, north-trending valleys. Two of these valleys are occupied by lakes (Coquitlam and Pitt), and one is a fjord (Indian Arm). The upper reaches of four of these valleys trend northwest, following the regional trend which is abandoned in their lower reaches.

Photograph 2

View of Capilano Valley showing the flat bottom typical of the major valleys, and straight V-shaped tributaries. (R. Christie)

Photograph 3

Cathedral Mountain, showing ridge top smoothed by glaciation. (R. Christie)

PRE-GLACIAL PHYSIOGRAPHY

Except for minor modifications the present drainage pattern in the Coast Mountains existed prior to glaciation. It is predominantly a rectangular, trellis pattern, developed parallel and transversely to the trend of the mountain belt. The transverse drainage occupies the larger valleys, and is the more extensively developed.

East of the Coast Mountains, north of latitude 52°, the same general pattern is present, but the better developed direction is the longitudinal rather than the transverse. (In the southern part of the province, between the Coast Mountains and the Rocky Mountain trench, the direction of the pattern changes to north-south and east-west.) How long the pattern in the Coast Mountains has existed is difficult to determine. It probably originated as a subsequent system etching out the trends of folded Paleozoic and Mesozoic strata during the Mesozoic era, developing at different places at different times as the sea made its final irregular withdrawal. Peneplanation may well have occurred several times during the Mesozoic and early Tertiary, temporarily erasing the pattern until re-etched by renewed uplift. Such happenings are, however, not well documented in the Coast Mountains, although it is fairly certain that the truncation of Cretaceous rocks in both the Interior Plateau, and in the Coast Mountains (Mathews, 1948) indicates an extensive old age erosion surface existed in the late Cretaceous or early Tertiary. In the interior of British Columbia the surface was doubtlessly a well developed peneplane --- the even upland surfaces are still very striking. Whether it also extended over the Coast Mountains has been the subject of considerable argument. Certainly the Coast Mountains exhibit no accordance of summits comparable to that of the interior. If the present summits are a reflection of the ancient surface, it must have had a local relief of 1,500 to 3,000 feet. Yet the distant skyline has a fairly even aspect that cannot be refuted in spite of a scattering of massifs rising above it. The difficulty of evaluating rates of erosion at different elevations makes any conclusion based largely on present summit heights highly speculative. It may be that the higher erosion rates acting on the higher peaks can produce general accordance, where none existed previously. Possibly, lack of accordance of peaks in a mountain belt is more demanding of an explanation than is their accordance.

The stronger development of the transverse direction in the Coast Mountains, and the longitudinal direction in the interior of the province justifies some comment. Normally subsequent drainage patterns are more extensively developed parallel to the major structures. Such is the case in the interior of the province, and in the past it was probably also true for the Coast Mountains. The mountain belt, however, appears to have been rising more or less continuously since the mid-Mesozoic, resulting in breaching of the controlling strata by erosion. Much of the area is now granitic and lacking in major structures. Thus the present drainage pattern seems in large part superposed on the granitic rocks. As erosion subdued the influence of the structure, the influence of the nearby sea increased and promoted development of the transverse drainage direction. Glaciation, subsequently, emphasized the result. But in the interior, where breaching of non-granitic strata has not been so pronounced the longitudinal direction still predominates (Photograph 1).

Peacock (1935, p.656) believed that the fjord pattern is controlled by the structure and jointing of the Coast Mountains, because of

> "the general coincidence of trends with those of the axes of the folds, strikes and contacts of dykes, veins and shear zones".

This conclusion is not corroborated in the Vancouver North area. Stereographic plots were made of both the joints and the dykes recorded over much of this region, but no predominant trend was revealed for either. It seems, however, that over a small area the joints occasionally show some consistency, but over areas of 100 square miles or greater, all possible directions occur in fairly equitable proportions. Yet it is probably best not to rely too heavily on the joint data obtained, since the number of joints at any one outcrop was frequently very high, resulting in the introduction of much insignificant data. Doubtlessly, the details in course of small streams are primarily joint-controlled, but overall trends, especially of the larger streams, appear to be independent of the jointing.

The area mapped shows in a rather striking manner the influence of nearby base level. The northern part of the area shows a predominant NW drainage trend, Eg. Seymour, Indian, Coquitlam Rivers, Pitt Lake, Stave River and Harrison Lake. To the south nearer Fraser River delta, the trends turn either to the southwest, the transverse direction, (Indian Arm, Pitt Lake, Alouette Lake, etc.), or, in disregard to all apparent structure, directly south, as in the case of Coquitlam, Stave and Harrison Lakes.

GLACIATION

The effect of the continental ice sheet on the Coast Mountains was very slight. The ridges are grooved along their sides and tops up to elevations of about 6,000 feet, but they have not been seriously affected. Very little rounding is found at high altitudes, although it is common along valley sides and lake shores. The lack of erosive energy of the continental ice sheet might be attributed to several factors, such as,

a) Small depth of ice overriding the ridges.

b) Lack of sheet movement over mountain ridges. I.e., the ice may have moved in the manner of valley glaciers in spite of its sheet-like extension, spilling out the fjords as in Greenland at present.

c) Short duration of the continental ice in the Coast Mountains.

It seems probable there never was an ice sheet moving across the coast mountains, and that it was rather in the nature of a large ice field, draining through the valleys and fjords. At times the valley glaciers leading from it may have become sufficiently thick to temporarily coalesce over the ridge tops, producing the slight ice grooves now visible on some. In a few instances, however, the ice, facilitated by appropriate jointing, smoothed the ridgetops (Photograph 3).

At lower elevations the effects of glaciation are quite pronounced. Between the south ends of Pitt and Stave Lakes, for instance major grooves and drumlin forms are common (Photograph 4). They trend nearly due south, in places cutting obliquely the low ridges. The effect is pronounced up to altitudes of 2,000 feet. In the region north of the photographs where the country is much higher and more rugged, ice grooves rarely appear on the air photographs. Minor grooves are, however, observed in the field, but invariably parallel to the major valleys. Ice contact features in the area are rather rare, except around the south end of

Alouette Lake, where some rather well-developed, if short, eskers are found. No distinct terminal or lateral morraines were noted in the region mapped, except for some minor ones at the mouths of some cirques. If they existed, they have been destroyed or buried beneath the tremendous thickness of outwash material now covering much of the Fraser delta region. The presence of ice shelf conditions during parts of the Pleistocene, as indicated in the delta by widespread glacial marine deposits, may also be responsible for the lack of morraines in the lower part of the Fraser delta.

There is no evidence that a large valley glacier moved westward down the present course of Fraser River. No west trending striae are found across the southern slopes of the mountains. The glacier which moved down Fraser canyon, however, must have been one of the largest valley glaciers in the province, but when it reached the delta, masses of ice moving off the mountains to the north seem to have turned it south.

All the major valleys, and most of the minor ones existed in the Coast Mountains prior to glaciation. These valleys have been widened and deepened by large valley glaciers. The result is a combination of "U" and "V" shapes. The valley bottoms are fairly flat in transverse profile. The lower parts of the valley sides are very steep, generally a series of cliffs. These steep walls rise in most cases to about 3,000 feet, then the slope suddenly decreases from about 60° to about 25°, producing a marked shoulder. The more gentle upper slopes appear to be of pre-glacial origin, while that below has been remodelled by ice.

Most of the minor tributaries are "V" shaped, with interlocking spurs, indicative of normal stream development. Their gradients are usually steep and relatively straight. In the larger valleys truncated spurs are fairly common, producing some of the more spectacular cliffs in the area.

Although the valley glaciers left distinctive topographical features very little evidence of alpine glaciation exists. Well-developed cirques are found only at the heads of fairly large valleys. The retreat of the ice in the Coast Mountains seems to have taken place quickly, and no lengthy period of alpine glaciation, so prevalent in the northern part of the province, lingered in the south. Nevertheless, in the high regions some remnant alpine glaciers still exist, and in rare cases, the heads of the long-extinct valley glaciers can still be found (such as the one at the head of Stave River).

In general glaciation made the mountainous regions more rugged and precipitous, with a negligible amount of rounding of the ridges. The most striking consequence of the ice are the numerous hanging tributary valleys with discordances of a 1,000 feet or more from the main troughs. Small insignificant streams often occupy valleys as large as those of the major streams; this is especially true of those streams flowing into the heads of the large fjords.

Till deposits are found covering most of the area. The valley sides and bottoms are generally thickly coated, but the upper parts of the ridges lack till, although erratics can be found on most of the ridge tops. Whether till also once existed on the ridge tops is dubious, for erosion is rapid on these areas and may well account for its absence. Numerous lake deposits of varved clays and fine silts are found in the larger valleys, the result of temporary damming during glaciation.

REGIONAL SETTING

If the rather arbitrary definition which terminates the Coast Range Batholith at the Fraser River is accepted, the thesis area represents a very small region lying in its southwest corner. To the south the area is bordered by the Fraser River delta, to the west by Howe Sound (a wide fjord), and to the north and east by the remainder of the Coast Mountain belt. The regional trend is northwest. Except around some widely scattered mineral properties little work has been done in the Coast Mountains. The regional geology of the interior of the Coast Range Batholith is at present unknown.

The results of the meager work available suggest, however, that non-plutonic rocks comprise a large proportion of the Coast Mountains. Of the 2,000 miles of coast line from Vancouver to Stewart, 680 miles or 32% is composed of non-plutonic rock. Perhaps the coast line is too marginal (in spite of its deep reentrant fjords) to be truly representative, but it is probable that more than 20% of the Coast Mountain belt is underlain by non-plutonic rocks. Although in the thesis area these non-plutonic rocks are chiefly volcanic, eugeosynclinal sediments such as greywackes, arkoses, limy argillites, etc., seem from the published data to predominate in the mountainous belt as a whole.

The plutonic rock of the Coast Mountains seems to be predominantly quartz diorite, followed in abundance by granodiorite, and next by diorite. Granite and gabbro are both rather rare, and occur only in relatively small bodies. Foliation in the plutonic rocks is not uncommon. Small inclusions amounting to about 2% of the plutonic rock appear to be scattered throughout.

GEOLOGY OF THE VANCOUVER NORTH AND COQUITLAM AREAS

GENERAL STATEMENT

More than 90% of the thesis area is underlain by plutonic rocks. Engulfed in them are several roof pendants, which are composed chiefly of granulites, with minor amounts of hornfels, fine-grained gneisses, quartzites, and lime silicates. These rocks are usually banded, and are characterized by medium and hotter mesozonal assemblages. They are tightly folded and steeply dipping. Some of these pendants are capped by a volcanic series (including minor intercalated sedimentary rocks) of andesitic flows, tuffs and breccias. These rocks give apparently conflicting evidence concerning their age relative to the granitic rocks. Conglomerate beds at the base of the volcanics usually contain a small percentage of plutonic boulders (most are volcanic), and yet these beds and the overlying volcanics may be partly feldspathized. The writer believes that these capping rocks were laid down contemporaneously with the very long period during which the plutonic rocks formed and evolved. Further evidence concerning this matter is presented later in the thesis.

Except where in fault contact with the granitic rocks, the pendant rocks usually grade into them through migmatitic zones of irregular width in which hornblende diorite predominates. In some places these zones are more than a mile wide, but more often they are restricted to widths of several tens of feet, and on occasion even less. The regional trend in the area is northwest but local trends fluctuate widely.

The plutonic rocks range in composition from nearly black gabbro to an almost maficless granite. As has been reported for the Coast Mountain belt as a whole, quartz diorite is the most abundant rock type, followed by grano-diorite and diorite. Near the bodies of pre-granitic rock, the plutonic rock tends to be poor in biotite and quartz, and rich in hornblende. Away from these bodies, the opposite tends to be true. In a general way, the plutonic rocks of the western third and of the south-eastern corner of the thesis area are hornblende-rich. This corresponds to the general distribution of the larger bodies of pre-granitic rock. The cores of the larger expanses of plutonic rocks are biotite-rich. The largest biotite-rich body is centered around Coquitlam Lake. Another occurs in the Capilano River watershed, north of the Lynn pendant. The proximity of this body to the pendant is unusual and is believed due to the fault which borders the Lynn pendant on the north east.

Throughout the area the plutonic rocks are exceedingly heterogeneous, especially those rich in hornblende. It is usual for small bodies of biotite-rich rock to be found amidst regions of hornblende-rich rocks, and vice versa.

Although the mafic minerals reflect the proximity of the plutonic rocks to pre-granitic rocks, potassium feldspar appears to show no such relationship. Consequently in choosing cartographic units, the ratio of hornblende to biotite was considered more important than the ratio between potassium feldspar and plagioclase. Therefore on the map the colour of the cartographic unit was determined by the mafic ratio, and the superposed line patterns by the feldspar ratio.

In addition to the large pendant bodies, the plutonic rock contains an almost universal scattering of small, fine-grained granulitic inclusions, averaging perhaps 4 inches in diameter. Some of these inclusions tend to occur in swarms unrelated to any major contact, yet it is rare to find an outcrop of plutonic rock within the area which shows no inclusions. The inclusions are most abundant in hornblende-rich rocks, and least abundant in those that are biotite-rich. The overall amount of inclusions is estimated as about 2% of the total area mapped as plutonic rock.

Dykes related to the volcanics which cap some of the pendants are found throughout the area. They number in the thousands. In age they are more or less contemporaneous with the orogenic period during which the plutonic rocks were formed.

Unconformably overlying the plutonic rocks south of the mountains are continental mid-Eocene beds, composed of sandstone, conglomerate and some shale. Cutting these Tertiary sedimentary rocks, and of distinctly post-plutonic age are dykes and flows of basalt. Within the mountainous area only about 1% of the dykes are composed of this basalt.

NON-GRANITIC ROCKS

GENERAL STATEMENT

As has been stated previously the pre-granitic rocks comprise less than 10% of the area. They occur in both large and small bodies generally isolated from each other by extensive areas of plutonic rock. The large bodies are termed "pendants" in this thesis. The term was first proposed by Daly (1906, p.336), in reference to a large patch of Chopaka schist in Similkameen Granite. The term carried implications of shape (a downward directed wedge), and of origin. Daly believed these blocks represented the lower portions of a downward projection of the roof rocks into the batholith, the upper portions having been removed by erosion, and the country rock between the pendants removed by magmatic stoping. The term "pendant" was actually derived from an element of Gothic architecture, somewhat similar in shape to Daly's theoretical structure. In this thesis, however, the term is used without connotation as to shape or to mode of origin, but simply as a reference to large bodies of pre-granitic rock isolated in plutonic rock.

Because of the complexity of tight folds and numerous faults, combined with heavy forest cover, it was not possible to correlate from one pendant to another (with one exception) on the basis of structure. Lithological similarities permitted some tentative correlation. No identifiable fossils were found within the thesis area.

In the thesis area the pendants are composed of near vertical, pre-granitic granulites. Some of the pendants, however, are capped by an assemblage of andesitic volcanic (and some sedimentary) rocks which are essentially contemporaneous with the formation and evolution of the plutonic rocks. They provide conflicting age relations with the plutonic rocks. In one place they may seem older, and in another, younger, than the underlying plutonic rocks. An unconformity is usually indicated between the pre-granitic and the capping rocks.

In the following descriptions of the individual bodies of non-granitic rock, the simple pendants are given first, then the capped pendants.

SIMPLE PENDANTS

LYNN CREEK PENDANT

The Lynn Creek pendant is roughly $5\frac{1}{2}$ miles long and $1\frac{1}{2}$ miles wide, the longer dimension northwest. It is fairly regular in outline except for a reentrant of diorite from the north which nearly separates the pendant into two parts.

LITHOGRAPHY

The rocks known to occur in the pendant include the following, in order of abundance.

1) Argillaceous rocks, including slates and knotenschiefer.
2) Porphyritic andesite.
3) Cherty lime silicate rocks.
4) Schistose hornfels.
5) Limestone, marble, and associated skarn.

Because of complex structure and heavy forest cover, no thicknesses could be measured, but the argillaceous rocks and the andesite comprise more than $\frac{1}{2}$ of the pendant, and are themselves about equal in quantity. The argillaceous rocks are found in the northwest part of the pendant, and the andesite in the southeast part. The other rocks, principally calcic types occur in the vicinity of the ore deposits along the central part of the southwest side of the pendant.

A brief summary of the pertinent data gathered from thin sections of the above rocks is given below.

1) Argillaceous rocks -

a) Slates - Comprising at least $\frac{3}{4}$ of the argillaceous rocks, the slates are extremely fine-grained rocks containing microlitic plagioclase, clay minerals, sericite and considerable carbonaceous matter.

b) Knotenschiefer - These rocks are essentially the same as the slates in the field and in thin section, but they contain small patches (about $\frac{1}{8}$" in diameter) of isotropic material. Some crystalline material is usually present in the centre of the patches, apparently albite. These "spots" comprise about 15% of the rock. Harker, in his well-known book "Metamorphism", believed that such spots in knotenschiefers represent glassy centres of recrystallization.

2) Porphyritic Andesite - The andesite was difficult to examine under the microscope because of intense alteration. The mafic minerals have been changed to chlorite and actinolite, and the plagioclase to a mixture of sericite and epidote. Originally they appear to have been normal calcic andesites, containing small ($\frac{1}{8}$" in diameter) phenocrysts of plagioclase, and some of hornblende. The original trachytic texture is seldom recognizable.

3) Cherty lime silicate rocks - These rocks are usually very fine-grained, and generally bedded. Some bands are very rich in quartz, and others are chiefly epidote and

pyroxene (diopside). Only in the coarser-grained bands can the minerals be identified with certainty. Phemister (1945) referred to these rocks as "calc-flinta" using Barrow's term for the finely banded lime silicates in the Devonian rocks near the Cornish granite.

4) Schistose Hornfels - This also is a fine-grained rock, with constituents averaging about .02 mm. The rock is composed principally of quartz and biotite, with a little plagioclase, potash feldspar and magnetite. The foliation is only weakly developed, and is more evident in the outcrop than in thin section. A small percentage of the plagioclase crystals are several times larger than the average grain size. These are amoeboid-shaped, inclusion-bearing porphyroblasts. It is possible that the grade of metamorphism is somewhat higher than the biotite would suggest since the rock was evidently (from the potash feldspar) high in potassium and low in calcium, retarding the formation of an amphibole.

5) Limestone, marble and associated skarn - All the limestone in the pendant is recrystallized, but the granularity varies considerably within short distances, apparently, as Phemister pointed out, without any direct relationship to the granitic contact. It may be a black limestone in one place and a few yards away, a white marble. Some of the limestone has been greatly

altered by siliceous metasomatism. These rocks are now skarns, and contain the galena and sphalerite which have attracted some economic interest to the area. The skarns are composed of numerous irregular bands differing in character. The types noted include diopside-plagioclase-vesuvianite, tremolite-dippside-garnet, epidote-hornblende-biotite, and garnetite. The grain size in the skarns averages about 0.5 mm, and ranges from 0.1 to 0.7 mm, calcite forming the largest crystals.

METAMORPHISM

The grade of metamorphism in the Lynn Creek pendant varies from the shales, which are virtually untouched, through the knotenschiefer, and the volcanics which are in the chlorite-actinolite stage, to the tremolite-diopside-garnet stage found in the skarns, an assemblage belonging in the medium or hotter mesazone.

STRUCTURE

The rocks in the Lynn Creek pendant are generally banded and highly contorted. The argillaceous rocks and the volcanics trend north west, but the banded lime silicates often run transversely, with trends ranging from north to northeast. The northwest trends of the argillaceous rocks are fairly consistant, and well-exposed on the high ridges near the northwest end of the pendant. Buckling of the beds and associated shearing is most evident near the ore deposits. It is possible that an unconformity occurs within the pendant between the argillaceous rocks and the lime silicates, but exposures could not be found in the critical areas to verify the supposition.

CONTACTS WITH THE PLUTONIC ROCKS

At no place is the actual contact exposed, although it is possible in several places to narrow its location down to a few feet. The northwest contact is almost certainly a fault. The contact, where it crosses the ridges is invariably marked by a gully, and the argillites, which appreach the contact very closely at the north corner of the pendant, show practically no metamorphic effects. The southwest contact is irregular in detail, but fairly sharp (not more than 10 feet in width). The grade of metamorphism near the contact is high, as represented by the skarns. The northwest and southeast ends of the pendant are deeply drift covered and no information is available concerning them.

UPPER SEYMOUR RIVER PENDANT

This pendant is located on the northeast side of the upper Seymour valley. Due to forest cover and heavy till deposits exposures are poor in this area, but the available outcrops indicate a considerable thickness of thick-bedded porphyritic flows with their matrix now altered to hornfels. Their total thickness is at least 2,000 feet.

LITHOLOGY

The typical rock in the pendant is a hornfelsized porphyry composed of matrix 50%, and phenocrysts 50%. The matrix is 85% plagioclase (An 29), and 14% olive-green biotite. The plagioclase crystals are irregular in shape, but more or less equidimensional, and average about .03 mm in diameter. Most of the biotite plates are about the same size, but locally much larger (approaching 1 mm). The biotite is restricted to the matrix material, and shows no preferred orientation. Associated with the biotite is a minor amount of magnetite and apatite. About $\frac{1}{2}$ the rock is composed of large (1 to 3 mm) plagioclase phenocrysts. The composition of the plagioclase is the same as the matrix plagioclase. The phenocrysts are subhedral, and irregularly embayed by the matrix material. In the phenocrysts are markedly euhedral plagioclase laths which are distinctly larger (.1 mm average diameter) than the matrix material, and are more calcic (An 32) than either the phenocrysts or the matrix plagioclase. These laths and the plagioclase phenocrysts which contain them are thought to represent the original texture of the rock. The matrix on the other hand is entirely recrystallized.

METAMORPHISM

The grade of metamorphism which these rocks reached is uncertain. Although green biotite is not usually considered a high temperature metamorphic mineral, the plagioclase seems to be too calcic to be epizonal. Also, the total recrystallization of the matrix into grains of considerable size suggests moderate temperatures. If one is justified in placing such a rock in a metamorphic grade, the cooler part of the mesazone is probably preferable. (However, as Misch (oral communication) has pointed out, green biotite is occasionally found in rocks of considerably higher grade.)

STRUCTURE

The structure of the pendant is not well-exposed, but the trends recorded are consistant, being 10 to 20 degrees west of north, and the dip is vertical. As seen on the map the pendant is cut in two by a narrow body of hornblende diorite. The pendant may, however, not be completely severed, near the river.

CONTACTS WITH PLUTONIC ROCKS

The southwest contact, although not exposed, is almost certainly a fault, marked by the Fanning Creek and the Upper Seymour River. The other contacts are sharp but complex in detail. The plutonic rock at the contact is a mixture of hornblende diorite, and hornblende quartz diorite. The plutonic rock is unusually porphyroblastic, especially northeast of the pendant where plagioclase crystals often exceed one inch in length.

MOUNT STRACHAN PENDANT

The best exposures of this pendant occur on the rather flat top of Mt. Strachan. It is composed of about 6,000 feet of finely banded hornfels, amphibolite, and schist. The pendant is greatly complicated by numerous basaltic dykes and sills, some of which are older, and some younger than the plutonic rocks. All the rocks in the pendant are dark (on the fresh surface) and practically aphanitic. They differ from one another in the degree of foliation, slightly in the shade of color, and in the texture of their weathered surfaces. Although most of these rocks contain a relatively high percentage of mafic minerals, they generally weather to light shades of grey and green.

LITHOLOGY

The great bulk of the pendant is composed of hornfelses, of which the two main types are described below. The two-types are interbedded and show no progressive change toward any contact. The amphibolites, described last, are characteristic of the migmatitic area lying east and south of the pendant.

1) Finely-banded Hornfels - In these rocks the individual bands seldom exceed an inch in width, though the bands themselves are commonly grouped into composite bands several inches to several feet in width. The fine-banded hornfelses comprise more than half of the pendant but the proportion cannot be determined accurately from the available outcrops. In hand specimen the rock is very fine-grained, and the darker bands are virtually black. The microscope reveals a rock composed of fine-grained, pale green hornblende (average dimensions, .05 mm by .007 mm), and clear, equidimensional plagioclase crystals (average size, .04 mm). The ratio of hornblende and plagioclase varies from band to band, but in overall total they are about equal. The plagioclase is usually untwinned. The refractive indices indicate a composition of sodic andesine. Amoeboid-shaped plagioclase porphyroblasts (average diameter, .6 mm) are scattered sporadically throughout the rock, and occasionally locallized in narrow stringers, seldom exceeding 1 mm in thickness. Porphyroblasts of hornblende of about the same size as the plagioclase also are present, but they are rather rare and they tend to be more brownish than the green hornblende of the matrix.

A small amount of granular quartz has been introduced along veinlets. Next to these veinlets the pale green hornblende crystals have been converted to olive green biotite plates about .5 mm long.

2) Medium-grained hornfels - This rock is black in hand specimen but far more granular (coarser) than the rock just described. The original rock appears to have been a basalt. Most of the plagioclase has recrystallized into irregular shapes, retaining in some cases twinning in the central part of the crystals. In places, however, the original trachytic texture is still recognizable. About half the rock is a bluish green hornblende in the form of irregular-shaped crystals, slightly altered to biotite. The plagioclase crystals, representing the original texture of the rock, are about An64, and the newly recrystallized grains are about An40. Some of the fractures in the plagioclase are filled with late albite. Magnetite makes up 1 to 2 percent of the rock.

3) Amphibolite - This rock is found with diorite and gneiss in the complex migmatite zone associated with the Strachan pendant. The rock is very dark, and fine-grained, although the chief constituents are recognizable to the naked eye.

Under the microscope the rock is found to be about 70% hornblende of a green to bluish green variety (average length about .6 mm, with maximum of about 3 mm). Only the smaller grains have regular crystal shapes, the larger ones are irregularly shaped. It is not a "sieved" hornblende, however, as even the larger crystals are almost entirely free of felsic inclusions . Plagioclase comprises the remainder of the rock. Some of it exhibits clear, rather euhedral, well-twinned forms (An35), but most of it is irregular in outline, untwinned, and partially altered to muscovite and a minor amount of albite. The rock contains only traces of magnetite, and no biotite.

In the field this rock is sometimes foliated, because of local shearing, but a true schist is rarely developed. Burwash (1918) stated that the rock on Mt. Strachan "is for the most part mica schist". Mica schist was not found by the writer anywhere in the vicinity of Mt. Strachan. It may occur somewhere in the migmatitic complex on Hollyburn ridge, or Burwash may have misidentified the schistose hornblende amphibolite in which the hornblende is characteristically black (megascopically) and shiny.

METAMORPHISM

The only minerals present in large quantity in the Mt. Strachan pendant are hornblende and plagioclase. The rock types listed represent only different proportions of the two minerals, and different textures. In some sections, believed to be sills, trachytic textures are still evident, others are completely recrystallized. The grade of metamorphism represented by medium andesine and hornblende in equilibrium is sufficiently high to have destroyed all original textures, consequently the rocks showing relict trachytic texture are believed by the writer to represent sills emplaced during the height of the metamorphic period or slightly later as seems possible from other evidence (see subsequent section concerning dykes). Thus the sills would have approached the temperature conditions of the contemporaneous metamorphism from higher temperatures rather than from lower temperatures under which original textures are usually destroyed. The result would probably be a flattening of the cooling curve which would destroy most of the original texture, but perhaps not all.

STRUCTURE

The attitude of the Mt. Strachan rocks is easily ascertained from the banding apparent in many of the outcrops. The general trend is slightly north of west, and the dip vertical. Locally, especially in the gneissose dioritic areas, the foliation sometimes becomes discordant with the overall trend. In general, however, the strike of the Mt. Strachan rocks is parallel to the smaller bodies of pregranitic rocks in the Caulfield and Horseshoe Bay areas.

CONTACTS WITH THE PLUTONIC ROCKS

Over a large area east and south of the pendant, the rock is migmatitic and often gneissose. This complex is mostly hornblende diorite, hornblende gneiss, and hornblende amphibolite in varying proportions. The different types are gradational into one another. The whole zone grades gradually into less contaminated, and rarely schistose hornblende quartz diorite. The contact to the north and west of the pendant is not exposed, but it is relatively narrow, and no complex migmatitic zone of appreciable width can be present. The northern contact may be a fault, represented as it is by a topographic gully. The western contact is concealed by the drift and forest cover of Cypress valley.

HORSESHOE BAY PENDANT

This pendant lies just north of Horseshoe Bay along the east shore of Howe Sound. It extends two miles along the shore and about $\frac{1}{4}$ mile inland. Whether the pendant is large or small depends on how far it extends under Howe Sound. This pendant is made up of several thousand feet of fine-grained banded gneisses, of which most are rich in hornblende, and some in biotite.

LITHOLOGY

1) Hornblende Gneiss - This rock which is by far the most common constituent of the pendant is very thinly banded. The bands range in width from less than a millimeter to about $\frac{1}{2}$ inch. Most of the rock is composed of fine-grained (average .2 mm) equidimensional crystals of plagioclase and quartz, the former predominating. The plagioclase is a calcic oligoclase, and forms occasional porphyroblasts, about 1 mm in diameter. Hornblende is

practically absent in the lightest bands, but comprises more than half the rock in the darker bands. The largest crystals in the rock are some elongated hornblende crystals which may exceed 3 mm in some mafic-rich bands. They are elongated parallel to the banding. Magnetite, associated with hornblende, usually makes up 1 or 2% of the rock. Biotite is generally absent, except as a minor alteration of hornblende.

2) Biotite Gneiss - The biotite gneisses are restricted to bands in the hornblende gneiss. The typical composition of these bands is medium oligoclase 40%, quartz 20%, orthoclase 30%, and biotite 10%; however, the ratios vary somewhat from band to band. The orthoclase is interstitial and has replaced some of the plagioclase. The average grain size of the rock is about .3 mm, with some of the biotite crystals exceeding 1 mm. The biotite plates are arranged parallel to the banding. Although some aspects of the plagioclase-orthoclase texture suggest that the orthoclase and biotite may owe their presence in part to hydrothermal solutions, the restriction of these minerals to single bands suggest differences in the original compositions of the bands.

METAMORPHISM

The mineral assemblage in this pendant is little different from the hornfels of Mt. Strachan and elsewhere in the map-area. The grade of metamorphism is thought to lie somewhere in the warmer part of the mesozone. These rocks differ from the hornfelses chiefly in grain size; they are considerably coarser, and in that respect are nearer to being plutonic rock. Except for the increased grain size, however, there is no evidence that these rocks reached higher metamorphic temperatures than did the hornfelses.

STRUCTURE

The rocks in this pendant apparently have a simple structure trending about 20° north of west, and dipping vertically to steeply north. This attitude is conformable to the trend on Mt. Strachan and at Caulfield. The thickness of the gneisses appears to be about 10,000 feet. However, isoclinal folding may be present, making this figure much too high.

CONTACTS WITH PLUTONIC ROCKS

Much of the eastern contact is with the Sunset Granite, and is very sharp. The contact with the granodiorite and quartz diorite around the southern end of the contact is not well-exposed, but appears to be more complex than that to the north. Probably a narrow migmatitic zone of several 10's of feet marks this portion of the contact.

TWIN ISLANDS PENDANT

The rocks comprising this pendant are found on Twin Islands in Indian Arm, on Bedwell Peninsula, and between these two places along the east shore of Indian Arm. Most of the pendant is made up of banded dark grey and dark green hornfels. Minor amounts of diopsidic quartzite and highly metamorphosed volcanic conglomerate complete the assemblage.

LITHOLOGY

1) Fine-grained Hornblendic Hornfels - These rocks are thinly banded, with individual bands ranging in width from hair-like stringers to ½ inch, forming in many places composite bands 6 inches to 1 foot in width. The dark bands are practically black when the mafic is hornblende, and grey green when it is diopside.

The most abundant rock is a fine-grained (averaging .05 mm) hornfels composed of 60% plagioclase (An30), 10% quartz, and 30% hornblende. In the dark bands the percentage of hornblende is higher, and in the light bands considerably less. The plagioclase is usually equidimensional, anhedral, untwinned and unzoned. The quartz has about the same habit as the plagioclase. The hornblende is fine-grained, pale green, and only moderately pleochroic. It forms flatly terminated crystals, generally euhedral, and about .05 mm long. The hornblende crystals are sufficiently well-orientated to give the rock a slight gneissosity parallel to the banding. Thread-like quartz stringers cut the rock in many places. Where these stringers cross hornblende-rich bands, the stringers become filled with a coarser-grained (.1 mm), olive green hornblende. This coarser mafic has also formed adjacent to the stringers where they cross the dark bands. Magnetite grains and veinlets are commonly found in the dark bands. Epidote and apatite occur sporadically in both light and dark bands.

Some sections of the above rock appear to have undergone some late low temperature hydrothermal alteration, which has clouded the plagioclase, and to a lesser extent, chloritized the hornblende. In these instances epidote is always present, and sometimes quite abundant.

Occasionally a feldspathic band will have numerous tiny plagioclase (An30) porphyroblasts in it (average size .1 mm). The bordering bands in these cases are unusually high in hornblende, giving the impression that they have been somewhat basified.

2) Medium-grained Hornblendic Hornfels -- Although its relative abundance could not be ascertained, medium-grained hornblendic hornfels is rather common in the pendant. The average grain size is slightly less than .1 mm. About 80% of the rock is a robust blue green hornblende. Although euhedral crystals are rare, these crystals are usually well-orientated parallel to the banding. The plagioclase (An33) is slightly more calcic than in the fine-grained hornfels.

Some plagioclase porphyroblasts, which are common in the rock, exceed 1 mm in length. Quartz is present in minor amounts. There is also a little orthoclase in the interstices, and a small amount of magnetite scattered throughout the rock.

3) Diopsidic Hornfels - Very similar megascopically to the above rocks is the banded diopsidic hornfels. It was found on the east side of Indian Arm, opposite Racoon Island. The diopsidic hornfels is a very fine-grained rock, with an average grain size of about .02 mm. Like the hornblende hornfelses, it is thinly banded. The felsic areas are chiefly plagioclase (An33) which comprises about 70% of the rock as a whole. About 5% of the rock is quartz. Fine-grained diopside granules make up the remaining 25%. These granules are about the same size as the plagioclase crystals, but are occasionally considerably larger, approaching 1 mm in length. Stubby, euhedral outlines characterize the diopside. The rock contains no calcite or wollastonite.

4) Diopsidic Quartzite - The last type, diopsidic quartzite, is also banded rock similar to the above. It is found only on the north end of Bedwell Peninsula, where it forms two narrow (20 and 30 feet) beds intercalated in the hornblende hornfelses. The quartzite is a light grey rock, and there is not much contrast in color between the dark and the light bands. About 70% of the rock is quartz which occurs in small (.01 mm) sub-rounded, poorly sorted grains. There has been considerable

recrystallization, but the texture still retains a distinctly clastic character. The larger quartz grains are well rounded. Approximately 20% of the rock is interstitial, faintly pink orthoclase. It is not in the form of distinct individual crystals, but in rather large irregular shapes, providing a kind of matrix for the other minerals. The remaining 10% of the rock is composed of diopside granules. They are about the same size as the quartz crystals, and have the same habit as they have in the hornfels. In very minor amounts, and scattered throughout, are grains of calcite and zoisite.

5) Volcanic Conglomerate - Along the shore of Indian Arm north of Twin Islands, a narrow (15 feet) bed of rather coarse volcanic conglomerate was found. It is a highly indurated rock, and the boulders do not ordinarily weather out separately from the matrix, and since they also do not differ much in composition from the matrix, the conglomeratic nature of the rock is easily overlooked. The conglomerate is composed of rounded pebbles and boulders which range in diameter from a fraction of an inch to about 6 inches. Both the boulders and the matrix are now hornblende hornfels like the surrounding rocks. Some of the boulders are porphyritic (plagioclase), and all appear to have been of volcanic derrivation. Because this rock is quantitatively unimportant, and appears to have no structural significance no thin sections were made.

METAMORPHISM

The mineral assemblages found in the rocks of the Twin Islands pendant include the following.

1) Plagioclase (An30)
   Hornblende
   Quartz

2) Hornblende
   Plagioclase (An33)

3) Plagioclase (An30)
   Diopside
   Quartz

4) Quartz
   Orthoclase
   Diopside
   Calcite

These mineral assemblages indicate a fairly high grade of metamorphism but the abundance of hornblende, and the lack of wollastonite in rocks with the bulk composition of 3) and 4) (especially the latter where free calcite and quartz in equilibrium with each other and with diopside), suggest a grade slightly less than the katazone. It is probable that this grade of metamorphism is the equivalent of that reached by the granulites of Mt. Seymour, and the Alberta Bay-Mt. Brunswick areas.

STRUCTURE

The thickness of rocks in the Twin Islands pendant is not accurately known, but unless the structure is considerably more complicated than is presently visualized, it is of the order of 5,000 feet. On the east shore of Indian Arm the general trend of pendant rocks is east-west, and the dips are nearly vertical but may dip either north or south. On Racoon Island and on Bedwell Peninsula strikes slightly west of north predominate. Possibly a fault lies somewhere between Twin Islands and the mainland, extending down Bedwell Bay. The rocks west of this line tend to more quartzose than those to the east.

CONTACTS WITH PLUTONIC ROCKS

On the north this pendant grades into a migmatite zone of diorite and hornfels, which in turn grades into a quartz diorite. The southern contact is not exposed on Indian Arm. On the hill west of Buntzen Lake the hornfels grades into a hornblende gneiss, then sharply changes to a hornblende granodiorite, which though structureless itself, contains near the contact bands of gneiss parallel to those in the main body of the pendant. At the contact, the plutonic rock is low in quartz, and is actually a monzonite. Quartz becomes visible within 100 feet of the contact. The contact across Bedwell Peninsula is not exposed.

GOLDEN EARS PENDANT BODIES

The Golden Ears pendant bodies lie on the east side of the sheet. There are three main bodies and numerous small bodies of pre-granitic rock, with intervening areas of migmatitic complex. One of the main bodies lies just east of the map-area. Hornfels is the principal pre-granitic rock in the area, forming all or the major part of all the pendant bodies examined. These rocks are usually very fine-grained, thinly banded, and locally slaty.

LITHOLOGY

The pendant bodies in the Golden Ears vicinity are composed principally of two types of hornfels, one rich in hornblende (the most abundant), and one poor in this mineral.

1) Plagioclase-Hornblende Hornfels - This rock is very finely banded, with bands often less than 1 mm wide. Most of

the rock is composed of calcic oligoclase in small crystals which average about .02 mm in diameter. Hornblende makes up about 1/3 of the rock. The smaller hornblende crystals, equivalent in size to the small plagioclase grains, are scattered throughout and show little preferred alignment. The larger hornblende crystals, however, are well orientated. As might be predicted, they occur in the bands where hornblende is most abundant, and have an average length of about .2 mm. Plagioclase porphyroblasts of about the same size are abundant in the more leucocratic bands. The rock is cut by numerous veinlets of fine-grained orthoclase.

2) Plagioclase Hornfels - This rock is light in color and in comparison with the preceding rock, the banding is very faint, although of about the same dimensions. The matrix of the rock is composed of a fine-grained (.02 mm), plagioclase (An30) granules. In this matrix are numerous amoeboid-shaped, tiny plagioclase porphyroblasts, averaging about .2 mm in diameter. Small green hornblende crystals, amounting to about 3% of the darker bands are scattered throughout the matrix, with some preference for the interstitial areas between plagioclase porphyroblasts. There is no preferred orientation of the hornblende, nor of the plagioclase crystals. About 10% of the rock is made up of comparatively large kaolinized plagioclase crystals, partly rounded, partly angular. They range from 1 to 2 mm in length.

In composition they are medium andesine, that is, considerably more calcic than the matrix. These crystals might be explained as relict phenocrysts from some sort of leucocratic andesite, but their origin is uncertain. Lenses and veins of granular quartz (.5 mm) are rather abundant in the rock. A minor amount of fine-grained pyrite is present, accounting for the rusty appearance of the outcrops.

3) Biotite-quartz Phyllite - This rock was found only in the pendant body lying just east of the map-area. It forms a bed about 30 feet thick. The rock is extremely fine-grained (average grain size, less than .01 mm). It is also thinly banded with band widths seldom exceeding 1 mm. Only the coarser bands contain determinable felsic constituents. These are mostly quartz grains and a minor amount of medium oligoclase. About 30% of the rock is composed of very fine-grained brown biotite, most of which is orientated parallel to the banding. About 10% of the rock is fine sericite. To complete the assemblage is a small amount of magnetite. In a few small lenses, the quartz crystals reach their greatest size of .1 mm. Although extremely fine-grained the rock appears to be almost wholly recrystalized.

4) Diopsidic Quartzite - This rock was found only in the most southern pendant body of the group, where it forms a bed at least 20 feet thick (limits not exposed). As in the preceding rocks the banding is very thin, and the average grain size very small (.01 mm). About 80% of the rock is

quartz. Small granules of diopside are disseminated thinly throughout the quartz, and concentrated, along with epidote and magnetite, in the darker bands. The rock contains, also, a small amount of zoisite, but no calcite or wollastonite. Although slightly finer-grained this rock closely resembles the quartzite found on Bedwell Peninsula in the Twin Islands pendant.

METAMORPHISM

The grade of metamorphism found in the pendant bodies in the Golden Ears district is comparable to that of the hornfelses of the Twin Islands pendant and elsewhere throughout the area. The grade represented by the diopsidic quartzite is probably in the higher grade portion of the mesozone, although the biotite phyllite is not typical of this grade.

STRUCTURE

The bedding in the three main bodies has a general northward trend but may vary 20° either way. The dips range from 45° east to vertical, with steep dips to the east being the most common.

CONTACTS WITH PLUTONIC ROCKS

No contacts in this area are exposed, but numerous outcrops of highly complex migmatitic rocks were found in the vicinity of the contacts (and on top of the Golden Ears ridge). It is probable that the contacts are complex zones of granulite, hornblende gneiss, and hornblende diorite of irregular width. The plutonic complexes of the Golden Ears area resemble those southeast of the Mt. Strachan pendant.

CAPPED PENDANTS

MT. SEYMOUR PENDANT

The non-granitic rocks on Mt. Seymour comprise a body 2 miles wide and slightly over 4 miles long. From the peak of Mt. Seymour to sea level along Indian Arm, these rocks are intermittently exposed through a vertical distance of about 5,000 feet.

The rocks capping the pendant include the following, in order of abundance: anorthothitic tuff 50%, andesite (usually slightly porphyritic) 35%, volcanic conglomerate 15%. Beneath this volcanic sequence the pendant is composed of quartzitic granulites. Their extent is unknown since they are largely overlain by the volcanic rocks.

The stratigraphic section of the rocks in this pendant is given below.

Porphyritic andesites Anorthothitic tuffs Volcanic conglomerate	2,000' approx.
Granulites	Thickness unkhown

LITHOLOGY

The more important details of these rocks are summarized below.

1) Granulites - These rocks are hard, dark grey, and nearly aphanitic in hand specimen. Usually they are banded.

The individual bands vary in width from a small fraction of an inch to several inches. Most of the bands are composed of plagioclase (andesine) quartz and hornblende, the ratios of the minerals differing from band to band. In other bands, quartz and biotite are the principal minerals, and plagioclase is present only in minor amounts. The greenish cast sometimes present in hand specimens, is caused by chlorite which occurs in stringers, and in the products of minor alteration of the mafic minerals. The mafic minerals are sometimes sufficiently well-orientated to give the bands themselves a slight foliation parallel to the banding.

2) Volcanic Conglomerate - This rock is well exposed only near the top of Mt. Seymour. It is composed of fairly large boulders, ranging in diameter from a fraction of an inch to over three feet, many exceeding one foot in diameter. The boulders make up about 70% of the rock, and are entirely of volcanic derrivation, except for about 1% which are composed of a chlorite (formerly hornblende) granodiorite, a plutonic rock fairly common north of the pendant. Many of the boulders and pebbles are anorthothitic tuff, similar to the overlying rock. Also present in quantity are boulders of andesite porphyry. The matrix of the conglomerate is a poorly sorted mixture of andesitic and anorthothitic breccia and tuff. The whole rock is very strongly indurated, and

the boulders do not ordinarily weather out separately from the matrix. Alteration by chlorite and epidote is very intense, and appears to be localized by the fault which separates the volcanic series from the plutonic rocks to the north. Many of the pebbles in the conglomerate are rimmed by epidote, and others have been wholly replaced by this ubiquitous mineral.

3) Anorthothitic Tuffs - The tuffs on Mt. Seymour are dark grey, or greenish grey in hand specimen. For the most part they are composed of extremely fine material, with even the larger fragments seldom exceeding $\frac{1}{8}$" in diameter. In thin section the tuffs are extremely difficult to examine because they are encumbered with the products of low temperature hydrothermal alteration. The larger plagioclase crystals have been converted to epidote and sericite, while the finer-grained material has been changed to a complex mixture of sericite and small felspathic grains. Determinations of anorthite content was feasible only on the larger plagioclase crystals. They are calcic andesine. For such dark rocks the lack of mafic minerals is surprising. Even chlorite patches which might represent destroyed mafic minerals are lacking. The only chlorite was found in the fine-grained matrix material, in the interstices among tiny sericite and plagioclase crystals. Although the lack of mafic minerals more or less compels the appellation "anorthothitic tuffs", it is possible that these

rocks were originally andesitic and that hydrothermal solutions have wholly leached them of mafic minerals. Aside from the hydrothermal alteration, there is no evidence that the metamorphism of the tuffs has passed the lowest grade.

4) Porphyritic andesites - These rocks closely resemble the tuffs in general appearance, but the place of the tiny fragments in the tuff is taken by plagioclase phenocrysts in the andesites. Generally these rocks are only slightly porphyritic, but in some places the phenocrysts are numerous and rather large. The calcic andesine crystals which comprise the phenocrysts average 1/16" in length, with a maximum of about ¼". The andesites are very hard rocks, and generally greenish grey, although purple shades also occur. Like the tuffs, the andesites have been altered, but not as intensely. The andesite matrix is a complex mixture of very small (nearly microlitic) plagioclase laths, having an almost fluidal type of trachytic texture, and slightly coarser granulitic material, composed principally of quartz. The quartz may have been introduced rather than indigenous. Also in the matrix is considerable kaolin, some chlorite, and minor magnetite. The plagioclase phenocrysts have compositions ranging from An_{35} to An_{40}. Originally there were also phenocrysts of hornblende, but these are now replaced by pseudomorphic patches of chlorite. Associated

with the chlorite is a minor amount of fibrous actinolite. Epidote is also present in most sections, and sometimes extremely abundant.

METAMORPHISM

The granulites at the base of the Mt. Seymour pendant have undergone medium grades of metamorphism. This grade of metamorphism is in marked contrast to the very low grade of the overlying volcanics, which have only been chloritized and sericitized, with a very minor amount of silicification.

STRUCTURE

The structure of the Mt. Seymour pendant is not wholly understood. The granulites are complexly folded, and are not sufficiently exposed to reveal details of their structure. They trend, however, in a general northeast direction, and are near vertical. The overlying volcanic series is made up of massive rocks whose attitude can be derived only from the outcrop pattern. The trend thus obtained is slightly south of west, with a moderate dip (perhaps 15°) to the southeast. Although it was not actually seen, an unconformity between the granulites and the volcanic series is strongly indicated.

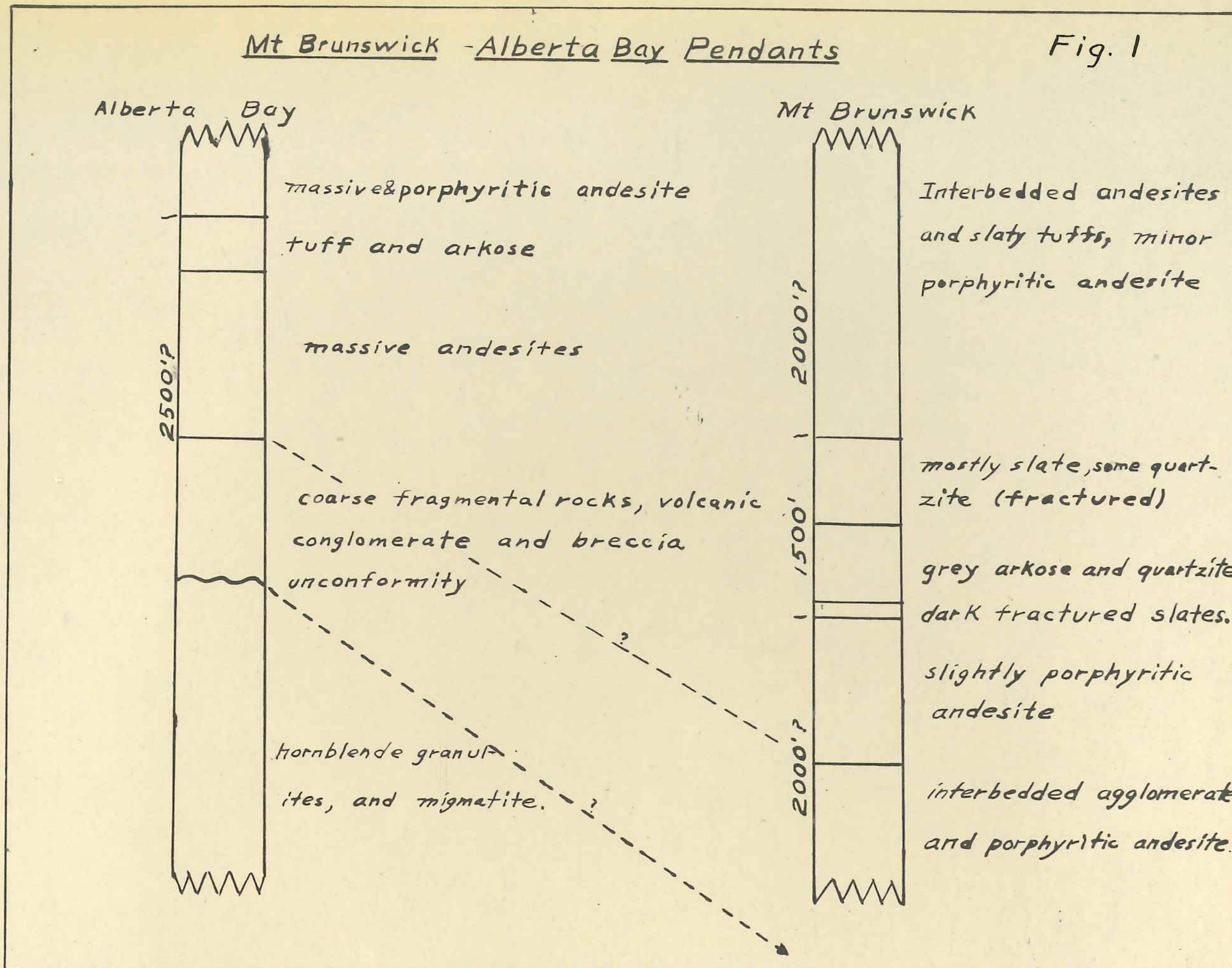
CONTACTS WITH THE PLUTONIC ROCKS

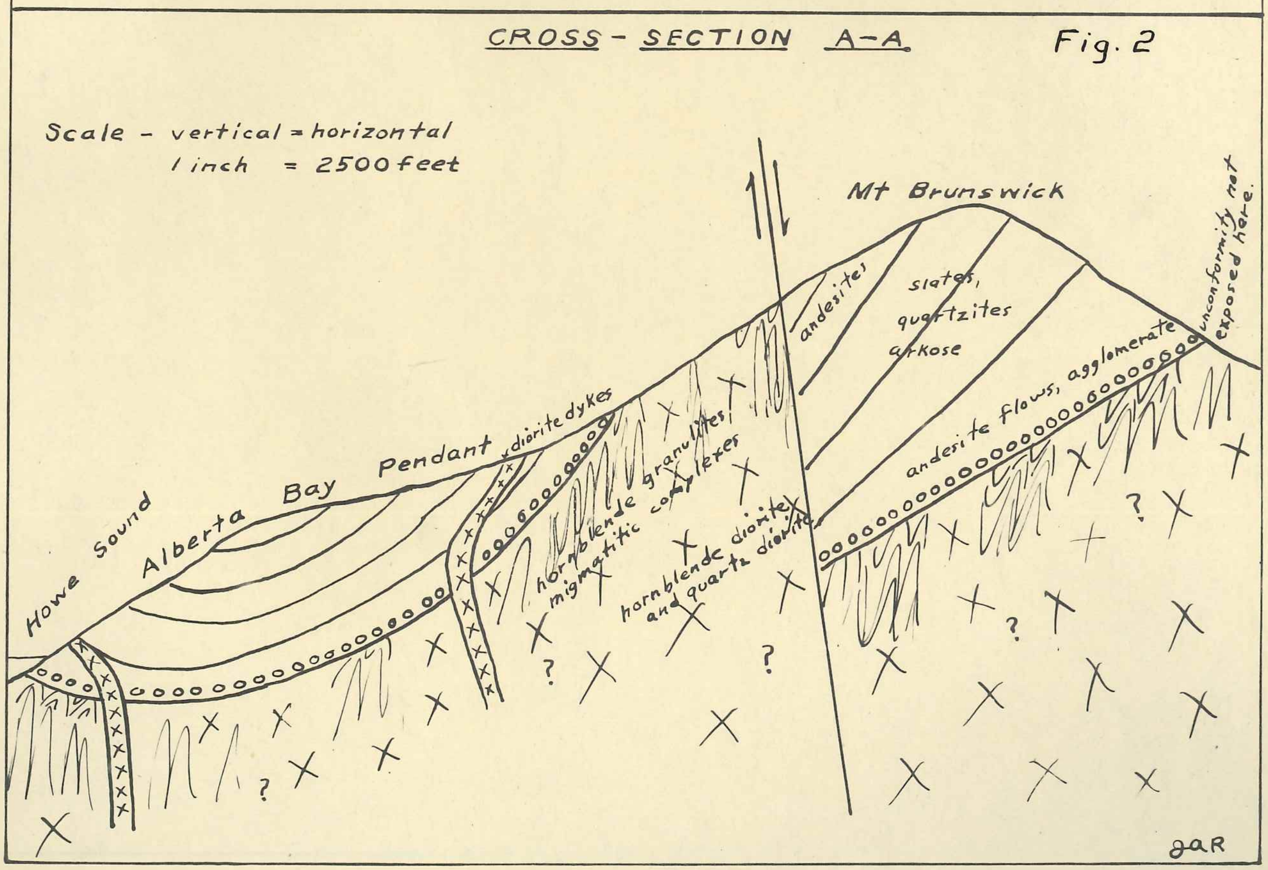
The contact between the plutonic rocks and the granulites appears, from a group of closely spaced exposures, to be irregularly gradational over a distance of several 100 feet. The plutonic rock into which the granulites grade is usually a fine-grained hornblende quartz diorite, differing from the granulites only in being coarser-grained. In traversing across the contact zone, one finds that the rock alternates many times between granulite and plutonic rocks, but there is no sharp division between the two.

The only contact reasonably well exposed between the volcanic series and the plutonic rocks occurs at the north edge of the pendant on top of the Mt. Seymour ridge. This contact is apparently a fault, and associated with it is a broad zone of extremely heavy epidotization. Since the fault lies in a small alluvium covered gulley no attitudes could be taken on it, but it seems to parallel the volcanic series in strike and dip steeply to the southeast. Along Indian Arm the contacts are obscured and complicated by numerous large dykes of porphyritic andesite dykes which are apparently feeders to the overlying flows.

MT. BRUNSWICK AND ALBERTA BAY PENDANTS

Along the east shore of Howe Sound, in the northern part of the map area are two closely associated capped pendants. They are separated on the steep slopes leading to the fjord by a narrow body of migmatitic rock which includes a mixture of granulite, hornblende diorite, and hornblende quartz diorite. The granulites in the two pendant bodies appear to be identical but they are not exposed in many places. The capping rocks of the two pendants are rather dissimilar in lithology, as shown in the two sections in Figure 1. Both caps are composed principally of andesitic flows and


Mt Brunswick -Alberta Bay Pendants
Fig. 1
Alberta Bay
Mt Brunswick
massive & porphyritic andesite
tuff and arkose
massive andesites
2500'?
coarse fragmental rocks, volcanic conglomerate and breccia
unconformity
hornblende granulites, and migmatite.
?
?
Interbedded andesites and slaty tuffs, minor porphyritic andesite
2000'?
mostly slate, some quartzite (fractured)
1500'
grey arkose and quartzite
dark fractured slates.
slightly porphyritic andesite
2000'?
interbedded agglomerate and porphyritic andesite


CROSS - SECTION A-A
Fig. 2
Scale - vertical = horizontal
1 inch = 2500 feet
Mt Brunswick
Howe Sound
Alberta Bay Pendant
diorite dykes
hornblende granulites, migmatitic complexes
hornblende diorite and quartz diorite
andesites
slates, quartzites arkose
andesite flows, agglomerate
unconformity not exposed here.
?
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pyroclastics, but the Mt. Brunswick cap contains in addition a considerable thickness of arkose, quartzite and slates which does not occur in the Alberta Bay cap. The sections in Figure 1 are postulated from the field data, but because of faulting and lack of exposures in certain places, small omissions of strata are probable. Error is especially likely in the more massive Alberta Bay pendant where bedding was found too seldom to determine definitely the structure.

LITHOLOGY

ALBERTA BAY PENDANT

1) Andesite flows - These rocks are bluish to greenish grey, and usually very fine-grained. In many places they are epidotized and pyritized. The massive andesites and the matrix of the porphyritic ones are usually microlitic. Even the andesites which appear to be massive in hand specimen are generally found to be microporphyritic in thin section. The plagioclase phenocrysts average about An43. Most of the plagioclase phenocrysts are euhedral, although highly sericitized and partly epidotized. Some are fractured, and the fractures have been filled with albite. The matrix is chiefly a complex mixture of chlorite, sericite, and microlitic plagioclase laths. Magnetite, although it amounts to only about 1% of the rocks, is always present. The mafic minerals have been completely destroyed and are represented only by chloritic pseudomorphs after hornblende (and pyroxene?). One section

examined contains, in addition to plagioclase, phenocrysts of quartz surrounded by reaction rims of mirmekitic quartz. The quartz was apparently foreign to the volcanic rock, and was probably plucked from the underlying granulitic and plutonic rocks.

2) Tuff and Arkose - Thinly bedded, water-lain tuff was found at an elevation of 1,500 feet below the north ridge of Mt. Brunswick. These beds are highly contorted, as if drag-folded between the more competent volcanic flows. Associated with the tuffs is a minor amount of highly feldspathic arkose, which is in part a breccia. The fragments (andesite) average about 3 mm in diameter, with some exceeding 10 mm. No thin sections of these rocks are available.

3) Coarse Fragmental Rocks

a) Volcanic Conglomerate - The conglomeratic nature of this rock is not always evident. The conglomerate consists of boulders of andesite (sometimes porphyritic) and a few of plutonic rock. The boulders are well rounded. The matrix has about the same composition as the andesite boulders, but is tuffaceous and more siliceous. The boulders average about 4 inches in diameter, with some exceeding 6 feet. This conglomerate is best exposed on the shore of Howe Sound near the south end of the pendant.

b) Agglomerate - These were recognized along the sea shore and on Bowyer Island, and in some parts of the conglomerate.

The fragments, composed mostly of porphyritic andesites, are angular and sub-angular and range from ¼" to 8" in diameter. The rock is typically highly epidotized, especially in the fragments, many of which have epidote rims, and some of which are entirely replaced.

4) Granulities - These rocks are best exposed between the two capping assemblages and are usually migmatitic. The granulites are hard, greenish grey, and fine-grained rocks, rather similar in hand specimen to some of the overlying andesites but distinctly more granular. Tiny grains of plagioclase are visible to the naked eye. Under the microscope the rock reveals a granulitic texture of quartz, plagioclase and hornblende, with an average grain size of about .04 mm in diameter. Considerable quartz and some plagioclase (calcic oligoclase) have recrystallized (or been introduced) in the form of amoeboid-shaped porphyroblasts, some of which exceed 1 mm in diameter. In most sections the quartz is slightly more abundant than the plagioclase. Although some large poikiloblastic hornblende crystals are present, most of the hornblende occurs in stubby somewhat rounded crystals, about the same size as those forming the feldspathic mosaic. The granulites are cut by numerous epidote veinlets. In bulk composition the granulites are much more siliceous than the overlying rocks. In the relatively few exposures of these rocks available, no

structure is revealed. But because of their similarity to the granulites on Mt. Seymour and elsewhere in the area, it is probable that an unconformity separates the granulites from the overlying volcanics.

MT. BRUNSWICK PENDANT

The rocks in this pendant include about 6,000 feet of volcanic flows, pyroclastics, quartzite, arkose and slates. As shown in the section (Figure 1), the flow rocks enclose the sediments above and below.

1) Lower Volcanics - These rocks include flow breccia, agglomerate, tuff, and a massive bed of blue-grey andesite. A volcanic breccia below Mt. Hanover contains fragments of volcanic material up to one foot in diameter, and is tentatively correlated to coarse agglomerate found in the Alberta Bay pendant. Some fragments show concentric banding, due possibly to heating, or hydrothermal alteration.

2) Sedimentary Rocks - The lower volcanic rocks are overlain by 1,300 feet of slate and 600 feet of quartzite. Virtually the whole of the peak of Mt. Brunswick is composed of slate. About 1/6 of the sedimentary rock is felspathic quartzite, most of which is interbedded with the upper half of the slates. The slate is dark, almost black, with fine bedding, often less than ¼" in width. The slaty cleavage is not well developed in most places, but where it is, it is parallel to the bedding. The slates are often highly fractured as

if more brittle than the surrounding rocks. For much of what has been called slate, "bedded argillite" would be an equally suitable term.

The quartzite is a light colored rock with a rusty weathering surface. The unit designated as quartzite includes many rocks that in thin section are seen to be fine-grained siliceous breccias. The rock is often made up of fragments (about $\frac{1}{8}$" in diameter) of fine-grained (average grain size about .06 mm) quartzose granulite, derived probably from the underlying granulites. The granulite fragments sometimes contain amoeboid-shaped porphyroblasts of quartz. The only mafic mineral is a little fine-grained biotite. The matrix comprises only a small percentage of the rock, and is extremely fine-grained (largely microlitic), with sericite being the only definitely identifiable mineral.

3) Upper Volcanics - These rocks are exposed on the northwest flank of Mt. Brunswick. They are massive, fine-grained andesites. The plagioclase is somewhat sericitized and in some places epidotized, but generally not much altered. Most of the mafic minerals, however, have been converted to chlorite giving the rock an overall green color. Minor slate and quartzite are interbedded with the andesite. Probably some of the andesite "flows" are actually sills, but contact details are lacking.

4) Granulites - These rocks are the same as those described from the Alberta Bay pendant.

METAMORPHISM OF THE ALBERTA BAY AND MT. BRUNSWICK PENDANTS

Although their lithology differs somewhat, the metamorphism of these rocks is essentially the same as for the Mt. Seymour pendant. In both cases the capping of the pendants represented chiefly by andesitic volcanics, have undergone only low grade metamorphism, resulting in the chloritization of the mafic minerals and the epidotization (and sericitization) of the plagioclase, and the pendants proper represented by granulites have reached a rather high metamorphic grade, where hornblende and calcic oligoclase are stable.

STRUCTURE AND AGE

No fossils have been found in either the Mt. Brunswick or Alberta Bay bodies. The slates on Mt. Brunswick can probably be correlated with the slates in the Britannia area, six miles to the north, although the two occurrences are separated by plutonic rocks. This, however, is not much aid in determining the age of the Mt. Brunswick slates since fossils are lacking also in the Britannia rocks. It might be possible to date the rocks by the following very circuitous route.

LeRoy (1908) in his reconnaissance of the coastal geology in southern British Columbia, originally defined the Britannia group as the middle member of a series of volcanic and sedimentary rocks occurring in various isolated areas along the western side of the Coast Range. Continuing northward to Texada Island, LeRoy placed the sedimentary and volcanic assemblage found at the southern end of the island into his Britannia group on the basis of a very general lithological similarity. McConnell (1914), working on Texada Island, renamed LeRoy's local representatives of the Britannia group, the Anderson Bay formation. These rocks underlie the Marble Bay formation which McConnell (1914), with rather poor fossils, determined to be Triassic or Jurassic. On this basis McConnell, with reservations, placed the Anderson Bay formation in the Triassic. If LeRoy's original correlation is correct, then the Britannia rocks might also fall in the Triassic period.

James (1929, p.24) in his report on the Britannia area, correlates the Britannia rocks with the Vancouver group on Vancouver Island, and arrives thus at a "Lower Mesozoic, probably in large part Upper Triassic" age.

Mathews (1947) correlates the Anderson Bay formation on Texada Island with similar rocks on the San Juan Islands in which McLellan (1927) found Upper Permian fossils.

If one assumes that the Anderson Bay beds are equivalent to those at Britannia, and those at Britannia equivalent to those on Mt. Brunswick, then the Mt. Brunswick rocks would be upper Paleozoic (per Mathews) or Triassic (per LeRoy, McConnell and James). Although the lithological correlation between Mt. Brunswick and Britannia is good, and in this writer's opinion, probably valid, the correlation from Britannia to distant Texada Island, is not well supported. The slates so prominent at Britannia and Mt. Brunswick are negligible in the Anderson Bay formation, and the limestone beds which are intercalated in the Anderson Bay rocks have no counterparts in the Britannia and Mt. Brunswick rocks. The present writer feels that the

Britannia and Mt. Brunswick rocks may be somewhat younger than those around Anderson Bay, because they (the former) appear to be essentially contemporaneous with the plutonic rocks, rather than entirely older as seems to be the case for the Anderson Bay rocks. In truth, of course, no conclusion is justified on the present data.

The examination of the capping rocks of the Alberta Bay and the Mt. Brunswick pendants indicated that they are closely related structurally even though different in lithology. The Mt. Brunswick pendant shows rather uniform trends of about 20 degrees west of north and dips of 30 to 50 degrees westward. The rock types cannot, however, be traced from one ridge to the next, suggesting that faulting or distortion is more extreme than is apparent. The Alberta Bay pendant is much more massive and attitudes are much harder to obtain. Those recorded indicate that the general trend is parallel to that on Mt. Brunswick. The dips are much gentler (almost flat) in the middle part of the Alberta Bay pendant than on Mt. Brunswick, but steepen to about 45 degrees east, on the coast. The section shown in Figure 2 seems to fit the available data, but it is nevertheless highly suppositional.

CONTACTS WITH THE PLUTONIC ROCKS

The contact between the granulites and the plutonic rock is a very complex migmatite in the only area it is exposed, between the two pendants.

The contact between the capping parts of the pendants and the granitic rocks is exposed only on the coast at the southern end of the Alberta Bay pendant. Here the volcanic conglomerate seems to lie on the granitic rock and contains granitic boulders, indicating that the volcanic rocks are younger than some of the plutonic rocks. However, the lower members of the capping rocks are locally felspathized, and is cut in several places by dykes of medium to fine-grained diorite. The capping rocks of these pendants are also folded into the plutonic rocks, although not nearly to the extent that the pre-plutonic granulites are infolded. That the capping rocks are essentially contemporaneous with the plutonic rocks is supported by subsequent data, especially that in the chapter on dykes.

CONCLUSIONS ON THE PENDANTS

The pendants in the thesis area can be divided into two groups, one simple, and the other capped.

Simple Pendants	Capped Pendants
Upper Seymour	Mt. Seymour
Mt. Strachan	Mt. Brunswick-Alberta Bay
Horseshoe Bay	
Twin Islands	
Golden Ears	
Lynn	

The simple pendants are composed chiefly of metamorphosed sediments, most of which have reached the middle or higher grade portion of the mesozone. The predominant rock types are hornblende-plagioclase granulites, hornfelses, and gneisses.

The capped pendants comprise two divisions. The lower divisions are similar in rock type and grade of metamorphism to the simple pendants. The upper divisions are composed of variable volcanic sequences, consisting primarily of calcic andesite flows, tuffs, and agglomerates. These rocks have suffered only low grade hydrothermal alteration resulting in epidotization, sericitization, and chloritization. The capping portions of the pendants appear to be separated from the lower portions by unconformities, but the difficulty of obtaining attitudes in the relatively massive volcanics, and the poor quality of the exposures makes the unconformities difficult to prove, although they are strongly indicated.

In general, the evidence indicates that the rocks comprising the simple pendants and the lower sections of the capped pendants are pre-granitic, while the upper sections, which have been only gently folded and slightly metamorphosed, are contemporaneous with the formation and evolution of the plutonic rocks. The volcanics in the upper sections probably represent the extrusive counterparts of the pre-Tertiary dykes (dealt with in a later chapter).

No fossils were found in any of the pendants or capping rocks, consequently nothing precise is known concerning their ages. Correlation between pendants on the basis of structure does not seem possible because of the difficulties of projecting structures across undetermined amounts of faulting in the intervening plutonic rocks. Tentative correlation on a lithological basis can be made with rocks of known age outside the thesis area, but little reliance can be placed upon it. The calcic andesites of the capping assemblages are similar to the Middle Jurassic volcanics that lie to the west of the lower end of Harrison Lake. The simple pendants and the lower portions of the capped pendants resemble lithologically parts of the Chilliwack Group found in the Hope Sheet, believed to be of Carboniferous and later age. The presence of limestone beds in the Lynn pendant supports this hypothesis.

THE PLUTONIC ROCKS

CLASSIFICATION

"Many and peculiar are the classifications that have been proposed for igneous rocks, ---------------. The trouble is not with the classifications but with nature which did not make things right." Thus Johannsen (1935, p.51) began his well-known treatment of the classification of igneous rocks. For plutonic rocks especially, it is so.

Johannsen incorporated into his classification much that was good and some that was bad from previous classifications, and infused the whole with the rigid order that was his nature. His classification has been subject to many modifications but in all, the essential principles of the classification remain. As an example of commonly used classifications the essence of his is summarized below.

Johannsen's classification is based, as for practical purposes it must be, on the quantitative mineralogy of the rocks. To classify a given rock by his method the following steps are taken, in order.

1. Quartz, more or less than 10% (2 divisions)
2. Ratio of dark to light minerals (4 subdivisions)
3. Ratio of Ab to An (4 subdivisions)
4. Ratio of potassium feldspar to plagioclase (4 subdivisions)
5. Ratio of mafic minerals to each other (4 subdivisions) for each pair of mafic minerals considered).

All the four-fold divisions are made using the 0-5, 5-50, 50-95, 95-100 system, except for the Ab-An ratio where 0-10, 10-50, 50-90, 90-100 is used to conform with the accepted plagioclase subdivisions.

Johannsen's classification is above all else, thorough. Many rocks whose existence is unrecorded, and occasionally extremely unlikely, find a place in his classification, often beside such plebian rock entities as grandiorite and diorite. His classification is essentially a product of the intellect rather than what it should be, a by-product of nature.

The most fundamental difficulty in classifying rocks lies in the fact that the most abundant of rock-forming minerals, feldspar, does not have a consistent composition, consequently a quantitative mineralogical classification, so necessary for practical field work, cannot accurately reflect the chemical composition of a rock. Authors of the better known classifications have chosen to emphasize one or more of the following ratios

a) Potash feldspar - Plagioclase
b) Alkali feldspar - Calcic feldspar
c) Albite molecule - Anorthite molecule

The first is primarily a rough estimate of the potassium - sodium ratio. Admittedly this ratio is sometimes important, but those elements are closely related and chemically very similar. They tend to react in similar ways, thus their ratio of abundance is a singularly insensitive detector of major differences between rocks. Even more frustrating is that this relatively insouciant ratio is not accurately measured, in as much as such prominent alkali carriers as the micas are ignored. The last two ratios listed measure more significant quantities, that is alkali-calcium ratios, but abandon the principle that the classification should be based on quantitative mineralogy. It serves no purpose to maintain that the arbitrary divisions of plagioclase represent individual minerals, since, even when coarse-grained, they cannot be distinguished in the field. Classifications based primarily on either the alkali-calcic feldspar ratio or the albite-anorthite molecule ratio seem to be peculiar hybrids of compromise, difficult to use in the field, and often misleading as indications of the chemical composition of plutonic rocks so classified.

In large plutonic areas, such as the Coast Mountains of British Columbia, the amount of statistical balancing required to determine the average Ab-An ratio for an average-sized plutonic unit of normal heterogeneity is enormous. Theoretically one should

1) Average all the outcrops within the body to determine which one is typical.
2) Average the different specimens obtained from the typical outcrop, and determine which is typical.
3) Determine the typical thin section from the typical specimen.
4) Determine the typical crystal from the typical thin section.
5) Determine the average Ab-An ratio of the zones of the typical crystal.

A more efficient alternative method is to determine Ab-An ratios of a large number of crystals from a large number of sections representing many points within the plutonic body in question. But, regardless of the method used, it is very arduous, and expensive to determine average Ab-An ratios, and in the end their value is dubious.

Most classifications assume that certain mineral constituents are not important. The assumption appears to be based chiefly on the fact that these minerals are not so abundant as the feldspars, rather than on the basis of experimental mapping. Far more unsound is the assumption that the minor minerals vary in accordance with certain ratios determined from the feldspars as dictated by certain physical chemistry laws applicable in the assumed igneous genesis of the rock.

The most neglected minerals are quartz and the mafics. For instance, quartz can vary from 10% to 80% in a plutonic rock which for feldspathic reasons must be called a granodiorite. Such a variance should not be ignored as being of no significance, not at least without considerable explanation. The mafic minerals make a parallel case. In virtually all large plutonic bodies, the important mafic minerals are hornblende, biotite and rarely pyroxene. The ratio of these minerals to the leucoratic minerals, and to each other must be incorporated into the classification if it is to prove useful, for when this is not done, the ferro-magnesium elements find virtually no expression.

Johannsen attempted to allow the mafic minerals some expression but his method was ineffective. First, in the matter of the ratio between mafic and leucocratic minerals, he has only one division covering percentages from 5 to 50. This division includes well over ninety percent of all plutonic rocks. Secondly, the matter of ratios between different mafic minerals, is relegated to the last step in his classification procedure. When one classifies a rock, according to his system, one arrives at a name for the rock on the fourth step, not the fifth (which considers the inter-mafic ratios). The mafic minerals play little part in determining the rock names because Johannsen justifiably wished to retain well-established rock names (granite, diorite, etc.), which regrettably were defined and redefined with little regard to the mafic minerals. To have employed the fifth step of his classification as rigorously as he applied the other steps would have necessitated renaming or redefining many common rocks. Johannsen realized that the primary purpose of a classification is to group rocks not name them, although in certain instances he seems to hold the principle in abeyance. Rather than eliminate the fifth step of his classification all together, Johannsen suggested that some such cumbersome terminology as "Hornblende-bearing biotite granite" might be used. Needless to say, it rarely has been, and he, himself, does not refer to the matter again.

Because of the heterogeneity of large plutonic bodies it is not practical to map them on the basis of selected thin sections. Consequently any classification which does not meet the requirements of the field geologist is largely useless even in a laboratory, since the material must come from the field, and its associations there are of the utmost importance. Many classifications for the field worker have been proposed ranging from the absurdly complex C.I.P.W. classification which Johannsen states "can hardly be improved" (Johannsen 1939, p.55), to gross over-simplifications designed for specific purposes. The field geologist is tempted to, and often does, distort classifications made for microscopic work into mutilations more or less usable in the field. Unfortunately when he returns from the field with the resultant map, he is reluctant to abandon his field classification and tends to apply it to his microscopic work. This is unsatisfactory, but not without some justification, for he cannot remap the area from his thin sections.

The underlying theme in many classifications is that they be in some manner related to the genesis of the rocks classified. This is probably desirable, but it is the ultimate goal, and cannot be applied until the genesis is known. As was learned by the author in the field season of 1949, and as is adequately shown by the preliminary map of Vancouver North area (Armstrong, 1950), it is very difficult to determine the origin of a batholith, if one uses a classification based on one of the contending theories. This applies particularly to the commonly used classifications of plutonic rocks, which are based on the magmatic theory to the extent that the mafic minerals and quartz are largely ignored, the assumption being that these minerals should not vary to any great extent independently of the feldspars if the rocks evolved from a melt.

The classification used in this thesis is based on the following facts,

1) Grouping of the plutonic rocks primarily on the basis of potash felspar to plagioclase produced a meaningless map in the Vancouver North area.

2) It is obvious in the field that hornblende-rich rocks are associated with hornblende-rich rocks, and biotite-rich rocks with biotite-rich rocks regardless of changes in the potash feldspar-plagioclase ratio. Thus a hornblende granodiorite is more likely to be associated with a hornblende diorite, than a biotite granodiorite.

3) It is possible in the Coast Mountains to distinguish
    a) potash feldspar from plagioclase
    b) hornblende from biotite
   but not, of course, the different types of plagioclase.

and on the following principles,

1) The classification must be primarily for field work.

2) All easily distinguished components should be recognized as factors influencing the grouping of the rocks.

3) The classification must be independent of any theory concerning the genesis of the rocks.

In practice it should be possible, once an area has been examined, to map it on the basis of any variable determinable in the field. For instance, it should be possible to base the cartographic units simply on the abundance of quartz, or on the biotite-hornblende ratio, or on the potassium feldspar-plagioclase ratio, or on any variable which might prove significant. In this thesis emphasis is placed on the biotite-hornblende ratio because it proved important in the field and it is felt that it provides an estimate of the potassium-calcium ratio, and that this ratio, even though roughly estimated, is more significant (because of the dissimilarity of the elements involved), than is the ratio of potassium to sodium-calcium, derived from the feldspars. In the intermediate and more acid plutonic rocks the latter ratio is chiefly a measurement of the potassium-sodium ratio, an ephemeral ratio not obviously significant.

The classification used in this thesis is presented in Figure 3. For the most part it is restricted to the plutonic rock found in the thesis area, but other fundamental plutonic types are included. It is doubtful whether such rocks as biotite diorite, and biotite gabbro occur anywhere, yet they are included to fill in two otherwise conspicious gaps.

A typical rock found in the thesis area is a medium-grained, hornblende-biotite quartz diorite, containing

Plagioclase An45	65%
Hornblende	10%
Biotite	6%
Quartz	20%
Minor minerals	2%

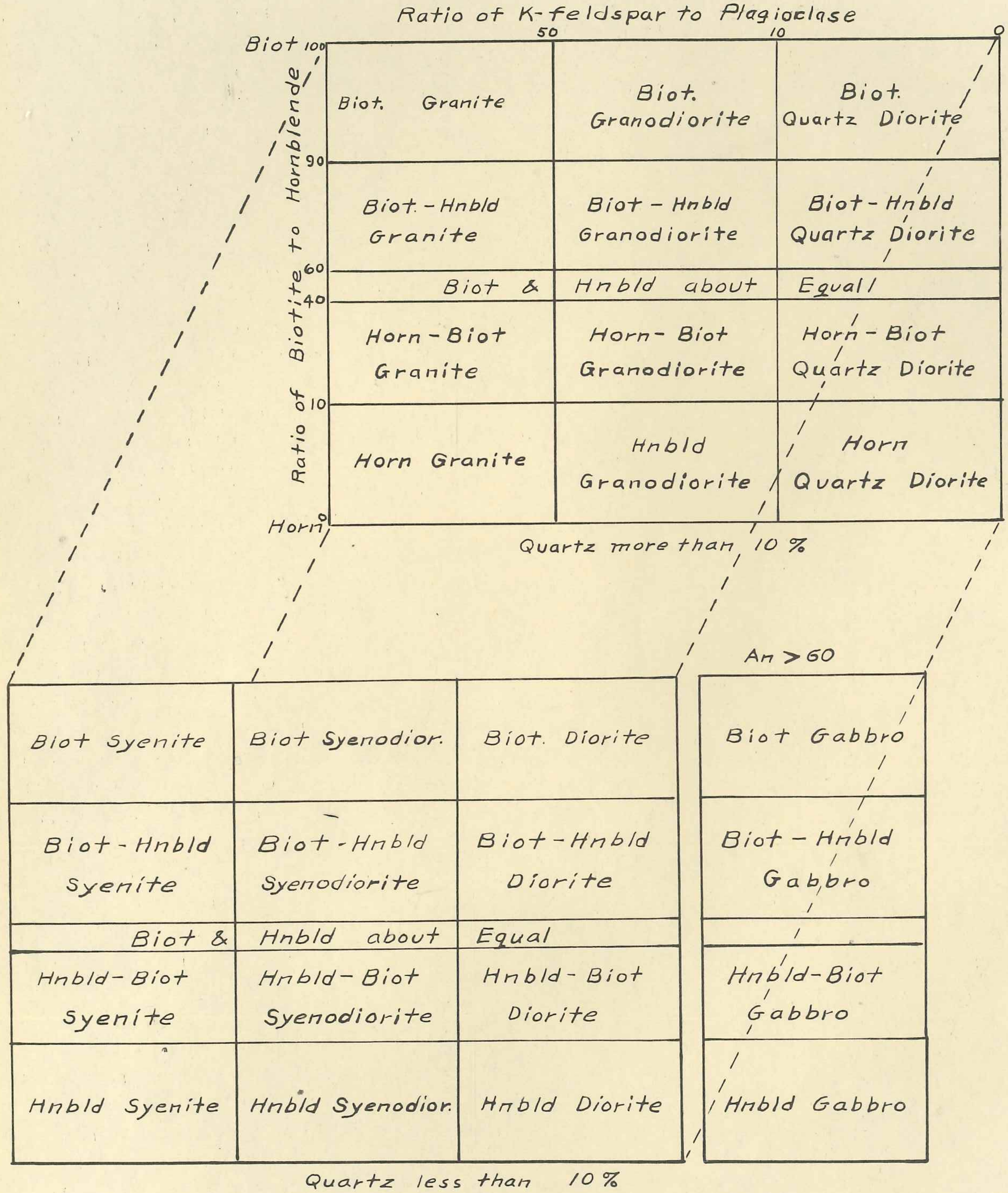
This rock would appear in the field notes as a mg 2/2 H-b Qtz d. The numerator of the fraction refers to the mafic class, and the denominator to the quartz class.

As another example, the following rock, a mg-cg $\bar{2}/3^{-}$ B-h gd, might be considered. This would be interpretated as a medium to coarse-grained granodiorite, containing approximately 10% mafic minerals, with biotite predominating over hornblende, and about 35% quartz. The term granodiorite implies a certain potassium feldspar-plagioclase ratio. Thus all the major variables obvious in the field are taken into account and readily noted (this of course does not include extraneous features such as foliation, inclusions, jointing, etc.). The system was developed in the field, and found to be very practical in the Coast Mountains. It is also applicable with little modification to undisputed metamorphic rocks, providing they are sufficiently coarse-grained.

One of the practical advantages of the system is that it counteracts a tendency to omit recording data which appears insignificant. This tendency is rather strong when mapping large areas of plutonic rock, where the overall picture is never clear until thousands of stations have been made and statistically balanced.

Another advantage is that, once an area has been examined one has the option of basing the major cartographic divisions on any one of many ratios. A few such ratios are: the potash feldspar-plagioclase ratio (the most commonly used ratio), the mafic ratio (used in this thesis), and the mafic-felsic ratio (essentially the mafic class), but many other combinations are possible. One can choose the ratio which appears most significant on the basis of experimentation. It is not wise to choose this ratio, before going into the field, which in effect is what is done when the common classifications are used.

Figure 3 Plutonic Rock Classification



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PLUTONIC ROCK CLASSIFICATION

In the table opposite, the gabbros have been set aside from the other plutonic rocks, although for most practical purposes they can be combined with the diorites. In the thesis area, the only gabbro represented is hornblende gabbro. This is the common gabbro of large plutonic areas and little resembles the pyroxene gabbros of distinctly magmatic origin. Probably the only criterion available for distinguishing hornblende diorite and hornblende gabbfo, which are essentially di-mineralic rocks, is some arbitrary anorthite content. An60 has been used in this thesis, but the type of plagioclase does not serve as a distinguishing feature in the field. In practice, it was found that when the plutonic rock was coarse-grained and the mafic content 50% or more, the anorthite content almost always exceeded An60, consequently such rocks were mapped as gabbro. Occasionally some rocks mapped as hornblende diorites proved to have more than 60 percent anorthite, although they were not coarse-grained nor did they contain the minimum 50% mafic. Since the anorthite content may fluctuate considerably within a few feet in the hetero geneous plutonic rocks of the thesis area, the field name was allowed to prevail.

In the field mapping the plutonic rocks were further subdivided on the ratio of mafic to feldspathic minerals, as shown. This results in mafic classes which are attached to the rock name as pre-fixes. Quartz is accommodated in an identical manner, and the quartz classes are subdivided at the same percentage as the mafic classes. In this way a prefix fraction is formed with the mafic class as numerator and the quartz class as denominator.

Mafic Class	Percent Mafic
	0%
1-	1
1	3
1+	5
2-	15
2	25
2+	30
3-	40
3	50
3+	70
4-	90
4	100

When pyroxene occurs, it is combined with the hornblende, never with the biotite.

MEGASCOPIC CHARACTERISTICS AND FIELD RELATIONSHIPS OF THE PLUTONIC ROCKS

GENERAL STATEMENT

The general features of the plutonic rocks in the thesis area are summarized under the following groups.

Complexes
Hornblende (only) plutonic rocks
Hornblende-biotite " "
Hornblende = Biotite " "
Biotite-hornblende " "
Biotite (only) " "

Under these groups, subdivisions are made, where applicable, on the basis of the potassium feldspar-plagioclase ratio, producing such sub-headings as quartz diorite, granodiorite, granite, etc.

The individual bodies of plutonic rock which appear as cartographic units on the map are treated in some detail in a Geological Survey of Canada memoir which is in preparation. So many of the features of the plutonic bodies are repetitious, that it was considered advisable to remove these descriptions from the thesis and to replace them with a summary of all the important features pertaining to each <u>type</u> of plutonic rock.

In order to determine the average rock of the thesis area, the outcrop areas of the various rock types were measured. Although the percentages are strictly valid only for the 500 square miles within the thesis area, they were found to check fairly closely with the percentages in the 2,000 square miles mapped in the adjacent regions. As was expected, the two most abundant rock types are hornblende-biotite quartz diorite, and biotite-hornblende quartz diorite, with the former somewhat exceeding the latter. The relative amounts of each rock type are listed below.

Pendants, simple	4.6%
" , compound	3.4%
Hornblende diorite, gabbro, and complexes	16.5%
" quartz diorite	5.8%
" granodiorite	3.1%
" granite	1.6%
Hornblende-biotite diorite	1.6%
" " quartz diorite	22.0%
" " granodiorite	12.2%
" equals " quartz diorite	3.2%
" " " granodiorite	.4%
Biotite-hornblende quartz diorite	16.1%
" " granodiorite	8.7%
Biotite granodiorite	.1%
Biotite granite	.7%

If all the above rocks were homogenized, it is estimated that the resulting rock would have the composition of a hornblende-biotite quartz diorite containing a small amount of potassium feldspar. This composition falls well within the likely limits of composition of a large geosynclinal assemblage containing argillaceous sediments, and andesitic volcanics, with interbedded, minor limestone and arenaceous sediments. Judging from the known exposures of pre-granitic rocks in the Coast Mountain belt, this is not an improbable assemblage.

COMPLEXES

Nearly all the plutonic rocks in the Coquitlam map-area are heterogeneous, but some are so extremely complex that they warrant separate treatment. These complexes are composed of both pendant and plutonic rock in varying proportions, and represent the most common intermediate stage between large bodies of pre-granitic rock, and plutonic areas.

The complexes are commonly adjacent to large pendant bodies, but only rarely entirely surround them. Yet the majority of the complexes are not closely associated with any pendant, and are often isolated in extensive areas of plutonic rock.

The rocks comprising the complexes are predominantly plutonic except for certain contact migmatites along the edges of some of the pendants. In the map-area this plutonic material is invariably rich in hornblende. In fact, hornblende is often the only mafic mineral present. Biotite tends to appear when the amount of quartz present is considerable.

As implied by the word complex, these areas are difficult to describe, not only because they are so heterogeneous within themselves, but also because they differ rather widely from one to the other. In the Coquitlam map-area there are a half dozen complexes of appreciable size, and many smaller ones. Probably the most typical complex in the area is the one associated with the Mt. Strachan pendant. In constitution it is like the other complexes but its position adjacent to a pendant, although not uncommon, is not typical. The complex includes about six square miles of wooded mountainous terrain east and south of Mt. Strachan pendant. At least 10 percent of the complex is made up of irregularly shaped bodies of hornblende amphibolite, and hornblende granulite. They are generally small, several feet in diameter, but some are several hundred feet in diameter. Their distribution throughout the complex is sporadic, with a tendency to localize in clusters. No general increase in the number of inclusions is apparent as the pendant is approached, except for a narrow zone right at the contact. Many of the inclusions are schistose or banded.

into which it grades, except for a much coarser grain-size, and some basification by increased hornblende.) The contacts between the leucocratic vein material and the dark country rock seem sharp from a distance but when closely inspected, are gradational. There is no evidence of any movement or dilation of the dark rock.

The complexes have no distinct contacts with the adjacent plutonic rocks, but merge gradually with them.

The complexes which are not associated with any pendant are thought to represent those pendants which were last to lose their identity, and were only incompletely converted to plutonic rock before "plutonism" in the region ended.

PLUTONIC ROCKS CONTAINING HORNBLENDE AS THE ONLY MAFIC MINERAL

The most common plutonic rock containing hornblende as the only mafic mineral is diorite. Nevertheless, other types occur. Within the map area hornblende gabbro, hornblende granodiorite, and even hornblende granite are found.

The hornblendic plutonic rocks differ little from those designated as complexes, except that they contain less non-granitic rock than the complexes. Yet these rocks are very heterogeneous. There is no consistancy in grain size, or in the ratio of feldspathic to dark minerals. Although, on the average, diorite has a higher percentage of mafic minerals (mafic class of 3 is typical) than the average quartz diorite, granodiorite or granite, some diorites are so low in mafic minerals that they approach anorthosite. At the other extreme, the diorite may approach an amphibolite.

A parallel situation exists in the variation in grain size. It may be so fine that the diorite must be called a granulite, or so coarse that a gabbroic rock results. In this connection it should be pointed out that within the area, the coarser the grain size of a hornblende-plagioclase rock, in general, the more calcic is the plagioclase, and the greater the percentage of hornblende. Thus, when the grain size of a diorite increases, as it does usually in a perfectly gradational manner, the rock name often must be changed to gabbro.

The hornblende diorites are often porphyroblastic, containing large porphyroblasts of plagioclase, or less commonly of hornblende.

The spacing of the jointing varies more or less with the grain size of the diorites. If they are medium-grained or coarser, the jointing tends to be widely spaced (2 to 4 feet); but if the grain size is fine, the jointing tends to be closely spaced ($\frac{1}{2}$ to 1 foot). The close-spaced jointing resembles that of the pre-granitic hornfelses and granulites, and since weathering characteristics are also similar, it is frequently impossible to separate pendant from plutonic rock by examining only the weathered surface.

Most of the hornblendic plutonic rocks, including most of the hornblende diorite, is not foliated. Yet hornblende diorite is more often foliated than perhaps any other plutonic rock type. This foliation, however, is seldom extensive, and usually sporadic.

Inclusions of pre-granitic rock are more common in hornblende diorite than in any other plutonic rock in the map area. They average about 5% of the rock in the diorites, as contrasted to 2 to 3% for all the plutonic rocks in the area.

Fluctuations in the amount of quartz result in the diorites grading locally into quartz diorite. Typically, a hornblende quartz diorite is low in quartz. This is also true for the hornblende granodiorites and hornblende granites. In all, the amount of quartz seldom greatly exceeds the minimum required for these rock names (10%).

The hornblende rocks are perfectly gradational from hornblende gabbro, through hornblende diorite, hornblende quartz diorite, and hornblende granodiorite, to hornblende granite. The characteristics of the intermediate rocks are also intermediate between the diorites, already described, and the granites whose description follows.

The hornblende granites result when sporadic fluctuation of potash feldspar, bring the percentage of this mineral above 50% of the total feldspar content. Only rarely are the minimum requirements exceeded. The grain size of the hornblende granites is variable like that of the diorites, but less widely so. On the average the granites are coarser than the diorites. The typical granite is medium to coarse-grained, and the typical diorite is medium to fine-grained. These are, however, broad generalizations, and one finds no difficulty in locating a specimen of diorite which is coarser than one of granite. Probably the greatest single difference between the hornblende granite and the hornblende diorite is in the percentage of hornblende in each. The granites are typically very poor in mafic minerals (usually less than 5%) resulting in a mafic class of about 1, in contrast to 3 for diorite. Inclusions are numerous in the hornblende granite (3%), but not nearly as numerous as in the diorites. They also tend to be smaller, many being only an inch or two in diameter. Within the area mapped the granite itself was never found to be foliated. Occasionally, however, mafic rich bands of hornblende diorite, several inches wide and several feet long, are found in the granite. It is not unusual to find hornblende diorite associated with hornblende granite, but never, to the writer's knowledge, with biotite granite.

HORNBLENDE-BIOTITE PLUTONIC ROCKS

These rocks contain both hornblende and biotite, but hornblende is predominant. Within the map area these rocks comprise bodies of diorite, quartz diorite, and granodiorite. No distinct bodies of hornblende-biotite gabbro, or hornblende-biotite granite were found, although these types do occur as local variations of the hornblende gabbro and the hornblende granite respectively.

Diorite

Hornblende-biotite diorite is, within the area, normally a very heterogeneous rock. With local increases in quartz, the diorite grades frequently into quartz diorite. Inclusions are numerous, averaging between 4% and 5%. For small areas, however, any amount from 3% to more than 30% may be present. The mafic class is typically about 2+, with a range of 2 to 4-. Biotite is extremely variable in abundance. It fluctuates from almost zero to equality with hornblende. These fluctuations tend to parallel those of quartz, but not necessarily so. Although biotite is the subordinate mafic, it often forms large crystals contrasting with the tendency of hornblende to be rather fine-grained. Most of the hornblende-biotite diorites are medium-grained, or slightly finer. Rarely, they are coarse-grained, and where they are, biotite is practically eliminated. The diorites are frequently laced with leucocratic feldspathic veins. Although most of the diorite (and most of the other plutonic rocks in the thesis area) is unfoliated, foliation of local extent is found. The diorite body with the best-developed foliation borders the Crocker Island granite on the northeast. The major occurrences of hornblende-biotite diorite in the area, besides the one just mentioned, include a body east of Widgeon Creek, and several on the northeast side of Pitt Lake. The diorite grades into hornblende diorite, and into hornblende-biotite quartz diorite. Where the hornblende-biotite diorite is in contact with biotite-hornblende quartz diorite, there is an intermediate rock, a hornblende-biotite quartz diorite, but it is generally too narrow to map on the scale used.

Quartz Diorite

Hornblende-biotite quartz diorite is the most common single plutonic rock type in the thesis area. Like the diorite, it also is a heterogeneous rock. The cleaner outcrops contain about 3% inclusions. Locally, however, the inclusions may exceed 20% of the rock, and at other places none may be visible. Erratic patches within the quartz diorite are low in quartz, and the rock therein is often dioritic, Most of the quartz diorite is medium-grained, although it may be fine or coarse. The coarse-grained quartz diorite usually has a kind of splotchy appearance because of large hornblende-crystals. Porphyroblastic tendencies are seldom pronounced.

Yet the crystals are commonly seriate from coarse to fine. When the rock is porphyroblastic, the large crystals may be either hornblende or plagioclase, or both. At the head of Indian Arm the quartz diorite contains large quartz crystals, but this is unusual. The average mafic class for a hornblende-biotite quartz diorite is 2+, though fluctuations are common. When the total mafic content increases the relative amount of biotite decreases. Commonly both mafic minerals are very fine-grained although the rock may otherwise be medium-grained or even coarser. The mafics tend to form medium-grained clots of tiny crystals. The quartz in the hornblende quartz diorite is often bluish. Since, however, it tends to be bluish in many diverse rock types in the northern portion of the map-area, its dominance in the hornblende-biotite quartz diorite seems to be chiefly a reflection of the concentration of this quartz diorite in the northern sections. Foliation is sometimes present, perhaps however, less common than in the diorites. When elongated inclusions are present in otherwise foliated rock, the two directions invariably coincide. Locally the quartz diorite is hydrothermally altered to a pinkish rock, but the feature (referred to also in respect to the complexes) is more common in the potash-rich rocks. The main bodies of hornblende-biotite quartz diorite occur between hornblende-rich and biotite-rich areas of plutonic rock. The quartz diorite is usually gradational into these adjacent rocks.

Granodiorite

Hornblende-biotite granodiorite is also a heterogeneous rock, but slightly less so than the quartz diorite. The grain size ranges from medium-fine to coarse, averaging slightly larger than medium. Locally the mafic minerals are fine-grained. The mafic class averages about 2. As in the quartz diorite the amount of biotite fluctuates widely. In some of the granodiorite the biotite crystals are distinctly larger than the associated hornblende. There seems to be some correlation between a low total amount of mafics (i.e. a low mafic class) and the tendency of the mafics to form fine-grained clots irrespective of the size of the feldspathic minerals. In these rocks the potassium feldspar is pink, and rarely abundant. It tends to be moderately abundant in certain patches, and low between these patches. In places it becomes so low as to be negligible, and the rock passes into a quartz diorite. Inclusions average from 2% to 3%, more or less equivalent to the percentage for the thesis area as a whole. The inclusions tend to be rather small, however, averaging about two inches in diameter and seldom exceeding six inches. At only one location (northwest side of Pitt Lake) was any foliation noted in hornblende-biotite granodiorite. Very common, however, are red hydrothermal alteration zones. Late epidote (and some apparently pre-granitic epidote) is also present in many outcrops. The rocks adjacent to hornblende-biotite granodiorite are normally hornblende-biotite quartz diorite, or biotite-hornblende granodiorite, and less commonly hornblende granodiorite.

PLUTONIC ROCKS CONTAINING BIOTITE AND HORN BLENDE IN APPROXIMATELY EQUAL PROPORTIONS

The rocks included in this section are those in which hornblende and biotite are equal in amount, and those in which biotite predominates at one place and hornblende at another, but the two are so intimately intermingled that their separation is not feasible on the map-scale used. No mappable bodies of gabbro, diorite, or granite in the map area belong to this group; only quartz diorite and granodiorite are represented and they are not particularly abundant.

Quartz Diorite

Typically, biotite-hornblende quartz diorite is medium-grained or slightly coarser. The mafic class stays closely within the 2 to 2+ range. Both mafic minerals are sometimes much finer-grained than the rest of the rock. The coarser biotite crystals reach larger sizes than do the hornblende crystals. Inclusions range from less than 1 percent to more than 5 percent, averaging about 2 percent. Their distribution is irregular, yet few outcrops are free of them. In two or three localities the rock was found to be foliated, but this is not characteristic. The main bodies of biotite-hornblende quartz diorite occur on the southern slope of Hollyburn Ridge in the southwest part of the map area, and southeast of Pitt Lake. The rock usually separates hornblende- and biotite-rich areas.

Granodiorite

In the matters of grain size, mafic content and inclusions, biotite=hornblende granodiorite resembles the equivalent quartz diorite. The amount of potassium feldspar is usually very low and commonly the rock passes into a quartz diorite. Hydrothermal alteration is often found in this rock. It results in local patches and veins of brilliant red rocks, chloritization of the mafic minerals and general epidotization of the plagioclase. Occasionally the rock is foliated. The granodiorite occurs closely associated with the quartz diorite described above, east of the south end of Coquitlam Lake.

BIOTITE-HORNBLENDE PLUTONIC ROCKS

This group comprises about one third of the plutonic rocks in the map-area. No diorite and, of course, no gabbro were found to come under this classification. Biotite-hornblende granite does occur within the area as local variations of the equivalent granodiorite, but not in bodies large enough to map on the scale used.

Quartz Diorite

This rock and hornblende-biotite quartz diorite are the most abundant rocks in the thesis area. Typically the biotite-hornblende quartz diorite is medium to coarse-grained. The mafic class ranges from 1 to 2 , and averages slightly less than 2. It was noted that where the mafic content increases, the grain-size tends to decrease. The mafics are frequently much finer-grained than the plagioclase and quartz. When unusually large mafic crystals are found they are nearly always biotite. One exception occurs around Munro Lake (just east of Pitt River) where half-inch hornblende crystals are common, greatly exceeding the size of the associated biotite which averages about an eighth of an inch in length. The quartz is very often blue, but as for the hornblende-biotite quartz diorite, it appears to be due to the northerly location of the quartz diorite bodies, rather than a characteristic of a certain rock type. Except for small areas where the amount of inclusions is unusually large, quartz is abundant. As in all the plutonic rocks in the area, the inclusions are sporadically distributed. Inclusions, however, are distinctly less abundant than in the hornblende-rich types. In the biotite-hornblende quartz diorite they range from almost zero to about 3%, and they average less than 2%. Indistinct nebulous inclusions, represented only by a slight increase in mafic minerals are common. Foliation is not unusual, about half of the bodies mapped showing some foliation. Pink hydrothermal alteration associated with the formation of epidote and chlorite was noted in biotite-hornblende quartz diorite, but rarely.

The largest body of biotite-rich quartz diorite is centered around Coquitlam Lake. The other bodies are rather small and largely restricted to the northern half of the sheet. The larger bodies of biotite-hornblende quartz diorite tend to be located at some distance from large pendant bodies. Occasionally juxtaposition of a pendant and a small body of biotite-rich quartz diorite occurs, the chief example in the thesis area occurring north of the Golden Ears complex and pendant bodies. Faulting is suspected here, but not otherwise proven. Gradations within biotite-hornblende quartz diorite bodies tend to be towards biotite (only) quartz diorite, and biotite-hornblende granodiorite. Gradations into the latter at several places has resulted in bodies large enough to map.

Granodiorite

In most respects biotite-hornblende granodiorite does not differ much from the equivalent quartz diorite. Typically it is slightly coarser than medium-grained, and the mafic class averages about 2 or slightly less. The mafic minerals are usually comparable in grain size to the feldspathic minerals, but are occasionally fine-grained. Hornblende may vary from zero to equality with biotite, although generally it is very low. Potassium feldspar is seldom abundant, and its absence in certain patches results in frequent lapses to quartz diorite. Bluish quartz is rather common. Inclusions vary in abundance from less than $\frac{1}{4}$% to 3%, and average between 1% and 2%. Some foliation is found in about half of the bodies mapped. In these bodies it is only locally developed. The most striking difference between the granodiorite and the quartz diorite is the amount of late hydrothermal alteration. The rock is often made brilliantly red by such alteration, and chlorite and epidote abound.

This granodiorite is closely associated with biotite-rich quartz diorite, into which it frequently grades.

BIOTITIC (HORNBLENDE FREE) PLUTONIC ROCKS

Only one representative of this type of rock occurs within the thesis area, namely the Crocker Island granite. Occasionally, biotite-rich quartz diorite and granodiorite will change locally to rocks containing only biotite, due to a drop in hornblende, but no mappable bodies of this sort were found.

The main occurrence of Crocker Island granite is the large-dyke-like body on the east side of Indian Arm. It is a coarse-grained rock low in mafics (class 1) and high in quartz. The potassium feldspar-plagioclase ratio fluctuates around 50:50, resulting in patches of potash-rich granodiorite. The rock is relatively free of inclusions; they average less than 1%. Throughout the body, foliation is faint but consistantly present. Red hydrothermal alteration, with its usual associates chlorite and epidote, is very common. The shape of the Crocker Island granite body, its position along a logical extension of the Fanning Creek fault, and its location in a foreign hornblende-rich environment, suggest that this granite body is truly intrusive.

CONCLUSIONS

The more important characteristics of the plutonic rocks which have just been described are tabulated below.

Rock Type	Average Grain Size	Average Mafic Class	Occurrence of Fine-Grained Mafics	Hydrothermal Alteration	Percent Inclusions (Average)
Complexes	Variable fg to cg fg-mg predominate	Variable 2+ to 4	Rare	Rare	10%-50%
gabbro	cg	3+	rare	rare	5%
diorite	fg-mg	3	"	"	5%
Horn.					
granod.	mg	2	"	moderate	3%-4%
granite	mg-cg	1	"	common	3%
diorite	Sl. mg	2+	moderate	rare	4%-5%
qtz dio	mg	2+	common	"	3%
Horn-biot.					
granod.	Sl. mg	2	common	common	2%-3%
qtz dio	Sl. mg	2-2+	common	rare	2%
Horn-Biot.					
granod.	Sl. mg	2-2+	common	common	2%
qtz dio	mg-cg	2-	common	rare	2%
Biot-horn.					
granod.	mg-cg	2-	moderate	common	1%-2%
Biotite					
granite	cg	1	rare	very common	1%

Certain trends are clearly shown in the above table. The average grain size gradually increases from fine to medium-grained in hornblende diorite, to coarse grained in biotite granite. Between the same two rocks, the mafic class decreases from 3 to 1, and the average inclusion content decreases from 5% to less than 1%. For most purposes the plutonic series should be considered as beginning with hornblende diorite, rather than with the complexes which are too heterogeneous, or with hornblende gabbro which in most respects can be considered a special variety of diorite.

Fine-grained mafics (tiny grains clustered in decussate clots comparable in size to the felsic grains) are rare at both ends of the series, but common in rocks containing both hornblende and biotite.

It should be noted that each of the four features just mentioned, varies primarily according to the mafic ratio, and more or less independently of the potash feldspar-plagioclase ratio. Only in the matter of hydrothermal alteration (as indicated by brilliant red alteration of the rock) does the potash feldspar-plagioclase ratio assume dominence over the mafic ratio. There is absolutely no doubt that this type of hydrothermal alteration varies according to the potash feldspar content. This alteration is very rare in diorites and common in granites.

From the magascopic and field evidence biotite granite is indicated as being more highly developed than is hornblende diorite; that is, it is coarser, freer of mafics, and freer of inclusions. The microscopic evidence presented in the following two chapters supports this conclusion, and suggests that not only have the plutonic rocks as a whole evolved, but also that each constituent mineral has likewise evolved.

TEXTURES OF THE PLUTONIC ROCKS

As commonly defined (by Holmes, Tyrell and others) texture is the intimate mutual relations of the mineral constituents and glassy matter in a rock made up of a uniform aggregate. Since in this area the plutonic rocks are definitely heterogeneous aggregates, it is doubtful whether they can be said to have textures under this definition. Certainly there is no single term which adequately conveys a picture of the mutual relations of the minerals in the plutonic rocks. Yet each of the different varieties of plutonic rock has certain characteristics which are more commonly found in that variety than in the rest, but none has a characteristic which is entirely unique to that single rock type. In general the textural variations found in one type of rock can differ as widely as the characteristic textures of very different types. This inconsistancy is a logical consequence of the classification of plutonic rocks, which is based entirely on composition, or more accurately, on an arbitrary portion of the composition, while texture is dependent on both composition and history.

Many textural features are discussed under the sections on individual minerals, and do not warrant consideration here. The numerous features which combine to produce a plutonic rock texture, are not in themselves of any great importance, but the trends of their changes from one rock to another seem to have considerable genetic significance. The tabular summary which follows was drawn up to emphasize the direction of these changes rather than to give a textural description of each type of plutonic rock (which cannot be done). Both field and microscopic work has indicated that a plutonic rock may develop along several different lines. These lines originate generally in the single rock type, hornblende diorite, and from it they diverge rather widely. If, however, the development is not arrested prematurely, the lines converge again, and meet usually in biotite granite. In the following table the textural features of certain plutonic rock types from the present area are given. The types selected represent the beginning of the plutonic series, namely hornblende diorite, two intermediate types, namely biotite quartz diorite and hornblende granodiorite, and the end of the plutonic series, namely biotite granite. It should be pointed out that biotite quartz diorite is in most respects a more highly evolved rock than hornblende granodiorite, and is in fact the final product of plutonic evolution in certain areas where potassium was not available when temperatures were favorable for the formation of potassium feldspar. The plutonic types not listed in the table can be interpolated between those given. For completeness, the metamorphic rock most closely associated with the plutonic rocks in the thesis area, namely hornblende granulite, is also given.

FORMS OF THE MAJOR MINERALS IN PLUTONIC ROCKS OF THE AREA

a) Plagioclase

1.	In Hornblende Granulite:	Anhedral crystals, often amoeboid; normally poikiloblastic with inclusions of hornblende, and less commonly of quartz and other minerals.
2.	In Hornblende Diorite:	Usually anhedral, occasionally subhedral. Euhedral forms common only as inclusions in hornblende porphyroblasts. A few inclusions of small hornblende and plagioclase crystals remnant from granulite.
3.	In Biotite Quartz Diorite:	Anhedral in contact with other plagioclase crystals. Subhedral to euhedral where contained in quartz or biotite. No inclusions of major minerals except for remnants of more calcic plagioclase.

4. In Hornblende Granodiorite: Anhedral in contact with plagioclase. Subhedral to euhedral in quartz or potassium feldspar. No inclusions of major minerals.

5. In Biotite Granite: Anhedral in contact with plagioclase. Subhedral to euhedral in potassium feldspar. Rarely included by quartz. No inclusions of major minerals.

b) Hornblende

1. In Hornblende Granulite: Small crystals generally subhedral. Porphyroblasts irregular and sieve-like. Contain all the crystals making up the granulite including small hornblende crystals.

2. In Hornblende Diorite: Irregular anhedral crystals. Commonly filling angular interstices among plagioclase crystals. Larger crystals poikiloblastic with numerous plagioclase inclusions, and occasional small hornblende crystals (remnant from granulite).

3. In Biotite Hornblende Quartz Diorite: Anhedral where surrounded by plagioclase crystals, otherwise subhedral, and in quartz occasionally euhedral. Inclusions of plagioclase fairly common if hornblende rather abundant.

4. In Hornblende Granodiorite: Subhedral to euhedral shapes generally predominate. Regular forms favored by abundant quartz and K-feldspar. Inclusions of major minerals rare.

5. In Biotite-Hornblende Granite: Euhedral shapes more common than in any of the above, but generally subhedral. Inclusions of major minerals extremely rare.

c) Biotite

1. In Hornblende Granulite: Generally lacking. A few small grains sometimes present, included in hornblende or plagioclase porphyroblasts. Fairly well-shaped usually.

2. In Hornblende Diorite: Absent except for small inclusions in hornblende or plagioclase, remnant from

the granulite. In hornblende-biotite diorite biotite porphyroblasts are very irregularly shaped and strongly poikiloblastic, containing crystals of plagioclase and hornblende. Also as alteration from hornblende, along its grain boundaries and cleavage planes.

3. In Biotite Quartz Diorite: Irregularly shaped in contact with plagioclase crystals, otherwise subhedral. Occasionally euhedral if quartz unusually abundant. Inclusions rather rare (only plagioclase involved).

4. In Hornblende Biotite Granodiorite: Generally subhedral. Euhedral forms common in quartz and K-feldspar. Inclusions rare.

5. In Biotite Granite: Euhedral shapes common, otherwise subhedral. Inclusions of major minerals extremely rare.

d) <u>Quartz</u>

1. In Hornblende Granulite: Small equidimensional grains. Porphyroblasts rare, but when present they have irregular amoeboid shapes, containing plagioclase and the mafics. Quartz porphyroblasts at this stage will remove the rock from the "normal" cycle.

2. In Hornblende Diorite: Small amount in interstices among plagioclase and hornblende crystals. In <u>hornblende quartz diorite</u>, irregularly shaped crystals containing numerous inclusions of plagioclase and hornblende.

3. In Biotite Quartz Diorite: Anhedral but generally equidimensional crystals. Inclusions (plagioclase, biotite) far less than in hornblende quartz diorite, but still fairly common.

4. In Hornblende Granodiorite: Same as 2.

5. In Biotite Granite: Generally anhedral equidimensional grains. Occasional crystal faces found in contact with K-feldspar. Inclusions of major minerals rather rare.

e) Potassium Feldspar

1.	In Hornblende Granodiorite:	Shape always irregular. Inclusions are numerous and involve all the other minerals in the rock.
2.	In Biotite Granite:	Crystals usually equidimensional. A few, but never abundant inclusions. Many sections show no inclusions.

It must be emphasized that the conclusions thus listed in the table are statistical results from many thin sections. The thin sections were grouped on the basis of composition alone, without regard to the probable history of the rock. Consequently, rocks with "normal" texture were combined with those which had obviously undergone shearing, or in other ways were obviously not "normal". These latter rocks almost invariably weighted the scales against the general trends, thus the conclusions were reached in spite of them, rather than with their aid.

The most conspicuous feature of all five major minerals is the tendency to clear themselves of inclusions as the rock develops from hornblende diorite towards biotite granite. Each of the minerals contains more inclusions and tends to have more irregular shapes in the less developed rocks. The shapes of plagioclase and the mafic minerals also tend to improve in the more advanced rocks. The author believes this is not so much due to their superior crystalloblastic power as to the shaping effect of the minerals replacing them. Quartz, however, only rarely attains euhedral form, probably because it lacks any strong micro-structure such as cleavage, by which its replacement (by potash feldspar) might be controlled. Euhedral crystals of potash feldspar are even rarer than those of quartz. The chief reason is thought to be that no major mineral replaces potassium feldspar. The "albite" member of perthite is considered to be a minor mineral, and since it operates internally and never entirely replaces a potash feldspar crystal, it is of no concern here. Thus, except for pseudomorphic crystals, and perhaps for certain extremely coarse-grained rocks, euhedral crystals of potassium feldspar are not found in the plutonic rocks. Yet even for this, the latest mineral, the ever present trend of eliminating inclusions in the more highly evolved rocks is present. Consequently, the most striking instances of poikiloblastic potassium feldspar crystals are found in hornblende-rich granodiorite whereas in biotite granite potassium feldspar crystals tend to be clear.

Another observation which supports the general contention of development of biotite-rich rocks from these rich in hornblende is the parallel increase in grain size. In spite of numerous exceptions, the average grain size of biotite-rich rocks is greater than the average grain size of hornblende-rich rocks. It is difficult to explain this fact on the basis of different cooling rates of a hypothetical magma.

Besides the so-called normal textures of the plutonic rocks there are numerous peculiar textures, some of which are rather common. The significance of many of these textural features is far from obvious, though some seem simple of explanation. One of the more transparent of these textures is that called "pseudocataclastic" (Anderson, 1938). It comprises a fine-grained granulitic groundmass, in which have grown large porphyroblasts of plagioclase and/or quartz (Photograph 5). Incidentally, the texture shown in Photograph 5 is practically identical to that of the granodiorite-porphyry described and photographed by Misch (1949, Pt II),

Photograph 5

Typical pseudocataclastic texture, showing large plagioclase porphyroblasts amongst small quartz and plagioclase crystals. (TS R197-49, from a hornblende quartz diorite from Kennedy Creek). X34.

Photograph 6

Small remnant plagioclase grains, commonly found between large crystals of potassium feldspar. X67. (TS R89-49, a biotite granodiorite from south of East Cap River).

which occurs in the Paiyenssu ("White Stone Cliff") southwest of Sheku in northwest Yunnan. To many there is little justification for using a term having the awkward pomposity of "pseudocataclastic" when the term "porphyroblastic" is available and better known. The term is used in this thesis because it expresses a somewhat clearer picture than "porphyroblastic", and is, actually, a type of porphyroblastic texture. In a pseudocataclastic texture the porphyroblasts and groundmass crystals differ greatly in size, and the porphyroblasts are often clear of inclusions. Of course, a complete lack of inclusions in the porphyroblasts would make it rather difficult to distinguish pseudocataclastic texture from cataclastic texture. In general, however, occasional inclusions of groundmass material are found. Other evidence often used is marked differences in composition between the groundmass granulite and the porphyroblasts. The groundmass material obviously cannot be "mortar" if it does not correspond in composition to the larger crystals from which it supposedly formed. In some cases the rock is evidently sheared, and the present texture is the result of recrystallization (chiefly of quartz) of a cataclastic texture (see section on quartz).

Pseudocataclastic textures were found in about 10% of the plutonic rock thin sections. In the great majority of these, it is not possible to suspect the texture from the hand specimen. Pseudocataclastic textures are especially characteristic of nebulitic, or "ghost" relict inclusions.

For reasons that are not clear to the author, the mafic minerals practically never form the porphyroblasts of a pseudocatclastic texture, although they are common in the ground mass material. The only instance noted was that of a single biotite porphyroblast, which, along with plagioclase and quartz porphyroblasts, in a fine-grained granulite combined to form a pseudocataclastic texture.

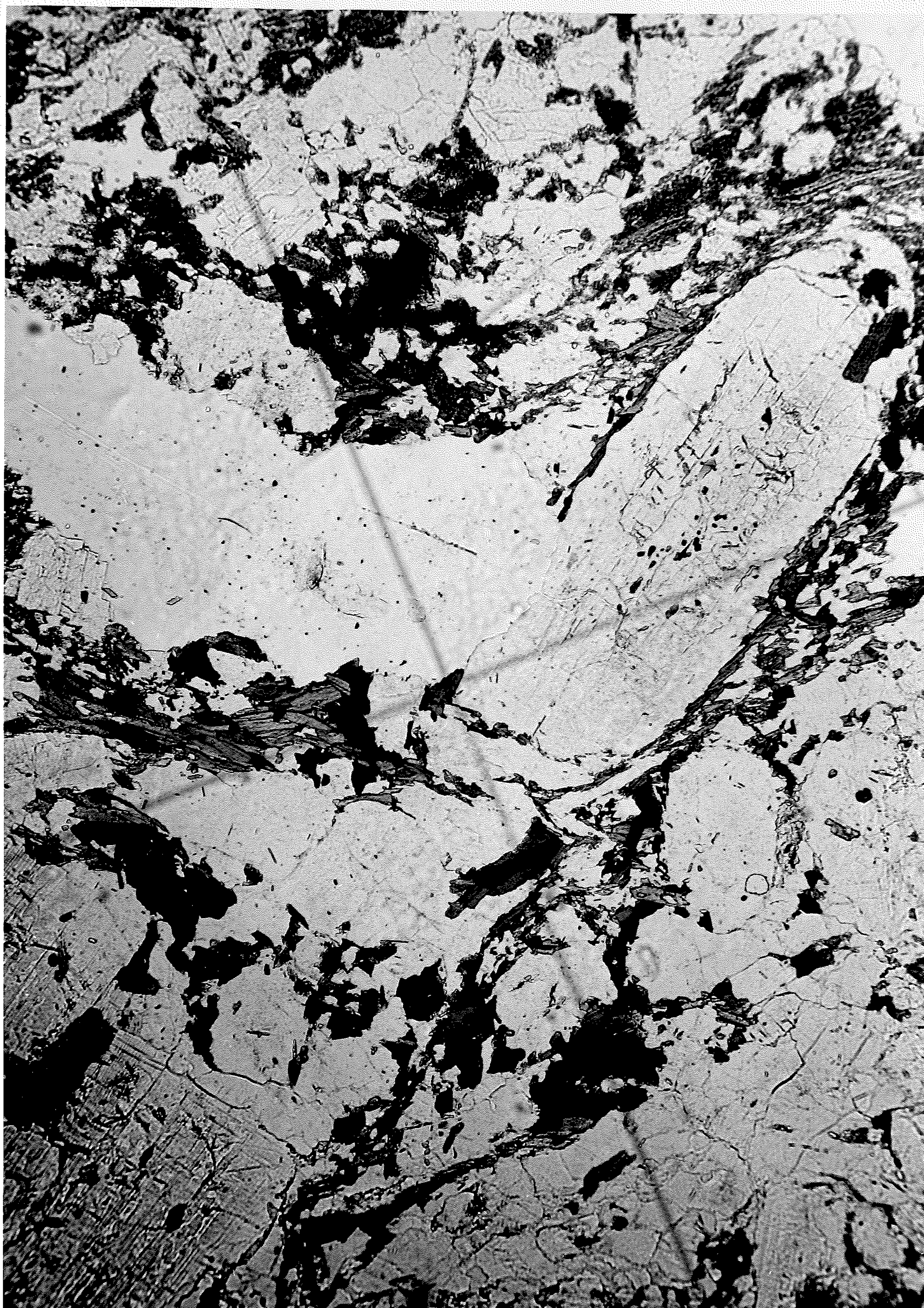
Vaguely similar in general appearance to pseudocataclastic texture is that resulting from small remnants of plagioclase crystals left clustered along K-feldspar-K-feldspar contacts (Photograph 6). The parallel orientation of small groups of these and the many stages of their development shown in various thin sections, indicate that they are remnants of plagioclase crystals which have been replaced simultaneously from opposite sides by potassium feldspar, but the process has been halted before completion. This feature requires stopping of the replacement process at a critical stage, thus one would not expect it to be common. Accordingly, it was found only in a few of the granites.

Somewhat more widespread than the feature just described is the occurrence of mafic minerals in fine-grained clots. The mafic mineral is usually biotite, but occasionally hornblende. The size of the clots corresponds roughly to the average grain size of the rock, but the grains comprising the clots are very small. Within the clot the grains are arranged in a random decussate pattern. These mafic clots were not found in plutonic rocks which contain no biotite. They are found most often in quartz diorites which contain both hornblende and biotite, although they may be found occasionally in any plutonic type containing substantial amounts of biotite.

In some sections fine-grained biotite, instead of forming clots, is strung out along plagioclase crystal boundaries (Photograph 7). On occasion these anastomosing trains of tiny crystals lace the rock in a very

Photograph 7

A typical occurrence of small biotite grains occupying interstitial areas between plagioclase porphyroblasts. (plain light, X46). (TS 162C-48, a biotite-chlorite quartz diorite, from near Enchantment Lake, Capilano area).



striking manner. Since their origin involves an explanation of the fundamental processes operative in forming plutonic rocks it will be left to a later section.

No treatment of textures is adequate without a mention of the para-genesis of the major minerals, since the order in which the minerals form strongly influences both their shapes and their mutual relations. The studies of the individual minerals given in the next section show that in the plutonic rocks the major minerals have a definite order, and exceptions are rare. This order is

1. Plagioclase (all varieties except the "albite" member of perthite).
2. Hornblende (except for remnants from granulites in undeveloped plutonic rocks).
3. Biotite.
4. Quartz.
5. Potassium Feldspar.

From the accumulated weight of all the evidence compiled in this thesis, this sequence is considered to be metamorphic, and it should be interpreted slightly differently from magmatic sequences, since solid rock was present before the process began. For example it must not be assumed that all the plagioclase formed, then all the hornblende, etc. This is often not so even for magmatic rocks, and could hardly ever be so for rocks of metamorphic origin. In the hornblende-plagioclase relationship, for instance, the impression is that hornblende continued to recrystallize and grow, after the general form (if not the final composition and detailed form) of the plagioclase had been established. Parallel relations exist for the other minerals. The end result, however, is much the same as if the history of each mineral occupied a separate period.

One aspect of the sequence is much different from that in magmatic rocks. It is that each of the minerals forms at the expense of the mineral or minerals which precede it. Consequently, the stage of development of a plutonic rock can be judged approximately from the ratio of the "late" minerals to the "early" minerals. The more abundant those minerals at the end of the sequence in relation to those at the beginning, the more highly developed is the rock.

The degree of euhedralism of a mineral does not seem to be dependent directly, as in a magmatic rock, on the fact that the mineral formed early, but rather on the fact that it was available for reshaping by later minerals which replace it. To determine the extent to which metamorphic minerals attain crystal faces by active growth rather than by the passive reshaping suggested here requires further study.

It is, of course, naive to believe that the innumerable textures possible in a plutonic rock can be arranged in one continuous series, because many are the result of special, and often unique circumstances. In many ways a given texture is analogous to a chess board half way through a game. One can make an intelligent guess concerning what has transpired before, but can never eliminate all the possibilities. It is, however, somewhat easier to deduce what is in progress, and what line of development will probably follow. Likewise the normal plutonic texture suggests the future the rock might have had, but merely hints at its past. Nevertheless, as it is usually easy to look at a chess board, and distinguish a game of which 15 moves have been played from that in which 30 moves are done, it is also possible to conclude from a certain texture that numerous or few events have transpired, and that these events trend toward a certain goal. The observation of many plutonic textures suggests that the ultimate result of the plutonic process is a biotite granite containing little besides potassium feldspar.

MICROSCOPIC FEATURES OF THE MAJOR MINERALS OF THE PLUTONIC ROCKS

GENERAL STATEMENT

The writer was impressed with the field evidence, which strongly suggests that the plutonic rocks evolve normally from hornblende diorite, through intermediate types, to biotite granite. It seemed logical that the individual minerals, if their habits were studied in the different plutonic rocks, might also give indications of such an evolution. The five major minerals of the plutonic rocks were studied separately and the more important results have been summarized in the previous chapter. Some of the features, however, seemed to warrant more detailed study, the results of which are presented in this chapter. The minerals are dealt with individually and in the following order

1. Plagioclase
2. Potassium feldspar
3. Mafic minerals
    a) Hornblende
    b) Biotite
4. Quartz

PLAGIOCLASE

PLAGIOCLASE COMPOSITION IN VARIOUS PLUTONIC ROCK TYPES

The composition of the plagioclase crystals were determined by measuring the extinction angles of albite twin lamellae, where possible, on sections cut perpendicular to 010 and 001, otherwise, by the Michel-Levy method. Where determinations were made on several "MP" crystals the average value was taken. Similarly, when the crystal was zoned, the mean value of the core and the rim was used. The values obtained often varied considerably even within one thin section, consequently little significance should be placed in the values obtained from any one section. However the ranges obtained in each plutonic rock type are interesting, and important to the extent that they indicate the heterogeneity found within plutonic rocks.

Biotite Granite

Section	An
115A-48	8
N29-52	11
K107-51	21
K88-51	14
K58-51	24
K43-51	24
J83-52	28
J62-52	27
J59-52	27
J20-52	5

Hornblende-Biotite Granodiorite

Section	An
206A-48	33
13 C-48	35
150A-49	36
R10 -49	11
H19 -49	35
H3 -50	35
H36 -50	20
H60 -50	30
R87 -50	33
J45 -51	28

Biotite Quartz Diorite

Section	An
256C-48	12
H63 -49	12
H106-49	9
R115-50	12
R162-50	33
R186-50	34
R220-50	34
R221-50	31
H181-50	31
A219-52	15

Hornblende Quartz Diorite

Section	An
53A-48	37
211A-49	37
H166-50	58
K24 -51	29
K33 -33	37
K50 -51	55
N21 -52	45
N178-52	36
N205-52	36
A275-52	33

Hornblende Diorites

Section	An
45C-48	43
89C-48	35
H104-49	40
H121-49	52
K47-51	51
N53-52	55
N192-52	55
A85-52	43

Hornblende Gabbros

Section	An
K75-51	75
H123-49	63
A61-52	63

The principal fact illustrated by the above figures is that even though the ratios of hornblende to biotite, and of potash feldspar to plagioclase, are held relatively constant, the anorthite-molecule content still fluctuates through a rather wide range. The results stress the inadequacy of naming a rock, simply a quartz diorite, or a granodiorite, etc., taking into account only the potash feldspar-plagioclase ratio (with a glance at the quartz). By many classifications rocks such as H106-49, and H166-50, would be called quartz diorites. Yet the anorthite content of the plagioclase in the former, a biotite quartz diorite, is An9, and in the latter, a hornblende quartz diorite, An55.

Such wide fluctuations should not be permitted within one rock name, if it is to be of any value. By designating the mafic ratio in the rock name, the range of the anorthite-molecule content is greatly reduced, and most important, the result can be effected without using a microscope.

SHAPES OF PLAGIOCLASE CRYSTALS IN THE PLUTONIC ROCKS

It is not the purpose of this section to list all the different shapes which plagioclase crystals may have in the plutonic rocks of the thesis area. They are infinite. However, the amount and significance of euhedralism seems worthy of, at least, brief attention.

A plagioclase crystal having an outline in thin section more than 4/5 euhedral is an exceedingly rare phenomenon in the plutonic rocks examined. In volcanic rocks, on the other hand, such crystals are reasonably common, and often abundant. To determine whether plagioclase crystals were more euhedral in certain types of plutonic rocks the writer examined a group of thin sections of granites and gabbros. The intermediate plutonic rocks were also considered, but a brief examination showed that far greater differences occur within one rock type than between different adjacent types. Therefore it was assumed that if a general difference existed, it would be most evident in a comparison of the end members of the plutonic series. The examination revealed that plagioclase crystals usually are not considerably more euhedral in plutonic gabbros than in granites. In fact some granites contain numerous euhedral plagioclase crystals, and some gabbros very few. On the whole, the relatively undeveloped rocks contain the fewest euhedral crystals. The most irregular crystals occur in highly feldspathized granulites, where the plagioclase often has rather amoeboid shapes. These shapes improve, on the average, as the plutonic rocks evolve.

The examination emphasized the deceptive appearance of most gabbro sections. Practically all the gabbros would be called "panidiomorphic", and most of the granites "hypidiomorphic". Yet the apparent abundance of euhedral plagioclase crystals in gabbro is largely an illusion, caused by the distinct, sharply contrastive twin lamellae. The illusion disappears when the actual crystal outlines are traced. In granite on the other hand the twinning is often irregular and indistinct, and the plagioclase is diluted, so to speak, with crystals of anhedral habits, namely quartz and potassium-feldspar, producing an overall impression of anhedralism.

In all of the plutonic rocks straight line boundaries between plagioclase crystals are rather uncommon, but common between plagioclase and other minerals such as quartz, potassium feldspar, hornblende and biotite. Within the thesis area these minerals are apparently later than plagioclase. In many sections the plagioclase crystals which are contained in other minerals, (potassium feldspar, hornblende, etc.) are more euhedral than those in contact with other plagioclase crystals. The inference is that when undergoing replacement, plagioclase crystals are often made more euhedral than their original shape, due to the exercise of cleavage control on the replacing material. Examples of such cleavage control are exceedingly numerous, and often very striking. When the replacement processes have greatly diminished their size, the plagioclase crystals usually lose their euhedral shape, and become very irregular before disappearing. Because of the orientation of the two cleavages, partially replaced plagioclase crystals can appear rectangular only in sections cut roughly perpendicular to the a-axis, but it is very common to find two straight edges. In some instances the replacing solutions enter the interior of plagioclase resulting in irregular shapes (though cleavage controlled).

ZONING IN PLAGIOCLASE IN THE PLUTONIC ROCKS

OCCURRENCE IN DIFFERENT TYPES OF PLUTONIC ROCKS

Not much quantitative information is available on the distribution of zoned plagioclasesin plutonic rocks, and the answers to many fundamental questions such as "Are zoned plagioclase crystals more abundant in granite than in granodiorite?, than in quartz diorite?, than in diorite?, etc." and "Does the zoning differ in character in various plutonic rock types?" are difficult to find in the literature. Consequently the facts investigated here deal with the elementary features of the subject.

In the rocks described in the present paper, plagioclase zoning was studied by plotting extinction angle of each zone rather than the actual composition, on the basis that the absolute composition of a zone is of less importance than the changes in composition from zone to zone, a reflection of which is shown by the curves derived from the extinction angles.* Obviously, differences in orientation and position of the thin-section plane in different crystals make any one curve unreliable, therefore many curves must be plotted and the conclusions must be drawn statistically from all the data. Although

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* This fact has since been borne out by the recent (1955) unpublished work of J.A. Chamberlain at the University of British Columbia, who has examined the zoning in the plutonic rocks from Caulfeild (a small peninsula on the north side of Burrard Inlet), using the universal stage to obtain the composition of each zone.

it is difficult to subordinate the exception, being as it often is, the most spectacular, the attempt has been made in the curves selected for the following plates. They are thought to be representative of the typical curves for the various zoned crystals in the plutonic rock types, and at the same time hint at the great variety that is found.

EXTINCTION ANGLE CURVES OF PLAGIOCLASE CRYSTALS IN THE PLUTONIC ROCKS

In selecting the crystals for the following curves, it was found that thin sections of intermediate plutonic rocks usually contain many zoned plagioclase crystals, but the end members of the plutonic series contain very few. It was rather difficult to locate zoned plagioclase crystals in hornblende diorite, and in biotite granodiorite. None at all could be found in the granites, that were suitable for plotting, although a few very slightly zoned crystals were noted.

In all cases, except where otherwise noted, the crystals were orientated perpendicular to the a-axis, or very near this position, and the extinction angles of the zones were measured from core to rim along a line perpendicular to 010. In some cases, noted below, the measurements were made along a line parallel to 010, which usually tended to broaden the individual zones, but changed nothing else. In order to avoid errors that might arise from measuring positive extinction angles in some places, and negative angles in others, the relative relief of the rim and core were always checked.

No.	Ts	Av.An of Ts	
1	R38-49	43	
2	"	"	
3	R39-49	43	
4	"	"	(orientation dubious)
5	190A-49	30	
6	"	"	(" ")
7	H77-49	37	(" ")
8	N205-52	35	
9	206A-49	33	
10	R6-49	60	
11	"	"	
12	"	"	
13	J45-51	36	(measured // to 101)
14	T115-53	60	(" " " ")
15	"	"	(" " " ")
16	N87-52	33	
17	R51-49	33	
18	H41-49	35	
19	H47-49	36	
20	H88-49	30	
21	186A-49	37	
22	$21A_2$-48	32	
23	"	"	(orientation dubious)

No.	Ts	Av. An of Ts	
24	19A-48	30	
25	21A-48	35	
26	18A-48	30	
27	M33-52	34	(measured // to 010)
28	A218-50	28	
29	"	"	
30	"	"	
31	"	"	
32	N184-52	24	
33	"	"	(orientation dubious)
34	N44-52	30	
35	"	"	(orientation dubious)
36	R15-49	32	
37	159A-49	36	(measured // to 010)
38	A124-52	24	
39	R115-50	30	
40	R186-50	22	
41	H106-49	11	
42	H106-49	11	
43	N124-52	20	
44	17A-48	23	
45	"	"	

The study of plagioclase zoning in the plutonic rocks led to the following conclusions.

1) Zoned plagioclases are rare in granites and plutonic gabbros (as distinguished from those having hypabyssal characteristics), yet a few are usually found in both rocks.

2) Zoned crystals are most abundant in quartz diorites containing substantial amounts of both hornblende and biotite. In these rocks also, are found the most complex types and the greatest range of zoning.

3) Most plagioclase crystals are oscillatorily zoned in the plutonic rocks, but the zoning tends to be relatively simple in most hornblende diorites, and even more so in rocks containing biotite to the exclusion of hornblende, such as biotite quartz diorite, and biotite granodiorite. Occasionally a complexly zoned crystal is found in these rocks, but the range tends to be narrow.

4) The range of zoning decreases from a maximum in quartz diorite with approximately equal amounts of hornblende and biotite, to a minimum in the end members of the plutonic series, gabbro and biotite granite.

5) The trend of zoning is normal (that is rim less calcic than core) in virtually all cases. The only exceptions noted involved obvious replacement of the core by sodic plagioclase of rim composition (frequently the connection with the outer rim is visible).

6) Highly complex oscillatory zoning is restricted to the intermediate zones. The "core" of course shows no zoning (almost by definition), and the rim is nearly always smoothly zoned throughout its width, and is never oscillatory. (The so called "core" represents only the deepest zone cut by the plane of the thin section.)

VARIATIONS IN PLAGIOCLASE ZONING WITHIN INDIVIDUAL HAND SPECIMENS

Drawing of the curves used in the previous section suggested that considerable variation might be found in the curves based on several crystals within a single hand specimen. Since such variations or lack of them would have genetic implications, twenty sections were made of two hand specimens, one a hornblende (augite)-biotite diorite, the other a hornblende-biotite quartz diorite. The spacing of the sections was considerably larger than the size of the larger crystals, so that the probability of the same crystals appearing in two sections was slight. These curves are shown in Figures 5a, 5b.

The curves establish beyond all doubt that each crystal has an unique history, which, although similar in overall trend differs greatly from those near it in detail. The cores, in all cases, were more calcic than the outermost rim, but frequently not as calcic as some of the intermediate zones, (see T2, b, c1, d2, i1, etc.). In some crystals, reverse zoning has evidently been caused by replacement of the core by plagioclase of rim composition. This process usually leaves remnants of the original core, and is easy to recognize. This explanation seems unsatisfactory, however, for the narrow, very regular zones of highly calcic material which are often found well away from the core.

Although individual crystals may show widely different curves, certain overall aspects characterize the curves from one rock, and distinguish it from the other. For instance, the curves from specimen T115 usually contain a highly oscillatory section, while the curves from T2 are somewhat simpler, having broader zones, and no highly oscillatory section.

No direct correlation can be made from the curve of one crystal to that of another. This can be explained only in part by differences in orientation of the crystals, and the position of the cross-section. Such geometry cannot account for a negative inclination in one curve being represented by a positive inclination in another.

It is concluded from the curves that the environment during the genesis of a given crystal in a plutonic rock is not necessarily, nor even

COMPARISON OF ZONING IN PLAGIOCLASE CRYSTALS FROM TWO HAND SPECIMENS

Figure 5a

Rock Specimen T115-53; a hornblende-biotite diorite. Curves 2, 3, 4, and 6, were plotted from traverses made perpendicular to the trace of 010. Curves 1, 5, 7, 8, 9, and 10, were plotted from traverses made parallel to the trace of 010. Curve 1 is from a crystal cut perpendicular to 010 and 001 (MP)

Figure 5b

Rock specimen T2-53; a hornblende-biotite quartz diorite. Curves 1, 2, 3, 4, 5, 7, 9, 12, 13, and 14, were plotted from traverses made perpendicular to the trace of 010. Curves 6, 8, and 10, were plotted from traverses made parallel to the trace of 010. Curve 13 is from a crystal cut perpendicular to 010 and 001 (MP).

commonly, identical to that of an adjacent crystal, and when the environment of one becomes more sodic, it is entirely possible for that of the other to become more calcic. This phenomenon is considered more likely to occur in a metamorphic environment, than in a magma.

LAMELLAR TWINNING IN THE PLAGIOCLASE OF THE PLUTONIC ROCKS

GENERAL STATEMENT

It is general knowledge that twinning is more abundant, and the lamellae are wider in the more calcic plutonic rocks. This was found true of the rocks examined, although finely twinned crystals were noted occasionally in gabbro, and coarsely twinned crystals in granite. Both the proportion of plagioclase crystals, and the proportion of twinned plagioclase crystals is higher in the calcic rocks. Lamellae of equal widths, however, are more abundant in granites than in gabbros. Calcic plagioclases commonly have one set of lamellae of hair-like fineness with broad interspaces. Sodic plagioclases are frequently without twinning, or have numerous fine twin lamellae of nearly equal width. The lamellae in calcic feldspars tend to widen suddenly, and, in general, assume erratic, though angular shapes, which are not truly lamellar, but always sharply defined. Those in sodic plagioclase, however, are usually regular and equal in width, but indistinct, and frequently die out before completely crossing the crystal.

RELATIONSHIP BETWEEN TWINNING AND ZONING

The principal features bearing on the twinning-zoning relationship are commonly found in the intermediate plutonic rocks. The most important fact is that lamellar twinning tends to destroy zoning. Close examination of many plagioclase crystals will often show that zoning is present only in one set of lamellae. In the other set it has been eliminated (Photograph 8). More often the development of twin lamellae causes only a decrease in the range of zoning, rather than its complete destruction (Photograph 9). In such cases the difference in extinction angle from the core to the rim may be as much as 10° less in the new lamellae, than in the remnant interspaces.

Normally, new twin lamellae originate in the sodic rims of zoned plagioclase crystals (Photographs 10 and 11). In the early stages the lamellae are wedge-shaped, narrowing, and finally dying out toward the calcic core. Once the lamellae have extended through the core, the opposite rim appears to be reached very quickly, for few instances were noted of lamellae dying out after passing through the core. Some crystals contain rectangular patches in which the crystal lattice has inverted ("twinned") for no apparent reason. Eventually these anomalous rectangles are usually incorporated into the normal twin lamellae.

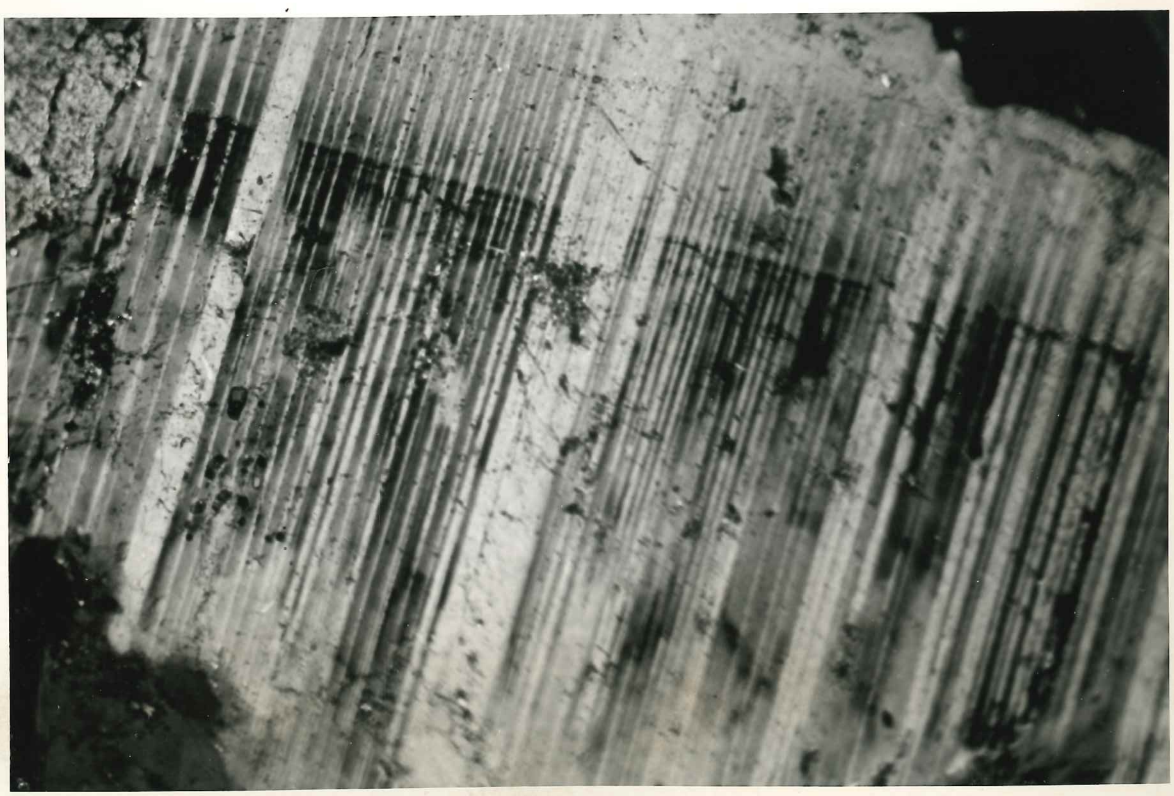
The above data may give the impression that twinning always post-dates zoning. This, however, is not the case. The cores of certain crystals contain well-developed twin lamellae which are truncated abruptly at the edge of the cores. The outer zones have apparently formed after the core, a smaller older crystal, was fully twinned. There is considerable additional evidence, given later, which further supports the fact that some of the plagioclase crystals have had a complex history. On the whole, however, twinning does post-date zoning.

Photograph 8

In the twinned, and partly zoned plagioclase porphyroblast shown, the light colored areas represent newly formed lamellae, and the dark areas interspaces. Zoning is well preserved only in the interspaces. X36. (TSN154-52, a hornblende-biotite quartz diorite from a mile east of Cacus Point, Pitt Lake).

Photograph 9

Illustrates same feature as above, except that the new lamellae (light colored) are still faintly zoned. The difference in composition from the rim to the core, however, is far less in the new lamellae, than in the interspaces. X97. (TS T2i-53, a Hornblende-biotite quartz diorite from near Devils Lake, a couple miles east of the map area).



Photograph 10

Normal development of twin lamellae is from the sodic rim to the core. At this stage the twin lamellae are characteristically wedge-shaped, as shown. X88 (T2d-53, a hornblende-biotite quartz diorite from near Devils Lake, a couple of miles east of the map area).

Photograph 11

Same as above, but the central lamellae are well-developed. There seems to be a general tendency for the central lamellae to develop before the marginal lamellae. X82 (TS R220-50, a biotite-hornblende quartz diorite from Cathedral Creek, tributary of the Upper Seymour River).

DISCUSSION

Emmons and Mann (1953) discuss the twin-zone relationship in plagioclase feldspar at some length in a recent joint paper. Their views are very interesting, although somewhat opposed to those of the writer. Nevertheless, the writer is in complete agreement with the following statement, taken from their paper.

p.41 "It is demonstrable further that pre-existing zoning has been eliminated in some crystals during the process of establishing equilibrium."

This feature is not only demonstrable, it is one of the common features of intermediate plutonic rocks (such as quartz diorites and granodiorites, with both hornblende and biotite). The "process of establishing equilibrium" refers here to the process of twin formation.

p.41 "However, since polysynthetic twinning develops so consistently at the time zoning disappears, the two must be related."

Emmons and Mann imply here and elsewhere that zoning is a necessary prerequisite to twinning. The writer disagrees because he feels it unlikely that all the twinned plagioclase crystals in highly calcic plutonic rocks and especially in certain metamorphic rocks were once zoned.

p.43 "Our overall conclusion is that twinning, which forms late in the history of the crystal and postdates zoning, is one of the factors and often a dominant factor in the elimination of zoning."

The writer is in agreement with the spirit of the sentence, but not with the letter. Although in the vast majority of plagioclase crystals twinning post-dates zoning, there are nevertheless examples of zones having been deposited after the core had been twinned. In such crystals, the core is twinned but the more sodic outer zones are untwinned. This cannot be satisfactorily explained by maintaining that the twinning developed in the core after the crystal was fully formed, because of the abundant evidence that twinning develops in zoned crystals from the sodic rim inwards, not vice versa. Also in crystals where the core only is twinned, the lamellae are sharply truncated, and retain their full width to the edge of the core. This suggests that the outer zones were deposited after the twins in the core were fully developed, for lamellae in the process of development tend to be wedge-shaped, as shown by crystals in which only the rim is twinned.

Both twinning and elimination of zoning seem to be manifestations of the same process, probably a weak ionic diffusion along preferred crystallographic directions. Emmons and Mann do not present their views on how twin lamellae form, but imply diffusion when they state that the lamellae may destroy zoning either completely or merely in part.

Concerning the width of twin lamellae Emmons and Mann (1953, p.46) point out that "the most fine-textured twinning is found in the most cataclastic rock" and from this deduce that twinning is finer in sodic rocks because their high viscosity when molten would favour stresses. As further support they state

p.46 "The low viscosity of sodic pegmatite feldspars leads to wide lamellae fully equivalent to those of calcic plagioclase."

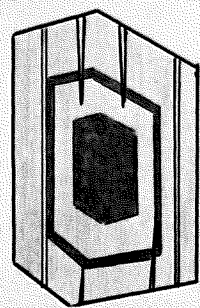
The implication is that acid plutonic rocks form in a distinctly different manner from pegmatites. The author disagrees with the implication, but is more concerned with the significance of the conclusions with respect to metamorphic rocks, for in these rocks also the lamellae tend to be narrower in the more sodic rocks. It seems to lead to the unreasonable conclusion that sodic metamorphic rocks are generally subjected to more stress than are calcic ones. A more obvious discrepancy in the theory that lamellae widths are stress controlled appears in the rocks which have evidently undergone considerable dynamic metamorphism and recrystallization and yet contain an abundance of untwinned plagioclase crystals. The problem of lamellae widths is not likely to be solved without experimentation, but most of the available evidence, although it comes chiefly as a by-product of observations made for other purposes, indicates that the chief factor involved is the composition of the plagioclase.

CONCLUSIONS

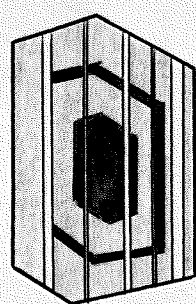
Because twinning is so commonly superposed on zoned crystals, it seems possible to trace the development of twinning through most of its stages. The process outlined below and illustrated by Figure 6, seems to be valid for some crystals at least.

Twinning begins as very narrow streaks, developed first in the rim of plagioclase. Usually they parallel 010, but sometimes they follow rarer twinning planes (Figure 6, 1). The new twin lamellae taper and disappear towards the core of the crystal. In a later stage, when they have widened, their width is fairly uniform throughout. As they widen, they also lengthen, extending through the core and opposite rim (Figure 6, 2). In these new lamellae the zoning has been either completely destroyed, or reduced to a faint shadow of the original. The original zoning remains sharp and clear throughout the rest of the crystal. The fact that some preservation of the zoning does occur in the new lamellae indicates that they have formed by diffusion processes, acting most vigorously parallel to the composition plane. Continuation of the process leads to a crystal composed largely of broad new lamellae, with a few narrow, old lamellae

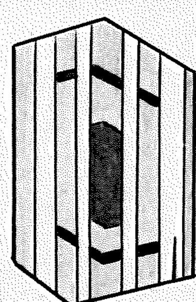
Plate 6. Diagrammatic Illustration of Twin Development



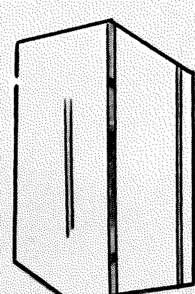
1. Twin lamellae developing in outer zones. Typically wedge-shaped Lamellae positions are sometimes controlled by zone boundaries as shown for lamellae on left.



2. Lamellae have extended through core. Zoning is shown as having been completely eliminated in the new lamellae, although frequently the zoning is only reduced in range from core to rim.



3. The lamellae have grown wider, eliminating much of the zoning.



4. Continued widening of the lamellae has resulted in coalescence, and consequently elimination of much of the twinning. The lamella on the right represents a second generation lamella beginning another cycle. The short lamella on the left is a remnant interspace partially destroyed by coalescence.

representing the former zoned crystal (Figure 6, 3). As twinning continues to develop it tends to destroy itself by eliminating the interspaces (Figure 6, 4). There is, however, some indication that the process tends to start over again once the new lamellae reach a certain width but the process is difficult to trace because there is little zoning by which you may separate the first generation of lamellae from the second, unless both generations are present in one crystal. Third generation lamellae were observed, however, in quite a few drystals.

The evidence available suggests that the formation of the twin lamellae is a gradual process, not an instantaneous snapping into place of certain ions in response to exterior stress. Because zoning is actually destroyed by the process, there is little alternative but to assume that some form of diffusion is operative. Yet diffusion in itself cannot be the whole explanation of twinning, for why should not the moving ions take up the same relative position in their space lattice when they have ceased to move, as the previously occupied, resulting in a kind of homogenization of the crystal but no twins. A factor of importance seems to be that the diffusion process does not take place in a closed system. If it did, the rims of the new lamellae should become more calcic as the cores become more sodic. But there is no evidence that the rim ever becomes more calcic in the process, rather the whole crystal becomes relatively more sodic. Thus sodium which leaves the rim to diffuse towards the core must be replaced by sodium from outside the crystal and the calcium which is displaced in the core is forced out of the crystal.

Although there is no obvious reason why closed-system diffusion should cause an inversion of the lattice, it is possible that the displacement of calcium by sodium in an open system could set up sufficient strain with respect to adjacent areas that inversion might be effected, the inverted position being one of less strain.

Since the twinning described seems to be due to a sort of diffusion process it can be effective only above certain temperatures, and this temperature should theoretically be higher for calcic than for sodic plagioclase. Also, at given stress and temperature conditions, somewhere above the critical temperature, the rate of lamellae development is probably more rapid in sodic plagioclases. Thus thread-like lamellae separated by wide interspaces are characteristic of calcic plagioclases. The lamellae of calcic plagioclases seldom develop to the point where twinning is eliminated because the process is usually arrested at a higher temperature in the calcic plagioclase. The generally wider lamellae in calcic plagioclase may be simply wide interspaces in which no lamellae have been initiated. Since, in references to average widths of lamellae, both interspace and new lamellae are considered together, and since one grows narrower as the other becomes wider, the average lamellae width is primarily a matter of the number of lamellae initiated, and this is probably controlled by both the composition and the temperature of the plagioclase during twin formation.

MISCELLANEOUS ASPECTS OF THE PLAGIOCLASE IN THE PLUTONIC ROCKS

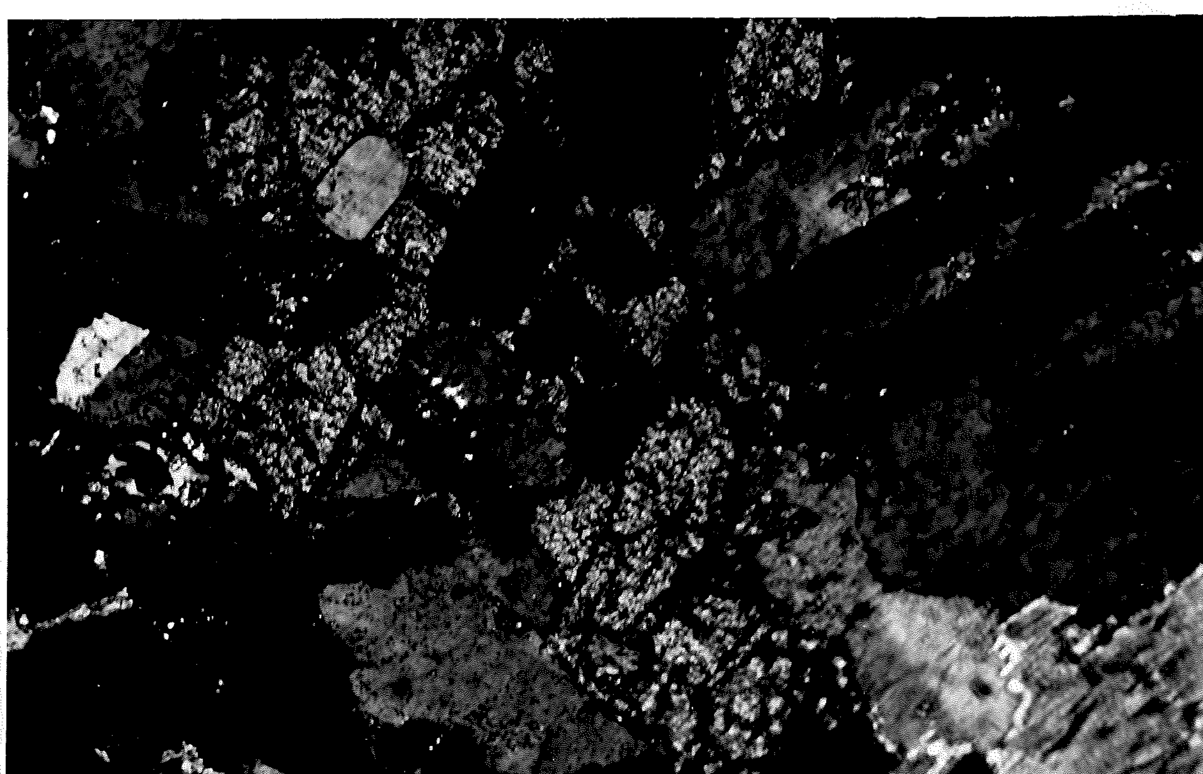
Small remnants of earlier plagioclase grains are quite often found within plutonic plagioclase crystals. The small remnants are derived chiefly from the hornblende granulites, and occasionally from other pre-granitic rocks. The phenomenon is illustrated by Photograph 12 from a feldspathized area within an inclusion in hornblende quartz diorite.

Photograph 12

Small plagioclase remnants from pre-existing granulite, contained in large plagioclase porphyroblast. The small included grains are slightly more calcic than the porphyroblast. X107 (TS A197-52, a biotite-hornblende quartz diorite from Cozen Point, Pitt Lake).

Photograph 13

An illustration of poikiloblastic sphene, including medium andesine crystals. Note that the sphene is irregular in shape. This is typical of the latest mineral in any metamorphic aggregation. X140 (TS 207A-49, a highly feldspathized inclusion in hornblende quartz diorite from near Dean Creek, tributary of the Capilano River).



In only one instance could the relative ages of sphene and plagioclase be established. In this case, illustrated by Photograph 13, the sphene is poikiloblastic, with plagioclase inclusions. Notice in this photograph that the sphene is irregular in shape, as is characteristic of the youngest mineral in any of the plutonic rocks in the area. Numerous indications were found in the thesis area that euhedralism of metamorphic minerals is more dependent upon the shaping effect of replacing activities of younger adjacent minerals, than upon any differences in crystalloblastic strength. The relationship between plagioclase and other major plutonic minerals is dealt with in later sections.

On the whole, there is little evidence in the thesis area that the minerals in the plutonic rock have suffered much physical deformation. Occasionally the twin lamellae are slightly distorted, but this is exceptional. An extreme example is shown in Photograph 14. Here, a plagioclase crystal in biotite granodiorite has been bent through about 45°, 10° of which has been accommodated by a wedge-shaped fracture (now filled with quartz). The extreme rarity of such features, however, indicate that either such high temperatures are rare, or subsequent recrystallization generally removes the evidence.

In a later section on sericite, data are presented which indicate considerable recrystallization of the plagioclase, after it has attained medium grain size. Photograph 15 also supports this contention. It shows a plagioclase crystal (from a biotite-hornblende granodiorite) which contains a string of quartz granules outlining the former shape of the plagioclase crystal. Subsequent growth of the plagioclase has extended its boundaries considerably beyong its former limits. The quartz grains are presumably relicts from a pre-granitic granulite.

Photograph 14

Bent plagioclase crystal, showing a total distortion of about 45°, 10° of which is accommodated by a quartz filled fracture. X29 (TS H223-50, a biotite granodiorite from just south of Bishop creek fan, on Indian Arm).

Photograph 15

String of quartz granules (derived probably from a pre-granitic granulite) outlining the former shape of a plagioclase porphyroblast. The porphyroblast has since grown considerably. X67 (TSK53-51, a biotite-hornblende granodiorite from the ridge between Indian Arm and Coquitlam Lake).

CONCLUSIONS OF THE PLAGIOCLASE STUDY

The more significant conclusions drawn from the study of plagioclase crystals in the plutonic rocks of the thesis area are listed below.

1) Plagioclase is the oldest major mineral in the plutonic rocks.
2) Inclusions in plagioclase decrease from a maximum in relatively undeveloped plutonic rocks, such as hornblende diorite, to a minimum (which is usually none) in the highly developed rocks, such as biotite granodiorite and granite.
3) Plagioclase crystals have slightly more regular shapes in the highly evolved rocks.
4) Zoning is usually oscillatory; usually simple and rare in the end members of the plutonic series; most complex and common in the intermediate plutonic rocks, containing both hornblende and biotite.
5) The development of lamellar twinning in a zoned plagioclase tends to destroy the zoning.
6) Adjacent plagioclase crystals often have different histories.

POTASSIUM FELDSPAR IN THE PLUTONIC ROCKS

GENERAL STATEMENT

Before launching into the description of the occurrence of potash feldspar in the area, some features of the terminology, especially the terms orthoclase, microcline and perthite, should be considered. Orthoclase and microcline appear to be a complex pair of minerals, and some of the data concerning them seems contradictory. The two minerals have about the same composition, as is suggested by the following statements taken from Winchell's (1947) textbook.

p.337 "((Chemical quantitative analyses))* do not distinguish between orthoclase and microcline (whether soda-bearing or not) nor between anorthoclase and microscopic intergrowths known as perthite."

p.320 "All proportions of Or ((orthoclase molecule, $KAlSi_3O_8$)) and Ab ((albite molecule, $NaAlSi_3O_8$)) seem to occur in homogeneous crystals in rocks, -----."

p.317 "Natural crystals of orthoclase and of microcline usually contain 10 to 25 percent of $NaAlSi_3O_8$."

p.361 "Orthoclase of nature is practically never composed of the pure substance $KAlSi_3O_8$ but usually contains about 20 percent of $NaAlSi_3O_8$ besides very small amounts of other molecules."

p.362 "Ordinary orthoclase (both adularia and sanidine) contains up to 30 percent $NaAlSi_3O_8$; crystals containing more than 30 percent $NaAlSi_3O_8$ are stable only at high temperatures, but they are not rare as metastable substances at ordinary temperatures."

p.364 "Natural microcline is practically never composed solely of $KAlSi_3O_8$ but usually contains about 20 percent of $NaAlSi_3O_8$, besides very small amounts of other minerals."

It does not matter much, that the two minerals do not differ in composition, for in routine work it is only necessary that they can be distinguished on the basis of their optical properties. Orthoclase has been well-defined as the monoclinic form, and microcline as the triclinic form.

Concerning this matter Alling (1936) states that

p.61 "Barth says that, if the alkali feldspars should prove to be all triclinic, then the present determinational methods would have to be greatly modified. Winchell does not think that this is so because triclinic feldspars are only slightly modified from monoclinic forms. Baier says 'There is little doubt that the apparent monoclinic symmetry of certain feldspars should be looked upon as a result of twinning of submicroscopically small triclinic units'. If the above is true determinations based upon axial angles or birefringences are obviously dependent on the type of twinning rather than on the chemical composition."

---

* Words in double brackets inserted by writer.

Winchell takes a more positive attitude, but approaches the subject with some caution.

p.354 "There has been much discussion concerning the relations between orthoclase and microcline. Many writers regard them as essentially identical, differing only in the coarseness of twinning, which is microscopically visible in microcline, and considered to be present sub-microscopically in orthoclase. However, the most accurate measurements of specific gravity, optical angle, and refractive indices seem to indicate slight differences between orthoclase and microcline, and the observation of Merwin (1911) that orthoclase inverts at about 900°C, while microcline is stable to its melting point, seems to show that the two are not identical."

p.317 "Crystals of orthoclase are monoclinic, and those of plagioclase are triclinic, but the forms are nevertheless, very similar with angles differing only 3° or 4°."

There seems to be an implication in the last statement that the difference between the forms of orthoclase and microcline is even less, than that between orthoclase and plagioclase. Yet, there is nothing dubious in the following assertion by Winchell.

p.363 "Being monoclinic, orthoclase has no multiple twinning and the cleavage angle is exactly 90°."

When the writer began his investigation of the potassium feldspars he called those crystals that showed grid twinning, microcline, and those which showed no twinning, orthoclase. It was simple, but was unacceptible because, as Winchell points out,

p.366 "Microcline devoid of multiple twinning is quite rare but not unknown."

It must be admitted that a hint of philosophical palliation clings to the view that the twinning itself is a more important difference between the two minerals than whether the angle between the a- and b-axes is 89°55' (microcline) or 90°00' (orthoclase), (angles from Winchell, 1947).

With the ordinary petrographic microscope the optic angle can only be estimated, but even if accurate measurement were possible in routine work, it would be of dubious value in distinguishing microcline from orthoclase. Winchell makes two statements on this subject.

> p.331 "The optic angle is about 70° in orthoclase and about 80° in microcline, -----."

> p.362 "In this way ((by heating above 600°C, and cooling to normal temperature)), the optic angle in orthoclase may be changed to almost any value less than 70° in the plane normal to 010, ---." "Natural orthoclase shows a similar variation in the size of the optic angle."

Apparently it is not only petrographers who experience some difficulty in distinguishing microcline from orthoclase, as Alling (1936) notes

> p.60 "The X-ray data of Kozu, Endo, and Hadding indicate that there is no difference in the Laue photographs between orthoclase and microcline. Vogt and Wyckoff question the value of their data. W.L. Bragg tells me that X-rays give the same microclinic structure for sanidine, orthoclase and microcline."

The perusal of the primary differences between microcline and orthoclase has led the writer to delete the terms "microcline" and "orthoclase" from the descriptive section, and to substitute the more cumbersome, but less ambiguous term, "potassium feldspar".

The term "perthite" causes somewhat less difficulty. Concerning its origin Dana's Textbook of Mineralogy contains the following statement.

> p.540 "As first described, a flesh-red aventurine feldspar from Perth, Ontario, Canada, called a soda-orthoclase, but shown by Gerhard to consist of interlaminated orthoclase and albite."

Originally, and to some extent still, "perthite" is restricted to varieties sufficiently coarse, that the two constituent minerals can be distinguished by the unaided eye. The term "microperthite" was coined for application to similar intergrowths visible only under a microscope. The trend was carried to the ultimate with the proposal of the term "cryptoperthite" for intergrowths invisible, with or without a microscope. It is unfortunate that microperthites are as common as perthites are rare. Many authors conscientiously use "microperthite", when the noun is required, but do not hesitate to use "perthitic" for the equivalent adjective. There seems to be a general feeling that the term "perthite" is too useful to be restricted to a very rare phenomenon. Consequently, they tend to define the term rather broadly, with no reference to coarseness. For instance, Alling (1936) states that

> p.69 "Perthites are intergrowths of a potash-rich feldspar and a soda-rich feldspar."

and Winchell (1947) expresses it this way

> p.363 "Regular intergrowths of orthoclase (or microcline) and albite, called perthite, ----."

The restrictions implied by the words "Regular" and "albite" are in the writer's opinion not necessary. More important, however, is the fact that grain size is not considered a factor of vital importance. He emphasizes his use of the term in the following phrase,

> p.337 "-------, microscopic feldspar intergrowths known as perthite."

In this thesis the term "perthite" is used according to Alling's broad definition. All the perthite in the thesis area is visible only under a microscope.

The terminology available for describing perthites is not very satisfactory either, and lacks standardization. The shapes of the "albite" elements are so varied, they almost defy adequate description. One is tempted to abscond with the set of meteorological terms used to describe various cloud formations and to apply them to perthites, but shrinks from the dubious distinction of further complicating geological etymology, already the most bizarre in scientific languages.

The perthite in the thesis area consists of small blebs, films, strings, stringlets, rods, veinlets and patches of "albite" in potash feldspar most of which does not show grid twinning. The "albite" may be as calcic as An15 but usually is considerably less, falling well within the albite range. The descriptive terms used refer to the appearance of the perthite in thin section, and although some of the terms (strings, rods, etc.) imply a restricted third dimension, such restriction may or may not be present.

During the investigation it was found that the coarseness of the perthite was largely dependent on the rock type in which it occurred. A simple classification was set up to distinguish three types of perthite, namely fine-grained, medium-grained, and coarse-grained, referring to the average size of the "albite" elements and not to the size of the perthite grain. This type of classification was preferred to one which is based on the shape of the "albite" elements, because the coarseness bears a distinct relationship to the rock type in which it is found, while the shape seems to represent only various stages of perthite development and is less directly related to rock types. The sizes chosen are based on practicability, and are otherwise arbitrary. They are, of course, applicable only under the microscope.

Fine-grained	---	.004 mm average width	(av. length .02 mm)
Medium-grained	---	.012 mm " "	(" " .08 mm)
Coarse-grained	---	.04 mm " "	(" " .30 mm)

The three types are gradational into one another. The fine grained perthite grades into potassium feldspar with no visible "albite" member. In rocks containing medium-grained or coarse-grained perthite, non-perthitic feldspar was not found (although occasionally patches within some perthite grains are non-perthitic). Potassium feldspar with grid twinning shows a strong preference for association with coarse-grained perthites. It was never recognized in rocks containing only non-perthitic, and/or fine-grained perthitic feldspar.

In the area under consideration potassium feldspar was found in both sodic and calcic rocks. This fact predestined the early attempts to map the rocks of the Coast Mountains to failure, because the classification of plutonic rocks used was based merely on the ratio of alkali feldspar to plagioclase, and resulted in rather meaningless maps which camouflaged significant detail.

EFFECT OF MINERAL CONTENT ON THE TYPE OF PERTHITE PRODUCED

Where the anorthite molecule of the plagioclase exceeds about 35%, the potassium feldspar tends to be non-perthitic and without grid twinning, although a little very fine-grained perthite is occasionally present. As the anorthite percentage declines, the coarseness of the perthite increases; medium-grained perthite is common at about An20-35, and coarse-grained perthite for values less than An20. Grid twinning also increases with the coarseness of the perthite. In 95% of the sections examined where hornblende equals or exceeds biotite, the potassium feldspar contains none or only fine-grained "albite" elements. On the other hand, medium-grained perthite, coarse-grained perthite, and grid-twinned potassium feldspar are each restricted to rocks in which biotite exceeds hornblende. Besides the calcium content of the rock, the quartz content also appears to influence the form of the potassium-feldspar but only if the quartz content is exceptionally high. When this condition exists the potassium-feldspar tends to be non-perthitic. This fact is evident even within single thin sections wherein the quartz distribution is uneven. The quartz-rich portions contain non-perthitic feldspar (or very fine-grained perthite), and the quartz-poor (plagioclase-rich) portions contain medium-grained perthite (Photographs 16 and 17).

PERTHITIC METASOMATISM AND PSEUDOSORPHISM

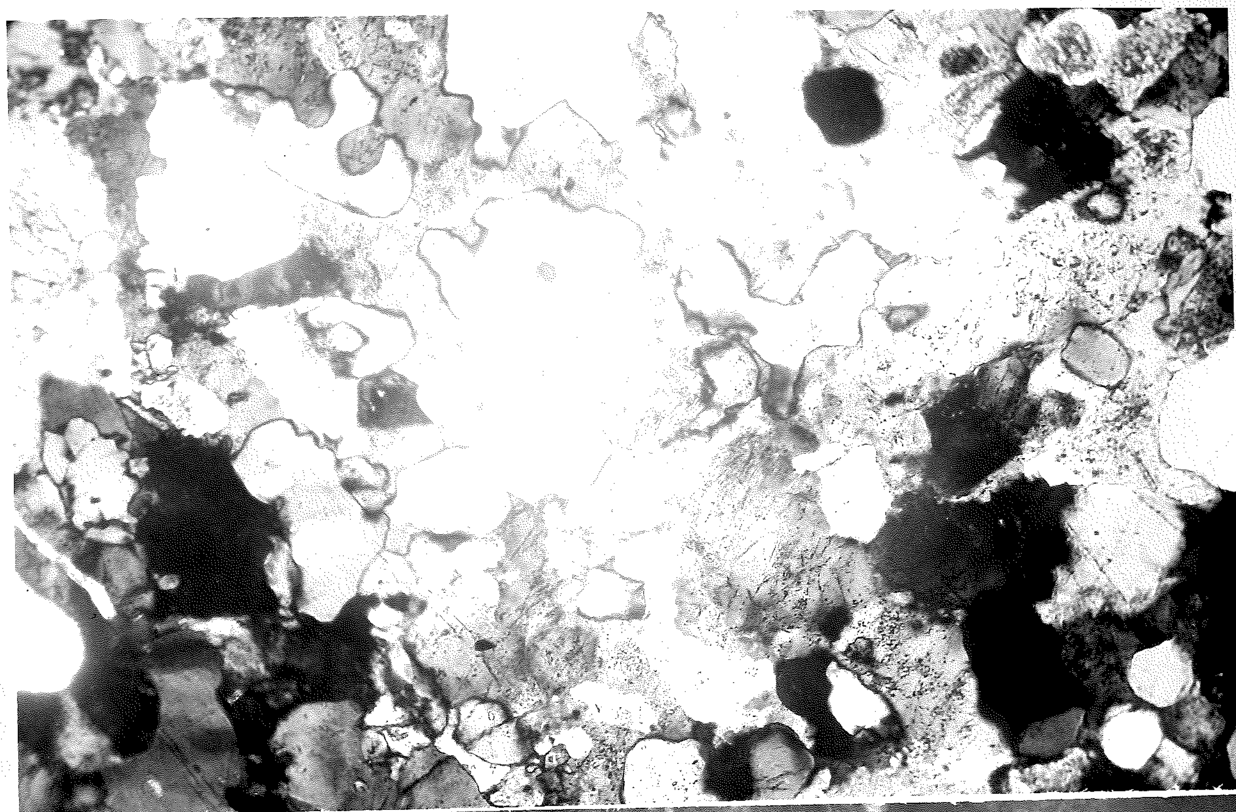
The sections show every stage of replacement of plagioclase by potassium-feldspar. The early stages (anti-perthitic) are found in rocks containing little potassium-feldspar, and sometimes in other rocks where the caprices of fortune have left some plagioclases only slightly altered. A typical example is a fairly sodic plagioclase (An20) containing small patches of potassium-feldspar (never perthite in these early stages). Under high power, the potassium-feldspar cleavage is found to parallel that of the plagioclase. Not only are the cleavages parallel but their traces often pass continuously from one mineral to the other. This indicates that the structure of sodic feldspar is sufficiently close to that of potassium-feldspar to permit pseudomorphism of internal structure. When several patches of potassium-feldspar occur in one plagioclase crystal,

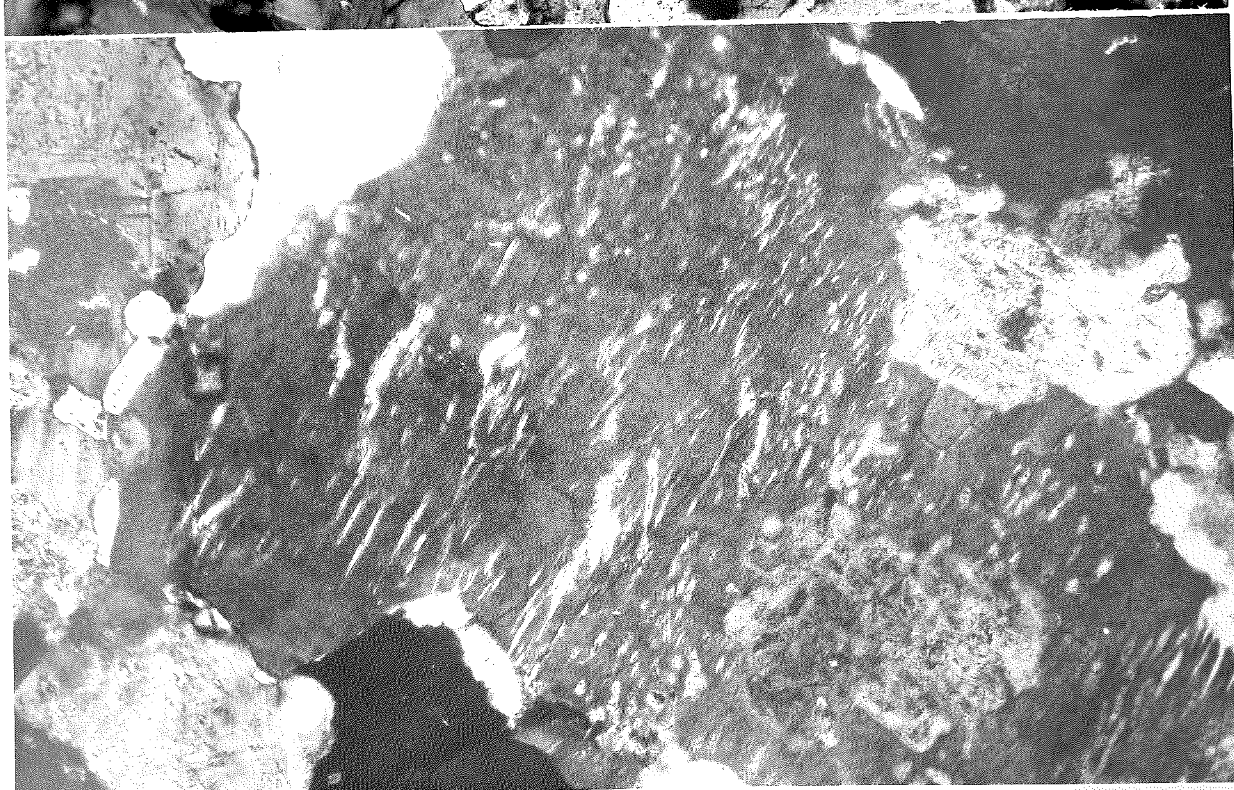
Photograph 16

Potassium feldspar tends to be non-perthitic, in quartz-rich parts of the thin section, and in fact in all places where sodium content is low. X75 (TS K32-51, a chlorite-biotite granite from the east side of Indian Arm, opposite Crocker Id.).

Photograph 17

The area shown here is ¼ inch away from the area shown in Photograph 16 above. Here the potassium feldspar has replaced a plagioclase-rich portion of the thin section, and is markedly perthitic. X140 (TS K32-51, etc. as above).

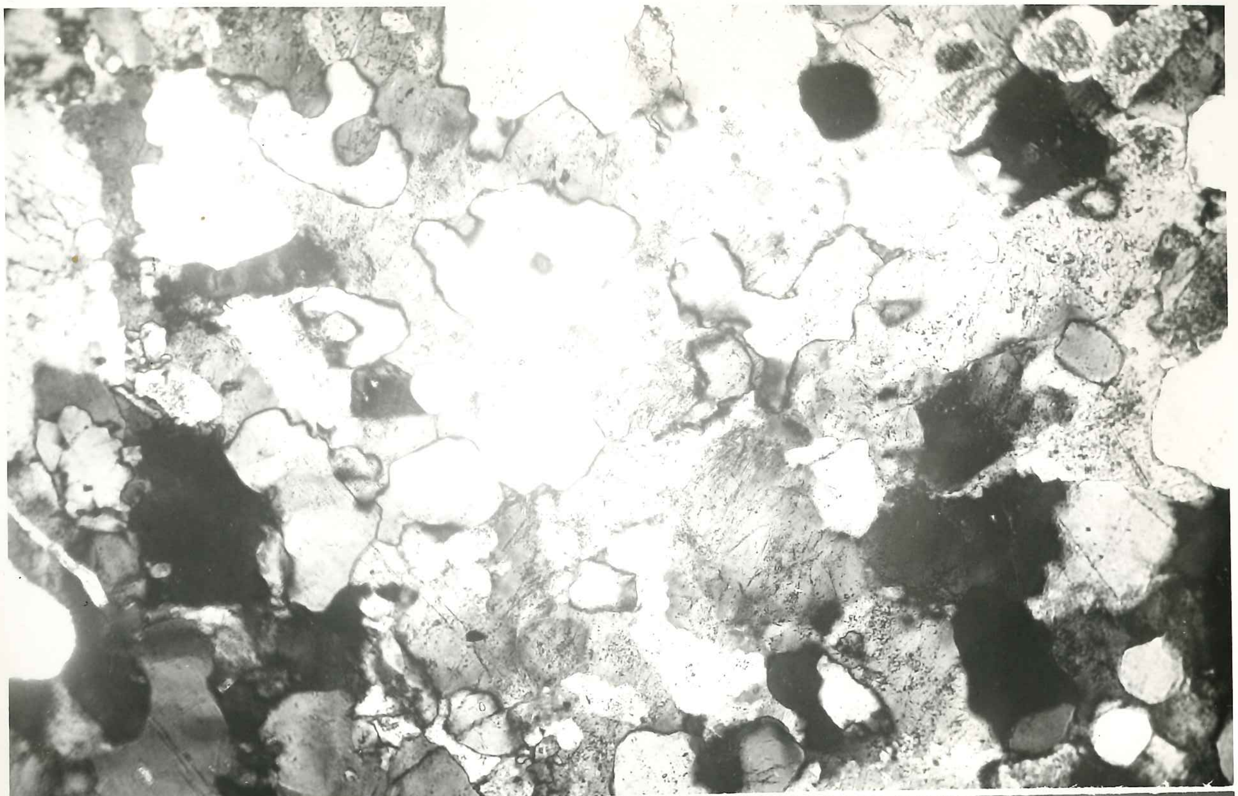




the various patches, even though separated, are pseudomorphic after the same host structure, consequently they have, perforce, parallel optical orientation. However, the structures of potassium-feldspar and sodic plagioclase are not identical, and if special circumstances give the potassium-solutions a choice between extending the structure of a previously formed potassium-feldspar crystal or assuming that of a sodic plagioclase, they naturally choose the former. This is illustrated in Photograph 18 which shows an oligoclase crystal containing a grain of magnetite. This crystal also contains several small patches of non-perthitic potassium feldspar, one of which has grown around the magnetite grain. All the patches are in optical continuity except the one surrounding the magnetite grain. This patch extinguishes 20 degrees off parallelism. This patch of orthoclase has assumed a random orientation, probably because potassium solutions initially replaced the magnetite, rather than a portion of the large plagioclase crystal. Once initiated the potassium feldspar expanded by replacing the oligoclase along the rest of the magnetite-oligoclase boundary, during which the orientation of the growing patch was controlled by the original potassium feldspar grain, not by the plagioclase structure surrounding it. Nevertheless, the shape of the potash feldspar patch in question is controlled in detail by the cleavage of the plagioclase.

Occasionally in the early stages, the potash feldspar patches in the plagioclase are somewhat elongate, producing a rather crude, angular antiperthite. No antiperthite of a different origin was recognized in the rocks from the thesis area.

As the replacement of plagioclase is continued, a stage is reached



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As the replacement of plagioclase is continued, a stage is reached

Photograph 18

Large dark grey area is part of an oligoclase crystal. The dark patches within it are composed of potassium feldspar, and are all in optical parallelism, and controlled in shape by the plagioclase cleavage. The light colored grain in the centre is also potassium feldspar, but it has grown around a magnetite grain, and apparently because of this has assumed a different orientation from the other grains. Potassium feldspar is rarely, if ever, perthitic in this early stage. X120 (TS K30-51, a biotite granodiorite from the east side of Indian Arm opposite Crocker Island).

Photograph 19

Local graphic texture, resulting from the replacement of quartz by potassium feldspar. X28 (Biotite granite from the east side of Indian Arm, opposite Crocker Island).

when the potassium feldspar patches begin to coalesce. The plagioclase is then reduced to isolated patches in the potassium feldspar, a kind of replacement microbreccia. A later stage not far removed, when the patches are smaller and more widely separated, is the patch "perthite" of obvious residual origin (Photographs 20 and 21). The term "perthite" is generally, and should, in the writer's opinion, be restricted to those mixtures in which the "albite" element is not obviously a replacement remant. Otherwise most porphyroblastic textures involving potassium feldspar and plagioclase and coarse replacement microbreccias would be included, although they look different, and have a different genesis than common perthite.

In the most abundant, or normal perthite, the "albite" member is non-angular, and usually untwinned. Various forms such as blebs, veinlets, patches, etc., are common, and their arrangement is not usually highly regimented, although spectacular cases of rigid order are described in the literature. Normally the "albite" is more sodic than the original replaced plagioclase, some calcium having been removed from the system. When the host plagioclase has an anorthite content exceeding 35%, "albite" is rarely deposited and consequently rocks containing such calcic plagioclase contain no or little perthite.

In any consideration of the origin of perthite, the degree of mobility of the "albite" should be established. Is it a relict remnant of plagioclase? Or is it reconstituted plagioclase that has changed in composition, and perhaps in orientation, but has not moved any appreciable distance? Or, finally, is it introduced material, foreign to its host? The behavior of the "albite" at the boundary between two perthite grains contributes some information on the matter. Almost invariably the "albite"

Photograph 20

Twinned plagioclase being replaced by potassium feldspar. The remnants of plagioclase left in the potassium feldspar lead eventually to a patch perthite, shown below. X115 (TS K58-51, Biotite granite from ridge between Coquitlam Lake and Indian Arm).

Photograph 21

Patch perthite of obvious residual origin. Twinned patches are plagioclase, dark matrix is potassium feldspar. X89 (TS N121-52, a biotite-hornblende granodiorite from one mile northwest of Widgeon Lake).

members stop at, or more commonly, before the boundary. Only rarely do they cross from one crystal to another, and these generally are simple fracture fillings. This evidence indicates that the "albite" is generally of local origin, that is, from within the crystal it now occupies. Some features suggest that the mobility of "albite" is sometimes extremely limited, even within a perthite grain. Perhaps the most striking example of this is the preservation of plagioclase zoning by perthite. In these instances (Photographs 22 and 23), the sodic rim of a replaced, zoned plagioclase crystal is represented by perthite (generally medium or coarse-grained), while the more calcic core is represented by non-perthitic potassium feldspar. Occasionally very calcic zones lying somewhere between the rim and the core are also preserved by non-perthitic bands within perthitite crystals, although the preservation is seldom perfect. These features are admittedly exceptional, but they indicate an extremely local source for the "albite" element of the perthite. It is not implied, however, that all of the sodium in the original plagioclase remains in the perthite crystal. On the contrary, a portion of the sodium is removed and sometimes fixed as "albite" in distant perthite crystals, but this is rare, and is easily recognized because of the type of perthite which results (Photograph 24). The most descriptive term for it is "Fire" perthite. It is formed when the "albite" stems away from a central fracture along which it is introduced, and the "albite" appears as flames extending from the fracture into the potassium feldspar. Even where this situation is present, most of the "albite" in the potassium feldspar will be of the normal type, that is having a local origin. It is not difficult to distinguish the two, as shown in Photograph 24.

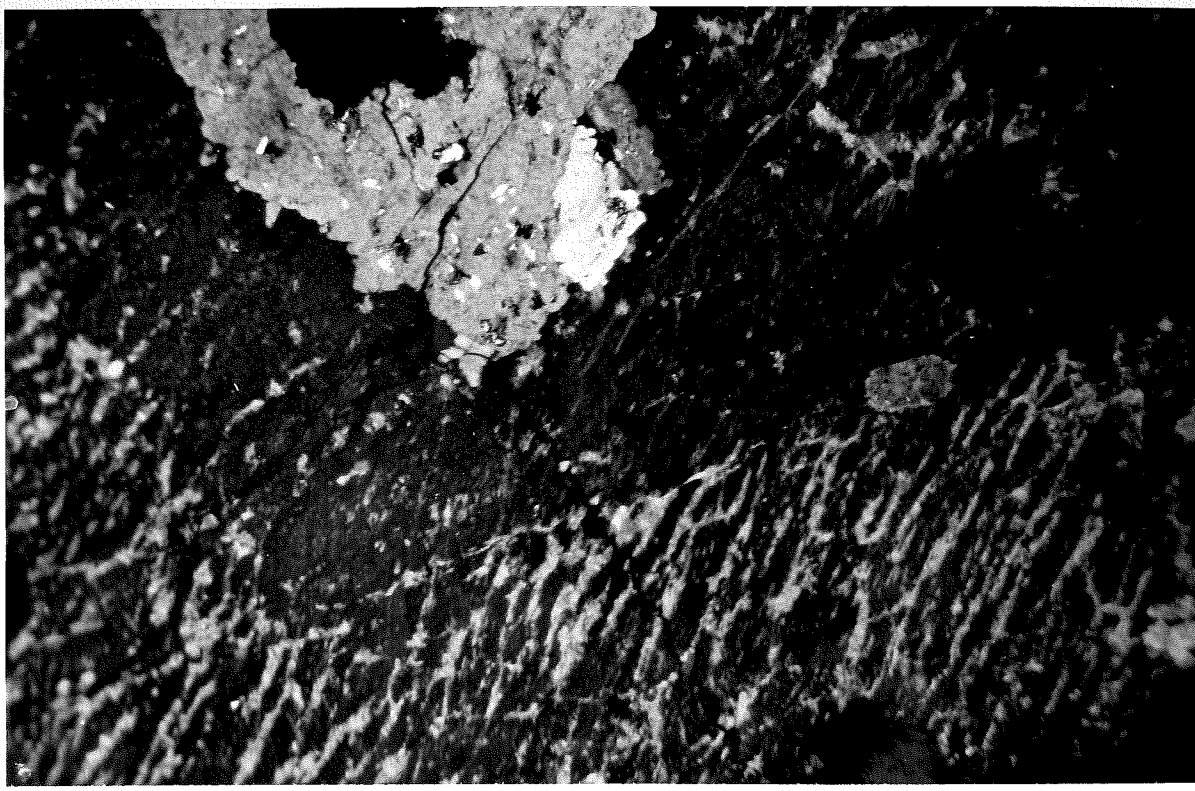
Also supporting this general contention of limited mobility is the rather rare case of a coarse-grained perthite being in contact with

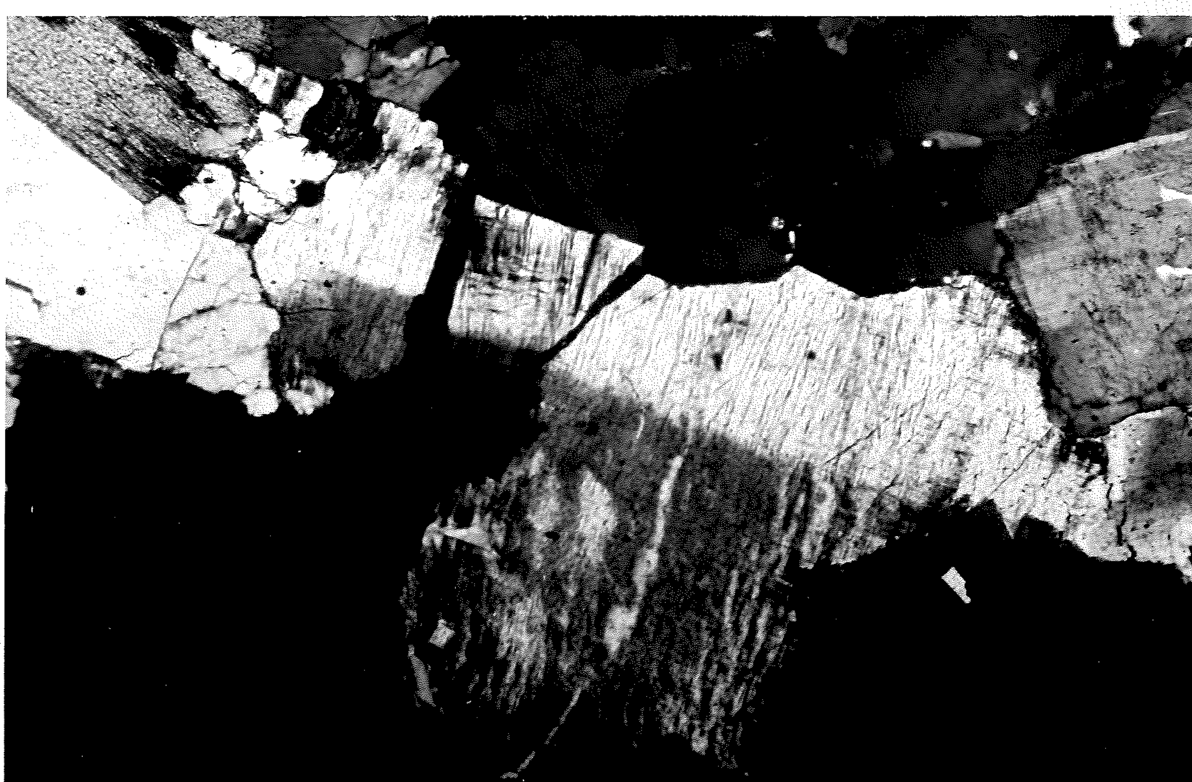
Photograph 22

Whole field is believed to represent former large plagioclase crystal now mostly replaced by potassium feldspar. The portion of the plagioclase remaining (upper edge) and the relatively non-perthitic area around it probably represents the former core of the pre-existing large crystal. The highly perthitic area bordering it is thought to represent the site of former sodic rim. X44 (TS N29-52, a biotite granite, from the west side of Coquitlam Lake, opposite the north end of the island).

Photograph 23

Another example of pseudomorphism of potassium feldspar after zoned plagioclase. Here, however, the potassium feldspar has assumed a different orientation in the site of the rim than in the site of the core of the former plagioclase crystal. No Becke line separates the two orientations of the potassium feldspar. Both are perthitic but the "rim" is considerably more so although in this photograph the orientation obscures the highly perthitic nature of the "rim". X54 (TS R112-50, a biotite granodiorite from just west of Burwell Lake).





Photograph 24

"Fire" perthite. Albite has been introduced along a fracture in the potassium feldspar, and then replaced some of the adjacent potassium feldspar, chiefly on one side (left). The flame-like extensions of albite from the fracture are in marked contrast with the narrow stringlets of local origin, best shwon on the right. X160 (TS K86-51, a biotite granodiorite from the east side of Indian Arm opposite Crocker Island).

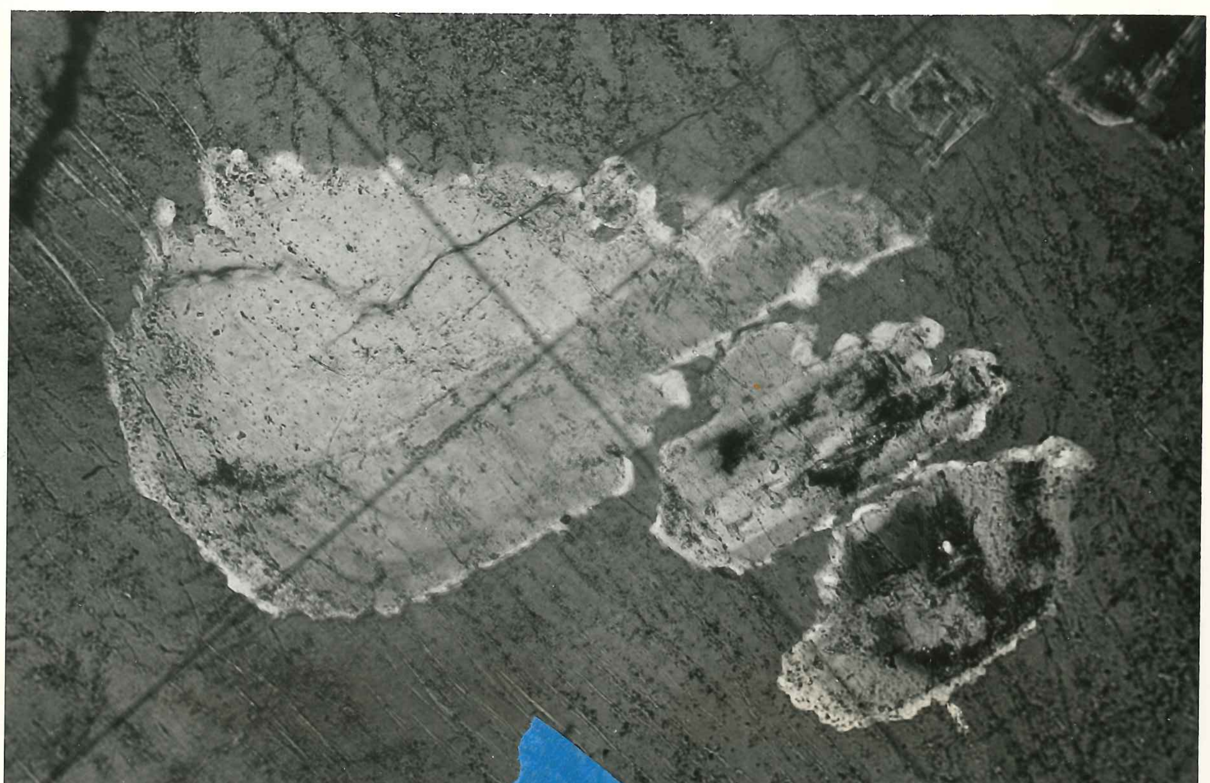
a crystal of non-perthitic potash feldspar (Photograph 27). This may have resulted from the replacement of an area of either calcic plagioclase, or quartz, in which there was a crystal of sodic plagioclase, and only the area of sodic plagioclase produced perthite. In the thesis area it is not uncommon to find a sodic plagioclase crystal among calcic crystals, because the latter are often subjected to incomplete sodium metasomatism and the process is found in all stages of completion. The opposite result, a calcic crystal in a sodic one is also found, representing a replacement remnant of a calcic plagioclase. When such a case is encountered by potassium solutions, the sodic plagioclase is replaced preferentially to the calcic plagioclase. Later if the solutions still have sufficient strength, the calcic crystal is also wholly or partly replaced, but more often it is simply included by the potassium feldspar, as it was previously by the sodic plagioclase. If the original plagioclase host was sufficiently sodic, and the resultant potassium feldspar a perthite, the included plagioclase grain is usually rimmed and partially replaced by the "albite". (Photograph 26). Misch refers to this feature as "superposed zoning induced by replacement of plagioclase by potassium feldspar" (oral communication). Drescher-Kaden (1948, p.55) in his excellent treatment of this and similar granitic textural phenomena, also illustrates this feature. There is evidence (Photograph 27) supporting the theory that the "albite" is far more effective in replacing calcic plagioclase than is potassium feldspar. When given a choice between calcic plagioclase and potassium feldspar the "albite" preferrentially replaces the plagioclase. This provides an additional reason for believing that very little perthite can be produced by "foreign" (originating outside the perthite crystals) solutions, for

Photograph 25

Highly perthitic area in the potassium feldspar is believed to represent a pseudomorph after a very sodic plagioclase crystal. The relatively non-perthitic areas may have been occupied formerly by calcic plagioclase, or more likely, by quartz. X30 (TS R25-49, a chlorite granite from Sunset Beach, east side of Howe Sound).

Photograph 26

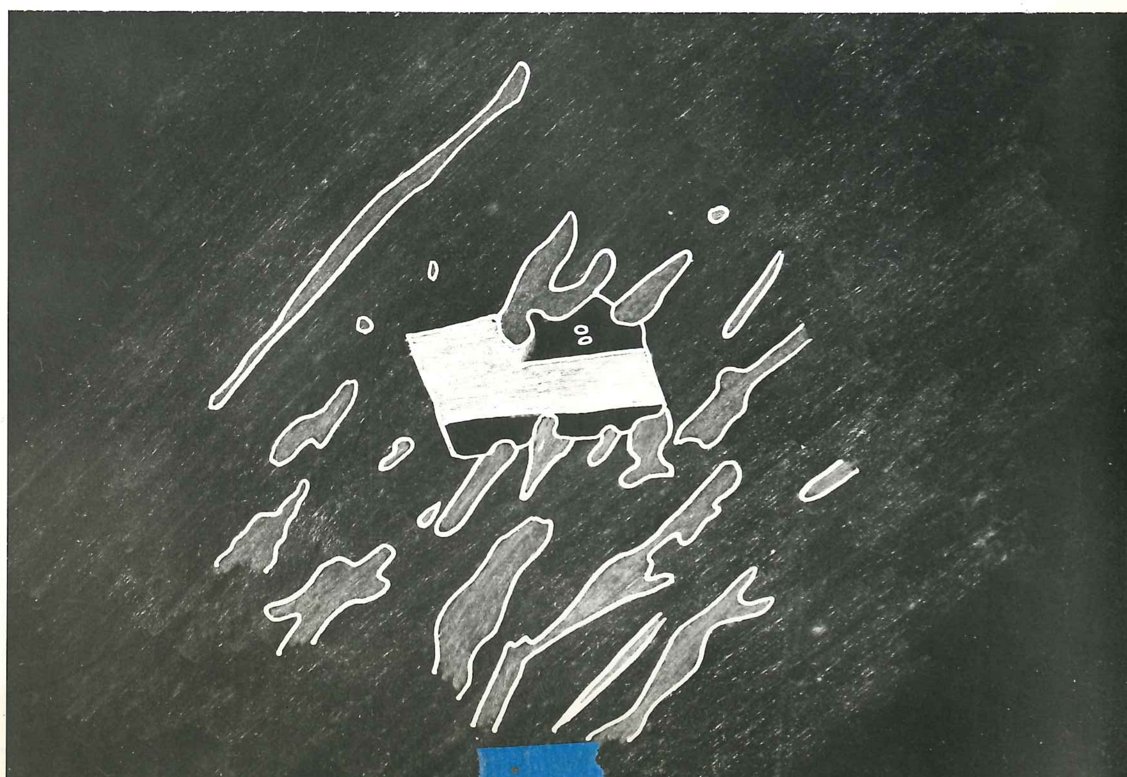
Piokiloblastic potassium feldspar containing partially replaced inclusions of plagioclase. The light colored albite rims on the plagioclase typically precede the advance of the potassium feldspar. X108 (TS 17A-48, a biotite-hornblende granodiorite from Caulfeild, north side of Burrard Inlet).



Photograph 27

A plagioclase crystal is shown included in perthite. The albite member of the perthite deeply invades the plagioclase, indicating that it is more effective than potassium feldspar in replacing plagioclase. X132 (TS K43-51, a biotite granite from ridge between Indian Arm and Coquitlam River).

(diagrammatic representation of the above)



if such sodium bearing solutions pass through plagioclase-bearing rocks, the potassium feldspar would be relatively immune until the plagioclase had been albitized.

Occasionally a sodic plagioclase crystal, before replacement by potassium feldspar, contains a small grain of quartz. After replacement, the potash feldspar includes the quartz grain, and, if the plagioclase was sufficiently sodic, the quartz grain has an albite rim. If the plagioclase is more calcic than oligoclase, the quartz is replaced by potash feldspar, before the plagioclase is much affected (Photograph 34).

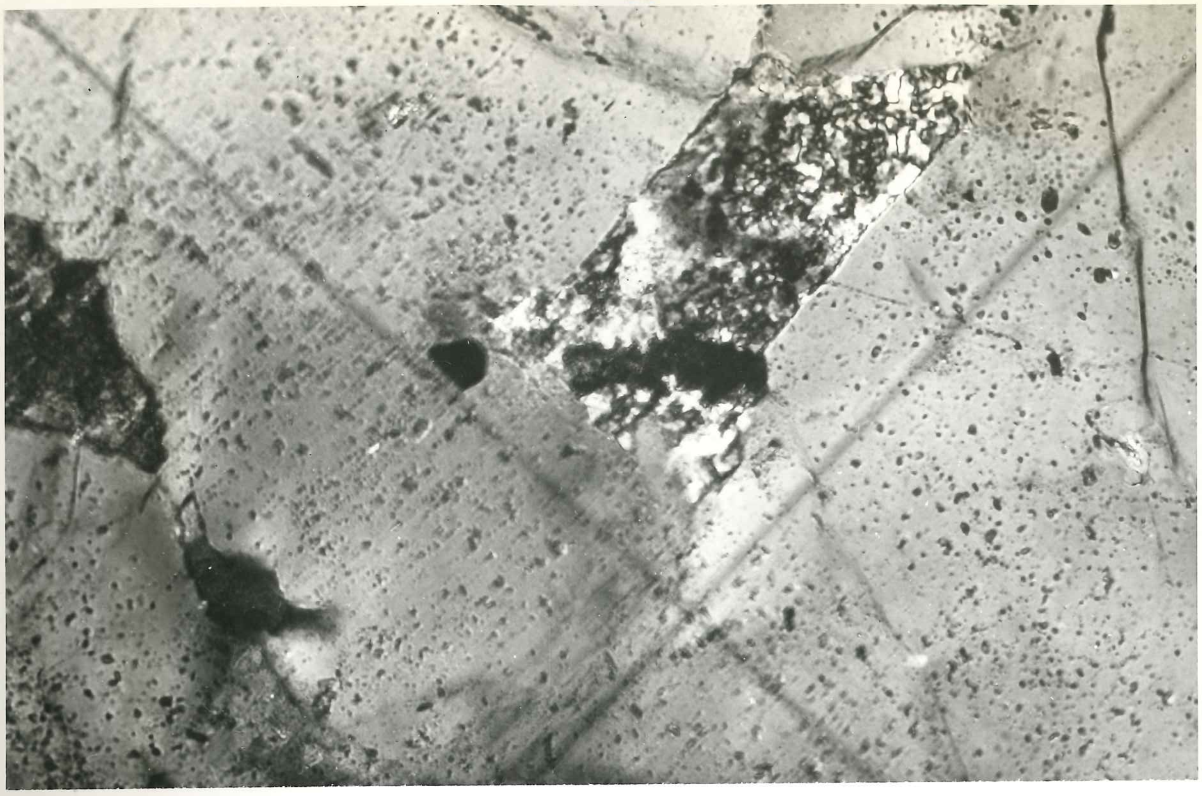
The preservation of plagioclase lamellar twinning in potassium feldspar, seems to require ideal conditions but several examples were noted. In one instance a medium-grained perthite has replaced a plagioclase crystal which was poikiloblastically contained in a large crystal of biotite. The plagioclase twinning (polysynthetic) is now faintly preserved in <u>both</u> the potassium-feldspar and the "albite". This inherited twinning is considerably fainter than that normally occurring in plagioclase, and is visible only at certain critical positions with respect to the crossed nicols. Another example is shown in Photograph 28. Preservation of twinning was noted also in the early stages of replacement, where the potassium-feldspar is restricted to small patches within the plagioclase. The inherited twinning is parallel to and continuous with that in the plagioclase, but tends to be less continuous and distinct, and, naturally, extinguishes at a different position (Photograph 29). Further proof that potassium-feldspar can assume plagioclase crystal structure when conditions are suitable is pointed out by Kennedy (1953). He shows an excellent photograph in which carlsbad twinning can be traced without a break or

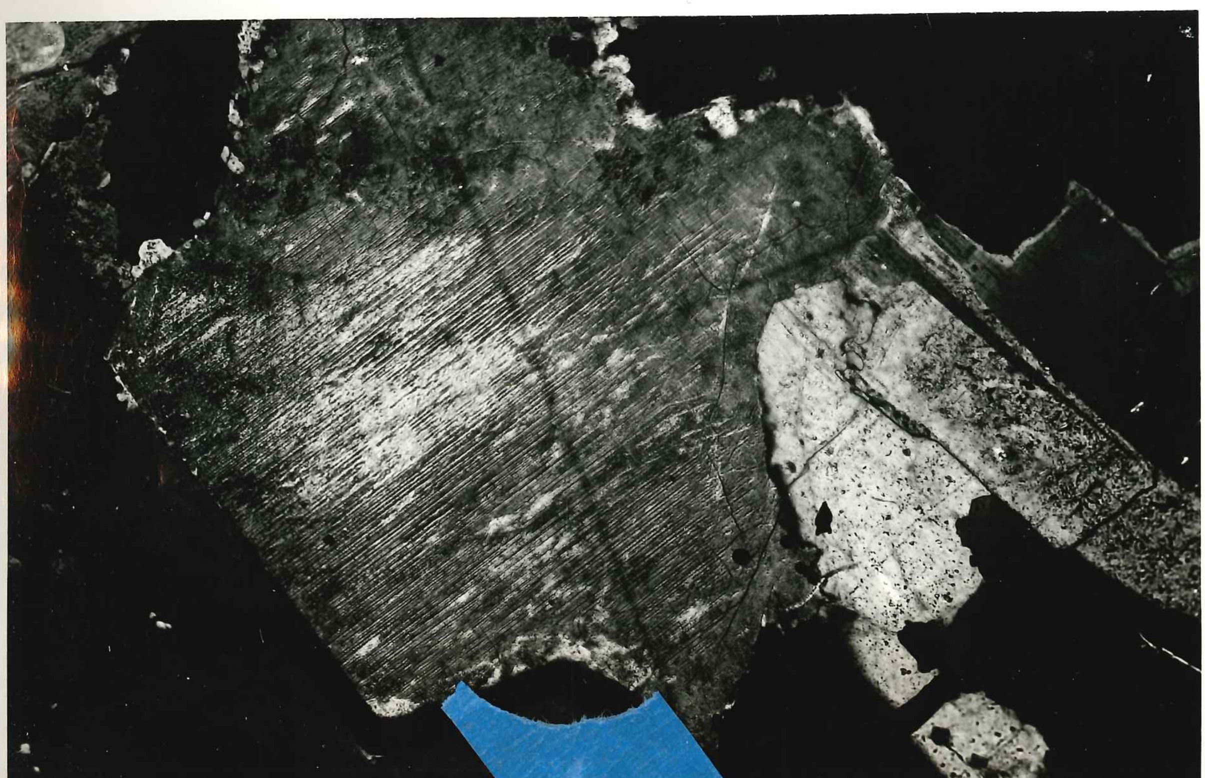
Photograph 28

Preservation of lamellar twinning in potassium feldspar. X70 (TS 19A-48, a hornblende-biotite granodiorite from Caulfeild, north side of Burrard Inlet).

Photograph 29

Large crystal is plagioclase, and the dark patches in it are potassium feldspar. Close scrutiny reveals that the plagioclase twinning passes through the patches of potassium feldspar. X95 (TS 115A-48, a hornblende-chlorite granite from the south side of Sisters Creek, a tributary of the Capilano River).





Photograph 30

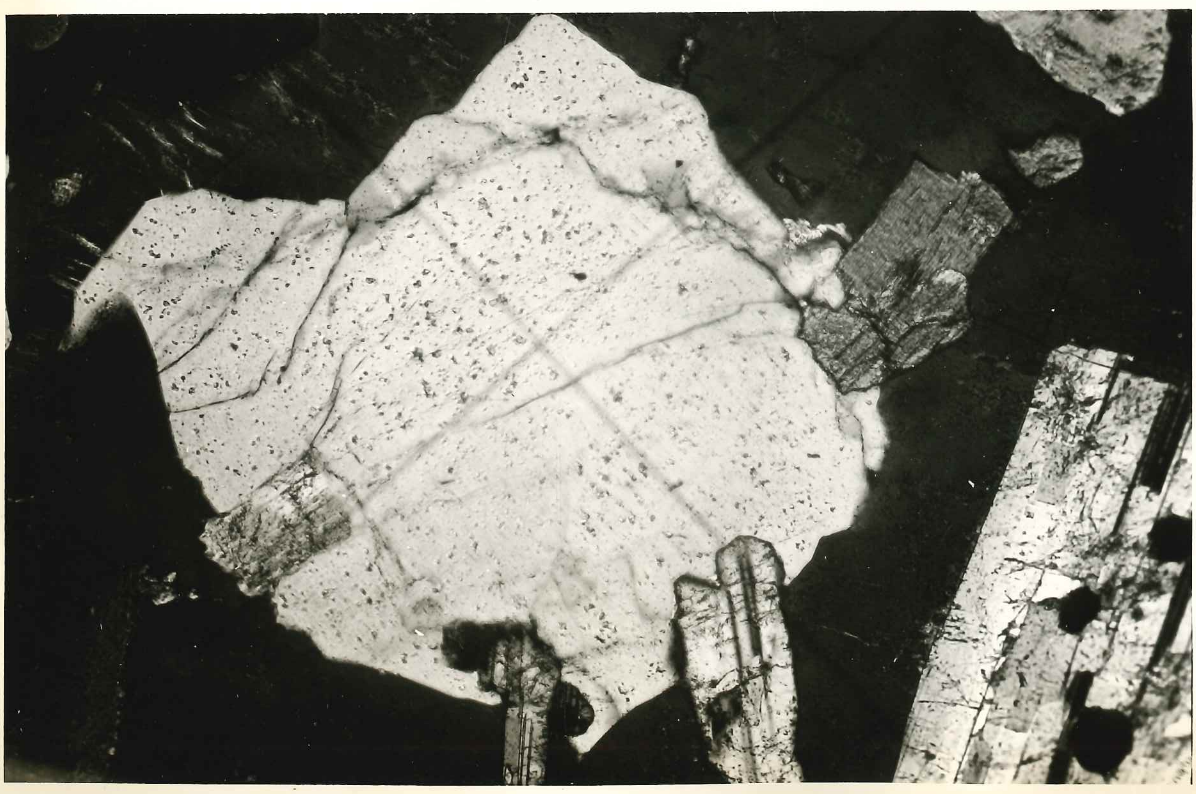
Potassium feldspar pseudomorphic after a sodic plagioclase crystal which was included in quartz. The potassium feldspar is irregularly perthitic. X57 (TS R166-49, a biotite-hornblende granodiorite from just northeast of The Needles).

Photograph 31

Illustration of gradation between albite and potassium feldspar. White areas are albite, and dark areas are potassium feldspar. The grey areas appear to be intermediate mixtures of the two minerals. No Becke line separates the albite from the potassium feldspar. X100 (TS 93A-48, hornblende granite from the south face of Grouse Mountain).

Also indicating the presence of considerable contamination of potassium feldspar by sodic elements are ghost plagioclase crystals occurring within the potassium feldspar. They are represented by areas which have a different extinction position from the rest of the potassium feldspar crystal, and, often, are characterized by grid twinning (Photograph 32). In this case, also, the extinction passes smoothly from one to the other without showing a Becke line. There is also an increase in relief indicating a higher soda content in the twinned areas. Perhaps, to the above forms of impure potassium feldspar should be added a very peculiar type noticed in several sections. It resembles tenuous cirrus clouds (marestails), and has no position of overall extinction. Its general appearance simulates a perthite in which "albite" is in imperfect solid solution in the potassium feldspar, and, where present, changes the extinction position of the potassium feldspar. The effect is rather similar to that of "strain" shadows in quartz, but is found in rocks wherein the quartz is not strained. A much closer analogy is seen in some copper ores, where covellite is contained in imperfect solid solution in chalcocite (excellently shown in ores from Cananea, Mexico).

It is apparently an arduous matter for potassium feldspar to replace calcic plagioclase. When confronted with a choice of replacing either quartz or calcic plagioclase, potassium feldspar selects the quartz (Photograph 33). The reason underlying the preference can only be conjectured, with the information available. Obviously, similarity in crystal structure is not the determining factor. Perhaps, excess silica is more easily removed in alkaline solution than is excess calcium.



Photograph 32

Except for the upper left hand corner, the entire field of the photograph is occupied by a large crystal of perthite. The light colored triangular patch near the plagioclase has microcline twinning. This patchy occurrence of microcline twinning in the potassium feldspar is rather common in the thesis area, although microcline twinning itself tends to be rare. X65 (TS K107-51, a biotite granite from the east side of Indian Arm, opposite Elsay Creek.)

Photograph 33

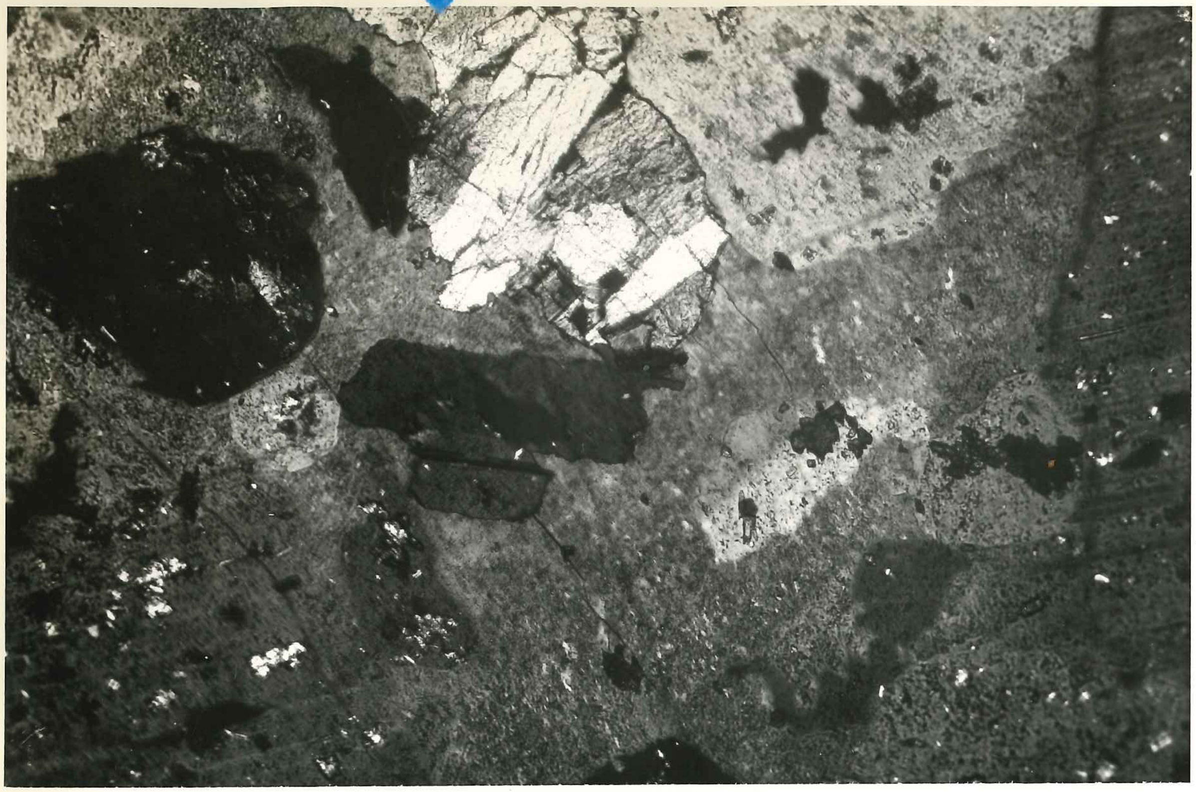
The white central crystal is quartz and the black area is potassium feldspar. The quartz, once poikiloblastic, has been replaced, preferentially to the hornblende, the calcic plagioclase, and biotite. X94 (TS 69A-48, a hornblende-biotite granodiorite from the south slope of Hollyburn Ridge).

When potassium solutions enter a calcic rock, such as hornblende diorite, there is little choice but to replace the plagioclase. This is done first along intergranular contacts, always replacing the calcic plagioclase from the outside inward, not vice-versa as is characteristic when a sodic plagioclase is involved. The resulting potassium feldspar usually contains many partially replaced crystals of plagioclase (Photograph 34).

One section shows the "albite" of a medium-grained perthite, containing numerous small inclusions of quartz and a more calcic plagioclase. The inclusions occur only in the occasional "albite" stringlet or patch, the others are clear. A few similar inclusions occur in the potash feldspar member of the perthite. The tiny inclusions are probably referable to identical material which forms the "mortar" in the pseudocataclastic texture in this section. It may be that these remnant strings (if they be so), served to localize the deposition of the "albite".

PARAGENESIS

Potassium feldspar, as has been pointed out, is the latest mineral in all the rocks which contain it. It replaces and includes all the other minerals, in such a manner that its relative age is never in doubt. The only later minerals are those due to very late alteration, such as, kaolin. The "albite" member of perthitic intergrowths is in a sense later than its host, but is such an integral product of the replacement of plagioclase by potassium feldspar, that it seems best to consider it contemporaneous with the potassium feldspar. At least some of the epidote is also earlier than the potassium feldspar. Photograph 35 shows potassium feldspar



Photograph 34

Illustration of the typical poikiloblastic nature of the potassium feldspar in the thesis area. X58 (TS 17A-48, a biotite-hornblende granodiorite from Caulfeild, north side of Burrard Inlet).

Photograph 35

The potassium feldspar here is shown including both plagioclase and epidote. It is an indication that potassium feldspar can sometimes be later than epidote. X100 (TS 70A-48, a hornblende granodiorite from the south slope of Hollyburn Ridge).

replacing and including plagioclase and epidote. Misch (1952) interprets pre-feldspar epidote as a criterion for granitization.

CONCLUSIONS ON POTASSIUM FELDSPAR

The examination of the potassium feldspar in the plutonic rocks of the thesis area brought these facts to light.

1) Potassium feldspar occurs in both sodic and calcic plutonic rocks.

2) In calcic rocks the potassium feldspar tends to be non-perthitic, in other rocks it is perthitic to some degree.

3) Coarse-grained perthite and potassium feldspar with grid twinning occur only in sodic rocks.

4) Where the plagioclase contains more than 35% anorthite molecule the associated potassium feldspar tends to be non-perthitic, and does not show grid twinning.

5) Where the plagioclase contains less than 20% anorthite molecule the associated potassium feldspar tends to be a coarse-grained perthite, and may show grid twinning.

6) Where hornblende exceeds biotite, the potassium feldspar tends to be non-perthitic, or only very finely perthitic.

7) Where biotite exceeds hornblende, the potassium feldspar tends to be a medium or coarse-grained perthite.

8) Where quartz is unusually abundant, the potassium feldspar tends to be non-perthitic, or only finely perthitic.

9) The orientation of potassium feldspar, where replacing sodic plagioclase, is controlled by the orientation of the crystal being replaced.

10) Plagioclase zoning and twinning is often preserved pseudomorphically in perthite.

11) Under special conditions coarse-grained perthite may occur adjacent to non-perthitic potassium feldspar.

12) Substantial areas within perthitic crystals may be non-perthitic.

13) Albite preferentially replaces calcic plagioclase to potassium feldspar.

14) When replacing minerals other than sodic plagioclase, potassium feldspar attacks the exterior of the grains and destroys the previous crystal lattice as it advances. Sodic plagioclase, on the other hand, may be replaced from various points within the crystal, and sometimes without destroying the former lattice.

15) Under special conditions, smooth optical gradations are possible from potassium feldspar to sodic plagioclase.

16) Potassium feldspar preferentially replaces quartz to calcic plagioclase.

17) Potassium feldspar is the latest major mineral in the plutonic rocks examined, and is also later than some of the epidote.

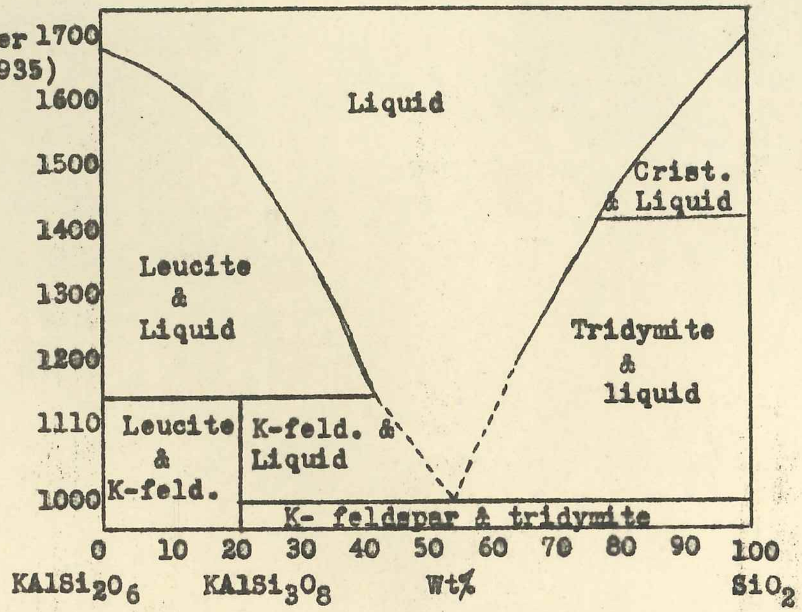
The above data is useful in the investigation of the genesis of the potassium feldspar. Is it magmatic or metamorphic? A perusal of the evidence reveals that virtually none of it favors a magmatic origin.

The phase diagrams shown in Figures 7a and 7b indicate what the quartz-potash feldspar relationship should be if they crystallize out from a melt. If the melt is rich in SiO_2, quartz should begin to crystallize before potassium feldspar, but when the temperatures have fallen to about 1000°C, an eutectic intergrowth should form due to simultaneous crystallization of the two minerals. Nothing that might be interpreted as such an eutectic intergrowth was found in the rocks examined. If the melt contained more $KAlSi_2O_6$ molecule than SiO_2, potassium feldspar would begin to crystallize before the quartz. Some of the hornblende granites and granodiorites, low in quartz, would be in this latter category, as far as composition is concerned, but in no case is the paragenetic order of the two minerals reversed, so that quartz follows the potassium feldspar.

PHASE DIAGRAM FOR THE SYSTEM LEUCITE*SILICA

(after Schairer and Bowen, 1935)

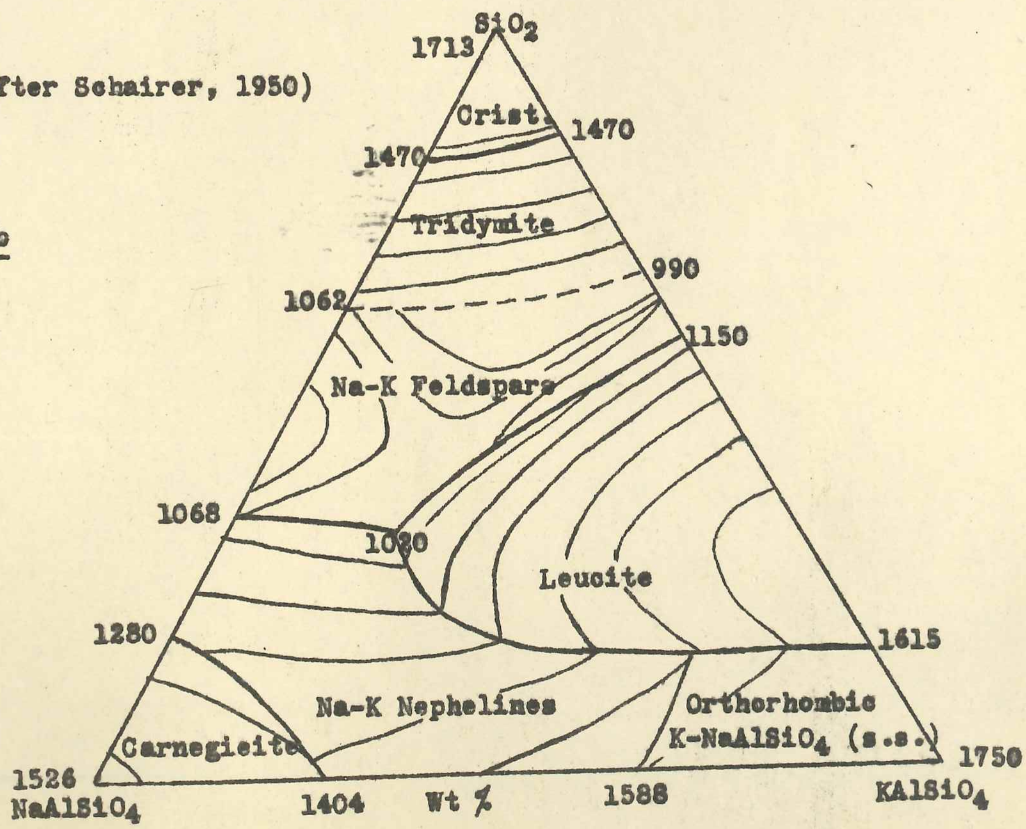
Figure 7a



PHASE DIAGRAM FOR THE SYSTEM $NaAlSiO_4$ - $KAlSiO_4$ - SiO_2

(after Schairer, 1950)

Figure 7b



Not only is there no evidence of a magmatic origin for potassium feldspar, but there is abundant evidence that it is a metasomatic mineral. The potassium feldspar replaces all the other minerals. Its form is controlled by the structure of the older minerals; when poikiloblastic, as it often is, it contains all the other minerals; and it shows definite pseudomorphic tendencies, particularly after plagioclase. After weighing the total evidence, one must conclude that the potassium feldspar in the plutonic rocks of the thesis area is a metasomatic mineral.

This conclusion made, a basis is provided for the consideration of the origin of perthitic potassium feldspar. Few microscopic features have received so much attention in the literature as have perthites. Unfortunately, in many papers it is difficult to know whether or not the authors have established the source rocks to be magmatic or metamorphic. Probably the most recent summary of the perthite problem has been presented by R.M. Gates (1953), and will not be repeated here. In brief, however, there are three major theories concerning the formation of pethite, namely, unmixing (or exsolution), simultaneous crystallization, and replacement.

Unmixing: Laboratory evidence indicates that potassium feldspar can hold more sodium feldspar in solid solution at high temperatures than at low temperatures. Perthites can be made to homogenize by heating, and to reappear by slow cooling. The orientation of the plagioclase element is not haphazard with respect to the potash feldspar. Perthite is not normally composed of two distinct structures, but rather, of two variations of one continuous structure. Bragg (1937, p.241) from X-ray studies of perthite, concludes

"The framework of linked Si and Al tetrahedra, being similar for the monoclinic and triclinic forms, is continuous throughout the whole structure. At high temperatures the K and Na atoms are evenly diffused in the framework producing a uniform crystal. At lower temperatures there is a segregation by diffusion into potash-rich and soda-rich lamellae, producing alternate sheets with monoclinic, or pseudomonoclinic, and triclinic symmetry respectively."

Simultaneous Crystallization: According to this theory, perthites have formed by simultaneous crystallization at the eutectic point between sodium and potassium feldspar. It is doubtful, however, whether this can occur. For most compositions the eutectic point between sodium and potassium lies above 1000°C, at which temperature the two are mutually soluble in solid solution. Because of this, and because of the extreme viscosity and sluggishness of these silicates near their melting points, the eutectic point has little practical significance. But even if the two feldspars were insoluble at high temperatures, it would be difficult to eliminate quartz as the third phase in the eutectic, so that the resultant "perthite" should be composed of potassium feldspar, sodium feldspar, and quartz.

At the eutectic point, the two feldspars are in solid solution, and subsequent slow cooling results in exsolution. Consequently, in practice, the simultaneous crystallization theory is essentially equivalent to the unmixing theory.

Replacement

As described in the past, the replacement process is very specific (Smyth, 1893; Andersen, 1928; Alling, 1938). Albite is thought to have been introduced from outside the crystal in which it appears, and replaces previously formed potassium feldspar.

Modern writers (Alling, 1938; Goldich and Kinser, 1939, etc.) have tended to combine the unmixing and replacement processes, emphasizing generally, one or the other. Yet even when combined, the two processes are kept separate and independent, the former being restricted to high temperatures and the latter to low temperatures.

In this thesis the writer proposes a theory for the formation of perthites which, although a combination of the replacement and exsolution theories, combines the two as integral parts of one process, so that the latter is a consequence of the former under certain conditions. The theory is summarized as follows.

The potassium feldspar in the thesis area (and in many other areas described in the literature) is formed by the metasomatism of pre-existing minerals by potassium-bearing solutions. In the vast majority of cases in the thesis area the mineral that is replaced by potassium feldspar is plagioclase. The composition of this pre-existing plagioclase determines whether or not the resulting potassium feldspar will be perthitic, and also how coarse the perthite will be. If the plagioclase contains more than 35% anorthite, the potassium feldspar tends to be non-perthitic. The sodium, in this instance, is not so abundant that it cannot be accommodated by the solutions and the crystal lattice. If the plagioclase contains less than 35% anorthite, the potassium feldspar tends to be perthitic (becoming coarser as the anorthite content decreases). In this case, the sodium in excess of that which goes into liquid solution, is held in solid solution in the potassium feldspar, until the temperatures decrease, and then it unmixes as albite. In the process of exchanging sodium ions for potassium ions in the feldspar lattice, the lattice of the plagioclase (if it is sufficiently sodic) is not destroyed but simply altered and often extended. If temperatures are fairly high during the process, there is sufficient diffusion within the lattice to prevent effective pseudomorphism. But if the temperatures happen to be low and diffusion is sluggish, sodium-rich zones in the plagioclase are preserved as the most perthitic zones in the potash feldspar crystal, while the calcic zones are preserved as non-perthitic, or only slightly perthitic areas. These odd pseudomorphs are rather rare but sufficiently common to be very instructive. Usually, however, considerable sodium as well as most of the calcium is forced into the solutions which brought the potassium. When the sodium in these solutions reaches a sufficiently high concentration, several phenomena may be produced. Most commonly the plagioclase crystals in other areas are albitized, often in advance of the potassium solutions. Occasionally albite is deposited in fractures. Although the calcium content of the solutions is doubtlessly sufficient to produce a more calcic plagioclase, the temperatures are seldom sufficiently high. Under exceptional conditions of very high sodium concentrations, the solutions may replace potassium feldspar, and produce a different type of perthite from that most common in the thesis area. In considerations of alkali-bearing solutions, it seems well to keep in mind the fact that potassium stands above sodium in the electromotive series. Consequently, relatively weak potassium-bearing solutions can displace sodium from the feldspar lattice, but unusually concentrated sodium solutions are required to effect the reverse process. In nature this fact is borne out by the fact that potassium feldspar is younger than plagioclase (even sodic plagioclase) in most plutonic rocks, and also in the less disputed metamorphic rocks.

Where the reverse order is found, a special reason is required, and is usually evident.

The above theory fits the general facts concerning perthite in the thesis area when the replaced mineral is plagioclase. It follows that where non-sodium bearing minerals are replaced, perthite is less likely to be produced. Such is the case. Even within single thin sections, quartz-rich areas contain feldspar which is less perthitic than that in adjacent areas. It might be asked why such minerals as quartz, hornblende and biotite, when replaced by potash feldspar, given rise to any perthite at all since they contain no sodium. The principal reason seems to be that the potassium feldspar which replaces these minerals usually does so by extensions from crystals formed by replacement of plagioclase. Diffusion within these potash feldspar crystals is generally sufficiently active, so that albite may unmix in areas which previously were occupied by non-sodium-bearing minerals, but the resultant perthite is usually finer-grained than that in areas formerly occupied by the plagioclase. It is not difficult to demonstrate that potassium solutions will attack relatively sodic (An less than about 30) feldspar in preference to such minerals as quartz, hornblende, and biotite, consequently the potash feldspar usually begins from plagioclase crystals. Where the plagioclase is very calcic, of course, the potash feldspar shows no such preference (in fact it prefers quartz if present, as was illustrated previously), but perthites are negligible in such rocks, at least within the thesis area, so this fact presents no complications in the theory.

It is difficult to compare the above theory with others concerning perthite, because the argument is generally taken up from the point after potassium feldspar has formed (by crystallization from a magma). The writer agrees essentially with Gates (1953, p.69) that most of the albite has appeared by exsolving from potassium feldspar, and that which reached fractures moved elsewhere and effected local replacement. The writer's principal argument is that the sodium appearing in the perthite was derived from pre-existing plagioclase, and the composition of this plagioclase dictates the coarseness of the perthite, and even whether or not perthite will form. In effect the albite in perthite represents a "distilled" plagioclase, which has undergone replacement, maintenance in solid solution, and finally exsolved in a purer (less calcic) form.

MAFIC MINERALS

GENERAL STATEMENT

In this thesis the mafic minerals are held in higher regard than the name often applied to them, "varietal", implies. In the commonly accepted classifications of plutonic rocks, the mafic minerals have little effect, whether they comprise half the rock or are completely absent. For instance, if quartz happens to be absent the name of the rock is changed, but if it happens to be hornblende which is missing, the fact is largely ignored. This laxity in using varietal prefixes, even though the minerals involved are obvious even to the unaided eye, seems to have been an effect of the name "varietal". The word has strong connotations of something unimportant in anything but very detailed work, so geologists tend to concentrate on "important" matters, such as the feldspars (though they cannot separate them in the field). It should be emphasized that the term "varietal" when applied to certain minerals, means only that those minerals find little expression in certain classifications. This seems more often a fault of the classifications than a fact of nature.

The mafic minerals in this thesis are considered to be equal in importance to quartz and feldspar. In ordinary field mapping, they often prove to be of greater significance than the so called "essential" minerals. In the thesis area the only important mafic minerals are hornblende and biotite. Some of the plutonic rocks contain pyroxene, but on the whole it is rare. The two major mafic minerals are considered individually below.

HORNBLENDE

GENERAL STATEMENT

Hornblende is the characteristic mineral of areas containing many relict inclusions of pre-granitic rock. Irregularly shaped aureoles of hornblendic rocks surround most of the inclusions. As an inclusion of pre-granitic rock is approached, the concentration of hornblende in these aureoles increases, but due to local fluctuations, the increase is often irregular. The large pendants sometimes have hornblendic aureoles of great size, measuring occasionally several miles in width. In general, however, the width of the aureole is not a reflection of the size of the pendant, but rather of the closeness, or concentration of pendant bodies.

Where the pendants in the thesis area are separated by distances less than about 10 miles, the intervening plutonic rock is almost invariably high in hornblende.

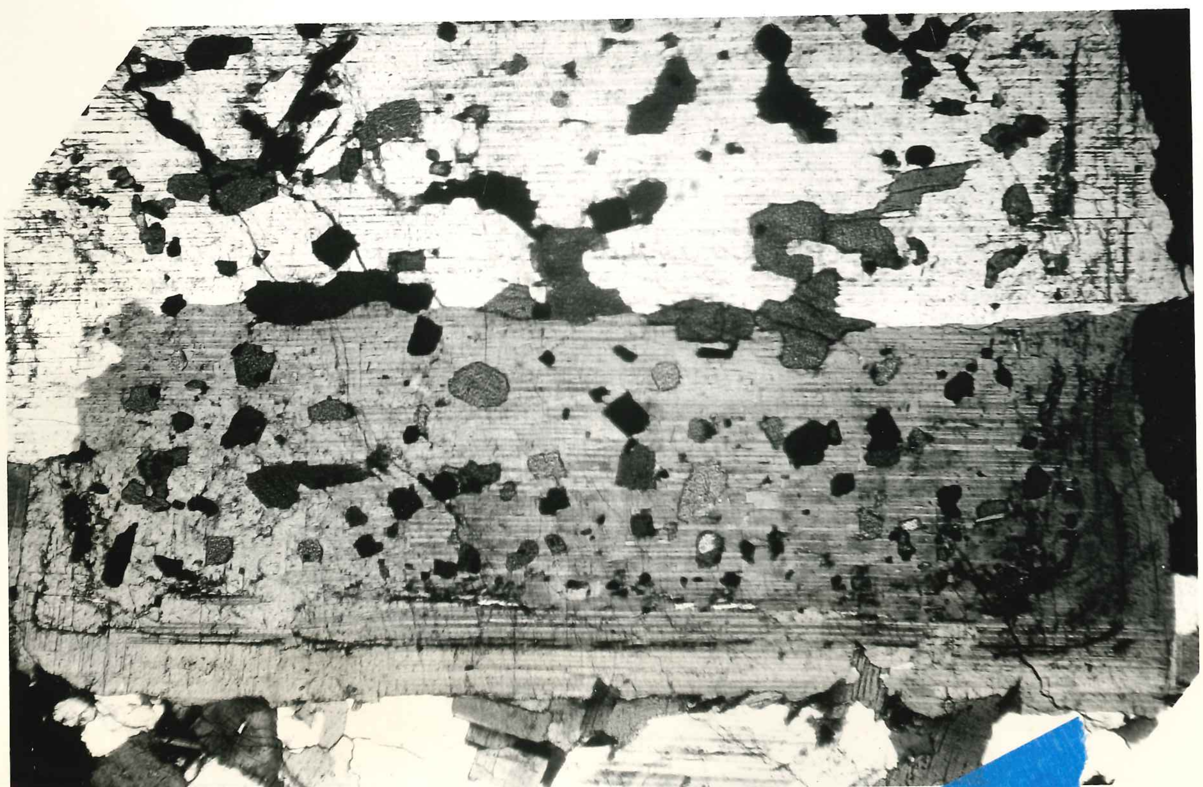
The area mapped, unfortunately, does not contain many pre-granitic rocks rich in biotite, consequently it is not known whether the composition of the inclusions exercises a pronounced influence on the composition of the associated aureoles, although this is suggested. The great majority of the inclusions in the thesis area are hornblende-rich granulites, and their aureoles are likewise hornblende rich.

OCCURRENCE OF HORNBLENDE IN VARIOUS TYPES OF PLUTONIC ROCKS

The title of this section is not overly appropriate, since the type of plutonic rock in this thesis is made dependent on the mafic ratio, but is probably permissable because matters of abundance (on which the classification is based) are not primary considerations in this section. Nevertheless, certain features of the distribution of hornblende in plutonic rocks are matters of common knowledge. For instance, hornblende is found most abundantly in diorites, and least abundantly in granites. This is more accurately a reflection of the calcium contents of the two rocks rather than the ratio of potassium feldspar to plagioclase. A hornblende granodiorite will almost invariably have a higher An/Ab ratio than, for instance, a biotite-hornblende quartz diorite. In general hornblende appears more dependent upon the calcium content of the rock than upon any other single factor.

Rather unexpectedly, hornblende was found to have different habits in the different plutonic rocks. In the diorites, hornblende is typically very irregular in shape, and often includes many plagioclase crystals. In granites and granodiorites, however, hornblende often exhibits well-formed crystals, in which partly euhedral crystals are common, and completely euhedral crystals not exceptional. Also, the hornblende in these alkali-rich rocks very seldom contains inclusions of plagioclase. Consequently the hornblende of the granodiorites and granites may be considered to be more highly evolved, that is, it has generally cleared itself of foreign material, and has assumed more regular forms than that of the diorite, which have been arrested in the early stages of development. This is probably the most significant fact discovered in the study of hornblende, and fortunately one of the most obvious when the mineral is examined in its different habitats.

The space relationships between hornblende and other minerals were studied in some detail. By far the most common position of hornblende (and biotite for that matter) is interstitial among plagioclase crystals. Plagioclase crystals with angular corners are often found jutting into the hornblende, but the reverse is quite rare. Occasionally interstitial hornblende is in the form of clots of fine-grained decussate crystals, although this habit is rather more characteristic of biotite. Probably, the most extreme case of the interstitial position is shown by thin anastamosing trains of small hornblende (and often biotite) crystals winding among the felsic grains. When large hornblende crystals occupy an interstitial position, they tend to include the plagioclase crystals. In some sections this feature is quite striking as shown in Photograph 36,



Photograph 36

Poikiloblastic hornblende, containing inclusions of plagioclase, typical of the less evolved plutonic rocks. X100 (TS R51-49, a hornblende-biotite quartz diorite from the east side of Howe Sound, opposite Boywer Island).

Photograph 37

Small hornblende granules included by plagioclase porphyroblast. The hornblende granules are believed to be derived from pre-granitic granulites. X25 (TS M17-52, a biotite-hornblende quartz diorite from the ridge between Jacobs Lake and North Alouette River).

where many plagioclase crystals appear to be floating in a sea formed by one large hornblende crystal. Poikiloblastic hornblende is a feature that is very common in, and even characterizes hornblende-biotite quartz diorite; in diorite it is also common; but in granodiorites and granites it is rare.

In some sections, small rounded crystals of hornblende are poikiloblastically contained by plagioclase (Photograph 37). These small grains appear from their individual orientations to be independent crystals rather than remnants of one large hornblende crystal. They are identical to the small grains in the pre-granitic granulites. When a granulite undergoes feldspathization the plagioclase porphyroblasts incorporate most of the small plagioclase and quartz crystals of the granulite, but, in the early stages at least, seem unable to replace much of the hornblende; thus the hornblende crystals are simply included. If the rock undergoes further metamorphic evolution these included crystals are removed by replacement and their constituents probably go to form the interstitial hornblende. This process has been described by Misch, under the descriptive phrase "relegation of hornblende to interstitial positions". On rare occasions, however, the small included hornblende crystals have survived, and are found in normal intermediate plutonic rocks. It should be emphasized that these are the only hornblende crystals which can definitely be proven older than the plagioclase. In all other cases, the evidence is either indecisive, or indicates that the hornblende is younger than the plagioclase.

In some sections of intermediate and alkali-rich plutonic rocks, the hornblende seems more or less equivalent to the plagioclase in grain size and development of crystal form. In these sections no reliable evidence bearing on the relative ages of the two minerals was found, but in the calcic rocks, the criteria used successfully on polished sections, leave no reasonable doubt.

The hornblende-quartz relationship was found to be somewhat simpler generally than that between hornblende and plagioclase. In the great majority of sections the mafic minerals have been embayed by quartz. The best examples occur in granodiorite and granite, in other rocks evidence is rarer, but never contradicts the conclusion that hornblende is older than quartz.

The normal hornblende-biotite relationship is that often illustrated of biotite replacing hornblende. The resulting biotite may take one of two forms: it may be pseudomorphic after hornblende; or it may be a clot of small biotite crystals, having an overall outline like that of the replaced hornblende. It is not evident why the replacement of the hornblende should produce one form instead of the other. Both occur in the same thin section. There are, however, indications that the clots of small crystals tend eventually to coalesce and form medium sized crystals. Although a rare phenomenon, hornblende occasionally includes euhedral crystals of biotite, in a manner suggesting that under special conditions hornblende porphyroblasts may enmesh remnant biotite grains (Photograph 38). These biotite crystals are not orientated parallel to the cleavage of the hornblende but at odd angles across it. Such biotite grains, like the small hornblende crystals previously mentioned, are thought to be remnants from pre-granite metamorphic rocks.

Hornblende is invariably earlier than the potassium feldspar, and the fact is so generally recognized and obvious that this relationship need not be dealt with in detail. In addition to relationships to other

Photograph 38

Hornblende including older biotite crystal. The biotite is thought to be a survival from a pre-existing granulite. Note that the biotite is wholly independent of the hornblende cleavage (which is about vertical in the photograph). X144 (TS N132-52, a hornblende-biotite diorite from the east shore of Pitt Lake, opposite Little Goose Island).

minerals hornblende is sometimes in contact with hornblende of a different generation. These usually involve large hornblende porphyroblasts containing small well-formed crystals of the same mineral. The small hornblende crystals are thought to be of the same origin as those sometimes found in plagioclase porphyroblasts, being relicts from the pre-granitic hornblende granulites.

On the whole hornblende (or more accurately the constituents of hornblende) seems to be quite mobile. Its tendency to fill interstices is almost as marked as that of quartz. Occasionally hornblende can be found filling fractures. One such instance is a boulder of hornblende-biotite quartz diorite, which is laced by numerous veinlets ($\frac{1}{8}$ to $\frac{1}{2}$ inches in width) of hornblende, found on the west slope of south Coquitlam ridge.

A most significant fact arising from the investigation of hornblende is that it occupies the same paragenetic position among the major minerals in all the plutonic rocks examined. The chief exception is the small hornblende grains in plagioclase, remnant from pre-plutonic hornblende granulites, but they apparently belong to a pre-plutonic generation. The paragenetic position of hornblende does not seem to be affected by the concentration of iron, calcium, etc. in the rock. The position remains unchanged whether hornblende is abundant or scarce. It seems probable that hornblende was constantly undergoing change during a rather extensive period of recrystallization (in the solid phase). The changes appear to have involved a more or less continuous round of replacement, movement in solution, and redeposition elsewhere by replacement of other minerals. It appears that where hornblende was being replaced by plagioclase, it was not being deposited, and where it was being deposited the plagioclase had become essentially stable. The normal paragenetic position of hornblende in the plutonic rocks in the thesis area, is after plagioclase (regardless of the An/Ab ratio, but excepting the albite of perthite), and before biotite, quartz, and potash feldspar.

A considerable proportion of the mineral referred to as hornblende is actually pargasite. The two minerals belong to an isomorphous series differing only in optic sign (pargasite is positive and hornblende negative), in dispersion, and slightly in composition (hornblende being higher in aluminum, at the expense of some of the magnesium, iron and silica). In the early part of the investigation an attempt was made to separate the two, but the indeterminate middle members were found to be so common that it was considered advisable to group the two minerals together and call them by the name of the more common end member, hornblende.

The color absorption of hornblende varies considerably from thin section to thin section. It was noted that hornblende which in certain positions is a deep blue green, is very rarely found in granites or granodiorites. It is most common in hornblende-biotite quartz diorite. In gabbros the hornblende tends to be brown, or brownish-green (as if it were somewhat basaltic). Deep blue green hornblende was not noticed in any gabbroic section examined. There appears to be some correlation between the color of the hornblende and that of biotite, for when the hornblende is blue green, the biotite tends to be the variety which is pleochroic from a golden brown to almost black (a very dark brown).

BIOTITE

GENERAL STATEMENT

The significance of biotite in the plutonic rock of the thesis area seems to be the opposite of that of hornblende. Whereas a preponderance of hornblende indicates an early stage of plutonic evolution, a preponderance of biotite indicates a fairly advanced stage of development. This matches the field observations wherein it was noted that the biotite-rich rocks usually contain considerably less inclusions than do the hornblende-rich rocks.

In thin section, also, the occurrence of biotite differs from that of hornblende, but, probably because both are ferromagnesian minerals, they have certain features in common. Although dealing primarily with biotite, this chapter includes the differences and similarities in the occurrence of the two minerals.

OCCURRENCE OF BIOTITE IN THE PLUTONIC ROCKS

Certain features of the occurrence of biotite are very obvious and are common knowledge. In general, biotite, in plutonic rocks is apt to be abundant in granodiorites and granites, and least in diorites and gabbros. Because granites usually contain very little mafics of any kind, biotite reaches its maximum abundance, relative to the felsic minerals, in certain granodiorites and biotite quartz diorites.

In the thesis area the crystal habits of biotite change in the different plutonic rocks in much the same manner as do those of hornblende.

In general, the crystal shape improves from very ragged and irregular, in diorite and hornblende-rich quartz diorite, to regular forms in biotite-rich granodiorite and granite. It is not implied, however, that all biotite crystals in the latter rocks are euhedral. Certain sections of granodiorite for instance, may contain fairly ragged-looking biotite. Nevertheless, regular biotite crystals are found far more commonly in the more acidic plutonic rocks. (Actually a wholly euhedral mafic mineral is a rather rare phenomenon in any of the plutonic rocks.)

With respect to inclusions, biotite crystals also appear to be more highly evolved in boitite granodiorites and granites. Inclusions of plagioclase in boitite are common in most of the quartz diorites, and characteristic of the biotite-containing diorites in the thesis area, but have generally been completely eliminated in the biotite granodiorites and granites.

The most characteristic position of biotite in the plutonic rock is in the interstices among plagioclase crystals. Narrow projections of biotite often extend outward from the main crystal, following plagioclase boundaries, and sometimes filling fractures in that mineral. The larger biotite crystals commonly contain euhedral, and partially replaced plagioclase crystals. Only very rarely is biotite included by plagioclase. When it is, the grains are small and seem to be remnants from pre-granitic metamorphic rocks, as has been suggested for grains of hornblende of similar size and occurrence.

Whether an interstitial mineral is younger or older than the crystals surrounding it is not a matter in which agreement abounds. In magmatic rocks certainly it is later; in metamorphic rocks it might be either later or earlier. In fact mention of interstitial mafics in plutonic rocks is not common in the literature, although Misch and others have referred to them in granitized rocks. Yet the present investigation shows that it is one of the most characteristic features of the plutonic rocks of the thesis area. The writer feels that because the interstitial position of the mafics is so often combined with definite proof of an earlier age, it can be safely concluded for these plutonic rocks, that the interstitial minerals are fine-grained and obviously control the detail of outline of the surrounding minerals, as for instance, when plagioclase porphyroblasts develop in a granulite, producing a pseudocataclastic texture.

Another fairly common habit of biotite is that of forming clots of small crystals occupying markedly interstitial positions. The crystals within the clots are generally arranged in a random, decussate pattern. The size of these individual biotite grains is much smaller than that of the average felsic crystals, although the dimensions of the clots themselves about equal them. The form of the small biotite crystals is often fairly regular, more so than might be expected from the type of plutonic rock. These clots are more common in the biotite-hornblende quartz diorites than any other plutonic rype. Thus, though their significance is not clear to the writer, the clots seem to represent a relatively early stage in the evolution of the plutonic rocks in this area. Misch believes that similar clots from plutonic rocks of the Okanagan result from the biotitization of large hornblende crystals under certain conditions. This explanation seems reasonable also for the writer's rocks. The individual crystals of the clots are gradually eliminated in the more advanced rocks through recrystallization and coalescence. This results in occasional large well-formed biotite crystals (of certain granodiorites) sometimes containing small euhedral biotite crystals orientated at some random angle to the cleavage of the host. Such a feature is most easily interpreted as an unintegrated relict from a former clot. Similar crystals are, on rare occasions, found also within large hornblende porphyroblasts as mentioned in the chapter on hornblende, but these appear to be rather unusual survivals of biotite from a pre-granitic rock. This, incidentally, is the only microscopic evidence noted which suggests that hornblende can be later than biotite, and is not very significant since, of course, all the minerals of the pre-granitic rocks are older than those forming the granitic rocks, except where they be the same grains.

The biotite-plagioclase relationship, when proof exists, is almost always that of biotite being later than the plagioclase. Biotite is often seen truncating the zoning of plagioclase, and replacing the sodic rim in preference to the core. The shape of the replacing biotite is often sharply controlled by plagioclase cleavage, resulting in many places in euhedral replacement remnants of plagioclase. Consequently angular, cleavage-controlled corners of plagioclase jutting into the biotite are a common feature. The excluded portions of the plagioclase generally show far less euhedralism than the included portions. The conforming of biotite, hornblende, and quartz to the shape and structure of plagioclase is in general a very prevalent feature in the plutonic rocks of the area. Large poikiloblastic biotite crystals containing euhedral, and less regular, remnants of plagioclase are characteristic of the more basic quartz diorites. Other evidence, such as islands of plagioclase contained in parallel optical orientation in biotite, and narrow stringers of biotite following crystal boundaries and fractures, combine to form a sound basis for the general statement that biotite is normally later than plagioclase in the plutonic rocks of this area. Only one or two sections show possible indications of the opposite relationship; but the biotite in these is more logically interpreted as relicts from pre-granitic rocks.

As might be expected the paragenetic evidence is more often indecisive in the granites and biotite-rich granodiorites than in the more basic rocks, contacts between plagioclase and biotite are less common, due to the minerals being less abundant, and less diagnostic, due to the increased regularity of the crystals. In addition both biotite and plagioclase are generally clear of inclusions in these highly developed rocks. Nevertheless, the biotite-plagioclase time relationship seems in no way dependent on the An/Ab ratio of the plagioclase.

With one exception previously mentioned, the biotite always appears to be later than hornblende. The hornblende cleavage and crystal boundaries exercise strong control over the biotite, offering excellent evidence of the relative ages of the two minerals.

The relation between biotite and quartz is not as clear as that between biotite and other minerals (apparently because quartz seems to take a long time to "settle down"). In the great majority of sections quartz is doubtlessly later than biotite. The evidence includes parallel orientated remnants of biotite within quartz, marked control over the shape of quartz by biotite cleavage, and relatively euhedral biotite crystals included in large quartz porphyroblasts. Probably the most common evidence is large cleavage controlled embayments of quartz in biotite. Occasionally biotite is definitely later than quartz, as, for instance, where it fills fractures within the quartz, and less definitely where it extends along quartz-quartz boundaries, but these are rare phenomena.

Potassium feldspar, the last mineral in the plutonic rocks of this and many other areas, shows abundant evidence that it is later than biotite. Most striking, however, are the large potassium feldspar crystals which contain all the other minerals in the rock. Virtually all evidence which can be imagined indicating a mineral to be late, can be found by a brief perusal of the potassium feldspar crystals.

A minor feature concerning biotite which was recognized, although its significance was not, is that when the plutonic rock contains two distinct grain sizes, as in cataclastic, and pseudocataclastic textures, biotite is always fine-grained, and a constituent of the "mortar" only. The same statement applies to hornblende, but to a lesser extent.

The absorption of biotite varies somewhat from section to section, but no general correlation between color and the plutonic rock type could be established. There may be a correlation with the absorption of the associated hornblende, as mentioned previously. The pleochroism is almost always strong and ranges from a pale yellow-brown to very dark brown (almost black occasionally).

CONCLUSIONS ON THE MAFIC MINERALS

The most significant conclusions derived from the study of the mafic minerals are listed below.

1) Hornblende is more abundant in rocks containing many inclusions of pre-granitic rock, and in those close to pendants.

2) Biotite is more abundant in rocks containing few inclusions, and those distant from pendants.

3) Both mafic minerals, in the less developed plutonic rocks, such as diorites, and hornblende-biotite quartz diorites, tend to be irregular in shape, and to contain numerous plagioclase inclusions, and in the more highly developed rocks, such as biotite rich granodiorites and granites, they tend to be regular in shape, and rarely contain any inclusions.

4) Both mafic minerals commonly occupy interstitial positions.

5) Biotite frequently forms tiny crystals clustered in clots pseudomorphic after hornblende.

6) In nearly all of the sections examined, the mafic minerals occupy a paragenetic position between plagioclase and quartz. This position is apparently independent of the anorthite content of the plagioclase, and of the ratio of mafic to felsic minerals.

7) The mafic minerals commonly replace plagioclase, and are themselves replaced by quartz and potassium feldspar.

QUARTZ

GENERAL STATEMENT

Quartz was investigated in the same general manner as were the other major minerals found in the plutonic rocks. Its abundance and habits were noted in the various plutonic rocks, and some attention was given to its behavior under cataclastic conditions. It is interesting to note that although quartz is the most viscous of minerals when molten, it seems to be one of the most highly mobile in metamorphic environments, as is evidenced by its presence in fractures and in pressure "shadows".

DISTRIBUTION

The abundance of quartz in plutonic rocks can be dismissed with the following generalization. Quartz is more abundant in biotite-rich rocks than in those which are hornblende-rich, and, the mafic ratio being held constant, quartz is more abundant in the more alkali-rich rocks. Exceptions, however, occur too frequently for the generalization to be used as a principle in the classification of plutonic rocks, but not so frequently as to invalidate the generalization.

CRYSTAL HABITS

As is true for the other major minerals, the poikiloblastic tendencies of quartz vary greatly with the plutonic type. Thin sections representing five different plutonic types were examined for poikiloblastic quartz, and the results are tabulated below.

Rock Type	No. of TS Examined	% Containing Poik. Quartz
Hornblende-biotite Quartz Diorite	52	73%
Hornblende-biotite Granodiorite	17	82
Biotite-hornblende Quartz Diorite	43	60
Biotite Granodiorite	34	32
Granite (mostly Biotite)	24	16

The above table shows a very marked decrease in the abundance of poikiloblastic quartz from calcic to alkali-rich rocks. Conforming with other major minerals in plutonic rocks, quartz is most poikiloblastic in calcic or relatively undeveloped rocks. As the rock becomes more highly evolved these inclusions are eliminated. It is interesting to note that this trend persists in spite of the fact that the quartz becomes more abundant, and generally coarser-grained toward the granite end of the plutonic series. Thus, from the purely physical viewpoint, quartz of granite is far more capable of containing other minerals than is the quartz of a hornblende-rich quartz diorite. Quartz in the latter rock is often restricted to small interstitial grains, which simply are too small to include the larger plagioclase and mafic crystals. Nevertheless, the impression gained is that wherever the quartz is sufficiently abundant it is poikiloblastic in the calcic plutonic rocks. It is this matter of abundance and grain size which causes the apparent discrepancy in the table between the hornblende-biotite quartz diorite and the hornblende-biotite granodiorite, 82 percent of the latter, and only 73 percent of the former thin sections contained poikiloblastic quartz. However, had there been more quartz in some of the quartz diorite sections it is estimated that virtually 100 percent of them would show poikiloblastic quartz.

The inclusions in poikiloblastic quartz are chiefly plagioclase (Photograph 39) (vacuole inclusions are present but were not considered in the present study), but in some cases comprise hornblende, biotite and/or minor minerals (principally magnetite). The plagioclase inclusions within the quartz are distinctly more euhedral than plagioclase crystals not so included. The included plagioclase is apparently made more euhedral by the corrosive action of the quartz under control of the plagioclase cleavage. In the more highly developed rocks, where poikiloblastic grains are much rarer, the plagioclase inclusions in quartz, when present, are much smaller than the surrounding plagioclase crystals which are not included, indicating that the elimination process in no way forces out the inclusions, but simply reduces their size.

In the plutonic rocks, quartz seldom develops regular crystal faces, and even instances of partial euhedralism are rare. A small degree of euhedralism is sometimes shown against potash feldspar, which replaces and often includes quartz crystals. In general, the more euhedral quartz crystals are found as large "eyes" in coarse-grained plutonic rocks, such as the Gambier granite to the west of the region mapped. Usually the margins of quartz crystals are irregular, varying from a rather simple interlocking to an extremely intricate sutured pattern. These complexly sutured boundaries are restricted entirely to quartz-quartz contacts in all the sections examined. Consequently it might be predicted that intricate suturing is characteristic of quartz-rich rocks. This is not exactly so, but it is found more commonly in such rocks. The trend is shown in the table below.

Photograph 39

Poikiloblastic quartz, typical of the intermediate plutonic rocks. Included plagioclase crystals usually are more euhedral than those not included. X98
(TS 69A-48, a hornblende-biotite granodiorite from the south slope of Hollyburn Ridge.)

Photograph 40

Small granules of quartz contained by plagioclase. The quartz grains are believed to be remnant from the pre-granitic granulites. X30
(TS A11-52, a hornblende quartz diorite from Coquitlam Mountain.)

Rock Type	TS Examined	TS Containing Suture Quartz	%
H - B Quartz Diorite	52	2	4
H - B Granodiorite	17	0	0
B - H Quartz Diorite	43	6	14
B - H Granodiorite	26	2	8
Biotite Granodiorite	34	8	23
Granites (chiefly B.)	30	7	23
	203	25	12½%

Slightly less than 25 percent of the thin sections of granite and biotite granodiorite examined contain sutured quartz crystals, whereas for hornblende-rich quartz diorite and granodiorite the percentage is less than 5. The proportion of sections containing sutured quartz appears to be slightly less for granodiorite than for the quartz diorite having an equivalent mafic ratio. This is probably attributable to sampling error. (It cannot reflect the fact, maintained in this thesis, that granodiorite is a somewhat more developed rock, giving the quartz more opportunity to simplify its shape, because the abundance of sutured boundaries increases toward the biotite granite end of the plutonic series.)

Sutured quartz is considered by some to be related to shearing, and this contention is supported by such sections as shown in (Photograph 41), which leads to the rather intriguing conclusion that more shearing has taken place in the more highly developed rocks, such as biotite granodiorite and granite, than in the more basic plutonic rocks. The same conclusion can be reached from other data, independent of this line of reasoning, and is dealt with in the final chapter.

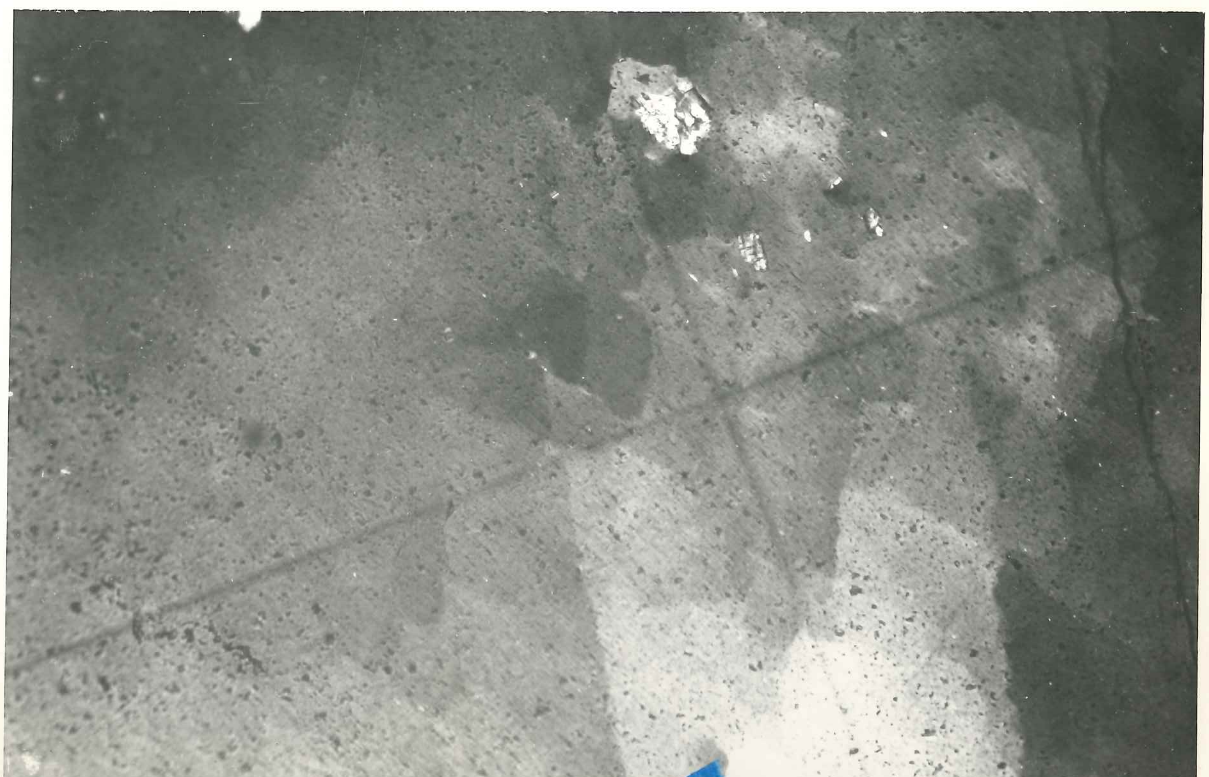
The examination of quartz, especially sutured quartz, led to an investigation of those rather peculiar composite quartz crystals which

Photograph 41

Highly sutured quartz crystals, tupically found in sheared plutonic (and other quartz-rich) rocks. X120 (TS H231-50, biotite granodiorite from Indian Arm, south of Bishop Creek fan).

Photograph 42

Vaguely outlined "ghost" granules, in a single large quartz crystal. X110 (A226,52, biotite-hornblende quartz diorite from Goose Island).



contain numerous vaguely outlined granules (Photograph 42). The purpose of the investigation was to determine whether such crystals in their present state are in a stage of incipient cataclasis, or in the final stage of coalescence by recrystallization of cataclastic grains. In the following descriptions "ghost" granules, refers to the vaguely outlined grains which compose some of the quartz porphyroblasts. The most important features of the phenomenon are listed below.

1) The "ghost" granules grade perfectly into the wholly independent granules of the "mortar" grains around the edges of some of the porphyroblasts, and if some of the "mortar" happens to be included by the porphyroblasts (without integration), the "ghost" granules grade into them.

2) The "ghost" granules each have a slightly different extinction position, yet are sufficiently integrated with the porphyroblast as a whole so that the extinction shadow moves across the porphyroblast, generally in a smooth sweep.

3) The occurrence of "ghost" granules is entirely independent of any fractures which may cross the porphyroblast. The quartz may be highly fractured, yet have virtually simultaneous extinction throughout (no "ghost" granules, or pronounced strain shadows), while an unfractured crystal is often loaded with "ghost" granules. Also, fractures developed through a cluster of "ghost" granules, cut across the granules, showing absolutely no tendency to follow their boundaries.

4) One crystal may be wholly composed of "ghost" granules, and yet the crystal beside it may be entirely uniform.

One interpretation of "ghost" granules in quartz is that they represent incipient cataclasis just prior to the complete breakup of the porphyroblasts. The large crystals, having first been strained (strain shadow stage), develop incipient fractures in such a pattern as to form "ghost" granules. Finally the "ghost" granules become distinct separate crystals, forming a kind of mortar material. In this process, it should be noted that the fractures do not actually develop as surface breaks before the formation of the "ghost" granules, yet in some manner each individual has been slightly rotated so as to exhibit a slightly different extinction position from the neighbouring "ghost". The fact that the fractures do not follow boundaries of granules detracts from this theory.

An alternative interpretation is that the "ghost" granules result from incomplete recrystallization, or coalescing of small grains (which probably have formed through cataclasis), wherein the individual grain is compelled to rearrange its structure to close, but not exact, accordance with that of its neighbour. This gives the porphyroblast an outward semblance of unity, though ghost outlines of the granules remain. Given sufficient time at a high enough temperature, the "ghost" granules would presumably become completely integrated and disappear. The resulting crystal for a time would probably have a sweeping extinction, or exhibit "strain" shadows. Strain shadows formed by this process are a prelude rather than a sequel to cataclasis.

On the whole the facts seem to favor the second explanation, but regardless of the interpretation, the phenomenon is one of the best examples of the degree of chaos that is permissable within the SiO_2 lattice.

Also interesting, but not particularly common in the plutonic rocks of the thesis area, is vermicular quartz. Irregularly shaped blebs of quartz were found only as obvious replacement remnants in potassium feldspar (Photograph 19), and very rarely in sodic plagioclase where the combination would be called a myrmekite. The quartz remnants have no consistent shape, or regular pattern of distribution, although closely associated individual blebs usually have parallel optical orientation.

In hand specimen the quartz often has a smokey blue color. This color does not seem to be restricted to the quartz of any particular plutonic rock type. It is seldom found in the southern quarter of the area, but is quite common in the north across the whole region from Howe Sound to Harrison Lake. The most intense blue color is found where quartz is fairly abundant in a rather highly calcic rock, such as hornblende quartz diorite. What actually causes the color is unknown, but fairly recent (1948) work at Pennsylvania State College suggests that it is due to slight distortion of the SiO_2 lattice by certain foreign cations present in exceedingly minute amounts. These cations can be detected by spectroscopic analysis, but not by chemical analysis. They are believed to be responsible for the coloring of many minerals which when pure are colorless (eg., chromium cations in beryl to give emerald). In the area mapped there also appears to be some correlation between the bluish color of quartz and the occurrence in thin section, of highly sutured patterns and of grains complicated by "ghost" granules. As suggested by Misch (oral communication) the bluish color may be characteristic of cataclastic quartz. The problem stands in need of further investigation.

The paragenetic position of quartz in the plutonic rocks is in general very consistent. It replaces plagioclase and the mafic minerals, and is replaced in turn by potassium feldspar. Exceptions are rare, and are restricted to undeveloped rocks, which in most instances have scarcely attained plutonic character. The only example of plagioclase replacing quartz is found in a partly feldspathized pre-granitic quartzose granulite. In this case, the quartz remains as relict inclusions (Photograph 40). In rather calcic plutonic rocks the quartz is often poikiloblastic, with plagioclase (Photograph 39) and other minerals as inclusions.

It seems rather surprising to the writer that quartz is so consistent in the paragenetic series, in spite of its readiness to move into low pressure areas as they develop. Possibly the surprise results from the tendency of geologists to imbue a process with an importance equivalent to the clarity of the example. Thus an insignificant process well demonstrated, may be elevated above one which is fundamental but difficult of demonstration. The implication here, of course, is that most silicon dioxide does not move any appreciable amount, but continues to be active within its local area, after the plagioclase and mafics have been fixed.

MICROSCOPIC FEATURES OF SOME MINOR MINERALS IN THE PLUTONIC ROCKS

SERICITE

Sericite is not a quantitatively important mineral in most of the plutonic rocks although some can be found in most thin sections. Yet, brief mention of this mineral seems justified, because it contributes information to the crystal history of the plagioclase in the plutonic rocks of the thesis area.

MODE OF OCCURRENCE OF SERICITE IN PLUTONIC ROCKS

Sericite can generally be found in any plutonic rock in the area, but it is rare in the highly calcic rocks. No sericite was found in the rather limited amount of gabbro occurring in the map-area. In diorites and calcic hornblende quartz diorites it is usually not abundant. In biotite-hornblende quartz diorite and in the more alkali-rich rocks sericite is often a common mineral. Every granite examined contains abundant sericite, while the granodiorites usually contain a large amount, although sometimes practically none. The overall distribution of sericite thus suggests a close relationship to the amount of potassium feldspar in a rock. Exceptions to the generalization however are sufficiently frequent to indicate that the relationship is not simple. More detailed observations, listed below, support this conclusion.

SERICITE AND PLAGIOCLASE ZONING

The most striking occurrence of sericite in the thin sections examined is in the cores of zoned plagioclase crystals. Where the plagioclase is sharply zoned, sericite is generally restricted to the core, although it may appear in an intermediate zone if, due to reversal of zoning, it too is highly calcic. The rest of the crystal is often clear. No case was found wherein an outer or intermediate zone of a zoned plagioclase was sericitized while the core remained unsericitized.

Not to be confused with the above is the circumstance of the gradationally zoned, or unzoned plagioclase containing a patch of sericite in its centre. The patch often has a regular shape like the core of a sharply zoned plagioclase, but bears no relationship to the shape of the crystal now containing it. Even more striking is the case of a polygonal-shaped string of sericite found in a wholly uniform plagioclase crystal, without a sericitized centre. Not uncommonly such a string of sericite crosses two or more plagioclase crystals (Figures 8 and 9).

Numerous examples were noted of a sharply zoned plagioclase crystal with a relatively large core, in which only a portion of the core was sericitized, although the core was of uniform composition (enough plagioclase remains among the sericite for checking its extinction against the rest of the core). Such patches of sericite occupy only part of the core and are independent of the boundaries of that core (Figure 10), but are often shaped like a smaller core that does not now exist.

The inference drawn from the above observations is that this particular type of sericite formed previous to the present crystal

Figure 8

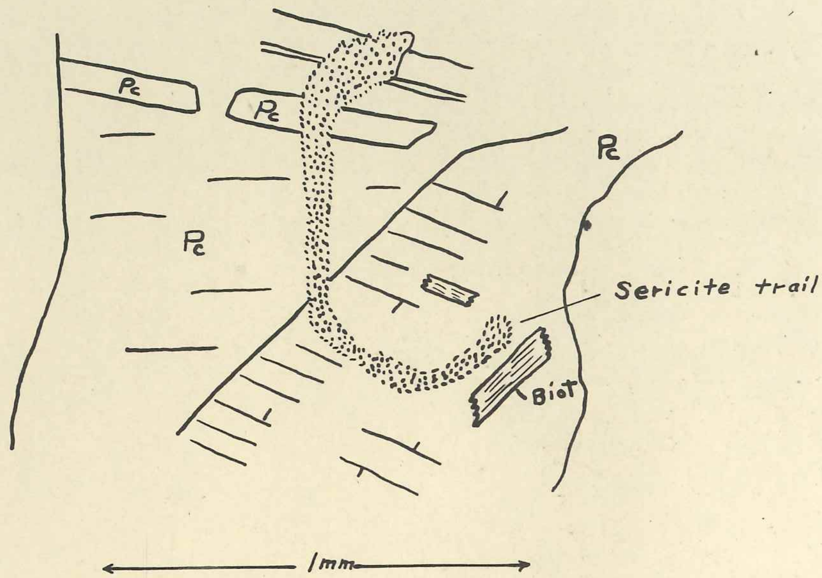
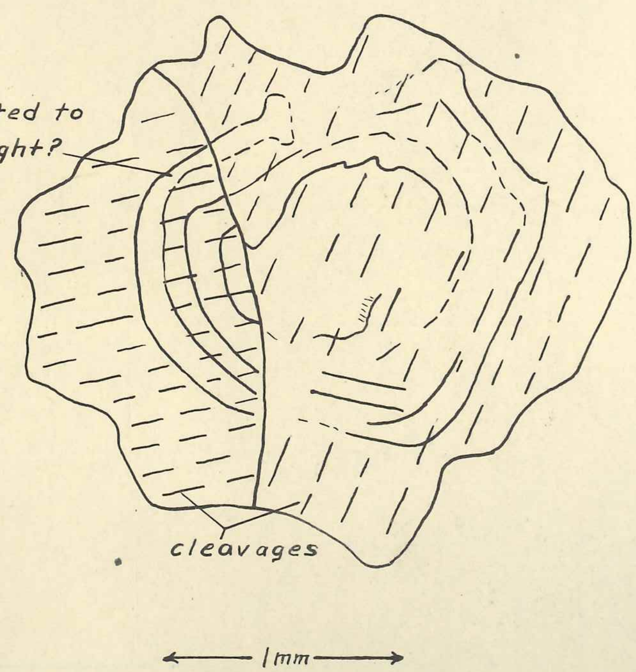


Figure 9



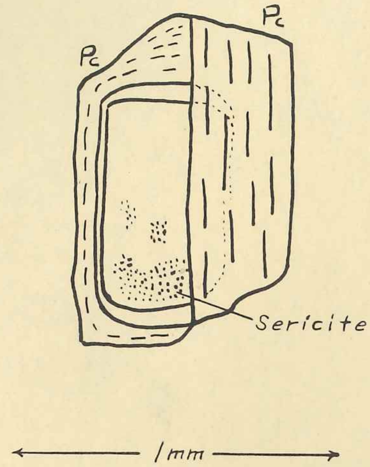


Figure 10

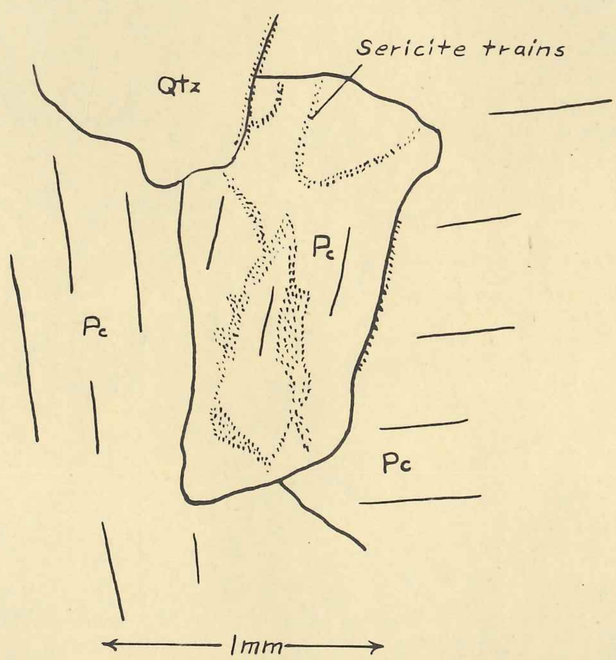


Figure 11

structure of the plagioclase and is a relict mineral, remaining from the sericitization of a former plagioclase crystal. This and the other data which follows is further discussed later in the chapter.

SERICITE AND TWINNING

In general no obvious relationship was found between the distribution of sericite and lamellar twinning in plagioclase. Yet in a few instances sericite was restricted to one set of twin lamellae. In the few examples observed, the sericite occurred only in the very narrow lamellae of crystals having lamellae of widely different widths. Where the twin lamellae were roughly equal in width no such relationship was noted. The distribution of sericite is independent of non-lamellar types of twinning.

SERICITE DISTRIBUTION IN IRREGULAR PATCHES, TRAINS, AND AS THIN SCATTERING

This occurrence of sericite is apparently unrelated to any zoning (past or present) or to any structure now visible in the rock. The sericite patches referred to are usually considerably larger than the average grain size of the rock, and cover all or a portion of several plagioclase crystals but do not overlap into other minerals. On occasion the concentration of sericite in these patches is very high, but usually not as high as in sericitized cores.

Trains of sericite are also fairly common in single plagioclase crystals or across several crystals (Figure 11). These average about .1 mm in width and about 1 mm in length, but may be much larger or much smaller. They are not controlled by any structure now evident in the rock, and have not the regular shape of the polygonal strings.

A relatively even scattering of sericite throughout the plagioclase is not as common as might be inferred from some of the literature, but in certain cases it does occur. It is entirely restricted to granites in the thin sections examined, but presumably could occur also in granodiorites. An even distribution was not approached in any of the more basic rocks, such as quartz diorite. As a rule this scattered type of sericite is somewhat coarser than most (excepting that found in fractures).

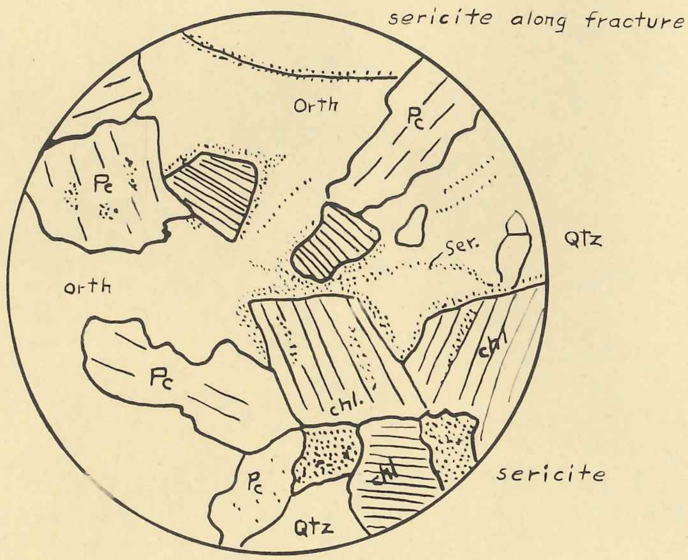
SERICITE AND OTHER MINERALS

As implied by the above descriptions sericite is most closely associated with plagioclase. A patch of sericite in the centre of one crystal, however, does not mean that all other similar crystals (with regard to zoning, etc.) will be likewise inflicted. On the contrary that would be the exception, which occurs where sericitization is evidently the last event which has taken place in the rock. Such late sericite is controlled by obvious structures in the rock as for instance, fractures, crystal and zone boundaries, cleavage, etc. The more typical situation is one in which about 20% of the plagioclase crystals contain sericite. Sometimes a section is examined in which only one plagioclase crystal contains any sericite at all, and that one may contain a large amount.

Except along fractures and certain crystal contacts sericite was never seen in potassium feldspar. As the last major mineral in granites and granodiorites, potassium feldspar frequently includes the other minerals. Plagioclase crystals thus included may be intensely sericitized (no structural control however) or completely clear. Both were often observed in the same potassium feldspar crystal. This and other phenomena suggest that there is no direct relationship between the potassium feldspar and the sericite. There is, perhaps, one exception, and that involves not potassium feldspar alone, but both potassium feldspar and chlorite. Sections were observed in which potassium feldspar contained plagioclase, quartz, and chlorite pseudomorphic after biotite (see Figure 12). The sericite in these sections is associated with calcite, and tends to be in fractures and along cleavage planes. The contacts between potassium feldspar and plagioclase, and between potassium feldspar and quartz are not sericitized, but the contact between potassium feldspar and chlorite is almost always the site of intense sericitization. All the sericite involved is obviously late and controlled by visible structures in the rock. The conclusion drawn from the phenomenon is that the solutions which converted the biotite to chlorite also found the potassium feldspar-chlorite contact suitable for the production of sericite, and probably drew elements from both minerals. Normally, however, sericite is not a mineral often found along crystal contacts.

Although the phrase "altered to sericite and kaolin" is often found in petrographic descriptions, no relationship could be found between the two minerals (kaolin is used broadly here, for clay minerals in general). They seem to be absolutely independent. Thin sections are common in which all the plagioclase crystals may be highly kaolinized while only one or two are seriticized. Conversely the plagioclase may be highly seriticized, but not kaolinized. Of course, it does happen that certain plagioclase

Figure 12

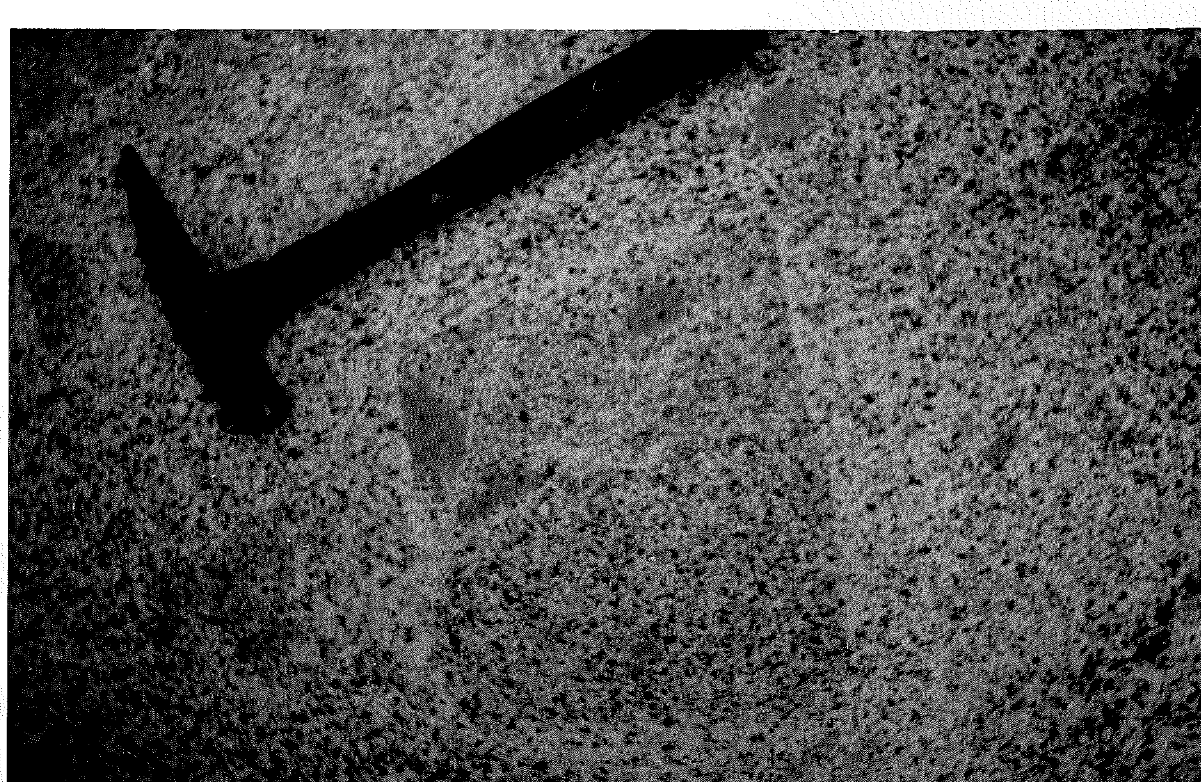


Field diameter - 2.34 mm.

crystals are both intensely sericitized, and highly kaolinized but this seems to be fortuitous. On the whole kaolin is not so much subject to structural control as is sericite, and, unlike that mineral, is rarely (if ever) deposited directly from solution into fractures. Kaolin must form as an alteration product, but sericite may or may not be an alteration product. The independence of distribution of sericite and kaolin supports chemical evidence indicating that each is deposited by a different type of solution, the former alkaline, and the latter acid (Sales and Myers, 1948).

SERICITE IN OPEN SPACES

In some rocks sericite distribution is controlled by evident structures. Not structures long since destroyed (as previously described) but structures still present in the rock and readily visible in thin section. These structures include shear zones, fractures, cleavage planes, and a few crystal contacts (minor). Sometimes associated with this sericite is a little calcite. This type of sericite may be found in structures cutting any mineral, including potassium feldspar, quartz and the mafic minerals, and as such, is not an alteration product of the mineral containing it. In contrast with the sericite dealt with in earlier sections, which is not controlled by present structures, and is presumably older than many of the surrounding crystals, this variety is the youngest mineral in the rock (kaolin excepted). Characteristically, it is somewhat coarser when deposited in fractures, than when it replaces plagioclase. In the sections examined, the later variety of sericite is somewhat <u>less</u> common than the relict type.



not the case in the thesis area, probably because no excessively high peaks occur within it.

In general the overall percentage of inclusions is higher near pendants than far from them. Yet, seldom is an orderly progressive change noted as one traverses toward a pendant body. Usually outcrops with numerous inclusions are interspersed with those of few inclusions right up to the contact. In some places a fairly regular progression exists; inclusions become more and more abundant, until the plutonic rock is restricted to a wide-spaced network in the pendant, before disappearing altogether. In the relatively rare instances where a biotite-rich plutonic rock closely approaches a pendant, there is likely to be no increase in the concentration of inclusions toward the pendant until the biotite-rich rock changes to a hornblende-rich variety.

Throughout the thesis area hornblende-rich rocks contain a higher percentage of inclusions than do the biotite-rich rocks. The average inclusion concentrations in some of the common plutonic rocks, as condensed from numerous recordings made throughout the thesis area, are listed below.

Hornblende diorite	- 5% inclusions
Hornblende-biotite diorite	- 4%-5% "
Hornblende granite	- 3% "
Hornblende-biotite quartz diorite	- 3% "
Hornblende-biotite granodiorite	- 2%-3% "
Biotite-hornblende quartz diorite	- 1%-2% "
Biotite-hornblende granodiorite	- 1%-2% "
Biotite granite	- less than 1%

As shown, the inclusion concentration is more sensitive to changes in the hornblende-biotite ratio, than to changes in the potassium feldspar-plagioclase ratio. This preference for hornblende-rich rocks is probably the most significant single fact derived from the study of inclusions. Interpretations concerning it are given later in this chapter.

Although the inclusions vary in amount in the different plutonic rocks, the inclusions swarms are peculiarly independant. The swarms range in width from 10 to about 300 feet, and are several times as long as they are wide. They tend to be elongate rather than tabular, and widths within an individual swarm are variable. Some clusters are more or less equi-dimensional. These concentrations of inclusions may be found almost anywhere. They are, perhaps, more common in hornblende-rich rocks, but may be found, also, isolated in biotite-rich rocks. The elongate swarms occasionally pass from one plutonic-rock type into another, with little apparent change. Emphasis should be placed on the fact that these swarms and clusters are wholly unrelated to present pendant bodies.

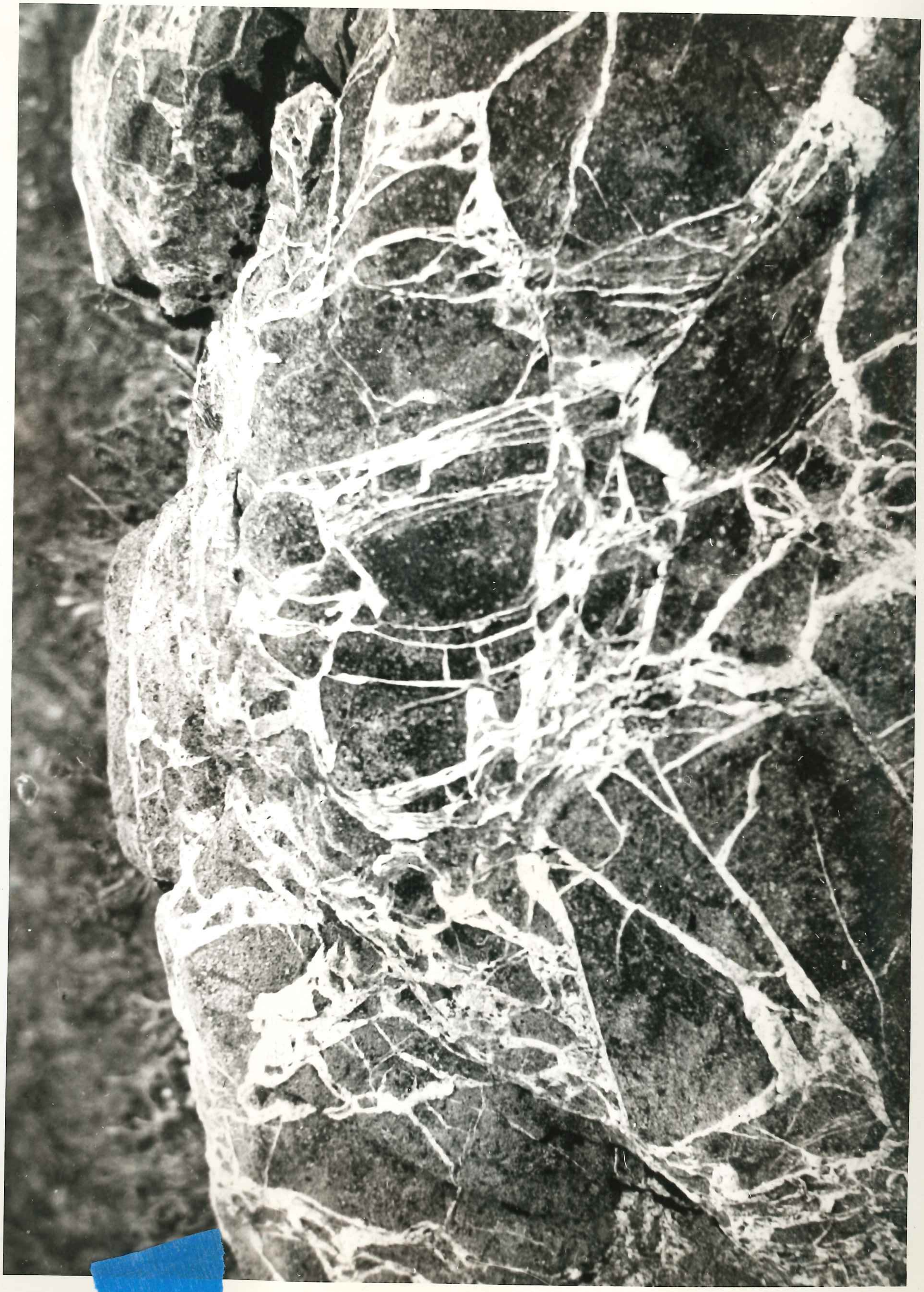
The inclusions come in all shapes and sizes, though color is limited to dark grey. The vast majority are rounded or sub-rounded, as shown in Photograph 43. Some, however, are angular. The angular inclusions are characteristic of the contact breccias bordering some of the pendants (as in Photograph 45), but are not restricted to these localities. Angular inclusions are occasionally found far from pendants, and in rock containing a relatively low proportion of inclusions. Photograph 44 is an example of such a case. It is remarkable how such inclusions remain angular up to the very point of disappearance.

A small proportion of the inclusions are elongate, and when thus, are invariably aligned parallel to any foliation which may be present in the plutonic rock. Small elongated inclusions are illustrated in Photograph 46 and examples of extremely long sinuous inclusions are shown in Sketch 46a.

The diameter of the average rounded inclusion is probably between

Photograph 45

A replacement breccia composed of porphyroblastic hornblende granulite fragments, and feldspathic stringers. There appears to be no displacement of the fragments. (Locality, ridge south of Sloquet Creek, twenty miles northeast of the thesis area.)



Photograph 46

Small elongated inclusions in biotite-hornblende granodiorite. (Near The Lions.) (Christie)

Sketch 46a

Extremely long sinuous inclusions in Hornblende-biotite quartz diorite. (West of Lynn pendant, in Capilano Valley.)

Photograph 47

Small rounded inclusions, typical of those found in biotite-rich plutonic rocks. (Armstrong)


1 Ft

4 and 6 inches. At any one place, however, inclusions may range from less than one inch to pendant size. After mapping several hundred square miles of plutonic rock, one gets the impression that they are smaller in biotite-rich rocks than in hornblende-rich rocks. Those shown in Photograph 47 are typical of the latter.

Most of the inclusions in the thesis area are entirely structureless. Occasionally one is found which is gneissic, but it is almost invariably closely associated with a gneissic body, of pendant size. At Caulfield, a gneissic inclusion shows evidence of having been rotated. This is the only example in the map area known to the writer where gneissic inclusions are not conformable in attitude with the associated pendant. Doubtlessly there are many inclusions within the area which have been rotated, but since they are chiefly structureless, evidence is very rare.

All phases of the disappearance of inclusions are exhibited innumerable times within the map area. In fact, all phases are commonly shown within one outcrop. Two steps are usually evident in the disappearance process. The first step separates the inclusion from others, and in general shapes the inclusions, usually to a rounded form. At this stage the inclusions are sharp in outline, and not dissimilar from the original country rock. The second stage is marked by the growth of plagioclase porphyroblasts within the body of the inclusion. These porphyroblasts are usually plagioclase, but may, in addition, include hornblende, biotite, and potassium feldspar. No matter what minerals form the porphyroblasts, they correspond in composition and crystal habit to their counterparts in the surrounding plutonic rocks. Photograph 43 shows the inclusions in a relatively early stage, Photograph 48 shows an intermediate stage, and

Photograph 48

Detail of porphyroblastic development in a hornblende granulite inclusion in hornblende-biotite quartz diorite. (Locality, Capilano Valley.)

Photograph 44 shows the final stage before disappearance.

Some inclusions apparently disappear by becoming steadily smaller in size, that is, the first process only is operative. This usually results in small clots of mafic minerals, before the inclusions disappear completely.

For sizes less than a yard in diameter, the density of porphyroblasts within inclusions shows no correlation with the size of the inclusion. An inclusion two inches in diameter may contain no obvious porphyroblasts while one adjacent, two feet in diameter may be thoroughly riddled by porphyroblasts.

Certain areas in some inclusions tend to resist the development of porphyroblasts. This leads to the formation of inclusions within inclusions (as shown in Photograph 44). These second generation inclusions can be located anywhere within the host inclusion, even along the edges. This may be the origin of the peculiarly resistant tiny inclusions which seem to persist in even the most biotite-rich plutonic rocks.

Nowhere within the area were inclusions found which were of a plutonic nature, and which could not readily be traced back through the various porphyroblastic stages to a fine-grained granulite or similar metamorphic rock.

MICROSCOPIC DESCRIPTIONS

Under the microscope the inclusions reveal a variety of textures which are classified as non-porphyroblastic, porphyroblastic, and plutonic. The least altered inclusions fall in the first group, the nebulous ghosts in the last group, and the great majority in the intermediate group.

NON-PORPHYROBLASTIC INCLUSIONS

There are two principal types included here, hornfelsic and granulitic. The latter are fine-grained, and the former extremely fine-grained; otherwise they are identical.

The typical hornfelsic inclusion is composed chiefly of very fine-grained (.01 mm - .02 mm) calcic oligoclase in irregularly shaped crystals. Pale olive green biotite and/or pale green hornblende comprise about 10% of the rock. Generally the rock contains a few, relatively untouched plagioclase (calcic andesine) phenocrysts inherited from a volcanic parent rock. Although the matrix is entirely recrystallized, the phenocrysts often survive unaffected. The plagioclase porphyroblasts, which are characteristic of the next group, are not found in these inclusions.

The granulitic inclusions, of the non-porphyroblastic type have an average grain size of about .05 mm. In other respects they are the same as the hornfelsic inclusions.

The non-porphyroblastic inclusions are considered to be the least metamorphosed inclusions in the area. They are, also, the finest grained.

PORPHYROBLASTIC INCLUSIONS

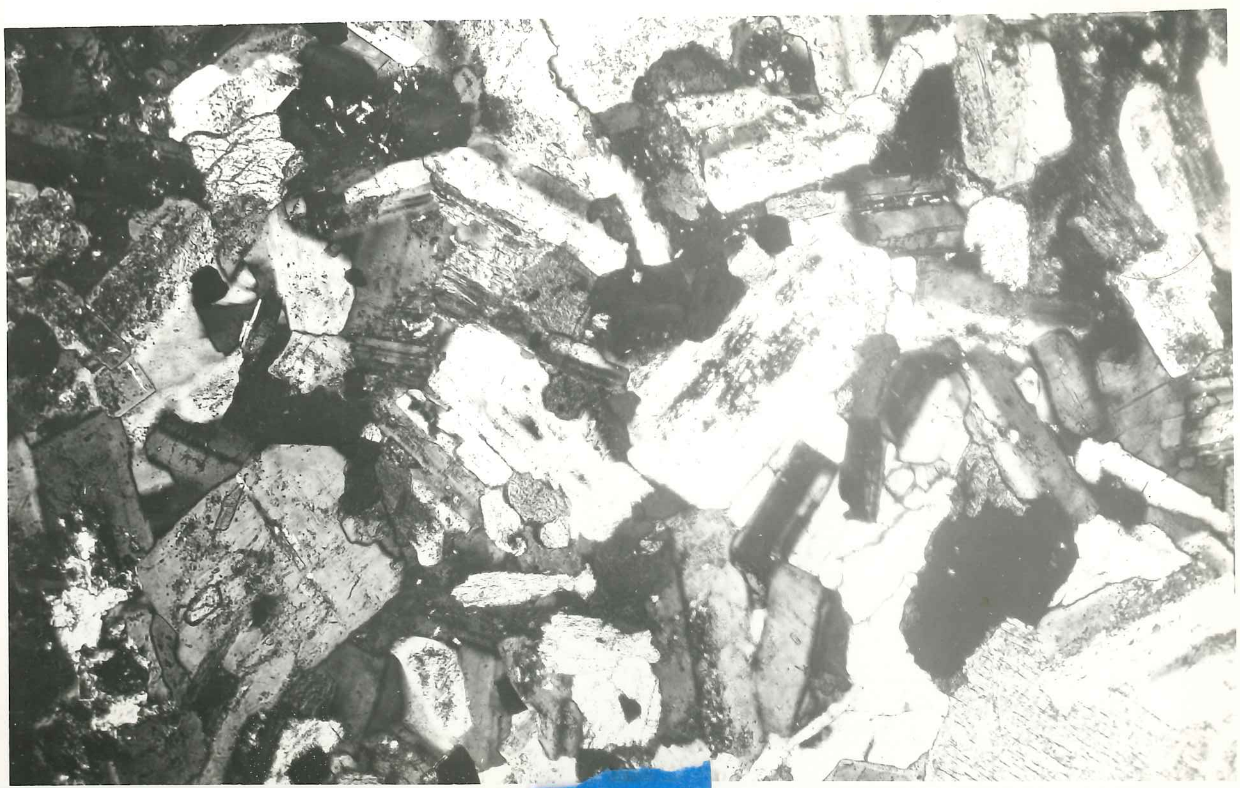
These inclusions are composed of a fine-grained matrix, and several or numerous porphyroblasts. The matrix shows two different textures, depending on the general shape of the plagioclase crystals. In one group they tend to be anhedral giving the matrix a typical granulitic appearance (Photograph 49); in the second group they tend to be more euhedral, and the resultant texture is best termed a fine-grained panidiomorphic type (Photograph 50). The latter tends to be slightly coarser than the former.

Photograph 49

Typical texture of the granulitic, porphyroblastic inclusions. It is characterized by anhedral plagioclase crystals. X60
(TS 70S-51, an inclusion in granite, from the south end of Bowen Island.)

Photograph 50

A fine-grained panidiomorphic texture characteristic of many of the porphyroblastic inclusions. The texture differs from the above only in that the plagioclase crystals tend to be more euhedral. X60
(TS 8311A-51, an inclusion in hornblende-biotite granodiorite from just east of Caulfeild, north side of Burrard Inlet.)



In the typical granulitic inclusion, plagioclase and hornblende are the dominant minerals. Their ratio varies widely, from 15% hornblende to about 60%. The average hornblende content is about 25%. Biotite may be present in minor amounts up to about 10%, but is usually absent. The hornblende is usually irregularly shaped with occasionally crystals being subhedral. When very abundant, it tends to be strongly poikiloblastic, containing numerous plagioclase grains.

Interstitial quartz usually comprises 10 - 15% of these inclusions, and plagioclase comprises the remaining 40% to 80%. In the matrix the plagioclase is usually a medium andesine (An35 - An45), and in the porphyroblasts, slightly more sodic (An25 - An35). The plagioclase porphyroblasts, often zoned (oscillatory), may be so abundant that the rock takes on a plutonic appearance. The porphyroblasts are of the same composition as the plagioclase in the surrounding plutonic rock. Small granules of matrix hornblende and plagioclase are often included by the porphyroblasts.

Whenever porphyroblasts are present in inclusions, most are plagioclase but porphyroblasts of other minerals occur. These are generally hornblende or biotite or both, and they tend to be poikiloblastic. Potash feldspar is rather rare in most inclusions, except where they occur in plutonic rocks particularly rich in this mineral. Potash feldspar porphyroblasts, when present, however, may be very large (exceeding one inch in some cases), but usually contain so many granules of the matrix minerals (Photograph 51), that it gives the impression of being interstitial. Quartz forms similar porphyroblasts but they are less poikiloblastic.

The average grain size of the matrix material of the granulitic inclusions is about .1 mm, and of the porphyroblasts about 1 mm.

Photograph 51

Highly poikiloblastic potassium feldspar, containing granules of hornblende and plagioclase. X98 (TS 83IIIA-51, a hornblende granulite inclusion in hornblende-biotite granodiorite, just east of Caulfeild, north side of Burrard Inlet.)

Photograph 52

Pseudocataclastic texture, characteristic of those inclusions which are so highly porphyroblastic that they have assumed a plutonic appearance in hand specimen. (TS H101b-49, a biotite granulite inclusion from near Crown Creek, Capilano Valley.)

An occasional granulitic inclusion is gneissic.

The inclusions with fine-grained panidiomorphic texture do not differ much in composition from those just described. The mafic minerals range from 10% to 30%, average 20%; plagioclase 70% - 85%; average 75%; quartz 0 - 30%, average 5%. In some of the inclusions potassium feldspar is abundant.

Biotite is more common in the inclusions with panidiomorphic textures, than in the granulitic ones. Except on rare occasions, however, hornblende is the predominant mafic mineral. The composition of the plagioclase ranges from An10 to An50, and is usually very close to that in the surrounding plutonic rock. This applies to both the porphyroblasts and the matrix plagioclase, although the latter tends to be slightly more calcic than the former.

As for the granulitic inclusions, the porphyroblasts are principally plagioclase, but may be hornblende, biotite, quartz, and potassium feldspar. The porphyroblasts tend to be somewhat more abundant in the panidiomorphic types than in the granulitic inclusions. This fact may have some bearing on the cause of the two different textures. Yet it is not known exactly why the plagioclase in certain inclusions should tend to be anhedral, and in others euhedral. There are indications that porphyroblast development under marginal (almost prohibitive) conditions can lead to euhedralism in the matrix crystals (see chapter on textures). Composition, however, is not apparently a decisive factor bearing on the shape of the crystals.

The average grain size of the matrix material in the panidiomorphic inclusions is about .2 mm, which is slightly larger than that of the granulitic inclusions.

PLUTONIC -APPEARING INCLUSIONS

These inclusions contain so many plagioclase and other porphyroblasts that the fine-grained, granulitic matrix material is practically eliminated, or relegated to minor interstitial positions. In the field these are the ghost inclusions, which are only slightly darker than the surrounding plutonic rock. In thin section they look even more plutonic, and must be termed diorite, quartz diorite, etc. They are distinguished from more highly developed plutonic rocks by the fine-grained interstitial material. Pseudocataclastic textures are best developed in such inclusions, and are in fact characteristic of them (Photograph 52).

INTERPRETATION OF INCLUSION PHENOMENA

From the general facts regarding the inclusions in the thesis area, it seems to be possible to establish their mode of origin. In doing so it is necessary to distinguish between those facts which have general validity, and those which represent special cases, and to bear in mind that the special case may be more spectacularly illustrated than the general process. Thus evidence which repeats itself over and over again throughout the region is weighted more heavily, than rare but forceful examples. The method is vulnerable to error, but there seems to be no reasonable alternative.

Only two fundamental processes need be considered. Have the inclusions resulted from magmatic activity, or from metamorphic processes? Much of the evidence is, unfortunately, bipartisan, and could logically result from either magmatic or metamorphic processes, and is of no deductive value.

The evidence which has been described above is condensed to phrase form below to assist in its evaluation. The first eight items are believed to be impartial in implication.

1) Irregular distribution of inclusions throughout the area.

This might be expected to result from either process, but stoping would presumably create more inclusions along the borders of magmatic flow, and in other ways locallize the inclusions.

2) Inclusions are more abundant near pendants.

This fact does not appear to favor either theory more than the other.

3) Most inclusions are rounded.

In volcanic flows and dykes, and in other rocks where forceful magmatic intrusion is not in doubt, the inclusions are predominantly angular, except, of course, where conglomerates are involved, or where the included material is of markedly different composition from the magma and consequently corrosion is vigorous. Perhaps, however, the comparison is not justified since the bodies which have clearly been forcibly intruded, have generally cooled relatively fast, while magmatic plutonic rocks are considered to have cooled slowly, and, under such conditions, may be more effective in rounding inclusions than are their hypabyssal in-laws. Thus the evidence is judged bipartisan.

4) Elongated inclusions parallel the foliation in plutonic rock.

This phenomenon can be produced by the replacement of sheared country rock, leaving elongated inclusions and foliated plutonic rock, and also, possibly, by viscous magmatic flow dragging out inclusions parallel to the flow lines. Yet, it is exceedingly difficult to prove that the latter ever occurs (except in marginal areas), first because of the difficulty of setting up powerful shearing forces in a liquid, and secondly because the strained, fractured, or bent crystals which should be present in the distorted inclusions are rarely found.

5) Inclusions within inclusions.

Magmatically, this fact could be interpreted as a result of stoping of a plutonic rock which already contained inclusions. Metamorphically, the inclusion inclusions can be interpreted simply as areas within the host inclusion where conditions (wetness probably being the most important) did not favor the development of porphyroblasts. The latter is the impression gained under the microscope, but since both origins are possible and equally favored, the evidence is considered to be neutral.

6) Rarity of gneissic, schistose, or bedded inclusions.

The pendants within the area are not lacking in gneissic or bedded rocks, but rarely do such types occur as inclusions. The implication, of course, is that structures of inclusions have been destroyed by metamorphism as a result either of soaking in a magma, or just soaking (in solutions of a hydrothermal type). The two media, magma and hydrothermal solutions, should cause different effects, but the difference is not well-established (or the granite problem would not exist), and therefore the phenomenon is interpreted as weighing no more in favour of one origin than the other.

7) Pseudocataclastic textures are typical of the plutonic-looking inclusions.

A pseudocataclastic texture, in the writer's opinion, can form only by porphyroblastic development (one exception; the recrystallization of the matrix of a porphyry), and may result equally well from assimilation processes either in a magma, or in a region of metamorphism.

8) Rotation of inclusions.

Rotation of inclusions is the exception rather than the rule for structured inclusions in the thesis area. Movement is proven by apparent rotation, providing the original rock was not highly contorted. Few persons would seriously maintain however that proof of movement is equivalent to proof of magma, although that tends to be the first rationalization that comes to mind. A region undergoing metamorphism may be considered a heterogeneous mass of intermingled areas, some relatively dry, and some relatively wet, which structurally may be interpreted as competent and incompetent areas respectively. Thus the masses of hot wet metamorphic rock may be induced to move much in the manner that soft shale is induced to flow between massive sandstone beds, or in the manner of salt beds forced through overlying strata. Metamorphic material, thus mobilized, generally has a texture even more metamorphic-looking (sheared and bent grains, sutured quartz boundaries, etc.) than its stationary equivalent, although if the mobilized material comes to rest in an area undergoing granitization, or, more likely, in an area that is later subjected to granitizing conditions, textural evidence of mobilization may be erased by recrystallization.

Some of the above items may be interpreted in one way by certain persons, and in another way by others. Since each item can be interpreted in two ways, each seeming logical to the writer, no decision is made on any of the above evidence, other than to note that none of it precludes the possibility of either origin.

The next nine items appear to favor the metamorphic origin for inclusions.

9) Omnipresence of inclusions throughout the region.

Forceful intrusion, judging from the undisputed examples, may produce an irregular distribution of inclusions, but also tends to concentrate them, so that large volumes of the intrusive rock are entirely free of inclusions. In the thesis area the distribution is admittedly irregular but within limits. There are practically no outcrops showing absolutely no inclusions. The omnipresence of inclusions regardless of distance from contacts seems to favor origin in the heterogeneous environment of regional metamorphism.

10) Abundance of inclusions is independent of elevation.

This is true for an elevation range of 7000 feet, although it obviously cannot be true for an unlimited range. It is not certain whether proponents of large scale magmatic stoping prefer to have the inclusions remain clustered near the roof, or sink beyond sight in the magma. In quiescent conditions the inclusions should sink, being heavier, but upwelling viscous magma might counteract this tendency. Whichever factor is dominant, the distribution of inclusions should bear some relations to elevation. Possibly, some degree of balance between floating and sinking tendencies might be attained under special conditions. Yet, as a general rule, the deeper inclusions, having been subjected to assimilation for longer periods than the higher inclusions, should be less in evidence than those at higher elevations.

11) Inclusions are more abundant in hornblende-rich plutonic rocks than in biotite-rich rocks.

According to detailed mineralogical and textural features, dealt with in an earlier chapter, hornblende-rich rocks appear to be less highly developed members of the plutonic series, and consequently more inclusions would be expected in them.

Should a hornblende-rich magmatic rock contain more inclusions than a biotite-rich magmatic rock? The writer does not think so, though it may be postulated that biotite-rich plutonic rocks are more effective in assimilating inclusions than the relatively dry hornblende rocks. Yet in hypabyssal rocks the opposite appears true. Basic volcanic rocks seem to attack inclusions more vigorously than do the more acid types.

12) Inclusions swarms cross boundaries of different plutonic rock types.

If multiple intrusions are used as the explanation of the different types of plutonic rocks within the area (as is often done in spite of the lack of sharp contacts, and the lack of inclusions of the earlier rock in the younger), inclusion swarms could not possibly pass from one intrusive to another. If the alternative explanation, differentiation in place, is employed, the problem of the inclusion swarms is explained, more or less, but all the problems sidestepped by the multiple intrusion hypothesis return, and when all the facts of the region are considered, assume monstrous proportions.

The inclusion swarms present no problems to the metamorphic hypothesis. The swarms themselves can be interpreted as segments of fairly large blocks of country rock which were cut off, during the early part of the tectonic period, from granitizing solutions, probably for structural reasons, leaving the replacement processes insufficient time to convert them entirely to plutonic rock.

13) Inclusions often maintain their shapes (even if angular) up to the point of disappearance

In the disappearance of inclusions two distinct processes are evident. The first shapes the inclusions, usually rounding them, the second obliterates them through the growth of porphyroblasts. The first is a corrosive process, and is dominant when physico-chemical conditions within the inclusions are not favorable for porphyroblastic development, probably because the interior of the inclusions are too dry. The second process is dominant when conditions within the inclusions are more or less the same as in the surrounding plutonic rock. When this stage has been reached it seems that the corrosive action is not only subordinate to the porphyroblastic development but is actually retarded by it due to the withdrawal of energy from the margins of the inclusions by the growing metacrysts.

The writer believes that the phenomenon in question favors a metamorphic origin simply because it differs radically from similar phenomena in lavas, where there is little evidence of anything other than corrosive action on inclusions. The fact that inclusions are assimilated by a single stage process in lavas, and a two stage process in plutonic rocks suggests a difference in the origin of the two rocks considerably more fundamental than slight differences in temperature and composition, rather, it indicates, to the writer, a difference in state of the host material.

14) <u>Average size of inclusions is smaller in biotite-rich rocks than in hornblende-rich rocks</u>

The same explanation holds here as for 11). Inclusions are smaller in the more highly developed plutonic rocks because the metamorphic processes have gone further towards completion, either because they were active for a longer period, or conditions were more favorable than in the hornblende-rich rocks.

From the magmatic viewpoint the fact might be explained by supposing biotite-rich magmas to be more effective in assimilating inclusions than are hornblende-rich magmas, although the writer knows of no supporting evidence for this supposition. As has been mentioned previously, the more basic varieties of the least disputed magmas, lavas, seem to be chemically the most active, and the most effective in the corrosion of inclusions.

15) <u>All phases of disappearance may be represented by the inclusions of one outcrop</u>

This is a very common occurrence, and one not easily explained by magmatic mechanisms. Although many properties have been attributed to the plutonic magma, few toll its abilities as a mixing agent. If the inclusions have not been mechanically mixed, then the relatively uniform conditions in a melt almost preclude the possibility of widely differing stages of assimilation being reached in one small locality.

In a region undergoing metamorphism, however, only the temperature may be considered more or less uniform over fairly large areas. The amount of water may vary widely from place to place, even on a microscopic scale, and since its presence is so favorable as a catalytic agent for recrystallization, the results found in the field could be logically expected.

16) <u>In medium and small sized inclusions, the abundance of porphyroblasts is independent of the size of the inclusions</u>

When porphyroblasts develop in an inclusion and are identical in composition to those in the surrounding plutonic rock (as they usually are), nearly identical physico-chemical conditions in the two media are required. Thus when the outer medium is a magma, porphyroblasts will develop in the inclusions when they too are close to magmatic conditions. Since such conditions are more readily reached in small inclusions, they should be more highly porphyroblastic than the larger inclusions. In this connection also, porphyroblasts should develop more rapidly along the outer margins of inclusions. Yet neither result is normally found in the field.

A metamorphic origin, probed along the same lines of reasoning, seems to provide the results actually found in the field. In the rock surrounding an inclusion conditions are wet (otherwise the plutonic rock would not have formed), and within the inclusion conditions are drier. Yet, within the inclusion, small areas may be sufficiently wet, or become so by the locallization of the available water within the inclusion, or by introduction of water from the wet surroundings, or some combination of both. In any event the wet areas would have no close relationship to the edges of the inclusion, but would be related to fortuitous circumstances and microscopic or submicroscopic structures in the inclusion. Small areas, even in large inclusions, may attain degrees of wetness and temperature identical to those in the plutonic rock, and provide a suitable environment for porphyroblastic growth. As a general principle the heterogeous results found in the field can only be explained as products of a heterogeneous physico-chemical system, which almost by definition is unlikely to be a melt, especially a slowly cooling melt.

17) No inclusions of apparent plutonic derrivation occur in the area

This is negative evidence, which is at best a rubbery crutch, but it is such a striking feature that it cannot be ignored. It follows from the assumption of magmatic intrusion that a tremendous number of inclusions result when non-plutonic rock is intruded. Yet when the older rock is plutonic there is no evidence of such inclusions. Admittedly some inclusions contain so many porphyroblasts, that they look plutonic, but under the microscope their metamorphic origin is evident, and in the field they can easily be traced back step by step to definitely non-plutonic rocks. Even if one assumes that the plutonic-looking inclusions are bona-fide magmatic, plutonic rocks, one will look in vain for a greater concentration of such inclusions along contact areas. Consequently, the multiple intrusion hypothesis can be maintained only if one assumes the first intrusion to be still molten when the second enters. Little is known about what happens when one magma intrudes another, or whether it can even occur, since it poses some difficult hydraulic and other problems.

In general, the lack of plutonic inclusions favors very strongly a metamorphic origin for the non-plutonic inclusions.

CONCLUSION

When all the phenomena are considered and weighted according to their apparent importance, one must conclude that a metamorphic origin for the inclusions in the thesis area is very likely. Much of the evidence is inconclusive, some of it favors metamorphism, but none points to magma only, and, in the writer's opinion, none even favors the plutonic melt.

DYKES

GENERAL STATEMENT

Many dykes lie in that part of the Coast Mountains dealt with in this thesis. These are divided into two groups, Tertiary, and pre-Tertiary. The Tertiary dykes are the lesser in number, and simple of interpretation, but the pre-Tertiary dykes are complex, and have caused confusion and uneasiness in the minds of those who have examined them in detail. The most consternation arises over what is usually the least contraversial features of dykes, that is, whether the dykes are younger or older than the country rock enclosing them. It is intended in this chapter to remove these dykes from their position as "erratics" in the geological history of the area, and to include them as a logical, and almost necessary phenomenon in large metamorphic belts.

PRE-TERTIARY DYKES

GENERAL STATEMENT

More than 70% of the estimated several thousand dykes in the thesis area fall in this group. They are found in the pendants and more commonly in the plutonic rocks, but do not cut the mid-Eocene Burrard formation. Possibly the age of some may be early Eocene or Paleocene, but because of the "synplutonic" nature of most of these dykes, and for convenience of terminology they are called pre-Tertiary in this thesis.

MEGASCOPIC DESCRIPTIONS AND FIELD RELATIONSHIPS

The least altered of these dykes are composed of dark grey to dark greenish-grey, aphanitic to fine-grained andesites. They are usually very hard rocks, sometimes almost flinty. Many are slightly porphyritic, usually with phenocrysts of plagioclase, but occasionally of hornblende. The altered dykes often do not look much different from the unaltered in hand specimen. The altered dykes tend to be dark grey and fine-grained, but rarely aphanitic. Usually they are more or less porphyroblastic. In some, plagioclase porphyroblasts are well developed and exceedingly numerous. The most highly altered dykes are merely nebulous outlines in the plutonic rock.

The most remarkable feature of many of these dykes is their capricious relation with the plutonic rocks which contain them. Because they are dyke-shaped they always appear at first glance to be cutting the plutonic rock. Yet when examined closely many are found themselves to be cut by the plutonic rock, either in relatively wide "counter dykes" (as in Photograph 53 and 54) or in numerous discontinuous stringers (Photograph 55 and 62).

Embayment of the plutonic rocks into the dykes frequently results in the development of irregular scalloped borders and complex intermingling of dyke and plutonic rock (Photograph 56).

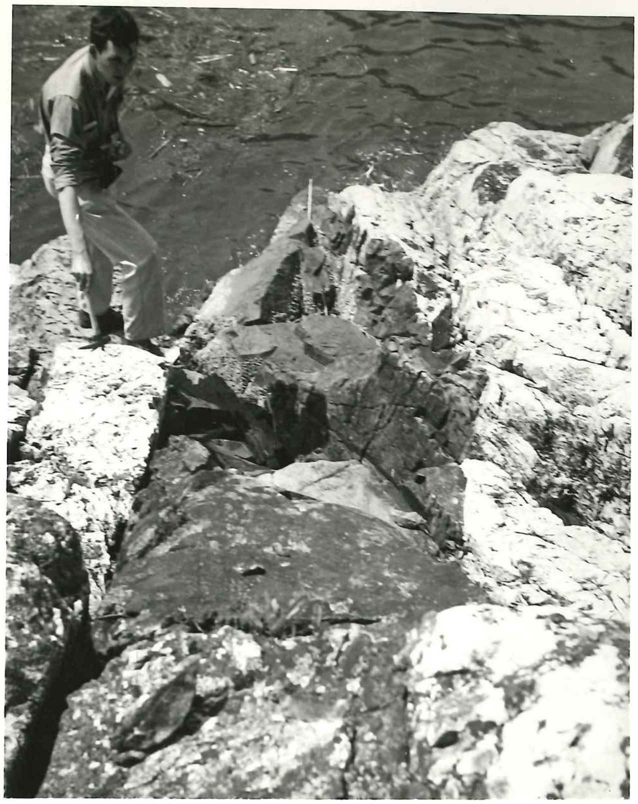
In Photograph 57, a dyke cut by several small faults is shown. The offsets are obvious, but no break occurs in the plutonic rock or the dyke. The breaks appear to have been healed by recrystallization. It might be argued, that the dyke is following a joint pattern (although the agreement in offset is rather against this hypothesis), in which case the joints in the plutonic rock have healed since the intrusion of the

Photograph 53

A pre-Tertiary dyke cutting rather coarse-grained hornblende-biotite granodiorite at Caulfeild, north side of Burrard Inlet.

Photograph 54

Same as above, but showing more clearly a "counter dyke" of the granodiorite cutting the pre-Tertiary dyke.



Photograph 55

Pre-Tertiary dyke, showing discontinuous granitic stringers and irregular border. (Christie)

Photograph 56

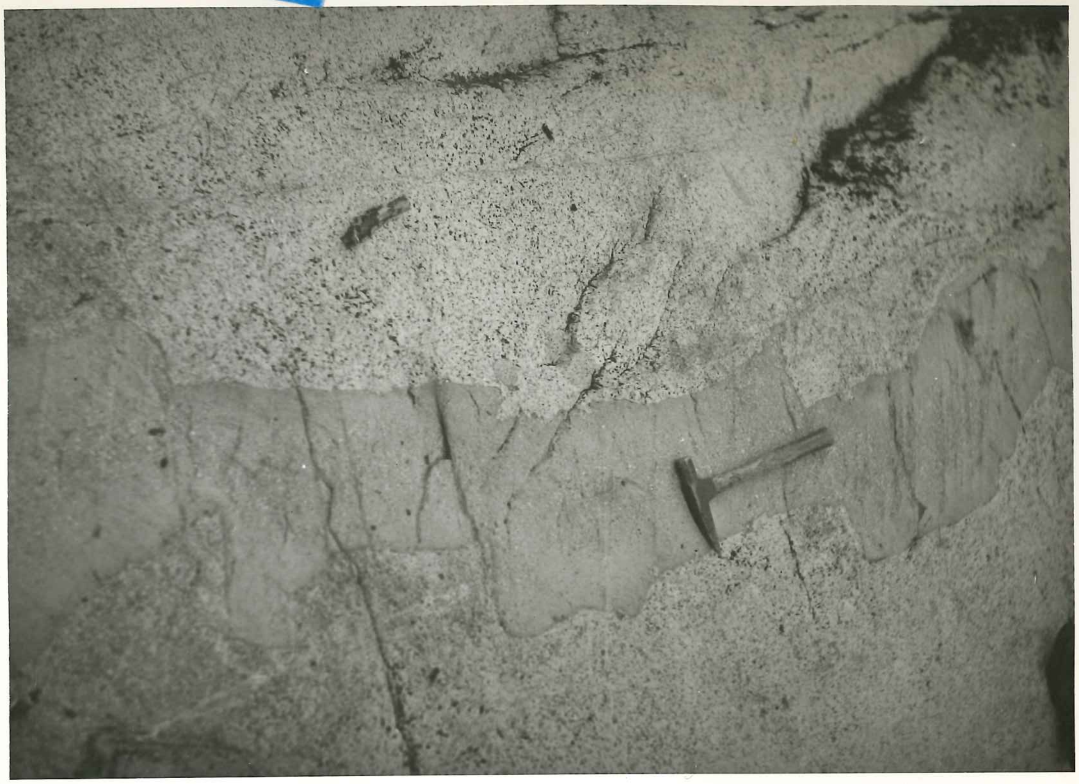
Pre-Tertiary dyke, showing the rather typical corroded borders and irregular shape. The enclosing plutonic rock is a hornblende-biotite quartz diorite. (Locality, Capilano Valley.)

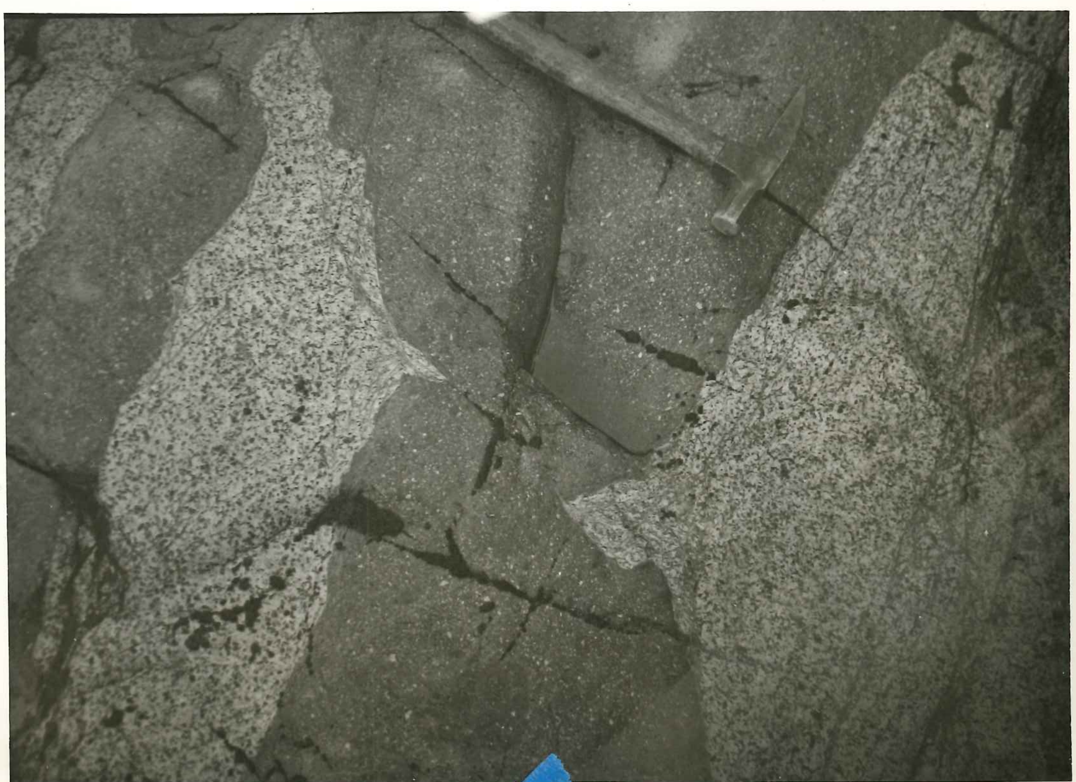
Photograph 57

Pre-Tertiary dyke. After intrusion, the dyke was faulted in several places, but the plutonic rock now shows no evidence of any fractures, implying that since the faulting, the plutonic rock has recrystallized. It is possible that the dyke was never faulted, but merely followed a peculiar joint pattern. Nevertheless, the above implication is still present, since no fracture, either of faults or joints remains. (Locality, ridge east of Coquitlam River.)

Photograph 58

Pre-Tertiary dyke. The plutonic rock here is shown invading the dyke (a composite dyke) along a joint plane, entering from both sides. Close examination reveals that the former boundary of the dyke is still faintly, but definitely preserved, indicating that the plutonic rock advanced here by replacement processes.





dyke. In any event crystallizing or recrystallizing took place in the plutonic rock after the dyke was emplaced.

Structures within the dykes sometimes show marked control ever the route of the encroaching plutonic rock. For example, Photograph 58 shows the plutonic rock entering a dyke, from both sides, controlled by a joint plane. It should be noted that although the invading granite essentially destroys the dyke outline, ghost outlines often remain as areas of slightly darker plutonic rock. This feature is well shown in Photographs 58 and 59.

Some dykes are wholly or partly converted to plutonic rock in a much different manner. Porphyroblasts of plagioclase develop throughout the dyke uncontrolled by any obvious structure. They form most abundantly in the centre of the dykes, and less along the edges. The process is illustrated in Photographs 60 and 61 (both of the same dyke).

None of the pre-Tertiary dykes show glassy chilled edges, but in some the grain size becomes slightly finer towards the edges. More often, an appearance of finer-grained edges is produced where none exists by an abundance of porphyroblasts in the center of the dykes, and a scarcity of them near the edges (Photograph 60 and 61). The borders are the last part of the dykes to be changed to plutonic rock. Many of the dykes show no evidence at all or marginal chilling and consequently it is very difficult to prove that such bodies are dykes, and not simply dyke-like remnants. Sinuous schistose bodies such as shown in Photographs 62 and 63 may be dykes (because of their isolation in relatively inclusion free plutonic rock, and their great length compared to their widths), but nevertheless doubts remain (because of the difficulty of explaining their

Photograph 59

Pre-Tertiary dyke. This narrow dyke has been breached in several places by plutonic rock (a biotite-hornblende quartz diorite), yet the former outline of the dyke is still evident. This is considered to be evidence of a metamorphic origin for the surrounding plutonic rock. Note, also, the ratio of length to width of some of these dykes makes it very unlikely that they possessed sufficient strength to act as barriers to magmatic flow. (Locality, Grand Creek.)

Photograph 60

Pre-Tertiary dyke. An illustration of the more abundant porphyroblasts in the central areas of the dyke. This results in a relatively fine-grained border phase, but the cause is different from that of normal "chilled borders". Here the greater heat in the central part of the dyke appears to have accelerated the metamorphic processes, which were operative in the plutonic rock at the time of intrusion of the dyke, resulting in more rapid porphyroblast development in the centre of the dyke, than along the edges. (Christie)

Photograph 61

Same pre-Tertiary dyke as shown above. Here the dyke is more highly obliterated by porphyroblastic development. It has evidently been faulted during the tectonic period, and this may have facilitated the access of solutions from the surrounding rocks. (Christie)

Photograph 62

Pseudo-dyke? These sinuous, rather schistose bodies are probably not dykes, but simply remnants of pre-granitic rock. They often are found, however, in relatively inclusion free plutonic rock. Such isolation suggests that they may in fact be dykes.

Photograph 63

Same as above, but showing the typical wispy terminations of these bodies.

Photograph 62

Pseudo-dyke? These sinuous, rather schistose bodies are probably not dykes, but simply remnants of pre-granitic rock. They often are found, however, in relatively inclusion free plutonic rock. Such isolation suggests that they may in fact be dykes.

Photograph 63

Same as above, but showing the typical wispy terminations of these bodies.

schistosity). Such narrow bodies usually disappear along the strike by grading into the plutonic rock as illustrated in Photograph 63.

Certain dykes on the west coast of Indian Arm, and elsewhere, show the strongest conflicting evidence concerning their age with respect to the plutonic rock. These dykes contain angular inclusions of the surrounding plutonic rock suggesting post-granitic age, and yet they are cut by granitic stringers of the same composition as the surrounding plutonic rock.

Aside from compositional differences, most of the pre-Tertiary dykes can be separated from the Tertiary on the basis of jointing. The pre-Tertiary dykes usually have no joint pattern which is unique to them, but rather one which is merely a continuation, generally without distortion of the jointing in the enclosing plutonic rock. The Tertiary joints on the other hand have well-developed joint patterns unrelated to the plutonic rock. These two jointing patterns are illustrated in Photographs 64 and 65. A few of the pre-Tertiary dykes have their own joint pattern, but it is weakly developed. Probably they were emplaced very late in the plutonic period when most of the chemical activity within the plutonic rocks was over.

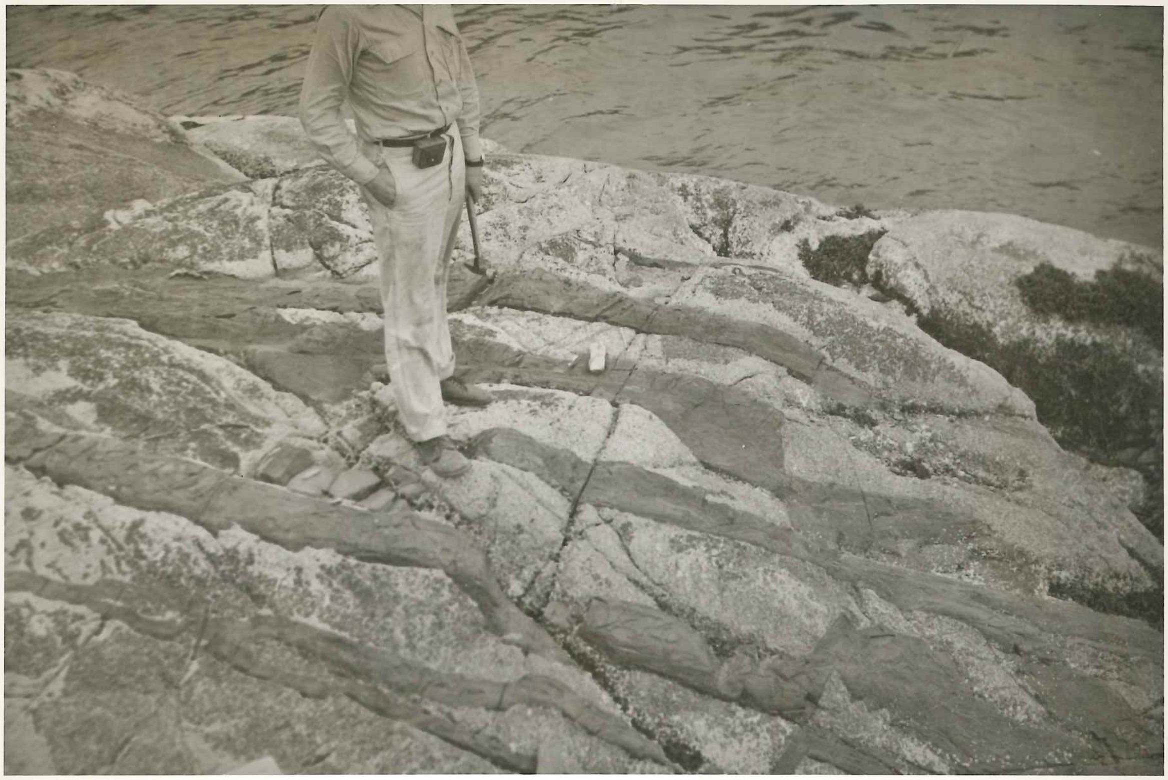
At several localities, fragments of pre-granitic gneiss have been found attached to the pre-Tertiary dykes in a manner suggesting that the rest of the country rock (gneiss) has been replaced by the granite, which also cuts the dykes. Phemister (1945) who was the first to recognize that the dykes in this area are not all they seem at first glance, was very impressed with this phenomenon and illustrated it in his paper. A similar phenomenon on a larger scale are the several dykes which

Photograph 64

Late pre-Tertiary dykes. These dykes appear to have been intruded late in the plutonic period. They have not been attacked by the plutonic rocks, but have no jointing of their own. The jointing in the plutonic rock passes through the dykes. These dykes rarely have chilled margins.

Photograph 65

Tertiary dyke. This is typical of the Tertiary dykes. They follow the jointing in the plutonic rocks, and have their own, well-developed, columnar jointing. Chilled margins are usually distinct in these dykes.



can be traced from the plutonic rock (which cuts them) into pendant bodies.

The pre-Tertiary dykes, taken as a whole, are distributed throughout the area, presenting no obvious pattern or preference for certain plutonic rock types. Preference is shown, however, by certain types of pre-Tertiary dykes, and is dealt with more fully in a later part of this chapter. Nevertheless, since only a small fraction of the thousands of dykes within the region were recorded, it must be concluded that data concerning the abundance of dykes in different plutonic types is too meager to determine whether more correlations exist than were found.

The dimensions of the pre-Tertiary dykes are variable. In width they range from about 4 inches to more than 30 feet. Most are between 4 and 10 feet in width. Exposures seldom permit determining the lengths of the dykes, but some were traced for more than 400 yards.

As Phemister pointed out, the pre-Tertiary dykes have a predominant north to northeast trend. Although the tendency towards this trend is strong in the comparatively small area mapped by Phemister it is weak over the thesis area as a whole. Yet, weak though it is, there is a definite tendency for the dykes to strike across the Coast Mountain structural trends.

MICROSCOPIC DESCRIPTIONS

In hand specimen the pre-Tertiary dykes all look very similar, but in thin section they are dissimilar. On the basis of texture the dykes are divided into three major groups, trachytic, hornfelsic, and granulitic. They represent, in order, increasing degrees of alteration.

The trachytic dykes are texturally relatively unaltered. The hornfelsic dykes are largely recrystallized, and composed chiefly of very fine-grained, irregularly shaped plagioclase and mafic minerals. The granulitic dykes are essentially granulites composed of distinct, equi-dimensional crystals. These three textures are shown in Photographs 66, 67 and 68. The more important characteristics of each group are summarized below.

TRACHYTIC DYKES

Elongated plagioclase laths characterize this group. Normally the anorthite content of the plagioclase falls between An_{43} and An_{55}. The mafic minerals comprise from 5% to 25% of the rock, and average about 15%. The principal mafic minerals are hornblende and chlorite in varying proportions. Biotite and augite are also found in some sections but are never abundant. In the trachytic dykes, hornblende and augite tend to be much more euhedral than in the other groups. Nevertheless, exceptions were noted, wherein, for example, hornblende crystals were anhedral in otherwise trachytic-textured rocks.

About half of the trachytic dykes are porphyritic, or micro-porphyritic. The phenocrysts are usually plagioclase alone but may include also one or more mafic minerals. In the latter case the ratio of mafic minerals to plagioclase is far higher in the phenocrysts, than in the matrix.

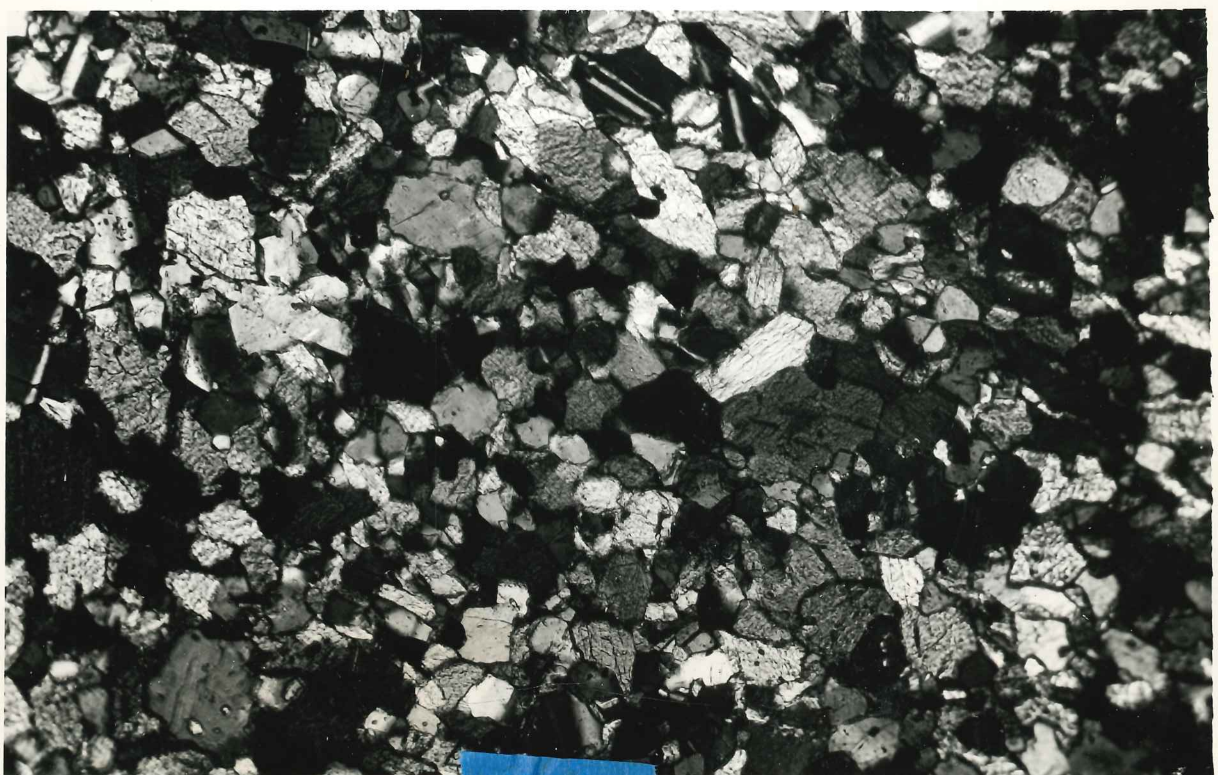
The dykes selected for thin-sections (about 50) came from all types of plutonic rock and some from pendants. About 1/3 have trachytic textures, and all these were found to have come from

Photograph 66

Example of the trachytic-textured, pre-Tertiary dykes. X65
(TS R242-52, a dyke near Admiraly Point, Burrard Inlet.)

Photograph 67

Typical example of the granulitic-textured, pre-Tertiary dykes. X50
(TS J43-52, a dyke in Grand Creek falls, pictured in Photograph 71.)

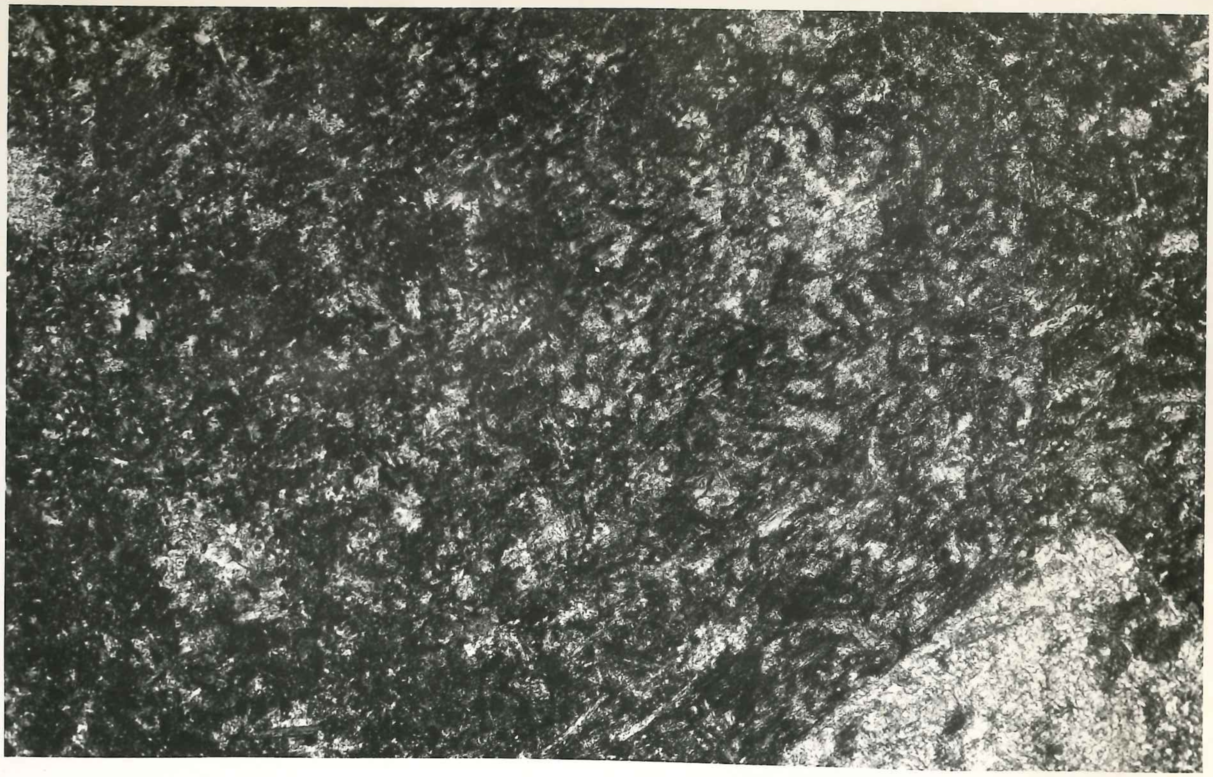


Photograph 68

Example of a hornfelsic-textured, pre-Tertiary dyke. X97
(TS R84-52, a dyke from the south slope of Seymour Mountain.)

Photograph 69

This rock was originally probably a calcic andesite dyke. Now all the plagioclase in the field, including the phenocrysts is albite (An8). Complete albitization with perfect preservation of texture is well-illustrated in this photograph. Even the broad twinning, typical of calcic andesine, or labradorite, is preserved. X45
(TS R189-52, a dyke in hornblende grano-diorite, a mile northeast of Deep Cove.)



hornblende-rock plutonic rocks, including granite, granodiorite, quartz diorite, gabbro, and pendant rock. This excludes of course, the basaltic Tertiary dykes, which may be found anywhere, and are entirely post-plutonic. They have trachytic textures but are easily distinguished in the field on the basis of their jointing, and in thin section by their composition. The close association of hornblende-rich plutonic rocks, and trachytic dykes was thought at first to be fortuitous, due to an almost incredible sampling error, until the diametrically opposite relationship was found for the granulitic dykes, which almost invariably cut biotite-rich plutonic rocks.

Two of the trachytic dykes show a rather remarkable alteration. Under the microscope they look like normal trachytic, porphyritic, calcic andesites. The plagioclase laths are broadly twinned in the manner of calcic andesines and labradorites which are found in many of the dykes. Yet all the plagioclase, both in the phenocrysts and in the matrix is albite (An8-10). The mafic minerals have been converted to chlorite. This process has left no remnants of unreplaced plagioclase or primary mafic minerals, but in no way has the textural appearance of the rock been changed (Photograph 69).

HORNFELSIC DYKES

These dykes are characterized by a matrix of fine-grained, irregular plagioclase crystals. Anorthite values usually fall between An20 and An30, but occasionally are as low as An10. When porphyritic, as these dykes often are, the plagioclase phenocrysts seem to be relatively unaltered, and sometimes much more calcic (An50) than the matrix. The content of mafic minerals ranges from 3% to 50%. Chlorite is by far the most abundant mafic mineral in the hornfelsic dykes. Both biotite and hornblende are rare, and augite is not present in any section examined. Epidote and magnetite are usually present, and occasionally abundant. The mafic minerals, on the whole, tend to be very irregular in shape.

Partial albitization in the trachytic or hornfelsic dykes within the area is rare, yet completely albitized sections are found in both groups.

With two exceptions (out of 16), the hornfelsic dykes cut the hornblende-rich plutonic rocks, including (diorite, quartz diorite, and granite), or pendant rocks.

GRANULITIC DYKES

The texture of these dykes differs little from a normal hornblende-plagioclase granulite, so common in the pre-granitic rocks. The plagioclase crystals are roughly equidimensional and anhedral. The anorthite content varies widely, from An5 to An60. For about half the granulitic dykes the anorthite values fall between 20 and 30. Unlike the trachytic and hornfelsic dykes, the granulitic dykes commonly contain two plagioclases of distinctly different composition, such as albite and labradorite. The albite is both interstitial and pseudomorphic after the more calcic plagioclase. Mafic minerals may be entirely absent (in the case of one totally albitized rock) or comprise any percentage of the rock up to 65%. On the average, however, the mafic content averages slightly less than 30%. The principal mafic minerals are hornblende and magnetite. Occasionally some biotite is present, but it is never abundant. Both chlorite and epidote are rare in the granulitic dykes. The mafic minerals may be either subhedral, equivalent (to plagioclase) grains or interstitial. Plagioclase phenocrysts, and some porphyroblasts are often present. Hornblende occasionally forms porphyroblasts, but large mafic crystals are generally rare.

As was previously mentioned under trachytic dykes, the granulitic dykes are generally found in biotite-rich plutonic rocks. Out of 18 granulitic dykes examined under the microscope, 16 cut biotite-rich plutonic rock, including quartz diorite, granodiorite, and granite. Of the three groups, the granulitic dykes give the best evidence in the field that they have been replaced by the plutonic rock they cut.

The above three groups include about 90% of all the pre-Tertiary dykes in the area. There are a few dykes, however, which represent transitions between the groups. Three transitional types are theoretically possible, and all were noted in the thin sections, namely trachytic-hornfelsic, trachytic-granulitic, and hornfelsic-granulitic. In one such section, a part may be trachytic with well-formed plagioclase laths, and another part may be hornfelsic with irregular fine-grained plagioclase crystals. Similar mixtures occur in the other transitional types. The presence of three transitional types is interesting, in that a two-step transition from trachytic to granulitic texture through a hornfelsic stage although common is shown to be unnecessary, since a trachytic texture can be changed directly into a granulitic texture.

CONCLUSIONS FROM THE PRE-TERTIARY DYKES

The dykes described above are complex, and the explanation of them poses some unusual problems.

The evidence appears overwhelmingly that some of the pre-Tertiary dykes are actually replaced by elements from the plutonic rocks which they cut. This is not the relatively simple case of a dyke cutting one plutonic rock, and both being cut by another plutonic rock. Nor is there any evidence of remelting of the plutonic rock and subsequent reintrusion, caused by the heat of the dyke.

Are these dykes, therefore, older than the plutonic rock surrounding them? Phemister thought so, and stated "That these dykes have acted as barriers to the invading magma is manifest -----" (Phemister, 1945, p.74). Phemister refers to these dykes as "pre-batholithic" throughout his paper.

Could the advancing magma by assimilation have carved the country rock away from the dyke, leaving only rare xenoliths of the country rock, and the dyke only slightly affected? Phemister does not delve deeply into the mechanism that performs the feat, but maintains that the agent is the advancing granitic magma, and that in some manner it effects the required result. In the thesis area are many examples of dykes which are less than two feet wide and more than a hundred yards long, and which show evidence of replacement by plutonic rocks. Applying the magmatic stoping concept to such an example, one can hardly fail to conclude that the dyke, being little different from the country rock in strength and usually in composition, must surely be brecciated and assimilated at roughly the same rate as the country rock. If granitic magmas are considered to be very viscous, because of their siliceousness and the low temperatures generally attributed to them, the inadequacy of any dyke to act as a barrier is further emphasized. It seems probable that no magmatic mechanism could be so perfectly selective as to cut away all the country rock and leave a brittle tenuous dyke floating in it oblivious to the enormous stresses which must be operative in plutonic flow.

On the whole, magmas seem to be crude mechanisms, too lacking in possibilities for refinement, to provide a satisfactory solution to the problem. The dining room floor cannot be swept with a bulldozer. The obvious alternative is some sort of replacement process, but even this mechanism at first glance seems to represent only a somewhat smaller bulldozer, as will be shown later.

Goodspeed (1955) working the Cornucopia area of Oregon found similar dykes, and felt that they could most easily be explained if the surrounding granitic rock was formed by metasomatic rather than magmatic processes. He concludes (p.159)

"The relict dykes at Cornucopia were probably replacement dikes, formed by structurally controlled feldspathization in the metamorphic rocks during an early stage of granitization. At the time of later widespread granitization, these replacement dikes which had previously been transformed from schistose hornfels to a less permeable igneous-appearing rock were not readily susceptible to further metasomatic changes and therefore remained as relics while the metamorphic rocks in which they had been formed were completely granitized. In other localities it is apparent that some relict dikes were early igneous dikes. For these a similar interpretation can be advanced, namely, that they were more resistant to granitization than their enclosing rocks."

The dykes in the thesis area are not replacement dykes, and would be correlated to Goodspeed's "early igneous dikes". The writer's original views more or less parallel those put forth by Goodspeed, but reconsideration of the problem in the light of considerable additional data produced a new theory, which is about to be presented.

If the granitic rocks formed by replacement processes, at least the physical strength of the dyke can be dismissed as no longer a significant factor. Certain sulphide deposits show, spectacularly, how extremely selective, replacement processes can be under favorable conditions. Individual beds may be almost entirely replaced, while others adjacent may be left untouched. Such highly selective replacement, however, implies either major compositional or structural differences, in the rocks replaced, or marginal energy conditions, that is, conditions such that replacement is just possible and no more. Low temperatures or very weak concentrations compel the solutions to take every slight advantage of structure and composition. Where such advantages can be found, replacement occurs, and only in such places. But, to return to the dyke in question, it is located in an area of clean plutonic rock, where inclusions may comprise less than one percent of the total rock. Assuming that the country rock has been replaced, the process has been extremely complete, implying very favorable conditions, certainly nothing marginal. If the partially replaced dykes occurred only in plutonic rock containing a high percentage of inclusions their explanation by replacement processes might be feasible, but they do not. In fact, they occur most abundantly in relatively clean biotite-rich plutonic rocks, where the replacement processes were so vigorous as to remove almost completely all the country rock. No dyke under such conditions, regardless of its composition, could remain as immune as some of those seen in the field.

The problem of exchanging a dyke's country rock without greatly affecting the dyke, could be investigated along many lines, all variations of either the magmatic, or metasomatic approaches. As is often the case, the possibilities of the impossible(?) permit tremendous verbosity. The writer believes the problem as stated is insoluble, and is best side stepped.

If the dykes are indeed older than the plutonic rock, one has no alternative but to devise some method of removing the country rock from around the dyke. But the dykes need not be older than the plutonic rock they cut. They are probably not pre-batholithic (or pre-granitic, etc.) as maintained by Phemister, but are contemporaneous with the formation of the plutonic rock. Their history is briefly interpreted as follows.

During the long period of metamorphism during which it is proposed that the country rock was changed to plutonic rock, the region was solid and capable of fracturing. Deeper portions of the country rock, being under higher temperatures than normal, melted and filled the fractures, formed by the periodically relieved stresses characteristic of regions undergoing major metamorphism. The dykes would be composed of about the same material as the country rock, and such is the case.

Many things can happen to a dyke thus injected into a region undergoing granitization. If the dyke cuts a pendant, and that pendant survives the period of granite formation, the dyke within it will probably maintain its original texture. If the pendant is replaced, the dyke will also disappear. Next consider the case wherein the dyke cuts a hornblende-rich plutonic rock, for instance, a hornblende diorite. This plutonic rock is at the bottom of the plutonic series (see section on plutonic rocks). If conditions remain wet, the rock will evolve through intermediate types (hornblende-biotite quartz diorite, biotite-hornblende granodiorite, etc.) to a biotite rock, for instance, a biotite granodiorite, a rather common endpoint. The cooling dyke will become solid long before the temperature of the surrounding plutonic rock is reached. The grain size of the dyke is unlikely to be much affected by the heat of the country rock, although glassy edges would be unlikely due to the slight retardation of the initial (after intrusion) cooling rate. Solutions from the plutonic rock would soon penetrate the dyke and its conversion first to hornblende granulite, then to a hornblende diorite and later into plutonic rocks would have begun. Whether or not the dyke is completely granitized depends upon how long favorable conditions (principally wetness and temperature) are maintained. Should conditions be dry in the hornblende diorite originally intruded, and remain so until the end of the metamorphic period, it is unlikely that the dyke would undergo much change.

If the dyke enters in the late stages of granitization when temperatures are low, and conditions are moderately dry, a very fine-grained hornfels will probably be produced. But if the plutonic rock is still quite wet, the higher temperatures within the dyke will promote the development of porphyroblasts within the dyke. Such porphyroblasts will be most abundant in the centre of the dyke where temperatures are highest, and fewest along the borders, and such is the case (see Photographs 60 and 61). The heat from the dyke may also promote crystal development in the plutonic rock at the contacts. This results in a discontinuous margin of white pegmatitic rock, generally less than an inch wide, along the dyke contact. It is discontinuous and often absent probably because it is dependent upon the wetness of the plutonic rock at the time of intrusion of the dyke as well as upon the heat of the dyke. Examples are shown in Photographs 70 and 71.

If a dyke comes in late, when conditions are dry and temperatures are low, nothing much happens to it. In this category, most of the dykes in the trachytic group would fall. If, however, there should be a resurgence of wetness, and accompanying it, probably a slight increase in temperature, replacement under marginal conditions may be possible. In such cases the dyke plagioclase may be entirely albitized, and the mafic minerals chloritized. Yet the original texture may be preserved, as shown in Photograph 69.

There is ample evidence that the conditions over the region during granitization were very heterogeneous. One area may be wet, another dry. Temperatures also are variable from place to place, although probably less so than the degree of wetness. Finally the stage of evolution of the plutonic rock differed from place to place. Thus the environment in which a dyke found itself immediately after intrusion was only one of many possible, and the subsequent events represent only one of many courses. It is quite possible (and occurs in the thesis area) for one part of a dyke, presumably under wet conditions, to be entirely granitized, while another part remains intact. Using Phemister's terminology, it would be quite possible to call such a dyke "pre-batholithic" at one place, and the same dyke "post-batholithic" at another place.

Photograph 70

A pre-Tertiary dyke, showing a narrow margin of mafic free plutonic rock. This is not a chilled edge of plutonic rock. It is in fact coarser-grained than the adjacent plutonic rock. This feature has been noted also by Goodspeed (1955, p148) near Cornucopia, Oregon.

Photograph 71

A pre-Tertiary dyke. Where the dyke is breached, the plutonic rock is coarser-grained (almost pegmatitic). If the dyke was folded after intrusion (as seems probable), it suggests that the plutonic rock had some degree of mobility during the plutonic period. (Locality, Grand Creek falls.)

In conclusion, the intrusion of many of the pre-Tertiary dykes is considered to be chiefly contemporaneous with the formation and evolution of the plutonic rocks and the variability of their present texture and composition reflect the heterogeneity of conditions during the metamorphic period. A broader study of these dykes than was possible for this project, may add considerably to our detailed knowledge concerning the formation of plutonic rocks.

TERTIARY DYKES

Less than 10% of the dykes in the thesis area fall in this group. These dykes are composed of augite-hornblende basalt. In the field their chilled edges and columnar jointing (see Photograph 12) make them easy to distinguish from the pre-Tertiary dykes.

The Tertiary dykes cut the mid-Eocene Burrard formation, and all older rocks in the region. They are overlain by the glacial deposits, In the Garibaldi region, 30 miles northeast of the sheet, the most recent flows were not glaciated. Some dykes related to these Pleistocene flows may occur in the thesis area but none were recognized.

The attitudes of the Tertiary dykes are obviously controlled by the local joint patterns in the plutonic rocks. Sharp changes in strike result when the dykes leave one set of joints to follow another.

Because the Tertiary dykes do not bear directly on the problem of the plutonic rocks little work was devoted to them.

STRUCTURES IN THE PLUTONIC ROCKS

There is not a great deal of structure in the plutonic rocks in the thesis area, but there is some. This chapter deals briefly with the more common structures, such as foliation, banding, faults, and joints in the plutonic rocks.

FOLIATION

Seldom in the thesis area is the plutonic rock strongly foliated. Usually it is truly "richtungslos". Perhaps, about 10% of the outcrops show some foliation. Often the foliation, which is marked by alignment of the mafic minerals, is so faint that it is easily overlooked. For the most part the foliation is rather ephemeral, present here, absent there, and rarely continuous for any distance. It is best developed, of course, in the vicinity of faults, but the more common, faint variety of foliation shows no such obvious restrictions. The plutonic rock near large inclusions and pendants is more often foliated than that some distance removed from such bodies. Where the inclusions are markedly elongate, the surrounding plutonic rock is foliated, and parallel to them.

Throughout the thesis area the trends are usually between west and north, and parallel to the structures in any local bodies of pre-granitic rock.

Between Indian Arm and Coquitlam Lake, near the north edge of the sheet the foliation in the plutonic rock appears to outline a large fold (anticline) plunging steeply to the north. This structure is about 3 miles wide at the base, and about the same in height. The core of the anticline is unfoliated. Unfortunately, since there are no large bodies of pregranitic rock in this region, the structure cannot be traced into pendants, but it parallels the small elongated inclusions found in Grand Creek, a locality which is coincident with the west limb of the fold.

The structure might be interpreted as a remnant outline of some prominent pre-granitic structure, or from the magmatic viewpoint, as some type of large scale flow phenomenon. No structural evidence favoring either interpretation was found.

Plutonic rocks of any type may exhibit some degree of foliation. It is, however, slightly more characteristic of the hornblende-rich rocks.

BANDING

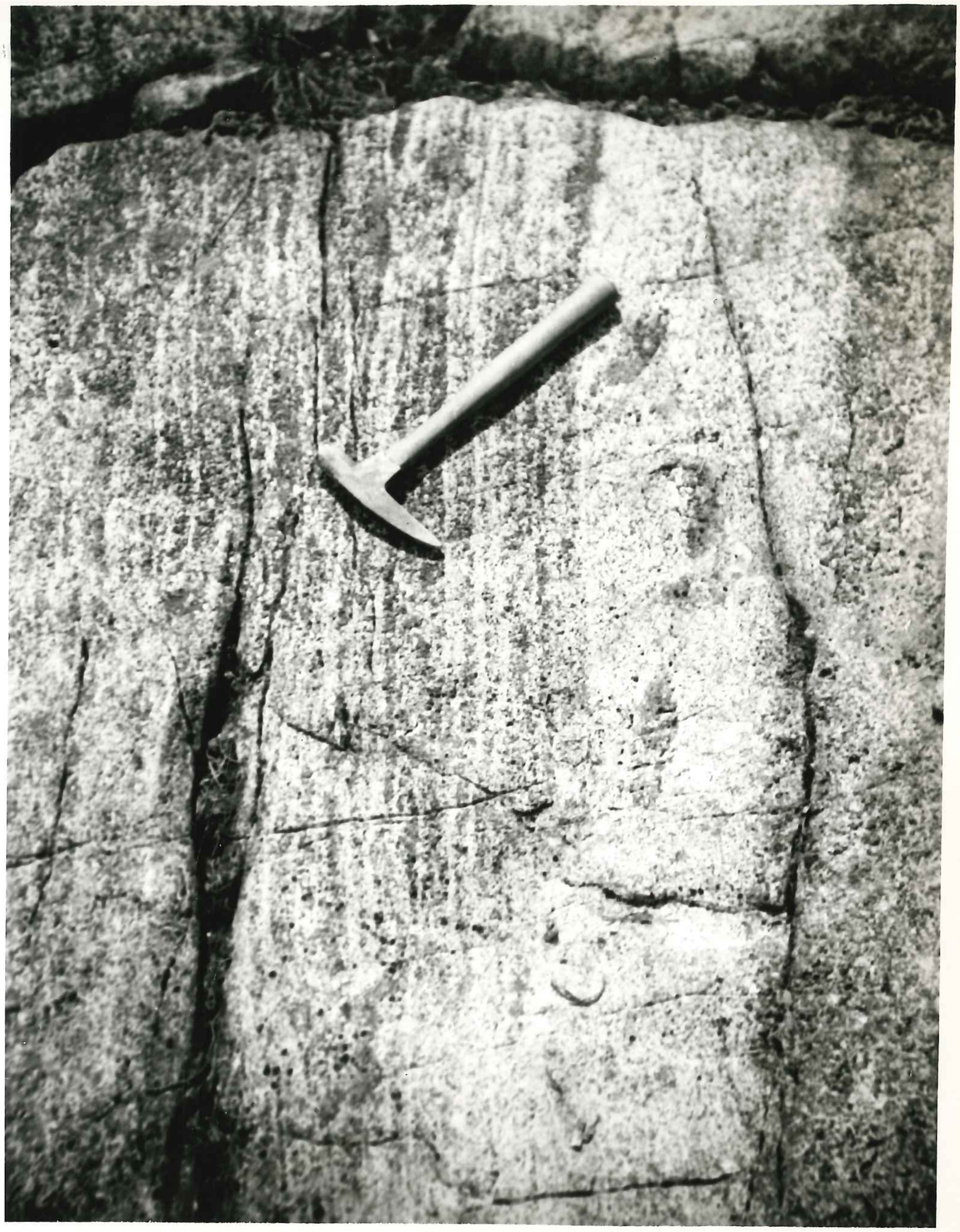
This is a much rarer phenomenon than foliation. It has been noted in several localities, all in hornblende-rich plutonic rock. It consists of segregations of mafic minerals, chiefly hornblende, into bands an inch, or a fraction thereof, in width. A typical occurrence is illustrated in Photograph 72. In no case is there a closely associated body of pendant rock, consequently it cannot be definitely proved that the bands are relict structures. Yet because of the characteristic straightness and regularity of the bands, the writer prefers to interpret them as relicts from former gneiss, rather than a flow structure, which appears to be the only reasonable alternative.

FAULTS

Innumerable small shear zones, a few known faults, and many suspected ones occur in the thesis area.

Photograph 72

Regular banding in hornblende diorite near The Lions. The dark bands are rich in hornblende. Because of its regularity, the writer believes this to be relict metamorphic layering, rather than a flow banding.
(Christie)



The most obvious fault is readily visible from the air (Photograph 73). It lies half way up the ridge east of the Seymour Reservoir, and is evident for about 4 miles, and is probably longer. The break appears to be quite recent, since erosion has not yet erased the ledge produced by the fault, and there is no substantial shear zone to allow its preservation by differential erosion. The rock on both sides of the fault is the same, so apparently the displacement is not very great. The fault may be associated with the relatively recent volcanic activity in the Garibaldi district to the north.

Because of the trellis-like drainage pattern present in certain parts of the thesis area, it is not difficult to line up several creeks in a manner suggesting that they are following a fault zone. The temptation is increased because shear zones are often found in the bottom of the major valleys. One such major shear zone follows the Upper Seymour River, to the southeast it crosses over to Indian Arm via Fanning Valley and the Bishop Creek cirque. On the east side of Indian Arm, where the fault might be projected, lies the dyke-like body of Crocker Id. granite. It is possible that the granite was intruded along this zone of weakness, or that this section of the fault was highly permeable and the shear zone was converted by metasomatism into granite. The strong foliation in the adjacent granodiorite into which the granite grades may represent mimetic preservation of the margins of a wide part of the former shear zone.

West of Indian Arm the plutonic rock along the shear zone tends to be rather complex. It is usually hornblende-rich, and contains numerous inclusions. Mineralization, chiefly pyrite, with minor chalcopyrite, is localized at various localities along the shear zone, especially in

Photograph 73

Air photograph of relatively recent faulting in the Coast Mountains. (Locality, along ridge east of Seymour Reservoir.)

(R C A F)

Bishop Creek cirque, where it has attracted some economic interest.

Shear zones occur also in other major valleys. When a portion of the lower Capilano Valley was scoured, in preparation for the Cleveland Dam, a rather narrow shear zone was revealed, trending parallel to the valley (Photograph 74). Such shear zones are common in the area, but seem too small to have localized valleys as large as the Capilano. Shear zones, however, swell and pinch out in unpredictable places, thus the width at any one place is not a reliable indication of their size or influence. In Capilano Canyon the shear zone is partly granitized, leaving numerous granulitic inclusions. Photograph 3 shows the typical heterogeneous complex resulting from such a process. The narrow zone of gouge shown at the edge of the canyon is of post granitic age.

A major fault may occupy Indian Arm. It is suggested by the difference in attitude and composition of the pre-granitic rock on either side of Bedwell Bay.

Several faults occur between Widgeon Creek and Pitt Lake, and are shown on the map. Except for their presence, little is known about them. The same applies to the fault which follows the North Alouette River and cuts across the eastern face of the Golden Ears ridge.

JOINTING

The jointing in the plutonic rocks is as heterogeneous as the plutonic rocks themselves. Close spaced jointing and sheeting identical to that found in much of the pendant rock may be duplicated in the plutonic rocks, particularly in hornblende diorite which commonly grades into the pendants. From a distance it is impossible to distinguish such

Photograph 74

General shearing, and a narrow gouge zone (next to the wall on the left) in Capilano Canyon. Feldspathic stringers are common in the fractured zone. (Locality, base of the Cleveland Dam.)

plutonic rock from the pendant. As a general rule the hornblende-rich rocks have closer spaced jointing than biotite-rich plutonic rocks. The slightly finer grain size of the former rocks may be partly the cause. The widest spaced jointing in the thesis area occurs in the relatively coarse-grained biotite-rich granodiorite of the Grand Creek area.

Some difficulty was experienced in recording the joints due to the great number of joints often present in one outcrop. Sometimes it was possible to decide what sets were the result of less significant events such as relief of ice pressure and irregular unloading dictated by recent topography. More often no decision was feasible, and all the joints were recorded. Thus much extraneous, insignificant data was incorporated into the results. Yet one can conclude from them that the joint patterns are not normally consistant over large areas, that is, those on the order of a 100 square miles or more. There is no doubt that small creeks and the details of larger stream courses are joint controlled, but the overall trends of the major valleys and fjords appear to be independent of joint control. The latter features are of a far greater magnitude than the areas of uniform jointing.

CONCLUSIONS AS TO THE ORIGIN OF THE PLUTONIC ROCKS

In the thesis area the plutonic rocks are very complex. In mapping them every effort has been made to avoid subjective thinking, yet a degree of collaboration with opportunity is probably unavoidable, and some of the aspirations expressed in classifications had to be laid aside. More detrimental, however, is that in the mapping process, phenomena must be recognized as well as be seen in order to be recorded, and even those phenomena seen represent probably only a small portion of those present. Nevertheless, the number of facts recorded is sufficiently great to make it difficult to hold them all in mind, balanced as to their relative significance, while formulating a theory of origin which satisfactorily accounts for them all. One must somehow decide whether the spectacular phenomenon is more indicative of some eternal verity, than is some shadowy, over-subtle clue, often repeated.

Although the area mapped is almost negligibly small, 500 square miles in the thesis area, and 2,000 square miles adjacent to it, the region is thought to be sufficiently large to permit the writer to balance many of the facts obtained according to their relative abundance. The facts described in the thesis which appear to have the greatest general validity are summarized and evaluated below.

1) The simple pendants and the lower portions of the capped pendants have reached a similar metamorphic grade, about the higher grade portion of the mesozone, and tend to have nearly vertical dips.

2) The pendant contacts with the plutonic rocks are in some places relatively sharp, and in other places, complex and gradational.

In the writer's estimate neither of the above items can be claimed to favor either a metamorphic or a magmatic origin for the plutonic rocks. The pendant contacts in particular seem largely insignificant. Large sulphide bodies of indisputable replacement origin commonly have sharp contacts with the country rocks. Even in polished section, sharp contacts are ordinary features of replacement origin. The concept that sharp contacts indicate a magmatic origin is not seriously maintained by many geologists, even among those who do not favor large scale granitization (as was pointed out by Grout, 1941). Gradational boundaries, likewise, are so disputed as to be of little diagnostic value. The phenomenon is easily dismissed as "marginal granitization from the true magma which is a couple of feet to the right". In this thesis, the contacts have been described, but purposely de-emphasized as an unsuitable basis for major conclusions.

3) With the exception of dyke-like bodies of plutonic rock, no sharp contacts appear to exist in the area between the different types of plutonic rock.

Although the writer feels that the lack of sharp contacts between plutonic bodies somewhat favors the theory of metamorphic origin, the opposing theories of multiple, and almost contemporaneous, intrusions with intermingling border areas, and that of differentiation in place have been advanced many times, and probably cannot be dismissed simply by a wave of the hand. The lack of sharp contacts is negative evidence at best, and is here considered impartial to the two contending theories.

4) All the plutonic rocks are heterogeneous in respect to mineral content, number of inclusions, and structures; the hornblende-rich rocks being more heterogeneous than the biotite-rich rocks.

Heterogeneity as a general property of the plutonic rocks favors a metamorphic origin. A heterogeneous rock implies a heterogeneous environment at the time of origin. Such an environment is far more likely to be attained in a volume of metamorphic rocks, than in a volume of magma. Perhaps, if the magma were highly contaminated with inclusions, a degree of heterogeneity might be attained which approaches that found in the field. Lavas, however, though often very rich in inclusions, are on the whole able to limit contamination to the immediate vicinity of the inclusions; elsehwere consistancy of composition and texture seems to be the rule. Moreover, simple mechanical contamination by inclusions, could not account for the observed fact that the degree of heterogeneity is considerably less in the rocks near the biotite granite end of the plutonic series. In the writer's view there is no very palatable magmatic reason why, for instance, the average number of inclusions should be less in a biotite granodiorite than in a hornblende-biotite diorite. Yet such is the case within the thesis area.

5) From hornblende-rich plutonic rock to biotite-rich plutonic rock the following changes are evident.
   a) The average grain size increases.
   b) The mafic mineral content decreases.
   c) The inclusion content of the rocks decreases.
   d) The average size of the inclusions generally decreases.

According to magmatic principles, plutonic rocks are coarser-grained than their hypabyssal counterparts, because their cooling period was longer. If this reasoning is applied to the hornblende diorite (average grain size, fine to medium) and to biotite granodiorite and granite (medium to coarse grained), one reaches the unlikely conclusion that the latter rocks cooled more slowly than the hornblende diorite, in spite of the fact that, for volcanics at least, the more basic magmas begin to cool from higher temperatures than do the more acid varieties. On the whole the increase in grain size appears to favor the metamorphic theory.

The parallel decrease in mafic minerals can be justified magmatically, by assuming different magma compositions, and metamorphically by a process (to be outlined) by which the plutonic rocks evolve towards low mafic varieties. This evidence seems impartial.

The significance of the inclusions was mentioned in 4), above, and in more detail in the chapter devoted to them. The metamorphic theory is favored.

6) Late hydrothermal alteration is characteristic of those plutonic rocks containing considerable potassium feldspar.

This feature is very prominent in the thesis area, although perhaps somewhat extraneous. Unfortunately, it can be adequately explained by both of the contending theories. Magmatically, it can be argued that potassium feldspar-rich magmas are also water-rich, and late alterations are likely. Metamorphically, it can be maintained (as it is in this thesis) that the rocks became potassium-rich because they were permeable and favorably situated with respect to the source of potassium-bearing solutions. Such permeability would be likely to persist to later stages, when the temperature had dropped below that at which major plutonic minerals could form, thus permitting the alteration seen in the field. It is interesting to note that hydrothermal alteration is characteristic of potassium feldspar-rich rocks even if they be calcium rich and silica-poor, as is the case of some of the hornblende granites and granodiorites. The writer does not know whether the magmas of such rocks would be water-rich or not, but feels that the magmatic theory is on somewhat more tenuous grounds for such rocks than is the metamorphic theory.

7) Each of the five major minerals of the plutonic rocks becomes more regular in shape and contains fewer inclusions in the more highly evolved rocks (those at the biotite-rich end of the series).

Although most of the widespread features of the thesis area favor, in the writer's estimate, a metamorphic origin for the plutonic rocks, none does so more conclusively than do the individual minerals themselves. As the plutonic rocks evolve, their mineral constituents do likewise. The clearing of inclusions and the assumption of more regular shapes is characteristic of porphyroblasts and, to the writer's knowledge, wholly foreign to the habit of crystals forming from a magma.

8) The paragenetic sequence of the five major minerals is consistent and independent of the composition of the plutonic rock. The order is 1. plagioclase 2. hornblende 3. biotite 4. quartz 5. potassium feldspar.

Magmatic theory, in as much as it can be based on phase diagrams, compels the paragenetic sequence to be based on the initial composition of the magma (an example was presented on page 176). In the thesis area the sequence is fixed, and independent of the composition of the rocks (although certain members may not always be present). Exceptions are present, but they are rare and can be attributed to special conditions (not related to composition). From the metamorphic viewpoint the consistency of the sequence is logical, according to the process outlined later in this chapter. In the writer's estimate the constancy of the paragenetic sequence favors the metamorphic theory.

9) Plagioclase zoning in the plutonic rocks is usually
   a) Oscillatory
   b) Relatively simple, and less common in the end members of the plutonic series.
   c) Most complex, and has the greatest range (between rim and core) in the intermediate plutonic rocks containing both hornblende and biotite.

Though there appears to be no sound theoretical reason for the assumption, plagioclase with oscillatory zones has often been regarded as evidence of magmatic origin. But such crystals occur in metamorphic rocks, as has been forcibly demonstrated by Misch (1954). Misch's conclusions are supported in the thesis area by the zoned plagioclase porphyroblasts occurring in the inclusions in the plutonic rocks. Perhaps, the point that should be emphasized is the fact that zoned plagioclase crystals are not characteristic of rocks which have undergone only progressive metamorphism, but are characteristic of rocks which have had an active retrograde metamorphic history (presumably because of wetness). Most of these latter rocks have taken on a plutonic aspect, but sufficient metamorphic rocks still recognizable as such have undergone retrograde metamorphism producing oscillatorily zoned plagioclase, to provide adequate ammunition against those who maintain that such crystals are limited to magmatic origins. In general conditions required to produce extremely complex zoning seem far more likely to be attained in a metamorphic environment, than in a magma. This is discussed further later.

According to the metamorphic theory, the most complex zoning would be expected in the intermediate plutonic rocks, as is the case. On the whole the mere presence of zoning is considered by the writer to favor neither a magmatic nor a metamorphic origin of the plutonic rocks, but the difference in zoning in different types of rocks, as was found in the thesis area, is thought to favor the metamorphic theory.

10) In the plutonic rocks, adjacent crystals may have different histories as demonstrated by the zoning in plagioclase.

It is difficult to imagine how adjacent crystals in a magma could have different histories, without adopting some mechanism involving large scale independent movements of individual crystals. It is doubtful whether such movements are possible. Perhaps special conditions could be invoked to explain a given example, but when such examples are the rule rather than the exception, as in the thesis area, there appears to be no acceptable magmatic explanation. Because the phenomenon in question is widespread in the area it appears to be an inherent effect of the processes which formed the rock. This requires a degree of heterogeneity that is likely only in a metamorphic environment, where solutions replacing complex mineral aggregations contaminate themselves, and change rapidly in composition. Since the thickness of the intergranular film is generally extremely small (more of this matter later), its composition will be dependent on extremely local factors (submicroscopic in many cases). Oscillatory zoning under such conditions is not only likely but almost inevitable. As a rule only a very general correspondence should be found in the histories of adjacent metamorphic mineral grains and that is what is found in the plutonic rocks of the thesis area.

11) Potassium feldspar occurs in both sodic and calcic plutonic rocks, and on occasion, may be abundant in the latter.

This fact, although interesting, does not appear to favor either theory, but is significant in the formulation of classifications of plutonic rocks.

12) Each of the major minerals in the plutonic rocks have apparently formed by replacing older minerals. (For plagioclase, the oldest plutonic mineral, the minerals replaced are usually those of hornblende granulite, the pre-existing metamorphic rock.)

This phenomenon is evident on a textural basis (see chapter on individual minerals), and strongly favors the metamorphic theory.

13) Hornblende is more abundant in plutonic rocks containing numerous inclusions, and in those adjacent to pendants; biotite is more abundant in those with few inclusions, and in those far from pendant bodies.

The writer believes the metamorphic theory is favored by this phenomenon. Similar facts, however, have been explained on a magmatic basis. Differentiation of the magma, once emplaced, is supposed to lead to hornblende-rich marginal areas. This is presumably an effect of the concentration of volatiles in the centre of the magma, caused by the encroaching crystallization from the borders, so that biotite, and more sodic plagioclase would more likely form at the centre. Whether this could account for zones several miles in width seems dubious but perhaps possible. The fact is more easily explained on a metamorphic basis.

14) Some of the plagioclase crystals in the more highly evolved rocks show evidence of having wholly recrystallized after attaining medium grain size.

There is considerable scattered evidence in the plutonic rocks which indicates a very complex history of crystallization. Outlines of former medium-grained plagioclase crystals are preserved, where other crystals now exist. It is not likely that the deuteric solutions of a cooling magma could account for this phenomenon. For such solutions tend to destroy textures and replace them by low temperature alteration products. The texture in question, however, could be produced if the cooling was arrested for a considerable period at relatively high temperatures. But some mechanism more effective than the latent heat of crystallization would be required to explain the cessation of heat loss; perhaps, another nearby intrusion.

Metamorphically, such textures are merely signs of the continuous recrystallization that must take place in a rock undergoing metamorphism, unless the rock is extremely dry (then recrystallization still takes place, but sluggishly). The solutions passing through it are sufficient cause for slightly fluctuating temperatures (at high temperature levels) which would promote recrystallization.

15) Data from the study of the inclusions (see previous chapter).

16) Data from the study of dykes (see previous chapter).

Both the above items were treated fully, and it was concluded that the metamorphic origin for the plutonic rocks is strongly favored.

From the accumulated weight of the above evidence, and the numerous minor phenomena mentioned earlier in the thesis, it is concluded that the plutonic rocks in the area mapped are mostly, if not entirely, of metamorphic origin. The process which formed the rocks is complex in detail, and one can only guess at the intricacies involved.

The writer believes the data tend to favor the wet granitization process as expounded by Read (1943), Misch (1949) and others, rather than the dry diffusion mechanism of Reynolds (1946) and Perrin (1954). There are features in the area such as zoned plagioclase, pre-plagioclase sericite, etc., which indicate that the temperatures fluctuated considerably during the formation of the plutonic rocks. The evidence also indicates that a continuous series of plutonic evolution exists from hornblende diorite to biotite granite, and that the more acid members of the series have evolved from the more basic members by metamorphic processes. Although the writer cannot substantiate his stand at present, he feels that most of the plutonic series represents rocks evolved essentially during a relatively high temperature retrograde stage of metamorphism, rather than at the maximum stage of progressive metamorphism. A great deal more study of this matter, which is probably best termed "plutonism", is required before a firm stand is justified, even on its most fundamental features.

In conclusion, the problem of the genesis of the plutonic rocks has been investigated along four major and independent lines of approach, namely,

1) The non-granitic rocks
2) The individual minerals and textures of the plutonic rocks
3) The inclusions
4) The dykes.

The evidence produced by each of these investigations is interpreted by the writer to favor strongly a metamorphic origin for the plutonic rocks within the thesis area.

THE THESIS AREA: A SAMPLE OR A SPECIMEN OF COAST MOUNTAIN PLUTONIC ROCKS

The purpose of this, the last section of the thesis, is to indicate that the thesis area is not unique in the Coast Mountains, but in all probability a fairly representative sample. Discussions concerning the so-called Coast Range Batholith have revealed a widely held impression that this great body is a composite of many large intrusive plutons, and that these plutons, except for minor border differentiation, are notably massive, and uniform in composition. This impression is in direct contradiction with the results of the study in the thesis area. In the writer's opinion, it is also in contradiction with the principal literature concerning the Coast Mountains. Admittedly, however, the literature is so scanty and lacking in detail that only very simple interpretations are possible, and these must be regarded as very tentative.

It was found that most of the workers in the Coast Mountains, especially the earlier ones, avoided almost religiously the plutonic rocks. They preferred to work around the granite rather than in it. Thus their descriptions of the batholithic rocks were restricted largely to whether the rock was granite, granodiorite, quartz diorite, etc., and to a sentence regarding the nature of the contact. Then, apparently relieved, they hasten into detailed descriptions of the country rock and the ore deposits. Certain authors, including the writer, however, being faced with the dilemma that their areas contained little else but plutonic rocks, were rather compelled to consider them more closely. In reading these older reports, one is impressed, not by the uniformity, but by the general heterogeneity, of the Coast Mountain plutonic rocks. Rapid and apparently disordered changes in composition are referred to again and again, and inclusions of pre-granitic rock seem to be almost always present. Gradational contacts, as well as sharp contacts, are very common, and gneissic structures seem to be scattered throughout. All these facts are equally applicable to the thesis area.

To some extent the reports may be misleading and represent, not the picture as a whole, but the grasping of reconnaissance geologists for something to write about in areas that are essentially featureless. Be this as it may, the following excerpts reveal many similarities with the thesis area.

The reconnaissance of the British Columbia coastal geology was begun by Jas. Richardson in the 1870's, and by G.M. Dawson in the next decade. A more systematic survey of the coast was begun by O.E. LeRoy in the first decade of this century, and continued by J.A. Bancroft and R.P.D. Graham. The work was completed in the early 1920's by V. Dolmage.

Concerning the relations between the Vancouver series (a catch-all term proposed by Dawson for a great assemblage of volcanics and interbedded limestone, argillite, and quartzite, underlying the Cretaceous) and the plutonic rocks on northern Vancouver Island, Dawson (1886, p.11B) stated

> "The relations of the granites to the rocks of the Vancouver series is peculiar, and appears at first sight to be of a very anomalous character. ------. The granites near this line (the contact) are usually charged with innumerable darker fragments of the Vancouver series, which, when in the immediate vicinity of the parent rocks, are angular and clearly marked, but at a greater distance become rounded and blurred in outline, and might then be mistaken for concretionary masses in the granite, into the substance of which they have been in the process of being absorbed. ------. It was in several instances found impossible to draw a distinct line between the granites and the Vancouver rocks, except on the assumption that this line should run where the two materials are blended in nearly equal proportions. ------.
>
> If the granite merely formed limited intrusive masses in the Vancouver rocks, no difficulty would be found in accounting for the above facts, but the circumstance that it appears everywhere to be the material upon which these rocks rest, and that it is, nevertheless, evidently of later date than these rocks, appears to call for some special explanation. The only explanation which appears satisfactorily to account for the appearances met with, is, that in consequence of upheaval and denudation we now have at the surface a plane which was at one time so deeply buried in the earth's crust that the rocks beneath it had become subject to granitic fusion of alteration."

These facts are identical to those found in the thesis area, although the interpretation is different. Volcanism which occurred contemporaneously with plutonism has caused perhaps more confusion in the geology of the Coast Mountains than any other single phenomenon. Dawson's * description of rocks around Malaspina Inlet applies equally well to those south of the Mt. Seymour.

p.27B "The rocks forming the shores of the main inlet belong entirely to the granitic series, but are rather peculiar in the paucity of quartz, which in some places is almost entirely absent, causing the rock to be more properly named a syenite or diorite than a hornblendic granite. The rocks are usually grey in general color, but in some places dark greenish grey. They hold often many darker masses of a fragmental appearance, and it was also here observed that they were frequently reticulated by pale lines, dependent on the bleaching of the rock by some subsequent action along the planes of jointage."

The last sentence refers to what has been described in this thesis as late hydrothermal alteration. Concerning dioritization in the Malaspina area Dawson continues,

p.28B "About the entrance to Malaspina Inlet, there is considerable areas of greenish granitoid rocks, some of which may be diorites, and, by their fine grain and much fractured appearance, suggest the possibility that they may represent the last stage in alteration of stratified rocks belonging to the volcanic series."

Irregular patches of this sort of rock, which is chiefly a fine-grained hornblende diorite, not far removed from a hornblende granulite, are very common in the thesis area.

---

* In the writer's opinion George M. Dawson was one of the most competent geologists to work in British Columbia. His works as a geologist, naturalist, and Indian linguist remain as classics. Considering the reconnaissance nature of his task, the accuracy of his observations and the genious of his deductions is a continual source of amazement to those who have since done more detailed work in the vast regions which he covered.

Dawson states with respect to foliation in the plutonic rocks in the region of Hardwick Island,

p.49B "The greater part of Hardwicke Island is occupied by granitic rocks which in a few places assume an appearance of gneissic lamination, possibly indicating the bedding of rocks from which the granites themselves have been formed, but more probably referrable to some species of superinduced foliation."

p.50B "Similar massive rocks (hornblendic granite) form both shores of the entire upper portion of Port Neville, but in a few places on the north side they become dioritic, and show the same appearance of gneissic foliation previously alluded to. The strike of the foliation is not discordant with the bedding of the altered volcanic rocks, the margin of which is found about a mile and a half south-westward."

In reference to Dawson's "superinduced foliation" it is very doubtful whether a massive granitic rock or any relatively coarse-grained rock, can be converted to a gneiss by compression, without first effecting a great reduction in grain size by intense shearing, and secondly, effecting a sustained period of porphyroblastic growth under continued stress. Shearing forces acting on a semi-molten rock could produce internal foliation providing the rock was sufficiently solid that it did not react hydrostatically to the stress.

No sharp contacts were found between major plutonic bodies in the thesis area. This agrees with LeRoy's (1908) views of the southern British Columbia coast.

p.19 "There is no hard and fast line separating the different varieties (he lists 8) and over comparatively small areas regular transitions may be found ranging from acid to basic."

Bancroft's (1908) observations on the northern coast of the province are in accordance with LeRoy's on the nature of the plutonic rocks.

p.83 "They are heterogeneous in character, including granites, granodiorites, diorites, gabbros and hornblendites among their number. Such close petrographical relationship exists between the different types that within comparatively small areas, one variety gradually passes into another."

From published work the conclusion seems warranted that plutonic rocks, such as granite, granodiorite, quartz diorite, etc., are not generally separated by sharp contacts, and usually do not represent different plutons but rather heterogeneity within large, genetically single, bodies. Homogeneity is the goal of equilibrium towards which all the chemical reactions in a melt proceed. It seems paradoxical that in volcanic rocks a high degree of homogeneity is attained in spite of contamination, and in plutonic rocks where the molten stage lasts presumably vastly longer, homogeneity is rarely attained.

In reference to inclusions of pre-granitic rock Bancroft makes the following comments.

p.107 "Quite frequently, at a distance of several miles from any compact areas of schist, the plutonic rocks will assume a banded appearance, owing to the presence of layers of schist, from mere films up to a foot in thickness, which weather out upon the surface in parallel position. Typical occurrence of such banded structures are exhibited on the northern shore of Knight Inlet, about a mile west of Lull Bay, and on the eastern shore of Loughborough Inlet, about three miles from Grismond Point."

p.108 "Many of the bands of schist exhibit definite evidence of absorption by the magma for their edges have a corroded appearance, and while of a dark grey colour at the centre, they shade into light grey at the margin, where they blend with interbanded granodiorite."

"The most remarkable feature in connection with such parallel injections is that even the most isolated bands of schist have a similar strike as the compact parent masses from which they have been separated. Erosion in laying bare the lower limits of the roof pendants has also demonstrated that at least in many instances these detached areas of stratified rocks are not true partitions between batholiths; but that the same body of magma has welled up on either side of the pendant."

p.109 "In many localities, far from lateral contacts with the invaded rocks, the more recent batholiths are sprinkled through with a multitude of dark, rounded inclusions, the majority of which are less than a foot across. -----. Some of these may be portions of the altered stratified series, but the great majority of them are presumably fragments of the older plutonic rocks, which have fallen from a roof shattered by recent advances of magma."

The writer does not agree with the conclusions, but the descriptive data could apply equally well to the thesis area.

A cross-section of the Coast Mountains was investigated by F.A. Kerr (1948) along the lower Stikine and Western Iskut Rivers. This area is probably as representative as any taken at random within the Coast Mountains. Most of the rocks are plutonic, but there is considerable older rock present. Concerning one of the largest masses in the map area, and "probably the most variable", Kerr gives the following composition.

p.52 "Orthoclase ----- usually constitutes 60-75% of the rock. Brown garnet and biotite form much of the remainder with some magnetite, apatite and sphene."

The presence of garnet is thus mentioned but unexplained (probably because the report is a posthumous compilation of Kerr's data). If its distribution was sporadic it might be attributed to contamination of the magma by metamorphic rocks, but if, as seems to be the case, the garnet forms an integral part of the rock, replacement of a garnet-bearing strata (with or without subsequent mobilization) is more likely. In British Columbia, garnet has often been reported in plutonic rocks without explanation of its presence.

Concerning another plutonic body which occupies more than 50 square miles, Kerr states p.58 "The granodiorite is a light grey, medium grained rock of granitic texture. Alteration, however, has given it green or pink tints in a great many places. Gneissic textures are locally present and schistosity caused by movements following consolidation is fairly common."

Thus, once again, the late hydrothermal alteration, so characteristic of the potassium feldspar-bearing plutonic rocks, is mentioned. Concerning foliation in the plutonic body mentioned above, Kerr states

p.58 "For several hundred feet from its contacts the granodiorite is generally fine-grained and highly gneissic. This is believed to be a secondary structure as nearby dykes of the granodiorite in the country rock do not display it, not even those as thin as ½ inch. At contacts with sedimentary rocks, lit-par-lit structures are well developed, and in places these mixtures have been sheared together yielding peculiar gneisses."

It seems that if the gneissosity were a secondary structure, it should be equally well developed in the dykes as in the main plutonic body.

McCann, (1922), working in the Bridge River area came up with this overall conclusion regarding the Coast Mountain plutons.

p.19 "The uniformity in composition of the great batholiths is very striking. Locally they vary in composition from granite to diorite and gabbro."

Besides McCann, other workers have used this method of expressing the uniformity of the heterogeneity of the plutonic rocks. Many have misinterpreted such statements as meaning that the plutonic rocks are uniform.

In general the above excerpts indicate that the Coast Mountain plutonic rocks are heterogeneous, and as more detailed work is done, the writer is convinced that the complexity of these rocks will be further brought to light. Although conclusions of the workers quoted do not agree with each other nor with those of the writer, the descriptive data in nearly every case could be applied to the thesis area. From this the writer concludes that the data presented in this thesis are probably equally prevalent in other areas in the Coast Mountains.

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GEOLOGICAL MAP OF THE VANCOUVER NORTH - COQUITLAM AREA

L E G E N D

Plutonic Rocks

Mid-Jurassic? to Upper Cretaceous?

I Ratio of Hornblende to Biotite	II Ratio of K-Feldspar to Plagioclase
Biotite only	Granite
Biotite > hornblende	Granodiorite
Biotite = Hornblende	Quartz Diorite
Hornblende > Biotite	Diorite
Hornblende only	Diorite-gabbro complex

o o Many inclusions (complex area)

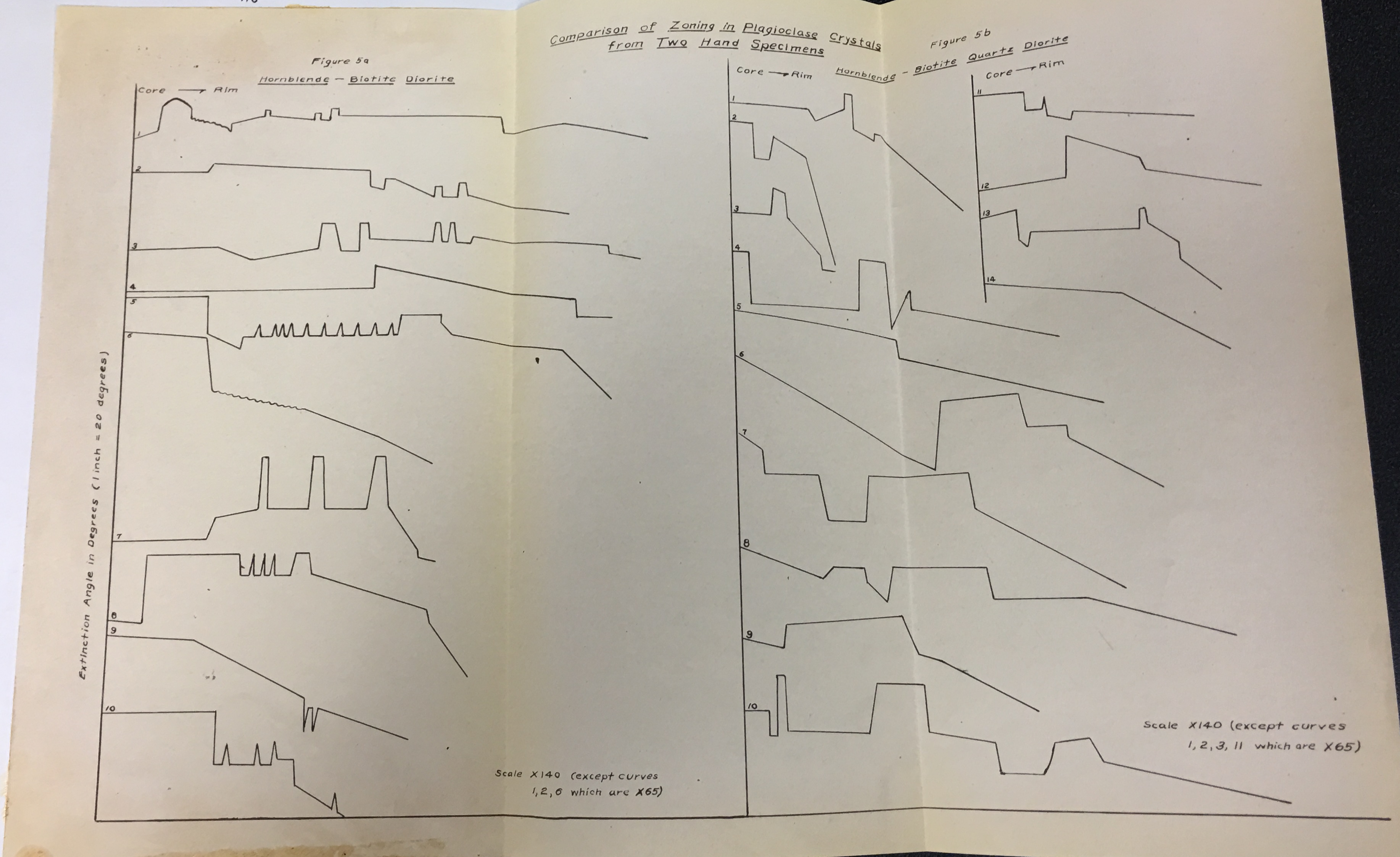
Non-Plutonic Rocks

Upper Jura. and/or Lower Cret. — Capping rocks, chiefly andesitic flows, tuffs, and breccias, with minor quartzite, slates, conglomerate

Pre-Cret — Pre-granitic rocks, chiefly banded hornblende granulites, with minor quartzite and schist. (limestone and argillite in Lynn pendant only)

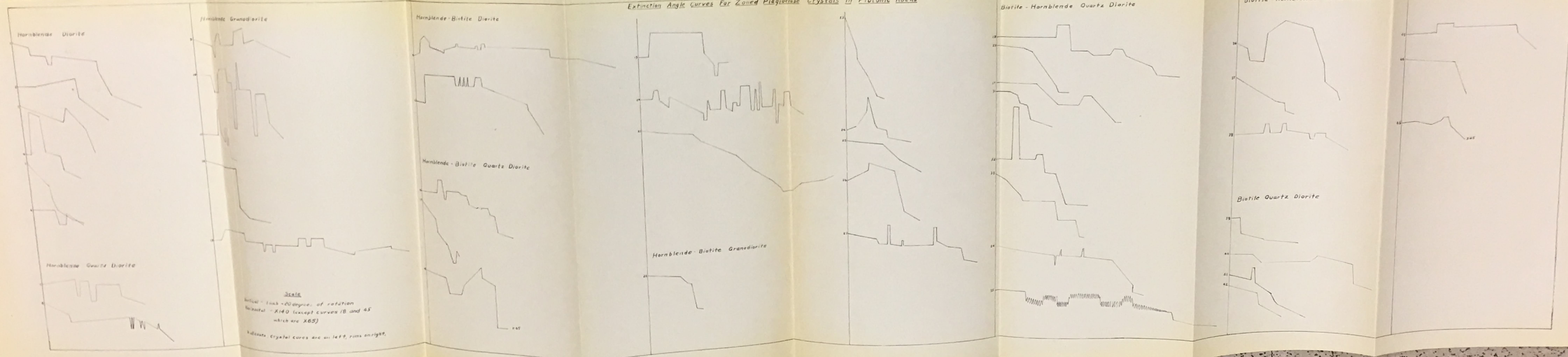
Symbols Used

- Contacts (all types)
- Fault
- Probable fault
- Foliation in plutonic rock
- Bedding in non-plutonic rock
- Elongation of inclusions
- Banding in plutonic rock



Comparison of Zoning in Plagioclase Crystals
from Two Hand Specimens
Figure 5a
Hornblende - Biotite Diorite
Core → Rim
Extinction Angle in Degrees (1 inch = 20 degrees)
Scale X140 (except curves
1,2,6 which are X65)
Figure 5b
Hornblende - Biotite Quartz Diorite
Core → Rim
Core → Rim
Scale X140 (except curves
1,2,3,11 which are X65)

Extinction Angle Curves For Zoned Plagioclase Crystals In Plutonic Rocks



Space Grant / Space Sci Net NW
Harrington, Shawn
Purell
Xerox Document Handler Anti-Static Fluid
ESS JHN 70
SCALE 1 INCH=1 MILE
CONTOUR INTERVAL 1000'
VANCOUVER
BURRARD INLET
HOWE SOUND
CAPILANO RIVER
LYNN CREEK
SEYMOUR RIVER
INDIAN ARM
COQUITLAM LAKE
COQUITLAM RIVER
PITT RIVER
PITT LAKE