THE GEOLOGY OF HAWKESBURY ISLAND
SKEENA MINING DIVISION, BRITISH COLUMBIA

by

PETER LAWRENCE MONEY

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ABSTRACT

Hawkesbury Island is in the Skeena Mining Division of British Columbia. It is underlain by Coast Intrusions, younger lamprophyre dykes and older metamorphic rocks. The latter form part of the Ecstall septum or roof pendant.

The metamorphic rocks are mainly amphibolites and quartz-feldspar gneisses. A few bands of quartzite, crystalline limestone, kyanite-staurolite-almandine mica schist and other rock types are present. These rocks have been formed by dynamothermal metamorphism of the regional type. They generally have assemblages indicative of the staurolite-quartz and kyanite-muscovite-quartz subfacies of the almandine amphibolite facies. Shear zones are strongly sericitized. Small percentages of sericite and chlorite are common throughout the metamorphic rocks. These minerals have been formed during retrogressive metamorphism.

Apart from a few small metamorphosed igneous bodies, these rocks were originally a thick eugeosynclinal sequence consisting mainly of tuffaceous sediments and semi-pelitic or arkosic sediments.

The metamorphic rocks have probably undergone at least two periods of deformation, so that their structure is complex. However, the foliation has a general trend of north 50° west to north 70° west in the northern part of the septum and of north 20° east to north 55° east in the southern part.

The Coast Intrusions have reached their present positions by intrusion. They have not been formed by granitization *in situ*. Some assimilation of the country rock has occurred but this is a marginal feature. The Coast Intrusions have had little affect on the grade of metamorphism of the metamorphic rocks.

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Department of Geology

The University of British Columbia,
Vancouver 8, Canada.

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CHAPTER I

INTRODUCTION

PRELIMINARY STATEMENT

This thesis is based on field work undertaken during the summer of 1958 while the writer was employed by the Ecstall Mining Company, and subsequent laboratory work carried out during the winter of 1958-59. Its object is to present an account of the geology of Hawkesbury Island, with particular emphasis on the petrology of the metamorphic rocks of the island and the relationship of the Coast Intrusions to these rocks and to the metamorphism.

FIELD METHODS

Compass and altimeter traverses were run at intervals of 2000 to 6000 feet over most of Hawkesbury Island. These traverses were supplemented by limited work with a helicopter, consisting of making confirmatory checks on geological features at a number of points.

Traverse routes were chosen with the aid of vertical aerial photographs and a topographic map. Owing to the steep gradient of the valley sides traverses were generally run along ridge tops and, to a lesser extent, on valley floors.

Points were located on steep slopes by use of an altimeter, which was corrected at points of known elevation.

These points are believed to be accurate to within one hundred vertical feet. Reference points on ridge tops, and in valleys, were located by use of aerial photographs, altimeter readings, and sightings on landmarks wherever possible. The location of points on the ridges is believed to be accurate. However, owing to the heavy timber cover in the valleys, points in these may be located very inaccurately. The possible error in one case is in the order of one thousand feet.

The field work was carried out from eight base camps. A Bell model G-2 helicopter was used for moving camp, carrying supplies, and sometimes carrying men to starting points of traverses. The only alternative method of mapping the island would be a combination of work from the shore, using a boat, and back-packing. It is doubtful, in view of the extremely rugged topography and very heavy undergrowth, and heavy rainfall, if mapping could have been completed during one field season by this method.

LOCATION AND ACCESS

Hawkesbury Island is located in the Skeena Mining Division of British Columbia. It is the largest of several islands in a fiord at the head of which Kitimat is located. It has an area of approximately 95 square miles. The northern tip of Hawkesbury Island is about 21 miles southeast of Kitimat. The island is about 80 miles south-east of Prince Rupert by air, and its southern tip is 85 miles by the shortest

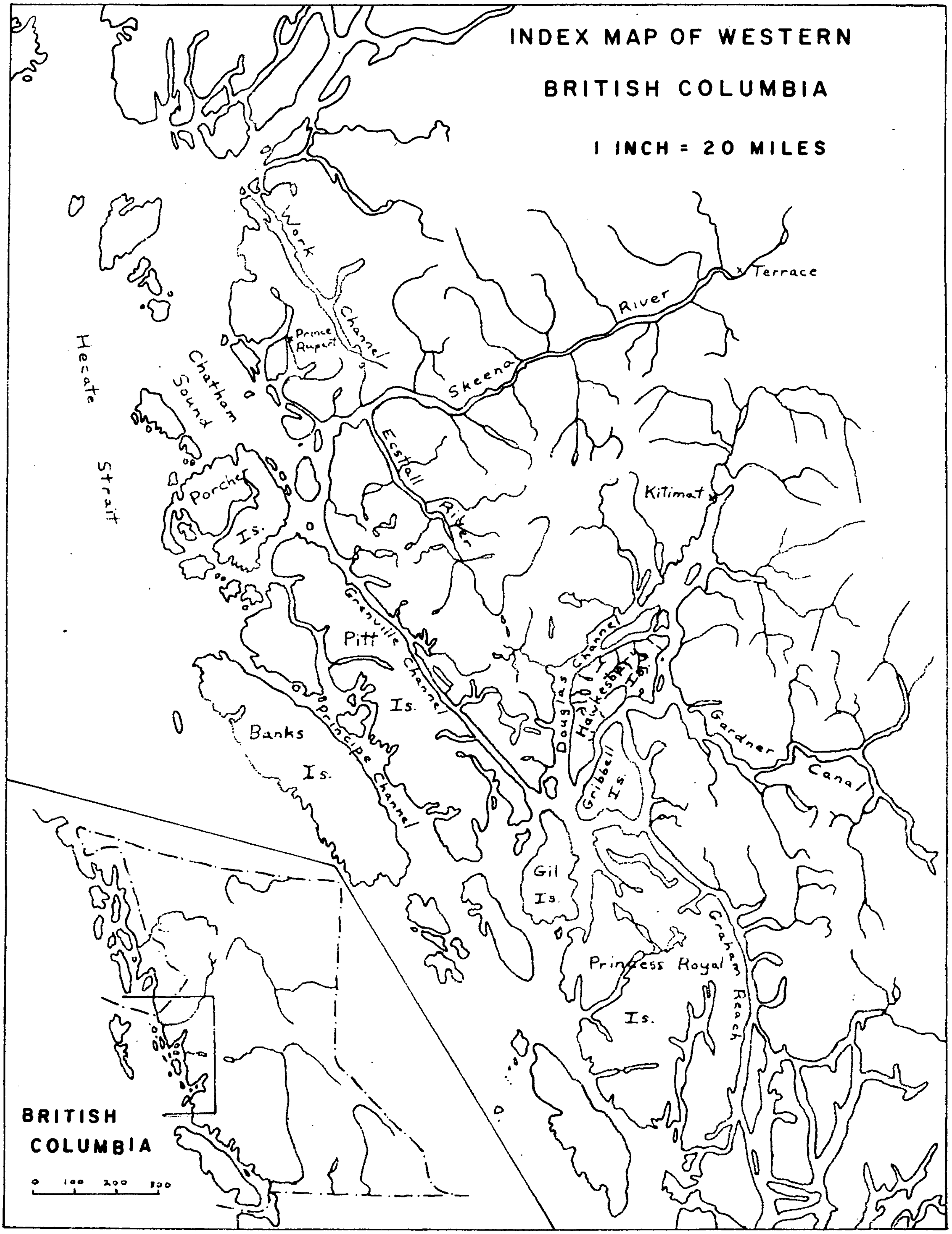
INDEX MAP OF WESTERN
BRITISH COLUMBIA
1 INCH = 20 MILES
Work Channel
Prince Rupert
Terrace
Skeena River
Hecate Strait
Chatham Sound
Porcher Is.
Ecstall River
Kitimat
Grenville Channel
Pitt Is.
Douglas Channel
Hawkesbury Is.
Banks Is.
Principe Channel
Gardner Canal
Gribbell Is.
Gil Is.
Princess Royal Is.
Graham Reach
BRITISH COLUMBIA
0 100 200 300

Figure 1

water route. The geographical centre of the island is at approximately 53° 06' North and longitude 129° 07' West.

Hawkesbury Island may be reached by boat from either Kitimat or Prince Rupert. There is a sheltered natural harbour between Kitsaway Island and Hawkesbury Island, but most parts of the island are difficult to land on, particularly with an onshore wind. It was found that a helicopter is ideal for working in this area and for easy access to any part of the island. It could be landed almost anywhere on the ridge tops and usually in at least one place in each major valley. A small float plane could probably land on the three or four largest lakes of the island, but it would be impossible to map the island adequately using a float plane alone.

TOPOGRAPHY AND GLACIATION

Hawkesbury Island is in the Coast Mountains subdivision of the Western System of the Cordilleran Region. The topographic features of the island have been developed mainly by an overriding ice sheet and later valley glaciers.

The area consists of numerous U-shaped, steep-walled glacial valleys separated by narrow round-topped ridges. Valley trends seem largely unaffected by a structural control, with the possible exception of Angle Valley, and it seems likely that the original control was largely topographic, snow and ice accumulating on the higher parts of the island and glaciers descending along former stream channels.

The rounded ridge tops, absence of matterhorn peaks, and the presence of glacial striae, chatter marks and erratics on the highest parts of these ridges suggest that at one stage glaciers had completely overridden the island. Glacial striae and chatter marks on the ridge tops indicate a direction of ice movement of 225° to 245° for this overriding sheet. Only three or four sets of striae were seen in valleys. These, as is to be expected, indicate a movement parallel to the valley wall.

In addition to the main glacial valleys numerous small tributary hanging valleys are present. These have the typical U-shaped profile and were obviously occupied by small tributary glaciers. These valleys have floors 500' to 1700' above the main valley floors.

The sequence of development of the glaciers probably included an early stage of valley glaciers, a second stage during which a large glacier was formed which apparently moved down Verney Passage to the east and Sue Channel and Douglas Channel to the west to the ocean, and at one stage completely covered the island; and a third stage during which valley glaciers were formed, possibly from remnants of the large overriding glacier. During the second stage the glacier immediately adjacent to the island may have been 4000' or more in thickness. The minimum figure is 3300 feet. This figure makes an allowance for later isostatic recovery and uplift of 500 feet, which is based on the presence of marine post-glacial clays at

300+ feet above sea level. It makes no allowance for the thickness of the glacier below sea level or its thickness above the highest point on Hawkesbury Island. The Glacial Map of Canada, published in 1958 by the Geological Association of Canada, shows the 4000 foot contour of ice thickness as crossing Hawkesbury Island in the vicinity of Gale Mountain, which has an elevation of 3900+ feet and is the highest point on the island.

The topography of areas underlain by metamorphic and granitic rocks has significant differences, apparently due to the far more homogeneous character of the igneous rocks. The valleys in granitic areas have a much more symmetrical cross-section and generally a more regular appearance than those in areas of metamorphic rocks. Cirques are practically hemispherical in the former rocks and generally very irregular in the latter rocks. On the mainland the granitic rocks form considerably higher peaks than the adjacent metamorphics but on the island the local relief is about the same for both types. This is probably due to the hard and resistant nature of the metamorphic rocks of Hawkesbury Island as compared with those of the mainland. Several truncated spurs were noted in valleys in the granitic rocks but none seem to be preserved in areas of metamorphic rocks.

Total relief on Hawkesbury Island is 3950 feet ± 40 feet. The highest point is the peak of Gale Mountain. Over most of the map area the tops of ridges have elevations ranging from 3000 feet to 3200 feet. The only major exception is the Gale Mountain-Sidebacon Lake - Backbacon Lake area, where ridge tops average 3600 feet. These ridge tops may represent an old, fairly level surface, as maximum elevations are so remarkably consistent over most of the island that it seems unlikely the glaciers could be wholly responsible. Valley floors generally have elevations of 100-500 feet above sea level, but reach up to 1000 feet at their heads. Average local relief, between valley floor and ridge top, is of the order of 2000 feet to 2500 feet.

DRAINAGE

Drainage on Hawkesbury Island is by innumerable tiny rivulets which fall over valley walls and coalesce to form streams draining out through the glacial valleys to the ocean. The larger tributary streams, and the main streams near their heads, have built up very large fans and generally flow beneath these, appearing only where ridges of bedrock cross their beds. In the upper parts of streams and near the coast where most of the valley floors drop off sharply to sea level waterfalls and rapids are usually present. Throughout most of their course the main streams flow over a combination of alluvial material and post-glacial marine clays. They are characterized by numerous abandoned channels and the presence of natural levees. The latter are particularly well developed in regions of marine clays. For the most part the old channels lie only a few feet from the new ones and have rarely been abandoned for more than a few tens of feet. It is probable that the channel used varies from year to year, controlled by where the bulk of the material carried by spring floods is deposited. The main streams have an average width of ten to twenty-five feet and a maximum depth of one to five feet, except for plunge pools which may be up to twenty feet deep. A most interesting example of channel control by alluvial material is South Beaver Creek, near the west coast of the island. This stream drains into Beaver Creek through two separate channels which reach the latter creek some 2000 feet apart. During the summer of 1958, due to most of the material from the spring freshets being deposited in the middle of the channel, this stream divided and flowed through both channels, which may be termed distributaries. It seems likely that during some years all the water flows through one of the alternate channels instead of forming this distributary system.

Most of the lakes on the island are of the tarn type. The principal exceptions are Sidebacon and Backbacon Lakes, which are finger lakes; and possibly Evelyn Lake, Roy Lake and Beaver Lake, which are in low overburden-filled valleys and appear to be held back by marine clays, alluvial material and possibly some morainal deposits.

CLIMATE

Hawkesbury Island, like most of the Coast Mountains of

British Columbia, has a very humid and fairly mild climate. The average annual precipitation at meteorological stations in Kemano, Kitimat and Prince Rupert, the three nearest stations to Hawkesbury Island is approximately 74 inches, 94 inches and 95 inches respectively. Average precipitation during the summer months (May-September) varies from approximately 15 inches in Kemano to 29 inches in Prince Rupert. Average monthly temperature for the total period of record for these stations is 49° - 50° in May, 53° - 55° in June, 56° - 61° in July, 57° - 61° in August and 54° - 55° in September. The average number of hours of sunshine for Prince Rupert varies from 136 hours in May to 95 hours in September, i.e from about 4.3 to about 3.1 hours per day. The summer of 1958 was exceptionally mild and dry. Most of the mapping on Hawkesbury Island was carried out between May 20 and July 23. During this period only 3 days were lost due to rain, and total rainfall was probably less than an inch. About one-third of the days were cloudy but total hours of sunshine was probably far above the average figure. The snow which usually mantles the higher peaks all summer, or until early September, had completely disappeared, apart from sheltered patches in some of the higher valleys, by the end of July.

FLORA

The valleys support heavy stands of hemlock, yellow cedar and balsam fir to an elevation of about 2000 feet. Hemlock is the most abundant species. Sitka spruce, jack pine, juniper and red cedar are abundant locally and a few tamarack were seen in particularly wet areas. Because of mild winters and heavy rainfall some of the trees reach a very large size and the undergrowth, mainly alder, Devil's Club, huckleberry, and similar shrubs, is luxuriant. Several hemlocks were found to have a diameter of about four feet. Lumbering has been carried out near the mouth of Evelyn Creek and along the shoreline between Danube Bay and Eva Point, but no work has been done elsewhere.

FAUNA

Wild life is not plentiful on Hawkesbury Island. Of the larger animals, only black bears seem common. Mountain goats are believed to be present but very scarce. They were never seen, but their trails run along the tops of all the ridges and tracks were seen on several occasions. Although the grizzly bear is common on the mainland, no evidence of its presence on the island was found. Old beaver dams and cuttings were found in the vicinity of Evelyn Lake and Roy Lake and in Angle and Beaver Valleys. No fresh cuttings were seen and the dams are in a state of disrepair, so that it seems likely the beavers have died out. Birds are numerous. All the larger ponds and streams seem to have one or two families of black ducks living on them. Geese were seen several times during the summer. Partridge are present but rare. The only fresh-water fish seen were brook trout, never over six inches long. These are not common.

CHAPTER II

GENERAL GEOLOGY

PREVIOUS GEOLOGICAL WORK

Little geological mapping has been done in the Coast Mountains, primarily because of the few known deposits of economic interest and climatic and topographic features such as heavy rainfall, ruggedness, scarcity of outcrop and heavy timber cover which make transportation extremely difficult and mapping slow and expensive.

The only previous work on Hawkesbury Island about which anything is published is the mapping of the shoreline during 1921 and 1922 by Dr. V. Dolmage,[1,2] for the Geological Survey of Canada. This mapping was of a very generalized reconnaissance nature, the coastline being mapped at an average rate of some 20 miles a day, and differentiated into only two divisions, Coast Intrusions and metamorphic rocks.

Previous work in the vicinity of Hawkesbury Island consists of (1) mapping of some 30 square miles around the Ecstall Mine in 1951, which was carried out in conjunction with

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1 V. Dolmage, "Coast and Islands of British Columbia Between Burke Inlet and Douglas Channel", G.S.C.Summary Report 1921, Part A, pp. 22-49.

2 V. Dolmage, "Coast and Islands of British Columbia Between Douglas Channel and the Alaskan Boundary", G.S.C. Summary Report, 1922, Part A, pp. 9-34.

extensive development work on this property, (2) the mapping of a large part of the Ecstall septum between the Skeena River and Douglas Channel during the summer of 1958 by W.A. Padgham[3] and (3) the mapping of the mouth of the Skeena river along the Grand Trunk Pacific Railway in 1912 by R.G.McConnell.[4] Of the reports on this work the first is not available to the public and McConnell's contains little about the metamorphic rocks of the Ecstall septum, so that the only work of any value in discussing the geology of Hawkesbury Island is Padgham's. Unfortunately this work was carried out on so large a scale that the numerous rock types present could only be subdivided into groups rather than separate petrologic units, as will be attempted in this thesis.

Other reports have appeared on mines and mineral occurrences in the Coast Mountains, but none of these has any direct connection with the geology of Hawkesbury Island, so they will not be discussed here. All of these reports which the writer has been able to find are listed in the bibliography.

GENERAL GEOLOGY

The rocks of Hawkesbury Island consist of metamorphic rocks of the Ecstall series, both igneous and sedimentary in

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3 W.A. Padgham, Geology of the Ecstall-Quaal River Area, British Columbia, 1958, Unpublished M.A.Sc Thesis, University of British Columbia.

4 R.G.McConnell "Geological Section Along the Grand Trunk Pacific Railway from Prince Rupert to Aldermere, B.C.," G.S.C. Summary Report, 1912, pp. 55-62.

origin, which are intruded by plutons of granitic rocks of the Coast Intrusions and of at least one andesitic(?) sill. The Ecstall Series rocks and Coast Intrusions are intruded by a few late hornblende lamprophyre dykes. The youngest deposits are unconsolidated alluvial material, marine blue-grey clays and scarce glacial and glacial-fluvial deposits. A table of rock units, showing the nature of the contact, the age of the units and their major subdivisions is on the following page.

The rocks of the Ecstall Series form a mass which is surrounded by granitic rocks of the Coast Intrusions. It is not known whether this mass is a roof pendant or a septum. The presence of small stocklike bodies of granitic rocks surrounded by extensive swarms of granitic dykes in the central parts of the Ecstall series in the map area suggests a granitic floor at no great depth, i.e. that this mass is a roof pendant. The rocks of the Ecstall Series, on the other hand, might actually not be floored by the Coast Intrusions but form a "screen" between several of the numerous intrusions i.e. be a septum.

The Ecstall septum, or roof pendant, is known to extend from north of the Skeena River south through the Ecstall River area, across Hawkesbury Island and up Gardner Canal. Its minimum length is 80 miles. Probably it continues south of Gardiner Canal to Graham Reach or Sheep Passage and north of the Skeena River to Portland Canal, which would give it a total length of some 180 miles. Its width ranges from less than 3

TABLE OF ROCK UNITS

Age	
Pleistocene and Recent	Unconsolidated sediments Clay, sand, gravel, etc., (including marine blue-grey clays)
	Unconformity
Age Unknown	Hornblende Lamprophyre dykes and sills
	Intrusive Contact
Jurassic-Cretaceous (probably Upper Jurassic)	Coast Intrusions: Pegmatite Granitic dykes Granodiorite, quartz monzonite, Monzonite, quartz diorite and diorite
Age Unknown	Andesitic (?) sills and dykes
	Intrusive Contact
Pre-Jurassic (possibly Ordovician-Devonian)	Ecstall Series Rocks: * "Meta-igneous amphibolites"
	Intrusive Contact
	"Plagioclase amphibolites," quartz-K-feldspar-plagioclase gneisses, kyanite-staurolite-almandine mica schists, quartzites, limestones, graphitic quartz-plagioclase schists, etc.

* The writer will refer to the metamorphic rocks forming the Ecstall roof pendant or septum as the "Ecstall Series" throughout this thesis. This is mainly a matter of convenience but also reflects the writer's believe that these rocks possibly do form a time unit.

miles at the Ecstall mine to more than 11 miles in the Amoeba Lake-Foch Lake area just to the north of Douglas Channel. The width on Hawkesbury Island averages 10 miles.

The metamorphic rocks of the Hawkesbury Island area may be subdivided into three broad groups. These are the metamorphosed igneous rocks, the "plagioclase amphibolites" and the metamorphosed sediments. The metamorphosed igneous rocks, the "igneous amphibolites", are of very minor extent. The "plagioclase amphibolites", rather basic rocks which seem to be conformable with the metamorphosed sediments, form some 55 per cent of the Ecstall series. The metamorphosed sediments consist of numerous rock types, the major divisions of which are listed in the table of rock units. Of all these types, the plagioclase-K feldspar-quartz gneisses are the most abundant. They make up about 40 per cent of the rocks of the septum. Of the other types the quartzites and kyanite-staurolite-almandine mica schists are the most important. Each of these makes up about one per cent of the rocks of the septum.

The metamorphosed igneous rocks are found throughout the Ecstall series cutting the other rock types, but are particularly common in the southern part of the septum. The "plagioclase amphibolites" are also particularly common in the southern half of the map area and the plagioclase-K feldspar-quartz gneisses in the northern half. Considerable interbedding between these units occurs. The quartzites, kyanite-staurolite-kyanite mica schists and limestones occur interbedded with the "plagioclase amphibolites" in the southern part of the septum only. The graphitic quartz-plagioclase schists occur interbedded with the "plagioclase amphibolites" in both the southern and northern parts of the septum.

The one known occurrence of the andesitic(?) rocks is in the Trench Brooks area where they form a 10 foot by 3 foot boudin. This rock type is believed to have been intruded later than the main period of deformation. Its relationship to the other intrusive rocks is unknown.

The Coast Intrusions examined on Hawkesbury Island consist of the North Hill intrusion, which is a marginal facies of one of the main batholithic masses to the north of the septum, and several small stock-like plutons and innumerable pegmatite veins and dykes and sills of granitic rocks within the septum. The stock-like plutons are the Sidebacon Lake pluton, underlying at least 13 squares miles, the Beaver Lake pluton, underlying at least 4 square miles and the Danva pluton underlying at least one square mile. Each pluton has a swarm of granitic dykes associated with it. The width of the zones in which the dyke swarms are found is roughly proportional in width to the size of the pluton. The dyke swarm around the Sidebacon Lake pluton is about 4 miles wide, that around the Beaver Lake pluton is one mile wide and that around the Danva pluton 2000 to 3000 feet wide. Within these areas granitic rocks may locally make up as much as 75 per cent of the total outcrop and average perhaps 10 to 15 per cent. Outside these areas dykes are quite scarce. There are very few dykes in the vicinity of the batholith exposed to the north of the septum on Hawkesbury Island.

Recent deposits are confined mainly to the valleys. They consist of talus, alluvial fans and other alluvial deposits and post-glacial blue-grey marine clays. It is probable some morainal material is also present, but none definitely was identified. Glacial erratics are found scattered over the ridges to an altitude of 3300 feet.

The alluvial deposits are unstratified or weakly stratified outwash and consist of well-rounded to sub-angular rock fragments ranging from boulders five feet or more in diameter to silt size particles. They generally carpet the valley floors in a thin veneer through which the bedrock commonly outcrops. Their thickness is believed to be five to fifty feet throughout most of the valleys, although the fans at the heads of some valleys are apparently much thicker.

The blue-grey marine clays are found principally in Angle Valley and in the vicinity of Evelyn Lake. Their maximum recorded elevation (in Angle Valley) is 330 feet above sea level, probably indicating an isostatic readjustment of at least 330 feet since the retreat of the valley glacier in this valley. At an elevation of 250 feet in Angle Valley several specimens of Saxicava arctica were collected from similar clays, establishing their marine origin. Unfortunately this pelecypod has a stratigraphic range of Miocene to Recent and a geographic range from Panama to Greenland, making it useless for age determinations or determinations of climatic conditions. The blue-grey clay is bedded and in most places is horizontal. However, at the locality in Angle Valley where the specimens of Saxicava arctica were collected, it strikes north 40° east and dips 20° S.E. It is possible this attitude may be due to slumping as this exposure is in a stream bank.

CHAPTER III

THE METAMORPHIC ROCKS

INTRODUCTION

The metamorphic rocks are sub-divided into the units listed in the Table of Rock Units and into smaller units on the basis of mineralogical composition, field relationships and textural features. The rocks included in the meta-sedimentary category have a lack of cross cutting relationships and all have compositions compatible with possible sedimentary origin. Recrystallization has destroyed any sedimentary features which may have been present in these rocks. The "plagioclase amphibolites" are rather anomalous. Their mode of occurrence suggests a sedimentary origin but their composition is far too basic for a normal sediment. The "igneous amphibolites" have compositions and in most occurrences textures which indicate they are not of sedimentary origin.

PETROLOGY OF THE PLAGIOCLASE AMPHIBOLITES

The plagioclase amphibolites are rocks containing more than 25 per cent and less than 50 per cent of combined hornblende, biotite and diopside. Rocks with less than 25 per cent of these minerals are included in the meta-sedimentary division and those with more than 50 per cent in the meta-igneous division.

The plagioclase amphibolites are subdivided into

(1) plagioclase-hornblende-biotite rocks, lacking diopside and containing 5 per cent or less of epidote group minerals;

(2) plagioclase-hornblende-biotite-epidote rocks, similar to the above but with more than 5 per cent epidote;

(3) plagioclase-hornblende-biotite-diopside amphibolites;

(4) plagioclase-staurolite amphibolites, containing both staurolite and hornblende.

These divisions are further subdivided on the basis of the relative proportions of these minerals.

All the plagioclase amphibolites have a similar appearance in hand specimen and may be described together. They are dark grey, generally fine-grained (1 mm.) but occasionally medium-grained (1 mm to 5 mm) rocks most of which are granoblastic in texture. A few specimens are porphyroblastic. The plagioclase amphibolites weather to various shades of brown or reddish brown. The weathered layer is normally quite thin, 1/4 inch or less, but in sulphide rich rocks it may be several inches thick, making it difficult to take a fresh sample.

Turner defines schistosity or foliation (which he considers to be synonymous) as "any parallel structure, of metamorphic origin, that induces a more or less planar fissibility in a rock."[1] In these rocks the degree of foliation is determined mainly by the percentage of biotite, chlorite and, to a lesser extent, muscovite, in the rock. Those rocks

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1 H. Williams, F.J. Turner, C.M. Gilbert, Petrography (W.H.Freeman and Co., 1955), p. 169.

lacking biotite have, in hand specimen, at best an extremely weak schistosity which is mainly due to a planar alignment of unusually flat and tabular hornblende crystals, as well as some slight tendency for the quartz and feldspar to be flattened parallel to the hornblende. The latter tendency is noticeable only in medium grained varieties and only then after etching with hydrofluoric acid. Lineation generally is weak or lacking. Segregation into mafic-rich and mafic-poor bands is present in one or more specimens of all the sub-types except the plagioclase-hornblende-staurolite amphibolite. It is quite common but in most occurrences is not well developed, separation of the light colored and dark colored minerals being far from complete. The average width of the bands is generally 1 mm (1/25 inch) or less. Near the eastern tip of Evelyn Lake, however, an area of amphibolite several hundred feet wide has bands up to 15 cm (6 inches) across, although averaging only 5 to 7.5 cm. (2 to 3 inches).

(1) The plagioclase-hornblende-biotite rocks

The plagioclase-hornblende-biotite rocks form the largest subdivision of the plagioclase amphibolites. Of 24 thin sections of the amphibolite group rocks, 17 belong to this subdivision. These rocks may be further divided into plagioclase-hornblende amphibolites containing 5 per cent or less of biotite; plagioclase-hornblende-biotite amphibolites, containing greater than 5 per cent each of hornblende and of biotite, and plagioclase-biotite gneisses, containing 5 per cent or less of hornblende. These divisions are so small that they are not mappable field units, on the present scale of mapping. The plagioclase-hornblende-biotite rocks are the main rock types in the major southern band of plagioclase amphibolites.

Figure 2 shows the approximate range of composition of

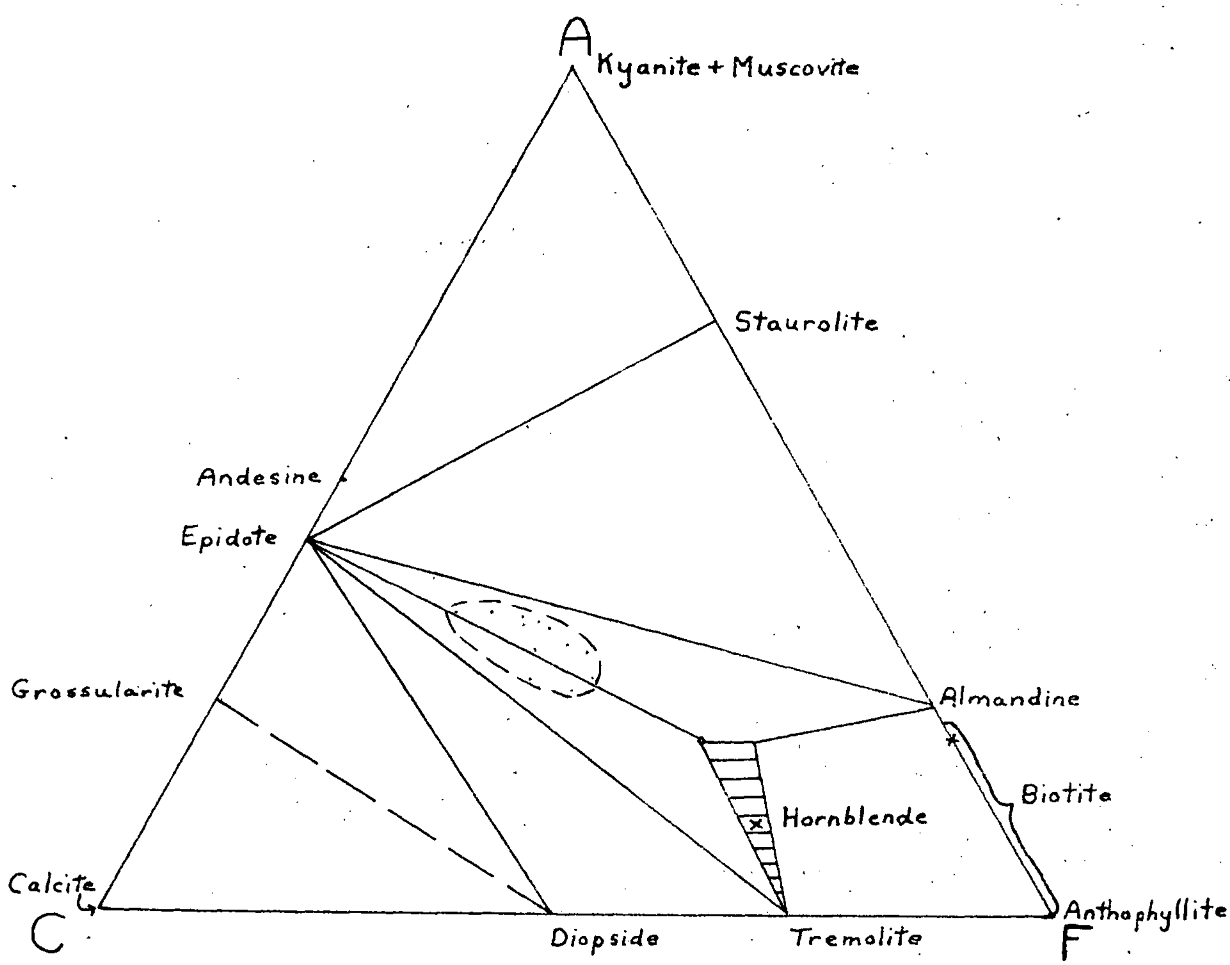

Figure 2. ACF diagram for the almandine at amphibolite facies, staurolite-quartz subfacies, showing the range of composition of the plagioclase-hornblende-biotite rocks

the plagioclase-hornblende-biotite rocks considered to be made up of stable mineral assemblages. For ease of plotting, arbitrary compositions of biotite and hornblende, indicated by crosses, were assumed. The composition chosen for the hornblende, which will be shown probably to be a rather aluminous variety, contains the maximum amount of aluminum possible without making any of these rocks fall in the staurolite-epidote-almandine field of the ACF diagram. A high alumina, low magnesia composition was chosen for the biotite as a trial and error plotting of certain specimens showed this was the most satisfactory.

Plagioclase-hornblende amphibolite and plagioclase-hornblende-biotite amphibolite are the commonest sub-types of the plagioclase-hornblende-biotite rocks. The plagioclase-biotite gneisses are comparatively rare.

The compositional range of these types are as follows:

1. Plagioclase-Hornblende Amphibolite
   (based on 8 thin sections)

Mineral	Total Variation in Percentage	Mean Percentage
Hornblende	30 - 35%	34%
Biotite	1 - 3%	1%
Plagioclase (An_{29} to An_{40})*	24 - 61%	59%
Quartz	3 - 22%	5%
Epidote	none - 5%	
Apatite	< 1%	
Sphene	< 1%	
Chlorite	none - 2%	
Sericite	none - 1%	
"Iron Ore"	< 1%	

* All determinations of An content were made by measuring X'∧010 for sections ⊥ a or by measuring N_x' on cleavage fragments using special index oils and a monochromatic light source.

2. Plagioclase-Hornblende-Biotite Amphibolite
(based on 7 thin sections)

Mineral	Total Variation in Percentages	Mean Percentage
Hornblende	15 - 35%	25%
Biotite	10 - 20%	12%
Plagioclase (An_{30} to An_{43})	40 - 58%	48%
Quartz	5 - 15%	8%
Epidote	none - 5%	2%
Almandine	none - 2%	
Apatite	< 1%	
Sphene	< 1 - 2%	
Sericite	< 1%	
"Iron Ore"	none - 1%	

3. Plagioclase-Biotite Gneiss
(based on 2 thin sections)

Mineral	Total Variation in Percentages	Mean Percentage
Hornblende	none - 5%	
Biotite	20 - 27%	
Plagioclase (An_{31} to An_{36})	54 - 63%	
Quartz	10 - 15%	
Epidote	< 1%	
Almandine	none - 1%	
Chlorite	< 1 - 2%	
Muscovite	none - 1%	
Sericite	< 1%	
Apatite	< 1%	
"Iron Ore"	< 1%	

These sub-types are quite similar in texture in thin-section. Most specimens of fine-grained plagioclase-hornblende amphibolites have a well developed granoblastic texture. In all medium-grained plagioclase-hornblende amphibolites, and in all the plagioclase-hornblende-biotite amphibolites, most of the hornblende grains and some of the plagioclase grains commonly enclose small grains of other minerals, so that a sieve or poikiloblastic texture is developed. Hornblende in the plagioclase-biotite gneisses also has this sieve texture.

Hornblende is generally euhedral but in some specimens subhedral. It is rarely twinned on (100) and is biaxial negative with a large 2V.

There is a systematic variation in pleochroic formula and $Z_{\wedge}c$ as shown in the following table.

Rock Type	Pleochroic formula	$Z_{\wedge}c$
Plagioclase-biotite gneiss	X pale yellow Y pale blue green Z blue green	21^{o}-22^{o}
Plagioclase-hornblende-biotite amphibole Plagioclase-hornblende amphibolite	X pale yellow Y blue green Z dark green	22^{o}-23^{o}
Plagioclase-hornblende amphibolite	X pale yellow Y brownish greenish Z dark brownish green	23^{o}-24^{o}
	X pale brown Y brown Z dark brown	

Increasingly deep pleochroic colors and higher $Z_{\wedge}c$ with increasing grade of metamorphism have been noted by Turner[2] and Compton[3]. The former found that most of the hornblendes of the amphibolite facies have Z = deep blue green but at higher grades of metamorphism (within the facies) Z = brownish green.

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2 H.Williams, F.J. Turner, C.M. Gilbert, Petrography (W.H. Freeman and Co., 1955), p. 242

3 R.R.Compton, "Significance of Amphibole Paragenesis in the Bidwell Bar Region, California," American Mineralogist Sept. 1958, pp. 890-907.

Both Compton[4] and Eskola[5] analysed a number of hornblendes and found an increase in Al_2O_3, MgO and CaO and decrease in FeO and Fe_2O_3 with a higher grade of metamorphism. They suggest that the color of hornblende is controlled mainly by the amount of alumina, a deeply colored hornblende being a highly aluminous one.

Biotite occurs as tabular plates, euhedral apart from ragged terminations. In thin sections containing hornblende most of the biotite is marginal to the hornblende or cuts through it, and is obviously a later mineral than the hornblende which it replaces. Most of the biotite grains are parallel or sub-parallel to the foliation, but in one section of biotite gneiss, in which the biotite lies along the grain boundaries of the plagioclase and quartz, many biotite plates have developed along these boundaries at large angles to the general foliation. These are noticeably smaller than the biotite plates parallel to the foliation. Most of the biotite is a strongly colored variety which is pleochroic from deep reddish brown (Z) to pale brown or straw yellow (X) but in some sections of plagioclase-hornblende-biotite amphibolite, Z is a very dark brown and in a section of plagioclase-biotite gneiss, it is brown with a greenish cast. In one

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4 Compton, loc. cit.

5 P. Eskola, "On the petrology of the Orijarvi region in southwestern Finland, "Comm. Geol. Finlande Bull. No. 40 (1914), p. 113.

thin section of plagioclase-hornblende-biotite amphibolite the biotite, in the vicinity of an opaque mineral, probably pyrite, is bleached and is pleochroic from golden yellow to pale straw yellow. The bleached portion has low birefringence, perhaps indicating alteration towards a chlorite. Biotite is bent and fractured in one thin section but in most sections shows no evidence of strain.

Plagioclase generally occurs in large subhedral to (rarely) anhedral grains, but also occurs in small rounded inclusions in poikiloblastic hornblende. The plagioclase in all of these rock types is, as shown in the table on page 25, generally medium or slightly sodic andesine, but is occasionally highly sodic andesine or highly calcic oligoclase. The feldspar is exceptionally fresh and sericite is very scarce. A few plagioclase grains are weakly zoned. The only satisfactory determination indicated a core of An_{31} and a rim of An_{39}, i.e. reversed zoning. Most of the twinned grains have only albite twinning. Many of the albite twins, probably 60 per cent or more, consist of as few as three to eight subindividuals. In most grains individual twin lamellae are very broad, although narrow lamellae are not rare. Perhaps 1 or 2 per cent of the twinned grains have complex twinning of a type in which two sets of polysynthetic twins develop at, or nearly at, right angles to one another. Where this type of twinning is present one set of lamellae are usually quite indistinct. It is not definite what types of twins are represented here, but albite-pericline is probably the commonest combination which would have this appearance. No Carlsbad-albite twins were noted.

Quartz occurs as large anhedral grains and also as small inclusions in poikiloblastic hornblende, and more rarely in plagioclase. In one thin section of plagioclase-hornblende amphibolite vein quartz is also present. It is not a major mineral, generally forming between 5 per cent and 15 per cent of the rock. As it is difficult to distinguish from untwinned plagioclase, particularly as this is unaltered or nearly so in most thin-sections, percentage estimates were checked by making optical determinations on ten grains per section, and by hydrofluoric acid etching on several specimens. Quartz only rarely shows evidence of strain.

The common epidote group mineral present, pistacite, is colorless, has a large negative 2V, anomalous "berlin blue" interference colors and a birefringence of approximately 0.03, which corresponds [6] to a composition of about 18 per cent $HCa_2Fe_3Si_3O_{13}$ and 82 per cent $HCa_2Al_3Si_3O_{13}$. The clinozoisite-pistacite boundary is drawn at about 10 per cent $HCa_2Fe_3Si_3O_{13}$. The maximum known percentage of $HCa_2Fe_3Si_3O_{13}$ in pistacite is about 40 per cent, so it would seem this is a moderately iron-poor pistacite. Turner[7] notes that the epidote

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6 A.N. Winchell, Elements of Optical Mineralogy Part II (John Wiley and Sons, 1948), p. 313

7 H.Williams, F.J. Turner, C.M.Gilbert, Petrography (W.H.Freeman and Co., 1955), p. 242.

(pistacite) of amphibolites is either colorless or very pale yellowish. In one thin section a pleochroic, yellow to colorless pistacite occurs as a rim surrounding a grain of "iron ore", probably pyrite. The "iron ore" is later than any of the other minerals, and might possibly be hydrothermal, as this is a rather altered thin section with bleached biotite and a high percentage of opaques. It seems probable this epidote is the result of hydrothermal alteration of plagioclase. An epidote of undoubted hydrothermal origin occurs in a thin section of plagioclase-hornblende amphibolite. This is a non-pleochroic, colorless pistacite with properties very much like those of the usual pistacite in these rocks, but it occurs along the margins of pyrite-quartz veins and irregular masses of pyrite, and is always anhedral and clearly replaces plagioclase. Allanite occurs in a thin section of plagioclase-biotite gneiss. It is pleochroic dark brown to pale brown, and occurs as cores surrounded by rims of colorless pistacite of similar crystal orientation but different extinction position. Most grains of epidote group minerals are euhedral or subhedral, and occur on grain boundaries between hornblende or biotite and plagioclase. Crystal form is particularly well developed when the epidote is partially enclosed in biotite, which apparently offered less resistance to its crystallization than hornblende or plagioclase.

Almandine garnet is a rare accessory mineral. It is found in only three thin sections, two of plagioclase-hornblende-biotite amphibolite and one of plagioclase-biotite gneiss. It occurs in colorless to pale pink, isotropic, ragged anhedral groups of grains, to euhedral, porphyroblasts which have sieve texture. Inclusions are mainly of plagioclase, but some are of sphene, apatite, quartz, biotite and "iron ores". The inclusions do not show any preferred orientation and there is no evidence of any "snowball" or similar effects. Biotite- and hornblende-rich bands appear to flow around the garnets.

Apatite and sphene are the only common accessory minerals. Apatite, in small, rounded grains to euhedral, short stubby, prismatic crystals, occurs scattered throughout crystals of the major minerals and also is found at grain boundaries. Sphene is found in all thin-sections of the plagioclase-hornblende and plagioclase-hornblende-biotite amphibolite, but is absent in the plagioclase-biotite gneiss. It is a faintly pleochroic brown variety which occurs as rounded granules and wedge-shaped crystals scattered throughout the rock, but particularly at the boundaries between larger crystals.

Chlorite occurs as rosettes and fibrous aggregates replacing hornblende and biotite in the vicinity of hydrothermal pyrite in one specimen of plagioclase-biotite gneiss. It is also found replacing biotite and almandine in the other thin section of this rock unit. The chlorite is pleochroic from green to colorless, length fast, has parallel or nearly parallel extinction, and anomalous pale yellow grey interference colors.

"Iron ores" consist chiefly of pyrite and magnetite. The pyrite is probably partially hydrothermal in origin as it forms veins in one section and is surrounded by a zone of pistacite in another section. In some thin sections the normally opaque "iron ores" are partially or wholly altered to a reddish translucent material which is probably hematite or limonite.

(2) The plagioclase-hornblende-biotite-epidote rocks

This unit forms a rather small subdivision of the sedimentary amphibolites. On the basis of thin sections this rock type is believed to be particularly abundant in that part of the main plagioclase amphibolite band which extends from the west side of Angle Valley north-west to the sea, and from the south side of Ice-Cake Lake south-west to the contact with the Sidebacon Lake stock. These rocks also occur elsewhere throughout the main plagioclase amphibolite band, but they are of very minor extent. Outside of this band the only area these rocks are known to occur in is Wye Valley where they are found interbedded with plagioclase-quartz-K feldspar augen gneiss.

The major minerals in the four thin sections made of these rocks are as follows:

	Thin Section Number			
	17-5	7-3	5-6	15-5A
Epidote	65%	30%	20%	15%
Hornblende	30%	28%	3%	--
Biotite	--	1%	25%	25%
Plagioclase (An_{37} to An_{38})*	--	27%	42%	43%
Quartz	5%	14%	10%	16%

* Determined by measuring $X'_{\wedge}010$ for sections $\perp$ a

Thin section #17-5 has very well developed banding. The bands vary in composition from 95 per cent epidote, 5 per cent hornblende to 45 per cent epidote, 55 per cent hornblende. Texture is generally granoblastic. In some sections hornblende may be porphyroblastic and have sieve texture (see figures 4 and 5)

Epidote in some sections occurs as a mosaic of small, rounded to subhedral grains and in other sections as individual subhedral to euhedral crystals most of which occur on the border of biotite flakes or completely enclosed by biotite. The epidote is pistacite which has the same properties as the pistacite in the plagioclase-hornblende-biotite rocks except in one thin section where the birefringence is 0.021 to 0.023, corresponding to 13 molecular per cent of $HCa_2Fe_3Si_3O_{13}$.

Hornblende is very similar to the hornblende in the plagioclase-hornblende-biotite rocks in occurrence and properties. $Z_{\wedge}c$ is 21° - 22° and the pleochroic formula is X = pale yellow, Y = blue green and Z = dark green.

Biotite in most sections is pleochroic from reddish brown or golden brown (Z) to straw yellow (X) but in a few sections is pleochroic from a very dark brown to straw.

Plagioclase is very similar in occurrence and properties to that in the plagioclase-hornblende-biotite rocks. A few grains are weakly zoned.

Quartz occurs as large anhedral grains and as small inclusions in sieve texture hornblende. It shows no evidence of strain.

Apatite and sphene are the only accessory minerals. They have similar properties and occur similarly to the apatite and sphene in the plagioclase-hornblende-biotite rocks.

Sericite replaces feldspars in all sections, but in minute quantities. Chlorite, of the type found in the plagioclase-hornblende-biotite rocks, is found replacing biotite around pyrite in one section. The pyrite is in irregular masses of no particular orientation and may be hydrothermal. Apart from this pyrite opaques are very rare in these sections.

(3) The Plagio-clase-hornblende-biotite-diopside amphibolites

The plagioclase-hornblende-biotite-diopside amphibolites are represented by only three thin sections. They are a very minor division of the plagioclase amphibolites.

The composition of the sections is as follows:

	Thin Section Numbers		
	8-6A	13-6	26-7
Hornblende	30%	20%	6%
Diopside	3%	25%	7%
Biotite	5%	--	22%
Plagioclase (An_{38} to An_{42})	53%	37%	25%
Quartz	5%	6%	9%
Epidote	3%	10%	13%
Chlorite	--	--	2%
Sericite	< 1%	< 1%	11%
Sphene	< 1%	< 1%	< 1%
Apatite	< 1%	< 1%	< 1%
"Iron Ore"	< 1%	< 1%	< 1%
Calcite	--	--	5%

In thin-section these rocks have essentially the same texture as the plagioclase-hornblende-biotite amphibolites and plagioclase-hornblende-biotite-epidote amphibolites. One section has porphyroblastic hornblende and diopside. Some of the porphyroblasts lie across the schistosity. The other sections are essentially granoblastic.

Hornblende occurs as subhedral grains replacing or being replaced by diopside and as euhedral to subhedral grains elsewhere. Twinning on (100) was noted but is rare.

Variations in $Z_{\wedge}c$ and the pleochroic formula follow:

Thin Sections #8-6A, #26-7

X = pale yellow   Y = blue green   Z = dark green

$Z_{\wedge}c = 22^{o} - 23^{o}$

Thin Section #13-6

X = pale yellow   Y = green   Z = brownish green

$Z_{\wedge}c = 24^{o}$

This hornblende is very similar to the hornblende of the other plagioclase amphibolite rocks.

Biotite replaces both hornblende and diopside. It is pleochroic from golden brown or reddish brown (Z) to colorless or straw yellow (X). In one thin section the biotite is partially altered to chlorite and sericite.

Diopside occurs as euhedral to subhedral grains. It is colorless or has a very faint pale green tint and is not noticeably pleochroic. The maximum interference color is second order yellow. $Z_{\wedge}c$ is -39^{o} to -41^{o} and the diopside is biaxial positive with a moderately large 2V.

The plagioclase, quartz, epidote (pistacite), apatite and sphene present have the same properties and occurrence as in the plagioclase-hornblende-biotite rocks.

"Iron ore" consists of small euhedral and ragged grains and, in #26-7, a few large anhedral grains. These opaques are probably mainly pyrite and magnetite.

The abundant sericite in #26-7 (11 per cent) includes 3 per cent of altered biotite, and 8 per cent of fine felty mass formed by the alteration of feldspar. This is a heavily altered rock, as the chlorite and calcite which are present in it are also probably alteration products, although the calcite may be introduced vein material. The chlorite has parallel extinction, anomalous yellow grey interference colors and a moderate relief. It occurs replacing biotite. The calcite occurs in elongate areas composed of mosaics of large grains.

(4) The plagioclase-staurolite amphibolites

This unit is represented by only one thin section from the head of South Beaver Valley, where this rock type forms a band some 20 feet wide on either side of a 5-foot wide band of kyanite-staurolite-almandine mica schist. It is probable that similar rocks may occur elsewhere in the vicinity of kyanite-staurolite-almandine mica schists, as this unusual rock type was not suspected to exist in the field and this is the only thin section made of an amphibolite from near the contact with these rocks.

The composition of this specimen is staurolite 5 per cent, hornblende 20 per cent, biotite 15 per cent, chlorite 5 per cent, plagioclase 44 per cent, quartz 4 per cent, almandine 5 per cent and less than 1 per cent of apatite sphene, "iron ores" and sericite.

Almandine and staurolite occur as porphyroblasts with a poorly-developed sieve texture. Almandine porphyroblasts reach 1/2 inch (1.2 cm) in diameter. The staurolite grains are much smaller and highly altered. The other minerals are medium-grained. Despite the high content of biotite foliation is only moderately well developed.

Hornblende occurs in euhedral to subhedral grains. $Z_{\wedge}c$ is 22^{o} and the pleochroic formula is X = pale yellow, Y = blue green and Z = dark green. This is the common aluminous hornblende of the amphibolites of this area.

Staurolite occurs in irregular grains being replaced by chlorite. It contains a few non-orientated inclusions of quartz and plagioclase. It is biaxial positive with a large 2V, has weak birefringence, high relief and strong pleochroism from deep golden yellow to pale yellow.

Biotite is found as subhedral plates replacing hornblende and possibly staurolite. It is pleochroic from dark brown (Z) to straw yellow (X).

Chlorite occurs as ragged flakes and aggregates of flakes replacing biotite, almandine, and staurolite. The chlorite replacing staurolite is partly strung out parallel to the foliation but in part preserves the shape of the original staurolite grains. All the chlorite has parallel or nearly parallel extinction, is pleochroic from medium green to pale green and has anomalous greyish yellow interference colors. It is length-fast.

Most grains of plagioclase are subhedral. Its composition (unzoned grains) was determined as An_{43} by finding N_{x}' for cleavage flakes with index oils and a sodium light source, and as An_{44} by measuring $X'_{\wedge}010$ for sections $\perp$ to a, i.e. this is a slightly calcic andesine. Many of the plagioclase grains are zoned. Generally zone boundaries are very vague and irregular. Some of the zoning appears to be cyclic but commonly it is of the reverse type. One determination indicated a rim of An_{46} and a core of An_{35}. Twinning is simple albite in about two-thirds of the plagioclase and complex in the rest.

Quartz occurs as anhedral grains which occasionally have undulatory extinction. It also is found as inclusions in staurolite and almandine.

The only almandine porphyroblast found in this thin section is almost euhedral, but marginal alteration to chlorite has rounded it. The garnet has a few non-oriented inclusions of plagioclase and quartz. It is pale pink and isotropic.

Apatite occurs in unusually large grains in this thin section. The largest are as big as the average plagioclase grain. It forms extremely short, stubby hexagonal prisms which may be euhedral or subhedral.

Sphene is not very common. It has the same properties and occurrence as the sphene in the other types of plagioclase amphibolite.

"Iron ore" forms large, anhedral grains replacing chlorite and the other minerals. Sericite is found in small amounts as a felty mass replacing plagioclase and also pseudomorphous after biotite and chlorite.

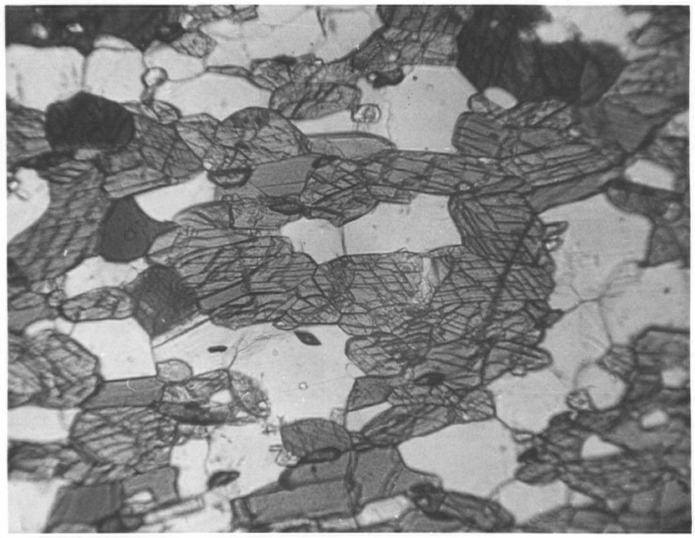

Figure 3. Photomicrograph of plagioclase-hornblende amphibolite. Plain light X64. Contains hornblende, plagioclase and quartz and minor sphene and apatite.

Figure 4. Photomicrograph of plagioclase-hornblende-epidote rock. Plain light X24. Coarse porphyroblastic hornblende, fine granular epidote, quartz and plagioclase.

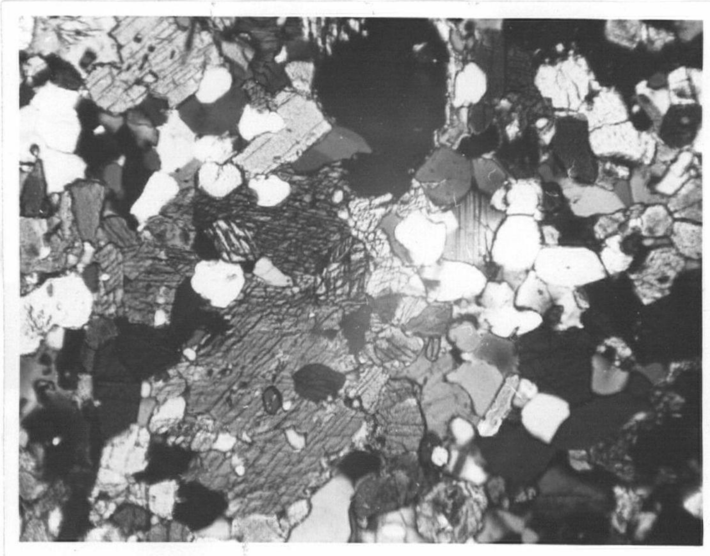

Figure 5. Photomicrograph of plagioclase-hornblende-epidote rock. Polarized light. X64. Same thin section as Figure 4.

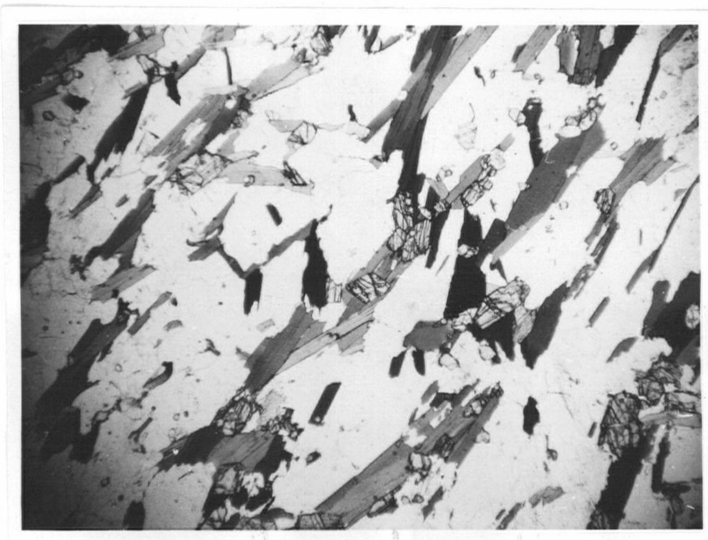

Figure 6. Photomicrograph of plagioclase-biotite-epidote rock. Plain light. X24 Elongate biotite laths, euhedral to subhedral epidote, plagioclase and quartz.

Figure 7. Photomicrograph of plagioclase-biotite-epidote rock. Polarized light. X24. As Figure 6.

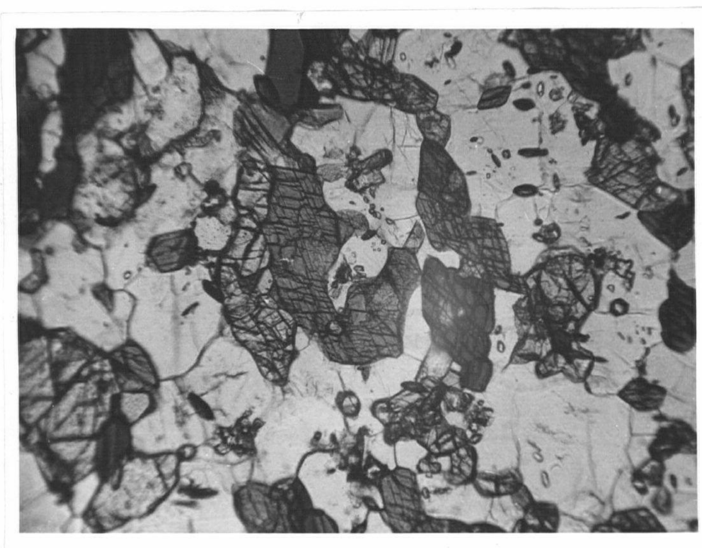

Figure 8. Photomicrograph of plagioclase-diopside-hornblende amphibolite. Plain light. X64. Dark hornblende, lighter diopside, plagioclase, quartz, and minor apatite and sphene.

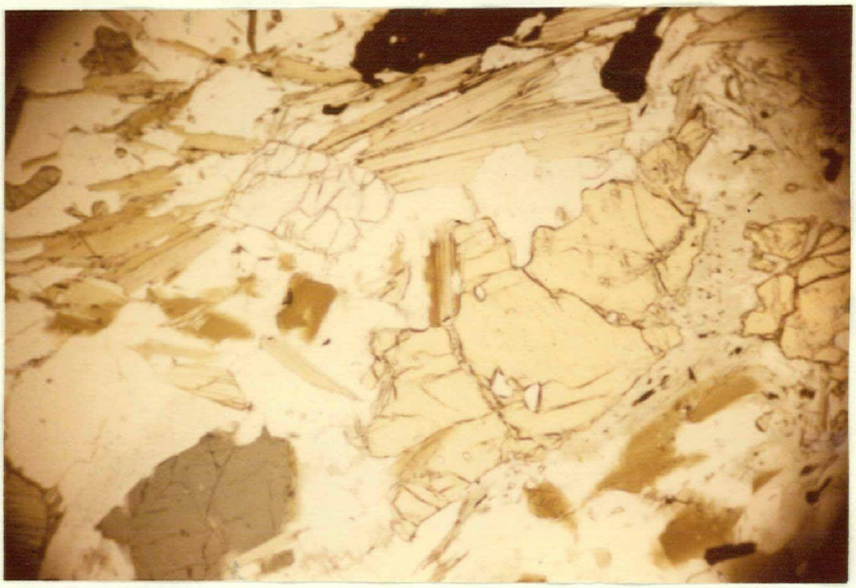

Figure 9. Photomicrograph of plagioclase-staurolite amphibolite. Plain light. X24. Staurolite, hornblende, biotite, chlorite, apatite, plagioclase and quartz.

Figure 10. Photomicrograph of plagioclase-staurolite amphibolite. Plain light. X24, similar to Figure 9.

PETROLOGY OF THE METASEDIMENTS

Major subdivisions of the metasediments are as follows:

(1) Plagioclase-quartz-biotite-hornblende gneiss
(2) Plagioclase-K feldspar-quartz gneiss
(3) Kyanite-staurolite-almandine mica schist
(4) Sillimanite-quartz-plagioclase gneiss
(5) Graphitic quartz-plagioclase schist
(6) Quartzite
(7) Quartz-tremolite-zoisite rocks
(8) Crystalline limestone
(9) Sericite-epidote schist
(10) Albitized and potash-enriched rocks

It is realized that the divisions in this classification are arbitrary, but it is felt that each division represents some real difference in composition or grade of metamorphism of the rock and hence is justified. A detailed petrological description of each rock type follows:

(1) Plagioclase-quartz-biotite-hornblende gneiss

This division was created to include rocks which do not contain K feldspar but contain less than 25 per cent of combined biotite and hornblende. It is represented by three thin sections, from widely scattered areas, and does not form any mappable units at the present scale of mapping. It apparently represents the extremes of composition of the two major metamorphic rock types, i.e. the K feldspar-bearing gneisses and plagioclase amphibolites, and may be important in a consideration of the origin and conditions of formation of the latter. (See the section on the origin of the metamorphic rocks in this chapter).

In hand specimen these rocks have a close resemblance to the plagioclase amphibolites. They are fine-grained to medium grained dark grey rocks which appear to almost completely lack schistosity. Lineation is weak or lacking. Hornblende may be porphyroblastic.

The composition of the three thin sections is as follows:

	Thin Section Number		
	15-3A	18-9	24-4
Plagioclase (An_{38} - An_{41})*	57%	65%	55%
Quartz	20%	15%	7%
Hornblende	13%	15%	3%
Biotite	8%	5%	15%
Epidote	< 1%	--	10%
Sericite	< 1%	< 1%	--
Sphene	< 1%	< 1%	< 1%
Apatite	< 1%	< 1%	< 1%
"Iron Ore"	< 1%	< 1%	< 1%

* Determined by measuring N_x' or $X' \wedge 010$ for sections $\perp$ a

It is apparent in thin section that all these rocks actually have a fairly strong foliation. Texturally they have little else in common. One section has an essentially granoblastic texture, modified by later dynamic metamorphism which has resulted in undulatory extinction in the quartz, granulation of quartz and plagioclase and a series of parallel fractures in the section at a large angle to the original foliation. The other sections have porphyroblastic textures.

Plagioclase is usually anhedral to subhedral. Twins are of the albite type (60%-85%) or are complex twins. No Carlsbad or Carlsbad-albite twins are definitely identified.

All quartz grains are anhedral. Undulatory extinction is well developed in #15-3A and is found in two or three grains in #24-4.

Hornblende is euhedral to subhedral except when it occurs as ragged anhedral porphyroblasts. It is the same type as the common hornblende in the plagioclase amphibolites.

Biotite occurs in subhedral plates, commonly with ragged terminations. In one thin section a few sections of biotite cut subparallel to the cleavage show that it is intergrown with vermicular quartz. The biotite is pleochroic from dark brown to straw yellow.

Epidote is generally euhedral but occasionally subhedral. It is almost always associated with biotite. The epidote is colorless pistacite, biaxial negative with a large 2V, and has a birefringence of about 0.03, indicating it contains approximately 18 per cent of the $HCa_2Fe_3Si_3O_{13}$ molecule.

Sericite is common in the section which has undergone granulation. Here it occurs as a fine felty mass replacing the plagioclase and also in a set of narrow fractures whenever these cross a feldspar grain. It is rare in the other sections.

Sphene is found as wedge-shaped crystals and rounded granules in all thin sections. It is a very faintly pleochroic (pale brown to colorless) type.

Apatite occurs in small hexagonal grains which are euhedral or subhedral. "Iron ore", found only in #18-9, occurs as large anhedral grains. It is probably pyrite.

(2) Plagioclase-K feldspar-quartz gneisses

This division contains some 40 per cent of the metamorphic rocks of Hawkesbury Island and forms, excluding the plagioclase amphibolites, the largest unit of probably metasedimentary rocks there. There seems to be distinct differences in composition and in texture in the rocks of this division in different parts of the island, so that three subdivisions have been erected. These are (a) the "Normal" type, (b) the Augen Mountain type and (c) the Sidebacon Lake type. The "Normal" type is the common plagioclase-K feldspar-quartz gneiss of the island. It forms the K feldspar gneisses which occur interbedded with plagioclase amphibolites in the area between Augen mountain and North mountain. It is also found in the upper part of Wye valley and interbedded with the main plagioclase amphibolite band in the south part of the island. The Augen Mountain type forms a band some 7000' wide which extends across Hawkesbury Island. It forms all of Augen Mountain except the north slope, and also underlies the northernmost branch of Wye valley and a small part of the ridge to the south of this valley. The Sidebacon Lake type is confined to the area immediately to the north of this lake, where it forms two separate bands; one about 3000 feet wide and the other of unknown width.

The "Normal" type and Sidebacon Lake type are very similar and will be described together, but the Augen Mountain type is so different in texture, appearance and composition it will be described separately.

(a) The "Normal" and Sidebacon Lake Types of Gneiss

In hand specimen these rocks are usually medium or fine-grained, and whitish to pink in color, but the varieties with a high percentage of mafics may be grey. The weathered surface has much the same color as the fresh rock. A given specimen may show a complete lack of foliation, but this is usually present although extremely weak. In the field, foliation is much more evident due to differences in weathering and grain size from band to band and the presence of occasional mafic-rich bands. Such foliation as is visible seems to be mainly due to the parallel alignment of biotite and other platy minerals. Compositional banding is lacking or weak. Where it is developed, three sets of bands are present - mafic-rich, feldspar-rich, and quartz-rich. All three sets tend to form elongate lenses rather than continuous bands, with a maximum length of an inch or so and width of about 1/10 of an inch. Rocks of this texture have been referred to as "leptynite", "granulite", "leptite", "quartz schist" and "gneiss" in the past. The term granulite is now reserved for rocks of the high temperature granulite facies. These characteristically lack mica and hornblende. The term leptite, and its variant leptynite, imply textural features lacking in the Hawkesbury Island K-feldspar rocks. The writer prefers to call these rocks gneisses rather than schists as he would reserve the term schist for rocks with a well developed foliation.

The composition of the "Normal" type of plagioclase-K feldspar-quartz gneiss is plagioclase 35 to 54 per cent, mean value 48 per cent; K feldspar 2 to 20 per cent, mean value 5 per cent; quartz 10 to 36 per cent, mean value 28 per cent; and biotite less than 1 to 20 per cent, mean value 8 per cent. Sericite, chlorite, epidote, allanite, sphene, apatite and garnet may be present, but generally occur in amounts of less than 1 per cent.

The Sidebacon Lake type gneisses have plagioclase 35 to 41 per cent, K feldspar 35 to 42 per cent, quartz 18 to 20 per cent, and biotite less than 1 to 2 per cent. Hornblende, epidote, chlorite, sericite, sphene, apatite and opaques are minor constituents. The differences between the two types are mainly in K feldspar and biotite content.

The texture, in thin section, is seen to be complex. A poor foliation has developed due to a rather incomplete sub-parallel orientation of biotite and hornblende, and a tendency for feldspar and quartz to occur in elongate leaves sub-parallel to these minerals. Superimposed upon this, however, is a well developed pseudocataclastic texture which is formed by a replacement of potassium in K feldspars by sodium and calcium to form plagioclase, with a consequent liberation of silica which appears as free quartz. This results in a texture in which large xenomorphic grains of quartz and feldspar are set in a fine-grained matrix of the same minerals. It differs from cataclastic texture in that finer grains of groundmass are not fragments of the larger grains and also in that there is a strong suggestion of corrosion of the larger grains by the groundmass. Cataclastic texture features granulation of quartz and bent twin lamellae in feldspars. The difficulty in deciding which texture is present is that rocks with a suitable chemical composition to develop pseudocataclastic texture usually have suitable physical properties to develop cataclastic texture. In the thin sections examined, however, only one feldspar grain was seen which is fractured, granulated quartz was not observed and the larger grains generally appear to have corroded margins. This suggests that, although minor cataclastic effects may be present, this texture is mainly pseudocataclastic.

Plagioclase has a composition of An_{36} to An_{39}, medium andesine, in both types of gneiss. These determinations are based on measuring $X' \wedge 010$ for sections $\perp$ a. Most of the twinned grains have simple albite twinning but complex twins are also present. Zoned feldspars are present but rare.

The potassium feldspar present is usually untwinned in the "Normal" type gneiss. Such twinning as is present is of the quadrille type, showing that the twinned feldspar is microcline rather than orthoclase. Twinning is usually present at the edges of grains only. Whether the untwinned K feldspar is microcline or orthoclase is not known. It has been suggested that orthoclase may invert to microcline under stress. If this is the case this untwinned K feldspar is probably orthoclase. In the Sidebacon Lake type gneisses the K feldspar is practically all twinned microcline. K feldspar, where in contact with plagioclase, is often fringed by "wart-like"[8] ~~by~~ myrmekite. The plagioclase of the myrmekite is optically continuous with the primary plagioclase, even to the extent that twin lamellae may extend without change into the myrmekite.

Large grains of quartz commonly have undulatory extinction. This mineral has no other unusual properties.

Biotite occurs in small plates with ragged terminations. It is pleochroic from dark brown to straw yellow, unlike the common red-brown biotite of the plagioclase amphibolite.

The minor minerals are hornblende, epidote, allanite, chlorite, sericite, sphene, apatite, garnet and opaques. Hornblende occurs as large subhedral grains in one thin section of the Sidebacon Lake type gneisses. It is a pleochroic dark brown type. The epidote group mineral present is probably pistacite, as its birefringence varies from about 0.026 to 0.031 indicating 16 to 19 molecular per cent of $HCa_2Fe_3Si_3O_{13}$. It occurs as small anhedral to subhedral grains scattered throughout the rock. In one thin section of the Sidebacon Lake type

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8 G.H.Anderson,"Granitization, Albitization and Related Phenomena in the Northern Inyo Range of California-Nevada, G.S.A. Bulletin, vol. 48, 1937, pp 37-39.

gneiss a few cores of allanite are present surrounded by a pistacite rim. Chlorite and sericite are alteration products of biotite and feldspar. They occur in ragged grains, and, in the case of the chlorite, as felty masses. Both are very minor constituents. The chlorite has "berlin blue" interference colors, parallel extinction, and is pleochroic from green to reddish brown. It is probably pennine, which is the only common chlorite with these properties. Sphene is present in almost every thin section, but is rarer than in the plagioclase amphibolites. It is weakly pleochroic from pale brown to colorless and occurs as small wedge-shaped euhedral and subhedral crystals. Apatite occurs in tiny hexagonal prisms. It is found in most thin sections. Garnet is found in about half of the thin sections of "Normal" type gneiss. It is isotropic and is found in small euhedral to subhedral crystals. It is a pale pink shade even in thin section. "Iron ores" are very scarce in all thin sections and consist of small anhedral grains, probably of magnetite.

(b) The Augen Mountain Type of Gneiss

In hand specimen these rocks are grey on both fresh and weathered surfaces. They always have a porphyroblastic texture. The porphyroblasts are oval feldspar augens which have a maximum diameter of about one inch (2.5 cm). A strong foliation and well defined banding is present in the varieties with well developed augens. Varieties with small augens lack banding and have comparatively weak foliation, although stronger than that of most specimens of the "Normal" and Sidebacon Lake type gneisses.

The composition of the Augen Mountain type of plagioclase-K feldspar-quartz gneiss is plagioclase 30 to 50 per cent, K feldspar 15 to 20 per cent, quartz 20 to 25 per cent, biotite 5 to 15 per cent, epidote 4 to 15 per cent, hornblende 2 to 3 per cent. Chlorite and sericite, may be present. Sphene, apatite and "iron ores" are always present as accessory minerals.

In thin section, the texture of these rocks is seen to be essentially porphyroblastic, modified to a minor extent by pseudocataclastic and cataclastic effects. A good example of cataclastic texture is present in one thin section (see figures 13, 14) in which a large grain forming most of a plagioclase augen is strongly fractured.

Plagioclase has a composition of An_{36} to An_{38}, medium andesine, as determined by measuring $X' \wedge 010$ for sections $\perp$ a. Twinned grains usually have albite twinning, although complex twins are present. No zoned grains were noted. Plagioclase occurs in the groundmass as subhedral to anhedral grains and also as larger grains forming augens. The only large plagioclase augen seen in thin section is composite, being composed of one very large and several smaller subhedral plagioclase grains.

K feldspar is all of an untwinned type, either orthoclase or microcline. It forms the largest augens in these rocks and also occurs as small anhedral grains. It is not known whether the augens are composite or not as none are found in thin section. They were identified in hand specimen by etching with hydrofluoric acid and staining in a sodium cobaltinitrite solution. The K feldspars are fringed by "wart-like" myrmekites of the type present in the other plagioclase-K feldspar-quartz gneisses.

Quartz, in anhedral leaves and grains, commonly has undulatory extinction.

Biotite is found in large subhedral plates. It is pleochroic from dark brown to straw.

Hornblende forms subhedral to euhedral grains fringed by biotite. It is biaxial negative with $Z_{\wedge}c = 22^{o}$, and a pleochroic formula of X = pale yellow Y = blue green, and Z = dark green, i.e. is the common aluminous hornblende of this area.

Chlorite and sericite occur in irregular shreds as minor alteration products. The chlorite is pleochroic green to brown, and has parallel extinction and "berlin blue" interference colors. It is probably pennine.

Sphene and apatite occur as small euhedral to subhedral crystals. Sphene is the common weakly pleochroic (pale brown to colorless) variety. "Iron ores" are scarce in most sections and consist of a few anhedral to cubic euhedral (pyrite? magnetite?) grains.

Figure 11. Photomicrograph of "Normal" type of plagioclase-K feldspar-quartz gneiss. Plain light. X24. Rounded garnets, plagioclase, K feldspar and quartz.

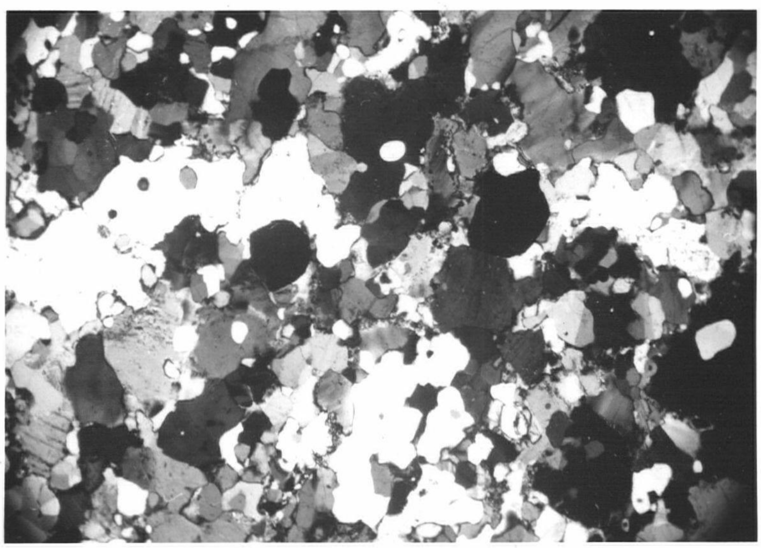

Figure 12. Photomicrograph of "Normal" type of plagioclase K feldspar-quartz gneiss. Polarized light X24. As Figure 11.

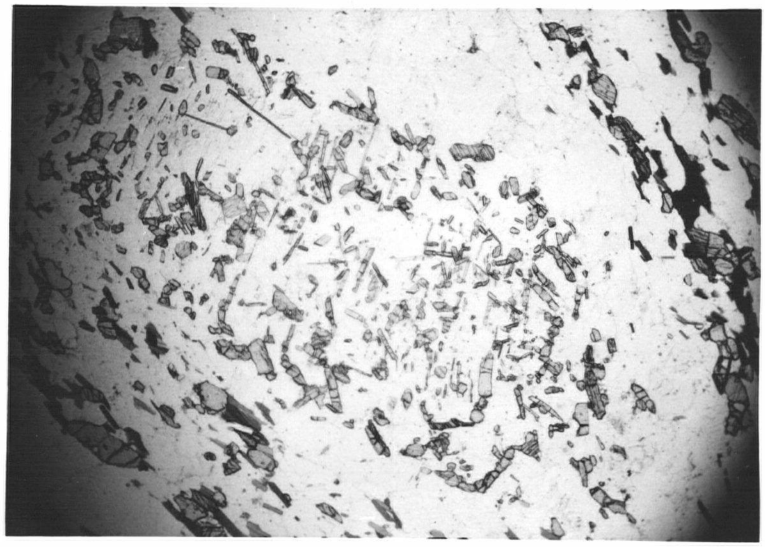

Figure 13. Photomicrograph of Augen Mountain type of plagioclase-K feldspar-quartz gneiss. Plain light X24. Large plagioclase augen containing small epidote grains. Some biotite outside of the augen.

Figure 14. Photomicrograph of Augen Mountain type of plagioclase-K feldspar-quartz gneiss. Polarized light X24. As Figure 13. Fracturing is evident in the augen.

(3) The Kyanite-staurolite-almandine mica schists

These rocks, although quite limited in extent, are among the most important of the septum from the point of view of determination of metamorphic facies and, to a lesser degree, of the history of the metamorphic rocks. This unit is better known than the other units of the Ecstall series as detailed field mapping of it was carried out. This rock type occurs as a series of bands interbedded with plagioclase amphibolites extending east from the head of South Beaver valley, through the Ice Cake Lake-Kyanite Pond area, almost to Ellen Lake on the east side of the island. The maximum width of the interbedded zone is 6000 feet. Most of the kyanite-staurolite-almandine mica schist are found in the southern half of this band. Individual bands vary considerably in shape and extent. Some bands vary from a few feet to over 100 feet in width in a very short distance. The longest band of this rock is 7000 feet long and has an average width of 40 feet and a maximum width of 89 feet. The three other major bands have lengths of 2000 feet to 5000 feet and similar widths.

These rocks, when seen from a distance, are white, pink, or grey, depending on the relative proportions of their constituent minerals. The weathered surface is much like the fresh surface, but kyanite, almandine and staurolite porphyroblasts become prominent as the muscovite weathers out from around them. The matrix is normally medium grained to coarse grained. A strong schistosity is normally present due to a parallel orientation of muscovite flakes and the formation of elongate leaves of quartz and feldspar, but this becomes much weaker when the porphyroblasts are large enough and common enough to distort this orientation. Banding into muscovite-rich and plagioclase-quartz-rich bands is occasionally weakly developed. Almandine occurs as deep red subhedral to euhedral porphyroblasts which may reach 2 inches in diameter. The larger crystals are usually euhedral dodecahedrons which are somewhat flattened parallel to the schistosity. Small crystals are commonly rounded and show no signs of this flattening. There are exceptions to this general rule, of which the most striking are large anhedral rounded aggregates of garnet up to 3 inches in diameter, which contain inclusions of quartz, feldspar, staurolite, and muscovite up to 1/4 inch in diameter. Staurolite occurs as stubby black prismatic crystals, the largest 1½ inches long, which lie parallel to the schistosity. Kyanite, which is varying shades of blue, occurs as acicular crystals a few millimeters long to large flat blades which may be 8 inches long, 1 inch wide, and 1/2 inch thick. Nearly all of these crystals are orientated with their length parallel to the schistosity and are sub-parallel to each other, producing a lineation.

The composition of this rock unit is extremely variable, as may be seen from figure 15, an ACF diagram for the staurolite-quartz subfacies of the almandine amphibolite facies to

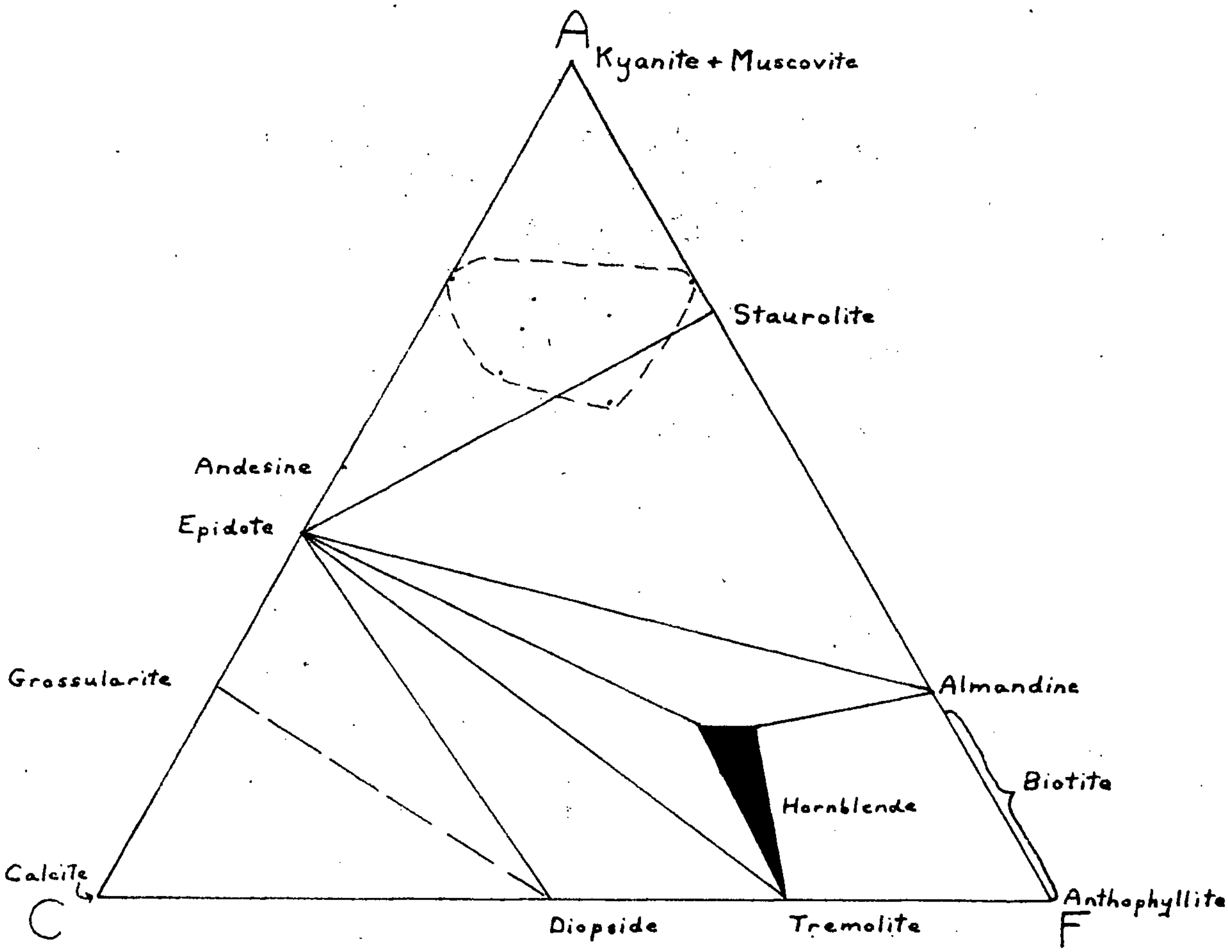

Figure 15. ACF diagram for the almandine amphibolite facies, staurolite quartz subfacies, showing the range of composition of the Kyanite-staurolite-almandine mica schists.

which the rocks in this unit with equilibrium assemblages belong.

Sample Number

	K-1	11-6A	24-7B	PX-3	17-6	11-4	K-2
Plagioclase	--	15%	31%	14%	51%	18%	50%
Quartz	55%	46%	23%	51%	3%	20%	4%
Muscovite	14%	3%	10%	15%	15%	35%	25%
Kyanite	---	---	15%	<1%	10%	---	20%
Staurolite	25%	30%	15%	10%	10%	5%	<1%
Almandine	5%	5%	5%	<1%	10%	20%	---
Chlorite	<1%	<1%	<1%	8%	<1%	<1%	---

Less than 1 per cent of apatite and opaques are present in all thin sections, minor biotite and sphene are present in a few and sillimanite(?) is present in one section.

In thin section the strong schistosity is the most noticeable feature. Banding is more noticeable than in hand specimen. An almost complete segregation into quartz-feldspar and muscovite bands is present in some specimens. The almandine and staurolite porphyroblasts are seen to have well developed sieve textures. In some thin sections the inclusions in the garnet are subparallel but are at varying angles to the schistosity, indicating rotation of the garnet after growth. In others there is no evidence of rotation. Staurolite usually shows little or no rotational effects, but in one thin section one large grain seems to have grown undisturbed for most of its formation, rotated about 80°, and then grown undisturbed again until the end of its period of formation (see Figure 18) Other grains in this section show other rotational effects. Kyanite porphyroblasts have few inclusions, whose orientation is evidently crystallographically controlled, and show no rotational affects. Another texture or microstructure is found in thin section PX-3. This is an alteration rim (see figures 20 and 21) surrounding all the staurolite porphyroblasts in the section. It consists of a broad rim of fairly fine-grained felty sericite outside of which is an incomplete rim of fairly coarse-grained chlorite. This is explained by Harker[9] as being due to the increase in volume which occurs when staurolite is altered to sericite-chlorite. The chlorite is more soluble and, because of this volume change, it is dissolved and redeposited away from the staurolite grain.

Plagioclase is anhedral to subhedral and occurs in grains and aggregates ranging from slightly elongate parallel to the foliation to lens-shaped elongate "leaves". It also occurs in poikiloblastic almandine. The composition of the plagioclase is quite variable. In the sections in which it was measured it was An_{25}, An_{26}, An_{30}, An_{34}, and An_{40}. The first two determinations are based on measuring N_x' using index oils and monochromatic (sodium) light source and the others are based on measuring $X' \wedge 010$ for sections $\perp$ a. Zoning is present but quite uncommon.

Quartz occurs as elongate anhedral leaves or as mosaics of anhedral grains with sutured boundaries. It usually has undulatory extinction.

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9 A. Harker, Metamorphism, (Methuen and Co.Ltd. 1950) p. 350

Muscovite is coarse-grained and generally occurs as bands or occasional isolated subhedral tabular crystals. In some places it has replaced kyanite, staurolite or plagioclase as tabular crystals and as fine-grained felty masses of sericite.

Kyanite is euhedral or subhedral. It contains inclusions of plagioclase, quartz and opaques. It is colorless, biaxial negative with a large 2V, has high relief, moderate birefringence, and two prominent cleavages.

Staurolite is euhedral to anhedral. It contains inclusions of quartz, opaques, and plagioclase. It is commonly pleochroic from pale golden yellow to almost colorless, but in one thin section is pleochroic from deep yellowish orange to pale orange. It has a distinct cleavage and also a parting and is untwinned.

Most of the almandine is subhedral to rounded anhedral. It contains inclusions of quartz, opaques and plagioclase. It is isotropic and a pale red color in thin section. It always is marginally altered to chlorite.

Sillimanite(?) occurs only in section #11-4. The mineral thought to be sillimanite is visible only under high power. It occurs as a few acicular needles replacing biotite and muscovite. It is length-slow, colorless, has high relief, rather strong birefringence, and parallel extinction. The only minerals with this description are sillimanite, anthophyllite and mullite, and it is extremely unlikely that anthophyllite or mullite would occur in this fashion or in a rock of this composition.

Biotite occurs as small subhedral plates. It is an uncommon mineral in these rocks, and, where seen, is usually altering to muscovite or chlorite. Its pleochroic formula is generally dark brown to straw.

Chlorite is found as irregular shreds and flakes. It replaces garnet (almandine) in all sections in which this mineral occurs, and is also found as an alteration product of staurolite and biotite. There does not seem to be any difference in the chlorites formed from these minerals. They all have parallel or nearly parallel extinction, are pleochroic from medium green to nearly colorless, and have anomalous "berlin blue" interference colors, indicating they may be pennine.

Apatite and sphene are the common accessory minerals in the kyanite-staurolite-almandine mica schists. They have the same properties as in all the previously described rocks.

Opaques are common in these rocks. They occur as fine films interlaminated with muscovite and as large anhedral to euhedral cubic grains. In reflected light they are always black. The films and possibly some of the anhedral grains are probably graphite whereas the rest of this material is probably magnetite.

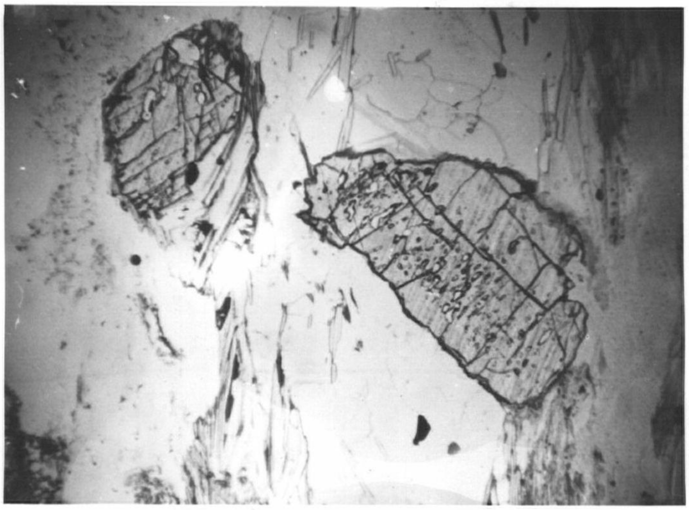

Figure 16. Photomicrograph of kyanite-staurolite almandine mica schist. Plain light X24. Porphyroblastic almandine (on the right) and staurolite (on the left) with muscovite laths, quartz, plagioclase and minor opaques and chlorite (rimming the almandine) Inclusions indicate rotation of the garnet.

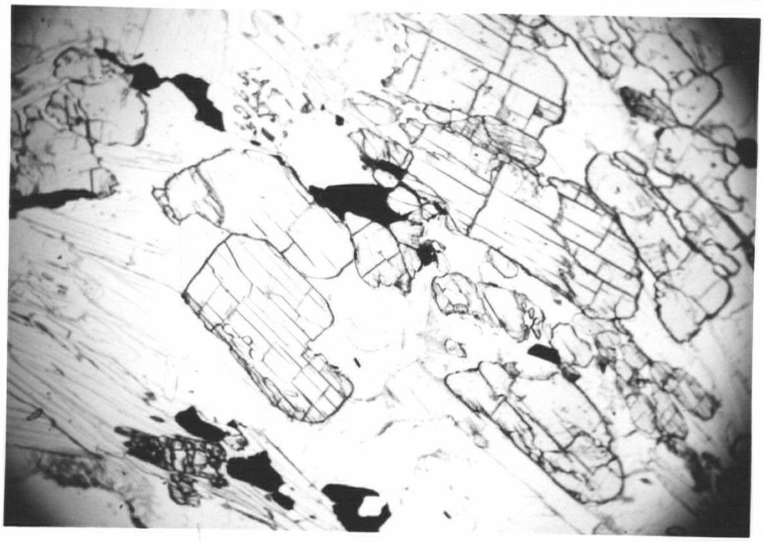

Figure 17. Photomicrograph of kyanite-staurolite-almandine mica schist. Plain light X24. Kyanite porphyroblasts (rectangular cleavage) muscovite laths, quartz, plagioclase, opaques. A small kyanite grain in the lower left corner is veined by opaques.

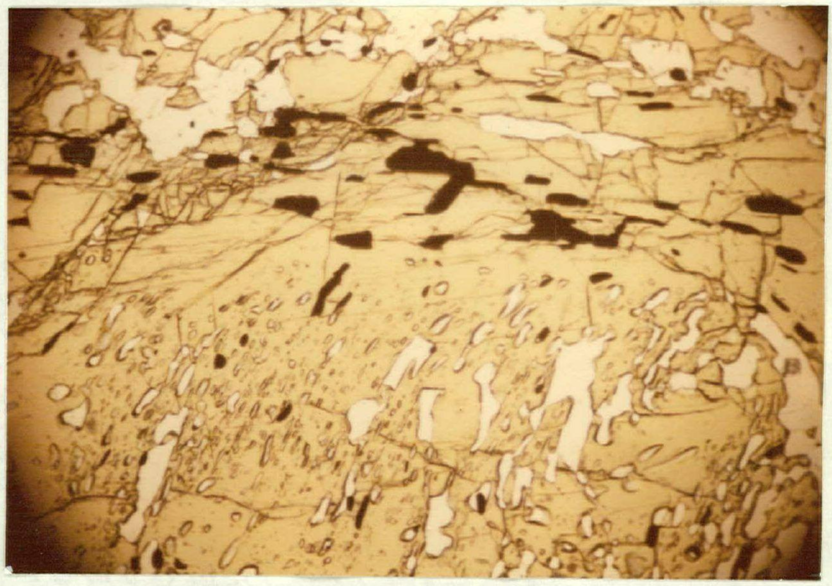

Figure 18. Photomicrograph of kyanite-staurolite-almandine mica schist. Plain light. X24. Part of a large rotated staurolite porphyroblast.

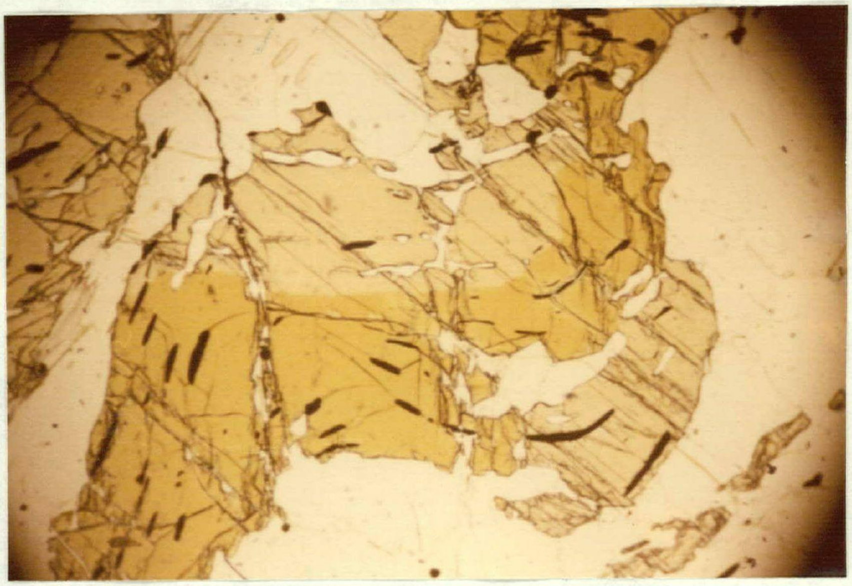

Figure 19. Photomicrograph of kyanite-staurolite-almandine mica schist. Plain light. X24, Twinned(?) rotated(?) staurolite porphyroblast.

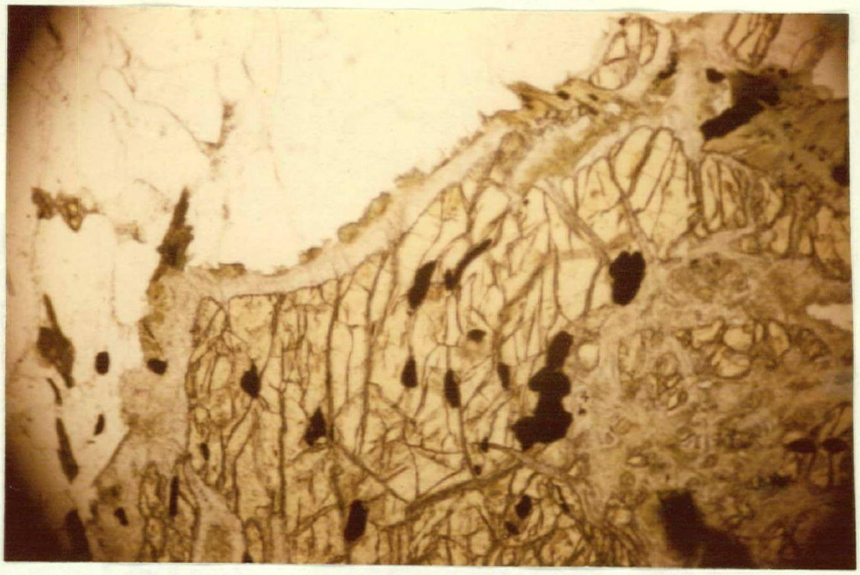

Figure 20. Photomicrograph of Kyanite-staurolite-almandine mica schist. Plain light X24. An alteration rim of sericite and chlorite surrounding staurolite.

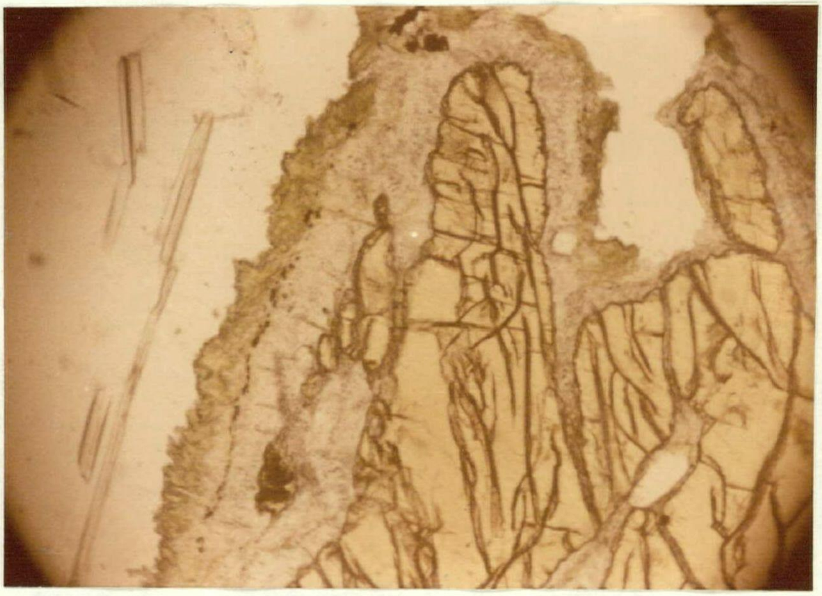

Figure 21. Photomicrograph of Kyanite-staurolite-almandine mica schist. Plain light X64. Similar to Figure 20.

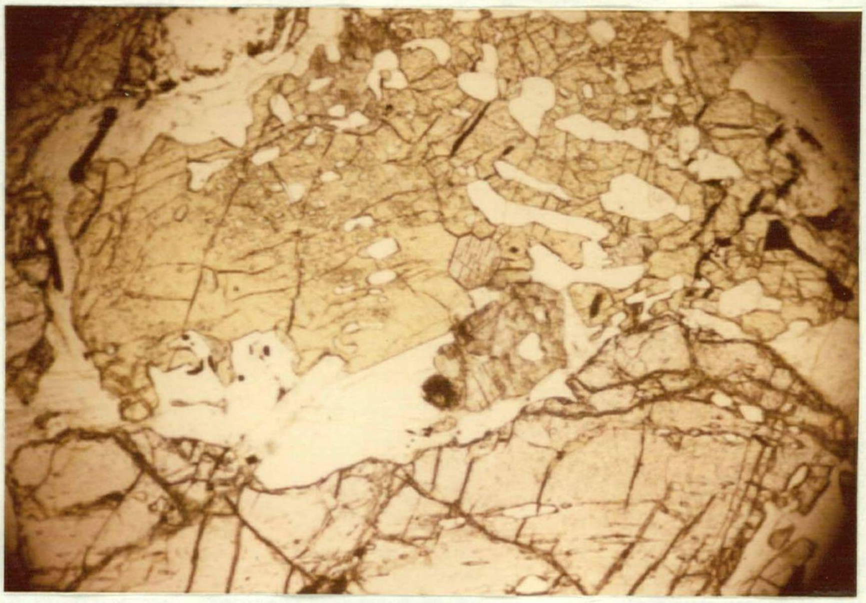

Figure 22. Photomicrograph of Kyanite-staurolite-almandine mica schist. Plain light X24. Kyanite, staurolite, almandine, muscovite, quartz, plagioclase and opaques.

Figure 23. Photomicrograph of Kyanite-staurolite almandine mica schist. Plain light X24. Similar to Figure 22.

(4) Sillimanite-quartz-plagioclase gneiss

This rock type has been found in one locality on the ridge between upper Angle Valley and Fishtrap Bay, where it occurs as a 25 foot wide band of unknown length interbedded with plagioclase amphibolite.

In outcrop this is a pale grey, fine-grained rock with conspicuous rounded knots of white sillimanite up to 1/5 inch across and 3/10 of an inch long. The sillimanite is resistant and stands out on the weathered surface.

This rock is represented by one thin section which has the following composition: quartz 36 per cent, plagioclase 38 per cent, biotite 12 per cent, sillimanite 15 per cent, muscovite 8 per cent and less than 1 per cent of sphene, chlorite, apatite and opaques. Under the microscope a strong foliation is seen which is due to a subparallel orientation of biotite, muscovite and bands of small sillimanite grains. The sillimanite bands are formed of numerous small acicular euhedral grains which are generally subparallel. These bands have great variation in width, occasionally swelling out into the "knots" noted in the outcrop. Biotite and muscovite occur in large elongate subhedral to anhedral grains apparently being replaced by the sillimanite. Chlorite is found in irregular shreds replacing biotite. The biotite lamellae are commonly bent and the sillimanite bands are gently folded. Quartz and feldspar are found in large anhedral grains with a

Figure 24. Photomicrograph of sillimanite-quartz-plagioclase gneiss. Plain light X24. Fine-grained acicular sillimanite in "knots" and swirling aggregates with biotite laths, elongate grains of opaques, plagioclase and quartz.

Figure 25. Photomicrograph of sillimanite-quartz-plagioclase gneiss. Polarized light X24. As Figure 24.

weak elongation sub-parallel to the foliation. Quartz occasionally has undulatory extinction.

The sillimanite is so fine-grained positive identification was made by powder X-ray methods.

Plagioclase was determined as An_{41} by finding N_X' for cleavage flakes. Most twins are of the albite type but complex twins are also present.

Biotite is pleochroic from medium brown to straw yellow. Sphene is the common weakly pleochroic variety. The opaques consist of ragged large anhedral pyrite grains.

(5) Graphitic quartz-plagioclase schists

These rocks are quite limited in extent. They occur interbedded with plagioclase amphibolite in the Trench Brook area and on the east side of Fishtrap Bay. In the former locality, although at most some 20 to 30 feet wide, they appear to extend across the island, a distance of a little under 3 miles.

In hand specimen these are fine-grained, black or dark grey layered rocks with or without a strong schistosity. The layers are sharply distinct, of widely varying composition, have great variations in thickness (paper thin to 1/4 inch) and are very persistent so that it seems likely they represent relict bedding. They do not resemble layers formed by metamorphic differentiation.

The composition, based on several thin sections, is quartz 42 to 62 per cent, plagioclase 16 to 30 per cent, tremolite none to 1 per cent, biotite none to 3 per cent, zoisite none to less than 1 per cent, sphene less than 1 per cent, muscovite-sericite less than 1 to 5 per cent, calcite none to 4 per cent, apatite less than 1 per cent, diopside none to 1 per cent and opaques 7 per cent to 20 per cent. The amount of graphite is estimated to be 6 to 15 per cent. One hand specimen contains about 80 per cent graphite. This is from a pinching and swelling lens of graphite-rich rock about 100 feet long and at the most 10 feet wide in the Trench Brooks area. In thin section the rock is seen to consist of a mosaic of anhedral quartz and plagioclase grains with sutured contacts and with a slight tendency to sub-parallel elongation, containing occasional small grains of euhedral to subhedral diopside and tremolite, the latter frequently rimming the former, subhedral zoisite, euhedral to subhedral sphene and ragged shreds of biotite and muscovite. The tremolite and micaceous minerals are orientated sub-parallel to the elongate quartz and feldspar grains, with the exception of felty sericite in the plagioclase. Graphite is found in elongate lath-like grains with a strong preferred orientation parallel to that of the quartz, biotite, etc. It occurs along the margins of the quartz grains or within one grain or cutting across several. Compositional banding into graphite-rich and graphite poor bands is well developed in the rocks from the Trench Brooks area but is lacking in most specimens from Fishtrap Bay. Quartz occasionally has undulatory extinction but rarely shows other evidence of strain.

Only two reliable determinations could be made on the feldspars. These are An_{33} and An_{36}, the former determined by measuring N_x' for cleavage flakes and the latter by measuring $X' \wedge 010$ for a section $\perp$ a.

Tremolite is the type found in the quartzites and calcareous quartzites. It has $Z \wedge c = 18^\circ - 19^\circ$. Diopside is a colorless variety. Its maximum interference color is second order yellow. $Z \wedge c$ is at least -38°. Zoisite is the non-ferrian variety. It is biaxial positive with a small 2V and deep blue interference colors. Biotite is a variety which is pleochroic from reddish brown to straw. Sphene as an extremely pleochroic variety, from deep red brown to almost colorless. Calcite and muscovite-sericite are secondary minerals, the former probably replacing plagioclase and the latter plagioclase and biotite. The calcite is found in large enhedral grains. The opaques, in addition to graphite, consist of euhedral to subhedral cubes of pyrite.

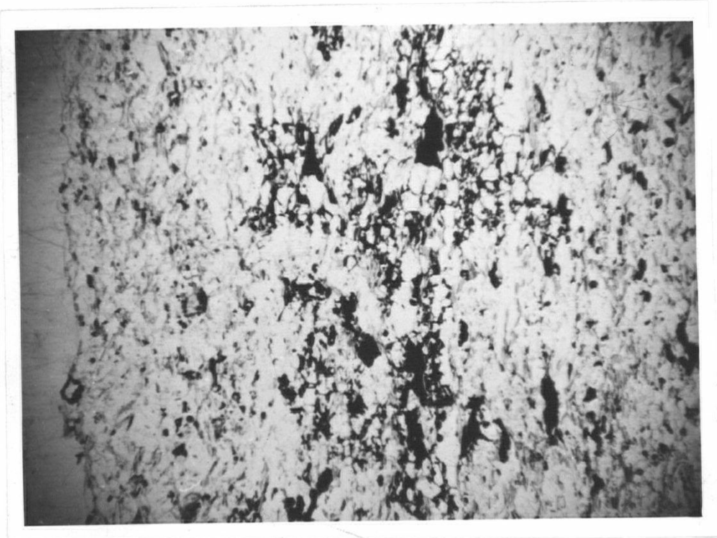

Figure 26. Photomicrograph of graphitic quartz-plagioclase schist. Plain light X24. Graphite, pyrite, quartz and plagioclase.

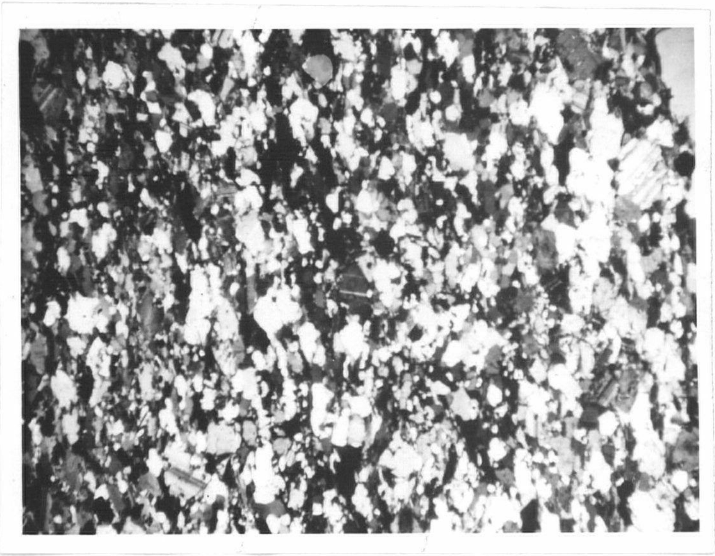

Figure 27. Photomicrograph of graphitic quartz-plagioclase schist. Polarized light X24. As Figure 26.

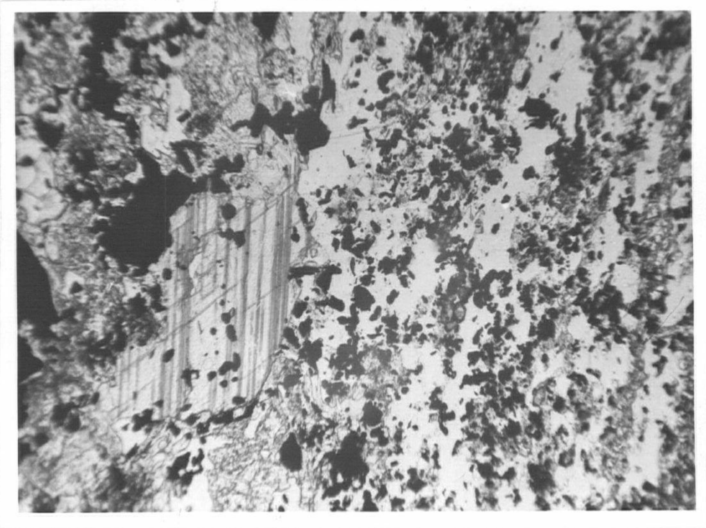

Figure 28. Photomicrograph of graphitic quartz plagioclase schist. Plain light X24. Calcite, pyrite, epidote, graphite, plagioclase and quartz. The calcite, pyrite and epidote are probably secondary

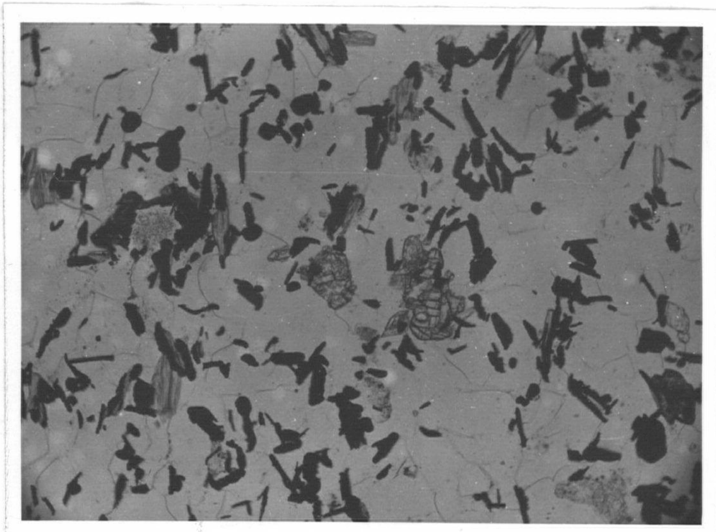

Figure 29. Photomicrograph of graphitic quartz-plagioclase schist. Plain light X64 Diopside, graphite, quartz and plagioclase.

(6) and (7) Quartzites and quartz-tremolite-zoisite rocks (Calcareous quartzites)

These rocks are of limited extent in the septum. They occur interbedded with the plagioclase amphibolites in three known localities, at one of which they are also interbedded with plagioclase-K feldspar-quartz gneisses. The thickest sequence of quartzites, to the north of Sidebacon lake, has a total true thickness of about 500 feet. The longest band, between the two southernmost branches of Exe Valley, has a minimum length of about 5000 feet. The calcareous quartzites are included with the quartzites as they occur with them and probably represent particularly impure bands in the original sediments. Both types are fine-grained white rocks which commonly have a banded appearance. In the calcareous quartzites this banding is marked by alternate whitish and very pale greenish layers. In the quartzites, quartz-rich bands 1/8 to 1/4 inch thick are prominent on the weathered surface, due to the segregation of a mineral or minerals which weather easily in paper thin bands between the quartz-rich bands. It is not known whether this is bedding or a result of metamorphic differentiation, but the writer is inclined to favor the former explanation on the basis of the sharpness of the contacts between the bands and their great extent and regularity. The weathered surface is normally white in the quartzites, but in a specimen of calcareous quartzite a 1/4 inch thick layer of rusty weathering is present due to a high pyrite content.

The composition of the two thin sections of quartzite and one of calcareous quartzite which were made follows:

	Thin Section Number		
	14-4	25-4	11-1
Quartz	91%	96%	62%
Plagioclase	3%	1%	8%
Tremolite	2%	-	15%
Zoisite	< 1%	-	13%
Biotite	2%	3%	1%
Muscovite	--	< 1%	< 1%
Sphene	< 1%	< 1%	< 1%
Apatite	< 1%	< 1%	< 1%

In thin section the quartzite is seen to consist of broad alternate bands of anhedral elongate grains or leaves of quartz of different grain sizes. Most grains have sutured contacts and undulatory extinction. The narrow bands, easily weathered, aremarked by a relative abundance of small generally subhedral grains of biotite, tremolite, plagioclase, zoisite and euhedral grains of sphene. The biotite and tremolite are orientated sub-parallel to the quartz bands. All of these minerals also occur as small grains between, and included in, quartz grains throughout the rock. In the calcareous quartzite similar bands of quarts of varying grain size are present. Subhedral zoisite and subhedral to anhedral tremolite, with minor biotite shreds, euhedral wedge-shaped sphene and small heavily sericitized plagioclase grains are partially segregated in bands or occur as single grains sub parallel to the elongation of the quartz grains to give a well developed foliation.

The quartz commonly is fractured.

The composition of the plagioclase is not known, as no suitable sections are present for determinations, but it is at least An_{30} on the basis of the Michel-Levy method. Its refractive indices are equal to or greater than those of quartz, putting it in the range An_{30} - An_{45}, within the range for andesine. Twinning is all of the albite type.

Tremolite is colorless in thin section and is biaxial with such a large 2V the sign could not be definitely determined. All known tremolite is negative. $Z_{\wedge}c$ equals 19°, which corresponds to a maximum of 2 or 3 molecular per cent of $H_2Ca_2Fe_5Si_8O_{24}$ and 97 to 98 molecular per cent of $H_2Ca_2Mg_5Si_8O_{24}$ Birefringence is moderate.

Zoisite is biaxial positive with a small 2V (about 30°), the optic plane parallel to 010,and first order white to deep blue interference colors. It is colorless. It is apparent this is the non-ferrian variety of zoisite, i.e. Termier's α- zoisite. A few grains have a parting parallel, or nearly so, to 001.

Biotite is pleochroic from golden brown to straw yellow. Muscovite is found as an alteration product of biotite as well as replacing plagioclase as sericite. Sphene is highly pleochroic from deep reddish brown to pale brown. In view of the apparent low iron content of these rocks it seems likely that sphene does not owe its pleochroism to iron.

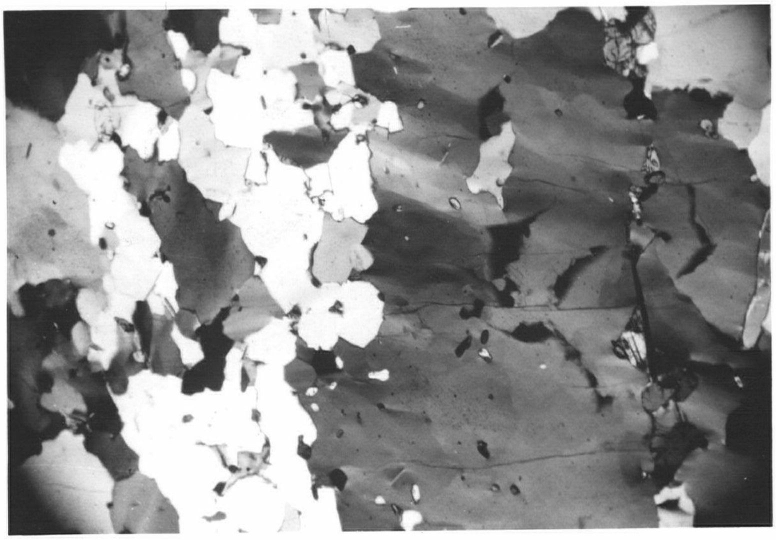

Figure 30. Photomicrograph of quartzite. Polarized light. X24. Strongly developed undulatory extinction in quartz. A few tremolite and zoisite grains are present.

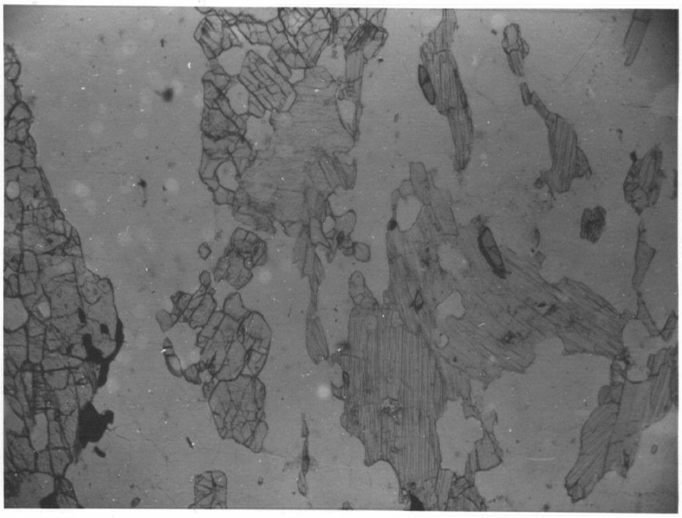

Figure 31. Photomicrograph of quartz-tremolite-zoisite rock. Plain light X24. Zoisite, tremolite (on the right) quartz and minor sphene

(8) Crystalline limestone

Crystalline limestone occurs interbedded with plagioclase amphibolite at the head of Angle Valley and on the east side of Evelyn Creek. Its thickness is unknown in both localities, as in the former it is much folded and crumpled, and in the latter it is exposed in a creek bed that parallels its strike.

In both localities it is a whitish to greyish, coarse to medium-grained, almost massive rock. A weak banding is visible due to dark, narrow parallel bands of impurities. This is probably an original bedding feature. The one thin section made from the Angle Valley occurrence, is mainly calcite. Minor minerals are quartz, feldspar, sphene, muscovite, apatite, tremolite, and opaques, all of which are present in amounts of less than 1 per cent. Calcite forms a mosaic of large anhedral grains through which the other minerals occur in small isolated grains. One of the bands of impurities is present and is found to consist mainly of ragged anhedral grains of opaques (? graphite) scattered throughout the calcite. Muscovite is found in large subhedral grains and tremolite as minute euhedral grains. Quartz and feldspar are found as very small rounded grains which may be of detrital origin. The composition of the feldspar is unknown as it is untwinned, too small to isolate and occurs in contact with calcite only. The tremolite is colorless. $Z_{\wedge}c$ could not be measured but this rock apparently has a very low iron content and this mineral has the same properties, as far as can be ascertained, as the nearly pure tremolite of the calcareous quartzites.

Figure 32. Photomicrograph of crystalline limestone. Plain light X24. A mosaic of large calcite grains containing a few small grains of opaques (?graphite), quartz and feldspar.

(9) Sericite-epidote schists and related rocks

The sericite-epidote schists are generally silvery white to pale green in color, depending on the abundance of epidote. They always have a high pyrite content and weather to a rusty red color. They are confined to shear zones and intensely drag folded areas. Most specimens, in addition to a strong schistosity, have a strong secondary foliation due to drag folding. This persists down to microscopic dimensions.

Only one large shear zone was found on Hawkesbury Island. This shear zone, at least 5000 feet long and up to 300 feet wide, is in Angle Valley about 10,000 feet from its mouth.

The composition of this unit is quite variable as indicated by the following table.

	Thin Section Numbers		
	2-1	6-1B	6-1X
Plagioclase	27%	15%	15%
Epidote	30%	5%	25%
Biotite	10%	1%	15%
Muscovite (Sericite)	10%	50%	15%
Quartz	20%	22%	25%
Pyrite	2%	5%	3%

Muscovite (sericite) occurs as large sub-parallel plates which are generally subhedral. Biotite and chlorite are found as small anhedral cores largely altered to muscovite. The biotite is pleochroic from golden brown to colorless. Biotite also occurs as small subhedral plates which appear to be replacing the muscovite. These are always associated with concentrations of pyrite.

Plagioclase occurs as small anhedral grains. It is usually clouded due to alteration. No sections suitable for determination of An content are present, but the relief, for all grains examined, was higher than that for N_O of quartz but lower or equal to that of quartz in other orientations, suggesting an anorthite content between An_{30} and An_{48} i.e. andesine.

Quartz is found as elongate anhedral leaves between muscovite grains and as mosaics of small granulated grains. The former invariably have undulatory extinction.

Epidote is always the variety pistacite. It is colorless, biaxial negative with a large 2V, and has a birefringence of 0.030 to 0.032 which corresponds to about 18 to 20 molecular per cent of $HCa_2Fe_3Si_3O_{13}$. In most sections the epidote is found as small anhedra, but in one thin section it occurs as large ragged anhedral grains with sieve texture which are elongate parallel to the schistosity and contain inclusions of biotite, muscovite, quartz and apatite.

Pyrite is found as large euhedral cubes and subhedral and anhedral grains. In part it is orientated parallel to the schistosity and in part transects it, so that it must have been formed both during and after active shearing.

Apatite is found as small colorless hexagonal prisms. Sphene occurs as small anhedral or subhedral grains. It is weakly pleochroic from pale brown to colorless.

Figure 33. Photomicrograph of sericite-epidote schist, Plain light X24. Folding outlined by muscovite (sericite) laths. Minor biotite, epidote, pyrite, plagioclase and quartz.

(10) Albitized and potash-enriched Rocks

Strong albitization and potash enrichment is very rare on Hawkesbury although myrmekites and augens indicate some metasomatic exchange in most of the plagioclase-quartz-K feldspar gneisses. The only known example was found interbedded with quartzite on the east side of the southernmost branch of Exe Valley, fairly close to the contact with the Beaver Lake pluton. It forms a band about eight inches thick of unknown length.

The hand specimen is a fine-grained white rock with a decided purplish tint. Examination with the binocular microscope failed to show any reason for this tint. It has a weak, scarcely visible foliation due to a sub-parallel orientation of biotite flakes and a tendency for the biotite to be segregated into narrow bands. The normal purplish rock has a few irregular veinlike patches of white material in it, some of which are at large angles to the foliation.

In thin section the composition of the rock is seen to be plagioclase 50 per cent, quartz 30 per cent K feldspar 15 per cent, biotite 2 per cent and less than 1 per cent of epidote, chlorite, sericite, sphene and apatite. The thin section does not contain any of the vein-like material.

The texture is essentially granoblastic and the foliation appears to be even weaker than it does in the hand specimen. The main minerals form a mosaic lacking any directional texture except for a few of the larger grains which have a weak sub-parallel elongation.

The feldspars present are (1) plagioclase An_{40}, (2) plagioclase An_{04} (3) microcline and (4) untwinned K feldspar. The andesine (An_{40}) occurs as numerous small, generally anhedral grains with well developed albite twinning, in myrmekites and in large grains of replacement type perthites in which it is being replaced by an untwinned feldspar of much lower relief. It was identified by measuring $X' \wedge 010$ for sections $\perp$a and by its high relief. The albite forms part of the white vein-like patches. It was identified by measuring N_x' for cleavage fragments from these patches. As it was not seen in thin section its relationship to the other minerals is not well known. Microcline occurs as a few small anhedral grains scattered throughout the thin section. It is usually fringed by myrmekite. K feldspar, either microcline or orthoclase, is found as small anhedral grains scattered throughout the thin section, probably replaces plagioclase in the perthites noted above, and forms part of the white veinlike patches. It was identified in the latter by etching with hydrofluoric acid and staining with sodium cobaltinitrite. Andesine, microcline, untwinned K feldspar (in small grains) and myrmekites are common features of the normal plagioclase-quartz-K feldspar gneisses so that it is felt these are probably early. The veinlike albite and K feldspar and possibly the K feldspar of the replacement perthites are probably the results of a local addition of soda and potash to this rock, later than the widespread addition of potash and soda which resulted in the myrmekites and augens of most of the plagioclase-K feldspar-quartz gneisses.

Quartz occurs as anhedral grains. Large grains may have undulatory extinction.

Epidote is found as small anhedral to subhedral grains. It is either pistacite or clinozoisite but could not be definitely identified. It commonly has "berlin blue" interference colors.

Biotite is found as small subhedral plates. It is pleochroic from golden brown to straw. It is commonly altered to a chlorite (? pennine) which is very weakly pleochroic from green to colorless and has deep blue anomalous interference colors. Strings of granular, weakly pleochroic sphene between folia of chlorite are also secondary after the biotite, being formed from the excess titanium present after the alteration of biotite to chlorite.

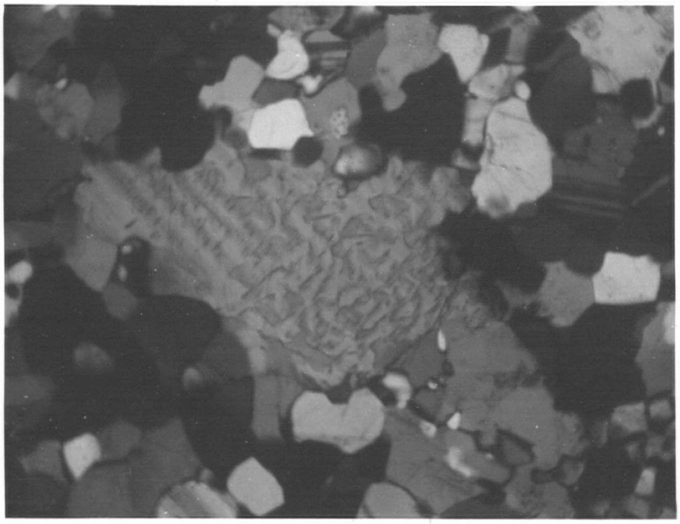

Figure 34. Photomicrograph of albitized rock. Polarized light X64. A large grain of replacement perthite. Andesite is being replaced by a lower relief feldspar. Twinning persists in the andesine in the perthite (recognizable to the left)

A little sericite is present as an alteration product of the feldspars and of biotite and chlorite.

Apatite is found as very small colorless prismatic grains scattered throughout the thin section.

PETROLOGY OF THE META-IGNEOUS ROCKS

(1) The "meta-igneous amphibolites"

The meta-igneous amphibolites are of very limited extent. They occur as small bodies, most of which are probably sills or flows, interbedded with or intrusive into the other rock types of the Ecstall series. They are especially common in the main plagioclase amphibolite band. The largest body, apparently conformable to the adjacent plagioclase amphibolite, is found just north of Sidebacon Lake. It is over 2000 feet wide. The average width of these bodies is probably only 50 to 100 feet.

In outcrop, hand specimen and thin section there is a great deal of variation in texture of these rocks, and also considerable variation in composition. Most of them are porphyroblastic. Foliation and lineation are either very poorly developed, or absent. Such foliation and lineation as is present is due to a subparallel orientation of elongate platey hornblende laths. The hornblende commonly occurs in elongate crystals from 1/8 of an inch long to one inch long and 1/2 inch wide, but in one specimen from a small pluton near the east coast of the island and just to the north of the north east branch of Wye valley, it occurs in short stubby crystals about one quarter inch across. The latter rock completely lacks foliation and lineation. A rarer type of metaigneous amphibolite is essentially granoblastic and fine-grained. It has a strong foliation due to a sub-parallel orientation of broad platey hornblende grains, and a weaker lineation due to a tendency of the hornblende grains to have their long axes similarly orientated in the plane of the foliation. These rocks vary from dark green to black in color, depending on the color of the hornblende, and have a brown or black weathered surface.

The composition of a number of selected specimens follows:

	Specimen Number				
	6-9B	10-4	14-6	16-9	PA-2
Hornblende	65%	55%	96%	55%	70%
Biotite	4%	2%	--	--	--
Plagioclase	30%	41%	--	26%	29%
Quartz	1%	--	--	4%	--
Epidote	<1%	<1%	3%	12%	--

Other minerals present include accessory apatite, sphene, and opaques in all thin sections, rutile in #6-9B, minor sericite, and 2% diopside in #16-9.

Hornblende is commonly euhedral to subhedral. Where porphyroblastic it occasionally has a sieve texture. In one section a few grains have twinning on (100). The pleochroic formula and $Z_{\wedge}c$ show considerable variation. Their range is as follows:

Sample No.	$Z_{\wedge}c$	Pleochroic formula		
		X	Y	Z
PA-2	24°	Pale brown	brown	dark brown
16-9	23°	very pale yellow	pale green	green
10-4	23°			
14-6	21°	pale yellow	blue green	dark green
6-9B	20°			

This relationship corresponds quite closely with the results obtained for the plagioclase amphibolites and other rocks, except for the hornblende in #16-9, which has very pale colors for a $Z_{\wedge}c$ of 23°. This hornblende occurs in stubby euhedral crystals and may be an original igneous hornblende, little affected by metamorphism, which would explain why its properties do not fit into the metamorphic hornblende series.

Biotite occurs in subhedral flakes. It is pleochroic from golden brown to straw. It is commonly found rimming hornblende or in small flakes cutting through the hornblende.

Plagioclase is usually found in small subhedral to anhedral grains. In most specimens it has a composition of approximately An_{36} to An_{40}, but in #6-9B the composition is An_{47}. Zoned feldspars are present but not very common. A single determination in #6-9B indicated normal zoning with a core of An_{51} and a rim of An_{44}. Complex twins are quite common. All seem to be combinations of polysynthetic twins.

Quartz occurs in anhedral grains. Most grains have undulatory extinction.

The epidote present is pistacite. It occurs as small euhedral to subhedral grains and as large masses composed of subhedral to anhedral grains. It may be pleochroic from colorless to pale yellow, or colorless. It has a birefringence of approximately 0.03 to 0.035 indicating a composition of 18 per cent to 24 per cent $HCa_2Fe_3Si_3O_{13}$ and 82 to 76 per cent $HCa_2Al_3Si_3O_{13}$.

Diopside occurs as small subhedral to anhedral grains rimmed by hornblende. It is colorless. The maximum interference color is second order yellow. The diopside is biaxial positive with a moderately large 2V and a $Z_{\wedge}c$ of -42^{o}.

Sericite is found in most sections as a few minute shreds formed by the alteration of feldspar.

The accessory minerals present include apatite, sphene, rutile and opaques. Apatite is found in small rounded grains to euhedral prismatic crystals. Sphene may occur as large subhedral to euhedral grains with sieve texture, enclosing plagioclase, or as strings and clusters of small anhedra, usually with opaque cores. It is a weakly pleochroic type. Rutile, occurs as small highly birefringent pale yellow acicular crystals. Geniculated ("elbow") twins, twinned on 101, are present but rare. Opaques are present as rounded to cubic euhedral grains. The opaque cores rimmed by sphene are probably ilmenite. The opaques in other sections are probably mainly ilmenite and/or magnetite.

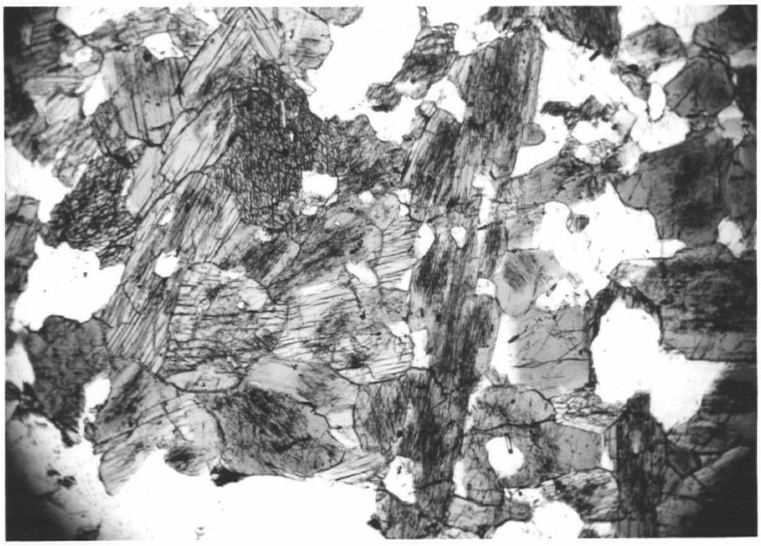

Figure 35. Photomicrograph of a meta-igneous amphibolite. Plain light. X24 Minerals are hornblende and plagioclase.

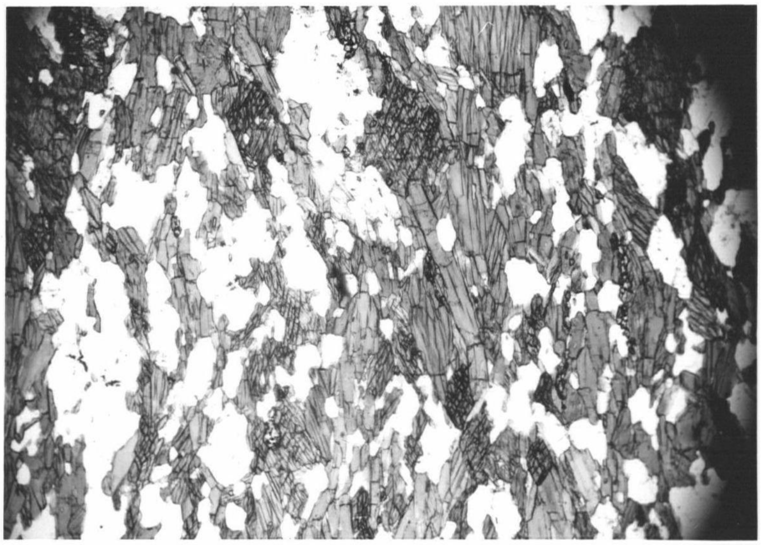

Figure 36. Photomicrograph of meta-igneous amphibolite. Plain light X24. Minerals are hornblende and plagioclase.

(2) Acid Pegmatites

Pegmatites which apparently have been involved in the metamorphism are not common but have been noted in the Evelyn Lake-Fishtrap Bay area. On the shore of Fishtrap Bay a two-foot wide band of pegmatite forms boudins and narrower bands of pegmatite have ptygmatic folding. Other small stringers of pegmatite have been noted folded with the metamorphic rocks in minor folds and crenulations. They consist of large white subhedral K feldspar grains with interstitial anhedral colorless quartz and occasional biotite flakes or shreds. They lack the greenish muscovite found in the later pegmatites.

ORIGIN OF THE METAMORPHIC ROCKS

The composition of the plagioclase amphibolites places most of this group in the basic class of Turner.[9] Part of it falls in the quartzo-feldspathic class near its boundary with the basic class (see figure 37). The "quartzo-feldspathic" members of this group actually contain little quartz, although they do have a rather high feldspar content. They are best considered as representing a high alumina variety of this rock unit. Turner's basic class includes derivatives of basic and semi-basic igneous rocks, tuffs and some tuffaceous

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9 W.S. Fyfe, F.J. Turner, J. Verhoogen, Metamorphic Reactions and Metamorphic Facies, G.S.A. Mem. 73 (Waverly Press, 1958), p. 200.

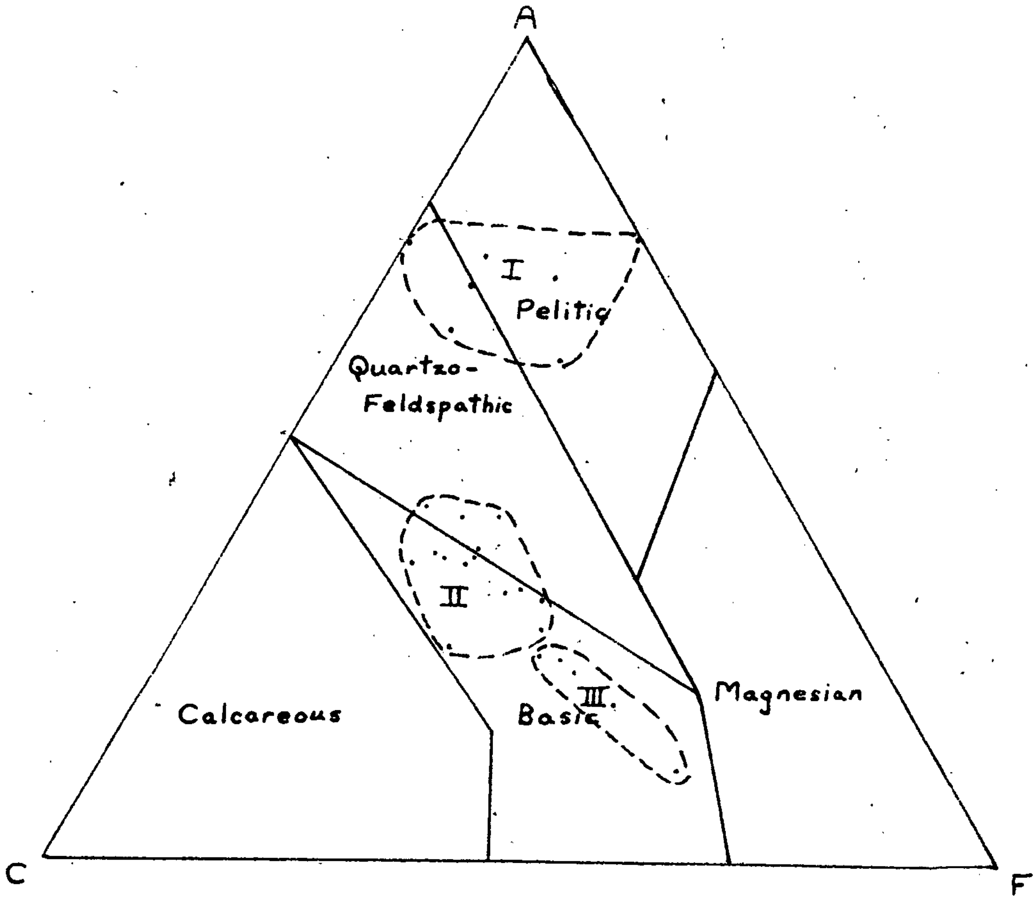

Figure 37. ACF diagram showing the compositional ranges of I. Kyanite-staurolite-almandine Mica Schist; II. Plagioclase Amphibolite; III. Meta-igneous Amphibolite.

sediments. Turner states that in the amphibolites derived from basic igneous rocks,

> ..."hornblende and plagioclase tend to be equally abundant. ... Quartz and biotite are generally minor minerals, though they may be conspicuous in rocks derived from tuffs." 10

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10 H; Williams, F.J.Turner, C.M.Gilbert, Petrography pp. 241-242.

The plagioclase amphibolites of the map area generally have about 55 to 60 per cent plagioclase and 35 per cent or less of hornblende. The percentage of biotite is 12 per cent or less in the commoner plagioclase amphibolites. Quartz averages about 8 per cent.

On Hawkesbury Island the plagioclase amphibolites occur, in at least one locality, interbedded with quartz-K feldspar-plagioclase gneisses in beds a few inches thick over several hundred feet. They show no evidence of intrusive relationships. The thickest band of plagioclase amphibolite has within it a number of small sub-parallel bands of crystalline limestone, calcareous quartzite and quartzite, kyanite-staurolite-almandine mica schist, graphitic quartzo-feldspathic gneiss and quartz-K feldspar-plagioclase gneiss. This indicates the plagioclase amphibolites are sediments.

On the basis of composition they must be tuffs or tuffaceous sediments. Tuffaceous sediments are rocks composed of volcanic material and normal sedimentation products. They may be formed when showers of pyroclastic ejecta fall into basins where normal sedimentation is going on, or by processes of erosion and redeposition.

It is interesting to note that in the Panhandle of Alaska tuffaceous greywacke forms a large part of the Devonian rocks, and greywackes form most of the Paleozoic rocks and are found in every system of Mesozoic rocks. Tuffs are also common. The Ecstall metamorphic series probably extends to

Portland Canal and from Portland Canal into Alaska, and may be the metamorphosed equivalent of part of the Alaskan sedimentary rocks. However, it is impossible to make any definite correlation at present between the Ecstall rocks and any system or systems in Alaska.

The above discussion has not taken into account the possibility of metasomatic effects caused by the Coast Intrusions. It is felt that these effects, if present, have not caused any large changes in composition. There does not seem to be any significant difference in composition between the plagioclase amphibolite, near the Coast Intrusions and a considerable distance from them. Any additions to metamorphic rocks from granitic rocks during metasomatism are usually mainly of potassium, sodium and silica. The plagioclase amphibolite is very low in potassium and sodium. No K feldspars are present and there is no evidence of alteration of the plagioclase to more sodic varieties.

The plagioclase-quartz-biotite-hornblende gneisses are very similar in composition to the plagioclase amphibolites, the only difference being a lower hornblende and biotite content. It seems most likely that they were formed by the contamination of tuffs by normal sedimentary materials or by the contamination of sediments by pyroclastic material. In either case the result would be a tuffaceous sediment i.e. a tuffaceous greywacke or some similar rock. The occurrence of these rocks interbedded with plagioclase amphibolite and plagioclase-K feldspar-quartz gneiss, which probably were tuffs or tuffaceous sediments and arkosic or pelitic sediments respectively, supports this view.

The mean composition of the various types of plagioclase-K feldspar-quartz gneiss is as follows: (1) "Normal" type; plagioclase 48 per cent, K-feldspar 5 per cent, quartz 28 per cent and biotite 8 per cent (2) Sidebacon Lake type: plagioclase 38 per cent, K feldspar 39 per cent, quartz 19 per cent and biotite 1 per cent (3) Augen Mountain type: plagioclase 40 per cent, K feldspar 18 per cent, quartz 23 per cent biotite 9 per cent, epidote 8 per cent and hornblende 2 per cent.

All of these rocks belong to the quartzo-feldspathic group and, if metasomatism has not been important, are derivatives of sandstones and/or of acid igneous rocks. Interbedding with other rock types and a lack of intrusive relationships suggests these rocks are probably metamorphosed sediments.

The "Normal" and Sidebacon Lake types have abundant myrmekites and the Augen Mountain type abundant K feldspar and plagioclase augens. These features are commonly interpreted as being caused by metasomation, in the former case involving introduction of soda and in the latter of potash and soda.

It seems probable therefore that metasomatism has, to some extent, changed the composition of these rocks. However they have at present such an extremely high silica and alumina content, and very low iron and magnesia content that it seems unlikely their present composition is due solely to metasomatism. The original sedimentary rock was therefore probably a high silica, high alumina type, i.e. semi-pelitic (quartz-feldspar-clay mineral) rock or an arkosic (quartz-feldspar) rock.

The kyanite-staurolite-almandine mica schists all fall into Turner's pelitic class or the quartzo-feldspathic class near its boundary with the pelitic class (See figure 37). The latter rocks may best be considered to be semi-pelitic. The pelitic class rocks are derivations of aluminous sediments i.e. of siltstones, shales, etc. The semi-pelitic rocks of this area probably represent metamorphosed sandy shales or siltstones rather low in calcium content. The erratic changes of composition of these rocks, both along and across strike, indicates poor sorting of the original materials forming the rock and, possibly, rapid deposition.

The sillimanite bearing rocks are equivalent to the kyanite-staurolite-almandine mica schists chemically. They also are metamorphosed pelitic rocks.

The quartzites are obviously metamorphosed quartz sandstones. The two thin sections examined of these rocks both contain over 90 per cent quartz and are the metamorphosed equivalent of Gilbert's[11] quartz arenite. The interbedded and

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11 H.Williams, F.J.Turner, C.M.Gilbert, <u>Petrography</u> (W.H.Freeman and Co. 1955), p. 291.

much rarer quartz-tremolite-zoisite rocks represent calcareous sandstones.

The crystalline limestones of the area, on the basis of their accessory minerals such as tremolite, muscovite, ?graphite, quartz and feldspar, and of textural features, must be sedimentary rather than hydrothermal. These accessory minerals represent siliceous and argillaceous impurities. The limestone, one occurrence of which is on a granodiorite contact, is composed of calcite rather than of dolomite, indicating a complete lack here of magnesium metasomatism, due to the Coast Intrusions. This limestone was probably deposited in a marine environment as it contains 97 per cent calcite. Fresh-water deposition of limestone does take place, but fresh water limestone is usually marly or contains other impurities.

The graphitic quartz-plagioclase schists have a general compositional range of quartz 42 to 62 per cent, plagioclase 16 to 30 per cent, graphite 7 to 15 per cent with minor tremolite, biotite, zoisite, pyrite, sericite, calcite, epidote, etc. One exceptional lens-like bed contains 80 per cent or more of graphite. This composition indicates a calcareous and aluminous quartoze rock. As the graphite is probably of organic origin it would seem these schists are metamorphosed sediments. It is possible the graphite-rich bed represents metamorphosed coal, which would indicate swampy or shallow water conditions of formation, but this is very problematical, particularly in view of the fact that none of the association rocks have compositions resembling that of the underclays usually found with coal beds.

The meta-igneous amphibolites are so classified on the basis of texture, composition, and field relationships. Most of these rocks are coarse-grained and lack or have weakly developed directional textures. They appear to be metamorphosed coarse-grained rocks of originally gabbroic composition and commonly form small stock-like masses. The fine-grained more schistose meta-igneous amphibolites seem to be conformable. They include probably ultrabasic and basic rocks which may be sills or pyroclastics or flows.

The origin of the pegmatites which have been involved in the metamorphism is unknown. If as the writer believes the Coast Intrusions of the area are later than the main period of metamorphism, then the possibilities are (1) that these are actually venites "sweated out" of the country rock during metamorphism (2) that these are true injection pegmatites associated with an older intrusion or (3) that these rocks actually belong to the Coast Intrusion series and have been involved in some later period of minor deformation. There does not seem to be any evidence of older acid intrusions in the area so that the second possibility can probably be discounted. Later minor deformation, such as is postulated in the third explanation, would probably cause some cataclastic effects in the metamorphic rocks, unless it took place at a very high temperature. A thin section cut from a plagioclase amphibolite sample taken right beside one of the boudins in the Fishtrap Bay occurrence shows no evidence of this. Although this is not conclusive, it leads the writer to think that these rocks are venites. The ptygmatic folding, not noted elsewhere on the island, associated with the Fishtrap Bay occurrence suggest plastic flow and possibly partial fusion of the amphibolites there. It is interesting to note that these occurrences of possible venites are all at altitudes of less than 300 feet above sea level, and that most of the well exposed outcrops, i.e. the ridge tops, are 1000 feet above sea level or more. No possible "venites" were noted on these ridge tops, suggesting that, if these rocks are venites, the metamorphic rocks currently exposed on Hawkesbury Island are those formed in the 700 to 4000 feet immediately above the zone of partial fusion. This is probably best considered as wild surmise.

If the analysis of the evidence provided by field relationships and composition is correct, the Ecstall series is composed mainly of metamorphosed sediments and possibly tuffs, with, perhaps, minor interbedded volcanics, intruded by a few small igneous bodies.

At present the Ecstall series rocks have a thickness of some 4300 feet between the contact with the North Mountain pluton and the bend in Angle Valley. Although there is no obvious duplication of folding the map area probably has been involved in at least two periods of deformation so that the thickness indicated may be greatly in error. A minimum thickness of somewhere between 10,000 feet and 20,000 feet seems reasonable.

Most of the sequence is composed of tuffs or tuffaceous sediments and arkosic or semi-pelitic rocks. The thickness of the series and the presence of limestones suggests marine deposition. The presence of abundant arkosic rocks (if these rocks are truly arkosic), the great variations of composition in the argillic rocks, the lens-shaped and local character of the quartzites, argillic rocks, etc., suggest lack of sorting and rapid deposition, presumably in shallow water. The thickness of the sedimentary sequence and probable shallow water conditions of deposition would seem to indicate deposition in a geosynclinal basin. This is supported by the presence of large amounts of material of volcanic origin associated with the sedimentation, which is not found in normal marine deposits. The volcanic material indicates a eugeosyncline, i.e. an actively subsiding geosyncline with associated volcanics. Padgham[12] came to the conclusion that the sedimentary rocks of the Ecstall series in the Ecstall-Quaal Rivers area to the north of Hawkesbury Island represent a shallow water marine shelf facies, laid down in part in a stable shelf environment but mainly in an unstable shelf environment. The concept of a stable shelf environment is based mainly on the presence of a thick sequence of quartzites and minor interbedded limey and ? tuffaceous material (the Mine Series and Agnes Lake Quartzites). These have a maximum

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12 W. Padgham, Geology of the Ecstall-Quaal Rivers Area, British Columbia, (unpublished M.A.Sc. Thesis, University of British Columbia,1958) pp.189-192

thickness of over 20,000 feet, assuming no repetition. These quartzites, on the western edge of the septum, thin out towards Douglas Channel and do not appear on Hawkesbury Island. The rest of the sequence in the Ecstall-Quaal Rivers area are very similar to the Hawkesbury Island rocks, although the plagioclase amphibolites, i.e. probably metamorphosed tuffs or tuffaceous greywackes, are much less abundant in the Ecstall-Quaal area. The writer feels the most likely explanation is that this region was originally stable and became an unstable rapidly subsiding basin. The quartzite series would represent deposits of the first stage and the series of tuffs or tuffaceous sediments and arkoses or semi-pelitic rocks deposits of the second stage. Whether there is an unconformity between the quartzite series and the later rocks is unknown. It is considered most unlikely that the quartzites are younger than the geosynclinal type sediments, as there is little or no evidence of geosynclines ceasing rapid subsidence and becoming stable areas, particularly immediately prior to orogeny.

Hawkesbury Island is in the area believed to have been occupied by the Pacific or western trough of the Cordilleran geosyncline during Paleozoic and possibly early Mesozoic time. According to Eardley

> "The sediments of the western trough from California to Alaska are characterized by a large amount of volcanic material and greywacke in every system. Phyllites, slates, argillites

> schists, gneisses, recrystallized chert, marble, metaconglomerate, meta-andesite and various metamorphosed pyroclastics make up the thick sequence."[13]

He suggests that the volcanic materials came from a volcanic archipelago to the west which was very similar to the island arc of the present Japanese archipelago.

This view strongly supports the idea of the Hawkesbury Island rocks being a eugeosynclinal sequence. They were probably deposited in the Alexander division of the Pacific trough, which is believed by Eardley[14] to have extended from southern Alaska into the region in which these rocks are now found. Their age may be Paleozoic or early Mesozoic. Dolmage[15] believes these rocks may be Upper Triassic in age on the basis of strong lithological similarities to rocks of known Upper Triassic age which are widely distributed along the coast to the south (Vancouver formation). White,[16] however, in a much more recent work, indicates that the map area was a site of deposition during the Ordovician to Devonian but not during later periods, as far as is known. He indicates that these rocks are probably the southern metamorphosed extension of the rocks of the Panhandle of Alaska, where the Ordovician

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13 A.J. Eardley, "Paleozoic Cordilleran Geosyncline and related orogeny", Jour. Geol., vol. 55 (1947), p. 309.

14 *Ibid*., p. 309-310

15 V. Dolmage, "Coast and Islands of British Columbia between Burke and Douglas Channels," *G.S.C. Summary Reports* (1921), p. 25A

16 W.H.White, "Cordilleran Tectonics in British Columbia", *AAPG Bull*., Jan, 1959, p. 63.

to Lower Devonian have a combined stratigraphic thickness of about 21,000 feet, mainly greywacke but with much interbedded cherty black slate, limestone, conglomerate, andesitic lava and pyroclastics.

THE GRADE OF METAMORPHISM

(1) Metamorphic Facies

In discussing grade of metamorphism the writer will use the concept of metamorphic facies as defined by Eskola and quoted by Turner, i.e.

> "In a definite facies are united rocks which for identical bulk composition exhibit an identical mineral composition, but whose mineral composition for varying bulk composition varies according to definite laws."[17]

The classification of facies used is that given by Fyfe, Turner and Verhoogen in Metamorphic Reactions and Metamorphic Facies (Geol. Soc. of America Mem. 73). This classification differs considerably from the older classification given in Igneous and Metamorphic Petrology by Turner and Verhoogen. In most cases some reference to the latter classification will also be made.

Among the plagioclase amphibolites the following assemblages may be regarded as stable: (1) Hornblende-plagioclase-epidote-almandine-(quartz-biotite) (2) Hornblende-plagioclase-epidote-(quartz-biotite) (3) Hornblende-plagio-

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17 W.S. Fyfe, F.J. Turner, I. Verhoogen, Metamorphic Reactions and Metamorphic Facies, G.S.A. Mem. 73, p. 9.

clase-diopside-quartz. All these assemblages belong to the almandine amphibolite facies (formerly part of the amphibolite facies). The first two are stable in the staurolite-quartz and kyanite-muscovite-quartz sub-facies (which were formerly combined into the staurolite-kyanite sub-facies), and the latter assemblage is stable in the sillimanite-almandine sub-facies. If small amounts of sericite and chlorite are disregarded, two thin sections of plagioclase amphibolite belong to the first assemblage, sixteen belong to the second assemblage, one belongs to the third assemblage and five do not belong to any of these assemblages. Sericite and chlorite, which are generally very scarce, are the results of slight retrogressive metamorphism as from their occurrence it is obvious they are late minerals.

The sole thin section indicating the sillimanite-almandine sub-facies is from the head of Angle Valley near the contact of the Sidebacon Lake stock. All the rest of the area underlain by these rocks has apparently reached the staurolite-quartz and/or or kyanite-muscovite-quartz subfacies, with the exception of the part that the five non-stable assemblages are from. Of these five, two are plagioclase-biotite gneisses which lack hornblende, two have assemblages containing hornblende, biotite and diopside and one is a plagioclase-hornblende staurolite amphibolite.

The two plagioclase-biotite gneisses probably indicate a lower grade of metamorphism. The presence of biotite and andesine and lack of hornblende indicates non-equilibrium conditions. It is not known whether these rocks reached their present state by retrogressive metamorphism, or if this is the highest degree of metamorphism they ever attained. Other thin sections indicate that most of the rock in the areas these specimens are from belong to the staurolite-quartz and/or kyanite-muscovite-quartz subfacies of the almandine amphibolite facies.

The hornblende-diopside-biotite bearing rocks probably represent a transition from the kyanite-muscovite-quartz subfacies to the sillimanite-almandine subfacies or vice-versa. One specimen is from upper Angle Valley near a large granitic dyke swarm and the other comes from the edge of the Danva pluton.

The specimen of plagioclase-hornblende-staurolite amphibolite, from South Beaver Valley, is a representative of a very interesting rock type. Although unstable on the basis of mineral assemblage it probably indicates approximately the same grade of metamorphism as the other amphibolites. Turner and Verhoogen[18] note that associations of kyanite or staurolite and amphiboles, although comparatively rare, have been recorded from widely separated localities. They suggest this paragenesis may be connected with the limited capacity for Mg to replace Fe in almandine garnets, which, in an MgO rich rock,

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18 F.J.Turner, J. Verhoogen, Igneous and Metamorphic Petrology, (McGraw-Hill Book Co. Inc., 1951), p. 455.

would result in too much Mg being present to be accomodated in the hornblende after crystallization of the almandine, if all the Al is to be accomodated. Crystallization of kyanite would result in the removal of much of the Al making it possible for the hornblende to accomodate all the excess Mg. However, it is difficult to see how this explanation could apply to the formation of staurolite in one of these rocks, as it does not seem likely an iron rich mineral such as staurolite would form in a Mg rich (and Fe poor) environment.

The plagioclase-quartz-biotite-hornblende gneisses all have the assemblage hornblende-plagioclase-epidote-(quartz-biotite) and indicate the almandine amphibolite facies, staurolite-quartz and/or kyanite-muscovite-quartz subfacies. Small amounts of sericite are a result of retrogressive metamorphism.

The plagioclase-K feldspar-quartz gneisses commonly have the assemblage quartz-microcline-plagioclase-biotite-muscovite-epidote, which is stable in the staurolite-quartz and kyanite-muscovite-quartz subfacies of the almandine amphibolite facies. The corresponding rocks of the sillimanite-almandine subfacies would probably contain small amounts of sillimanite and almandine. No other stable assemblages are represented by these rocks. Small amounts of sericite and chlorite, present in some sections, are the results of slight retrogressive metamorphism.

The kyanite-staurolite-almandine mica schists always contain quartz, staurolite and muscovite and usually contain plagioclase, kyanite and almandine. When almandine is present it is always accompanied by small amounts of chlorite. This chlorite is considered to be a result of retrogressive metamorphism. Disregarding the chlorite, however, only two specimens, with assemblages quartz-staurolite-almandine-muscovite-biotite and plagioclase-quartz-staurolite-kyanite-muscovite respectively, have equilibrium assemblages. Both of these are stable in the staurolite-quartz subfacies. All the other thin sections and/or hand specimens contain kyanite, staurolite and almandine. According to Turner and Verhoogen

> "Staurolite appears to be stable over a narrowly limited range of temperature. At the boundary between the zones of staurolite and kyanite, almandine-kyanite becomes a stable association at the expense of staurolite."[19]

$$3\ FeAl_4Si_2O_{10}(OH)_2 + SiO_2 \rightleftharpoons Fe_3Al_2(SiO_4)_3 + 5Al_2SiO_5 + 3H_2O$$

Staurolite Quartz Almandine Kyanite Water

Kyanite-almandine is stable at a higher temperature than staurolite. Any assemblage containing all three of these minerals is presumably unstable, although generally indicative of a transition from the staurolite-quartz subfacies to the kyanite-muscovite-quartz subfacies. It is interesting to note that one specimen also contains a few needles of a mineral tentatively identified as sillimanite. If this mineral is actually sillimanite, it suggests the reaction staurolite + quartz $\rightleftharpoons$ almandine + kyanite + water is so slow that it may

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19 F.J.Turner, J. Verhoogen, <u>Igneous and Metamorphic Petrology</u>, (McGraw-Hill Book Co.Inc.,) 1951, p. 454.

be incomplete when sillimanite begins to form. There are two other possibilities concerning the staurolite-kyanite-almandine assemblages. One of these is that these three minerals actually do form a stable assemblage. This, however, is apparently not supported by any evidence from other districts. The other possibility is that the composition of these rocks is so variable they may be regarded as being composed of two separate systems, one of which has a composition which results in the formation of kyanite and staurolite and the other a composition which results in the formation of staurolite and almandine. If this were the case these rocks would actually be stable in the staurolite-quartz subfacies. The composition of the kyanite-staurolite-almandine mica schists is extremely variable, as may be seen by referring to figure 15. However, in at least one place (see figures 22 and 23) these three minerals are seen almost in contact with one another, which is hardly suggestive of two separate compositional systems.

The quartzites and calcareous quartzites have the assemblage quartz-plagioclase-tremolite-biotite-zoisite-sericite. This is not an equilibrium assemblage but does closely approach the assemblage quartz-plagioclase-tremolite-epidote (zoisite), particularly since both biotite and sericite are very scarce constituents. The latter assemblage is stable in the staurolite-quartz and kyanite-muscovite-quartz subfacies of the almandine amphibolite facies.

The assemblage of the graphitic quartzo-feldspathic schists is commonly quartz-plagioclase-graphite-sericite-pyrite. Tremolite, biotite, epidote, calcite and diopside may be present. None of the thin sections have a stable assemblage, although their assemblages are close to those stable in the almandine amphibolite facies.

The sillimanite-quartz-plagioclase gneiss has the assemblage plagioclase-quartz-biotite-sillimanite-muscovite. The stable assemblage in the sillimanite almandine sub-facies is quartz-microcline-sillimanite-almandine-(plagioclase-biotite) The presence of abundant muscovite in place of microcline indicates that either this rock was not sufficiently heated to reach this grade of metamorphism, or that later retrogressive metamorphism has taken place. The muscovite and biotite are apparently being replaced by the sillimanite, suggesting the former is the case.

The assemblage of the crystalline limestone, calcite-quartz-feldspar-muscovite-tremolite is a non-equilibrium one which is, however, also suggestive of the almandine amphibolite facies.

The sericitic schists and related rocks, with quartz-plagioclase (andesine)-epidote-biotite-muscovite (sericite-chlorite and similar assemblages, are plainly unstable, as the presence of andesine indicates the almandine amphibolite facies or a higher grade of metamorphism, and the abundant sericite and biotite the greenschist facies. Their occurrence in shear zones and intensely drag folded areas suggest these rocks were formed by retrogressive metamorphism, probably largely dynamic in nature. The presence of relatively abundant pyrite suggests the presence of sulphur and possibly iron bearing solutions, although there was probably sufficient iron in the original rock to account for its forming pyrite.

The meta-igneous amphibolites all have assemblages similar to those of the majority of the "plagioclase amphibolites" and also indicate the staurolite-quartz or kyanite-muscovite-quartz sub-facies.

To summarize, the rocks of the Ecstall series underlying Hawkesbury Island have, on the whole, reached the almandine amphibolite facies, staurolite-quartz and/or kyanite-muscovite-quartz sub-facies. Locally rocks of slightly higher or lower grade exist, but only one specimen belongs to the sillimanite-almandine sub-facies. Widespread minor retrogressive metamorphism has taken place, which may be intense locally in shear zones and strongly drag folded areas.

(2) Temperature-Pressure Conditions

Bowen[20] has given a series of curves for the stability relationships of the various minerals which form during the metamorphism of silicous limestone and dolomite. The assemblage calcite, tremolite and quartz, found in thin section #13-4, is stable between 100^{o} C and 200^{o} C at 1 atmosphere,

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20 N.L.Bowen, "Progressive Metamorphism of Siliceous Limestone and Dolomite," <u>Jour. Geol</u>. 48 (1940), p. 256.

between 475° C and 525° C at 500 atmospheres and between 540° C and 560° C at 1800 atmospheres, estimated from these curves. Increase in pressure above 1800 atmospheres has little effect on the temperature boundaries of the stability field.

F.G. Smith[21] determined the decrepitation temperatures of 23 specimens of almandine garnets and found that their temperature of crystallization averaged 607° C and had a total range of 463° C to 707° C. A pressure correction must be made but Smith feels this is small.

Barth[22] gives a figure showing the temperature of formation of equilibrium assemblages containing epidote and plagioclase of various anorthite contents. On the basis of his figures the temperature of formation of the rocks is equilibrium on Hawkesbury Island ranges from 395° C to 420° C. However, this figure is based on the assumption that epidote group minerals are unstable above 450° C. Clinozoisite has been observed forming at 600° C and 12,000 atmospheres and epidote has recently been synthesized at 900° C[23] so that it is obvious his figures must be considerably revised.

Turner, Verhoogen and Fyfe place the upper limit of the greenschist facies at about 400° C[24] and suggest that if

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21 F.G.Smith, "Decrepitation Characteristics of Garnet" American Mineralogist, Vol. 37 (1952), pp. 470-491.

22 T.F.W.Barth, Theoretical Petrology, (John Wiley and Sons, Inc., 1952), p. 285.

23 W.S.Fyfe, F.J.Turner, J. Verhoogen, Metamorphic reactions and Metamorphic Facies, G.S.A. Mem. 73, 1958, pp 165-166

24 Ibid., p. 173

this is due to depth of burial alone load pressures of 3000 to 4000 bars should prevail. The almandine amphibolite facies presumably forms at higher temperatures. Due to a lack of knowledge of the stability fields of hornblende, kyanite and sillimanite it is impossible to give any definite figures based on these minerals. It is stated by Turner, Verhoogen and Fyfe that for the amphibolite facies

> "it would seem that the pressure-temperature field is extensive. The composition of garnets, the occurrence of sillimanite and andalusite, and the marked prevalence of hydrous minerals .... constitute strong evidence point to pressures and temperatures lower than those of the granulite facies. Water pressures are high enough to allow hydrated silicates to crystallize. At constant pressure of water, increasing temperature alone will lead to a transition from amphibolite to hornblende-biotite granulite and eventually to pyroxene granulite. At constant temperature, in the high pressure range, a fall in the water pressure might induce transition of amphibolite to granulite, and in lower pressure regions to pyroxene hornsfels."[25]

In connection with the various sub-facies they state

> "From the meager physical data available it is tentatively conjectured that the sillimanite-almandine sub-facies corresponds to maximal temperatures in the amphibolite facies. From its field relationships to the staurolite-kyanite sub-facies, it might reasonably be inferred that load pressures of the two are approximately the same."[26]

To sum up, the possible temperature range for the almandine amphibolites is probably 400° C to 700+°C and pressure conditions are unknown. The assemblage in thin

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25 Turner, Verhoogen and Fyfe, op. cit., p. 170

26 Ibid., p. 166

section #13-4 (limestone) suggests this rock was metamorphosed at under 600° C.

The above discussion largely ignores Yoder's work, in which he claimed to have produced assemblages supposedly belonging to a number of facies at 600° C and 15000 psi water pressure (about 1000 bars). Turner, Verhoogen and Fyfe[27] find most of Yoder's statements unacceptable, and give detailed reasons for this, but they state he has successfully shown that the boundary between the amphibolite facies and pyroxene hornfels facies at 600° C is determined by the water pressure, a fact of great significance to metamorphic petrology.

THE CAUSES OF METAMORPHISM

The preceeding discussion has shown that the rocks of Hawkesbury Island were metamorphosed under conditions of raised temperature and probably of strong compressive forces. It also seems probable that these rocks, which seem to be eugeosynclinal sequence, have been carried to a great depth at some time during the orogeny or orogenies which resulted in the disappearance of the Pacific geosyncline and the formation of the Coast Intrusions. It would seem there are two possible causes of metamorphism. One of these is the above-mentioned deep burial, which was presumably accompanied by raised tempera-

27 Ibid., p 19-20

tures and pressures. The other possibility is essentially thermal metamorphism due to the Coast Intrusions, accompanied by strong compression due to some other cause –. The possibility that the Coast Intrusions were produced by granitization _in situ_ of the metamorphic rocks at depth is disregarded because the former rocks have an obviously intrusive character. This is discussed more fully in chapter IV which deals with the igneous rocks.

If the metamorphism is due to the Coast Intrusions these must have been intruded during a period of strong compression. The writer does not feel this has occurred as (1) the Coast Intrusions of the map area lack any strong foliation or granulation which is attributable to compression during emplacement (2) there does not seem to be any marked tendency for elongation of the plutons parallel to the foliation of the metamorphic rocks i.e. perpendicular to the direction of maximum compression during their period of formation (3) dykes of the Coast Intrusions series appear to have essentially random orientation (4) there is little evidence of a difference in metamorphic grade near the Coast Intrusions, and such evidence as is present is compatable with thermal metamorphism of previously dynamothermally metamorphosed rocks.

Such granulation and fracturing of quartz and feldspar as is present in these rocks is much more intense near the contacts of the intrusions and becomes very weak away from the contacts. It is most likely this feature was developed during intrusion of a partially solidified magma i.e. is not attributable to compression during emplacement.

The only evidence of a difference in metamorphic grade near the Coast Intrusions are (1) the occurrence of diopside-bearing amphibolites within 200 to 300 feet of the Denva and Sidebacon Lake plutons and (2) the occurrence of a sillimanite-bearing rock some 13,000 feet from the Sidebacon Lake pluton. Other samples of amphibolite from almost as close to the plutons, i.e. about 500 feet, are normal hornblende-biotite amphibolites, so that the higher grade amphibolites, even if they form a zone around the pluton, are minor in extent. Unfortunately the age relationship between the hornblende and diopside in the diopside-bearing amphibolites is not clear, so that it is not known whether this localized higher grade of metamorphism was produced during the major period of metamorphism or is later superimposed thermal metamorphism. The kyanite-staurolite-almandine mica schists, the lower grade equivalents of the sillimanite-bearing rocks, outcrop within about 4,000 feet of the Beaver Valley pluton and within some 15,000 feet of the Sidebacon Lake pluton, so that the one known outcrop of sillimanite bearing rocks can hardly be regarded as proof of higher grade metamorphism near plutons.

To summarize, there does not seem to be any strong positive evidence that the Coast Intrusions, accompanied by compression due to some other cause, were responsible for the metamorphism of the Ecstall series rocks. The writer feels it is unlikely that they were responsible for most of the metamorphism, although the diopside-bearing amphibolites (and sillimanite-bearing rocks?) may be the results of later superimposed thermal metamorphism.

It would seem that the metamorphism of the rocks of the Ecstall series is probably due to deep burial of these rocks in a high pressure high temperature environment during orogeny. This must have occurred prior to the intrusion of the Coast Intrusions, as if these were older they should show much evidence of compression.

The Coast Intrusions may be related to a later phase of this orogeny or possibly to a separate orogeny.

CHAPTER IV

THE IGNEOUS ROCKS

PETROLOGY OF THE COAST INTRUSIONS

The rocks of the Coast Intrusions on Hawkesbury Island have considerable variation in composition. Diorite, quartz diorite, granodiorite, monzonite and quartz monzonite (adamellite) are all present in the major intrusive bodies. The dykes and sills examined are mainly quartz monzonite or granodiorite. In addition quartz-K feldspar pegmatites are common. The dykes and pegmatites intrude the plutons and are in part at least, definitely younger than them.

The North Mountain intrusion presumably part of the margin of one of the major batholithic masses of the Coast Intrusions is particularly interesting. It consists of a 4000-foot wide band of diorite and quartz diorite to the south which grade into quartz monzonite to the north.

The diorite-quartz diorite rocks are coarse to medium-grained dark grey rocks with a pronounced foliation and/or lineation in outcrop. This foliation or lineation is due to a sub-parallel alignment of individual hornblende crystals, biotite flakes, clots of mafics and inclusions of mafic-rich rock. The latter resemble plagioclase amphibolite. This is a contaminated border facies of the batholith.

The foliation is parallel to both the margin of the batholith and the strike of Ecstall series rocks immediately to the south, so that it is not known whether it is a result of flow banding formed during injection of a partially crystallized magma or of granitization and partial assimilation of the rocks of the Ecstall series. Similar clots and inclusions of plagioclase amphibolite in the Danva pluton are sub-parallel to the strike of the plagioclase amphibolite near the pluton and, in some places, nearly perpendicular to the margin of the pluton. These must have formed by partial assimilation of the plagioclase amphibolite of this area. However, the granulation of these rocks sub-parallel to their contacts and a weak lineation in the quartz monzonite seem to be results of flow.

The composition of the diorite-quartz diorite group is approximately 50 per cent to 70 per cent plagioclase, 8 to 15 per cent quartz, 8 to 20 per cent hornblende, 5 to 17 per cent biotite with minor apatite, sphene, zircon, opaques, chlorite, epidote, allanite and sericite. No K feldspar was noted in thin section or by using staining tests. It may be present in very small percentages however. The mafic percentage may be much higher locally than that recorded above.

In thin section plagioclase is seen commonly to be anhedral or subhedral, although occasionally euhedral, and to vary greatly in grain size. Quartz is found as small anhedral grains interstitial to the plagioclase. Hornblende occurs in large generally subhedral crystals some of which have sieve texture. Biotite is found as small subhedral platey grains. There is usually extensive granulation of the quartz and feldspar.

Plagioclase has a composition of An_{36} to An_{38} (medium andesine). This was determined by measuring $X' \wedge 010$ for sections $\perp$a and, in one case, by measurements on a Carlsbad-albite twin. Complex twinning is common although Carlsbad-albite combinations are rare. Zoned feldspars are very rare, which is unusual in rocks of this nature. The zoning is of the reverse type in one grain the core being about An_{34} and the rim An_{40}.

Hornblende is biaxial negative. $Z \wedge c$ equals 22^{o} - 23^{o} and the pleochroic formula is X - pale yellow, Y - green, and Z - deep green to brownish green. Simple twins on 100 are very common.

Biotite is pleochroic from dark brown to straw. It is occasionally altered to a chlorite with anomalous deep blue interference colors, possibly pennine.

The commonest variety of epidote present is pistacite. It is strongly pleochroic from yellow to colorless, highly birefringent, and biaxial negative with a large 2V. The pistacite occasionally enclosed cores of allanite with the same crystallographic orientation but different extinction position. The allanite is pleochroic from deep brown to colorless. These minerals occur as small subhedral or anhedral grains.

Sericite, never in amounts of greater than 1 per cent, is present as small flakes and felty masses in most plagioclase grains.

Accessory minerals present include apatite, sphene, zircon and opaques. Apatite is found as very small subhedral or euhedral prisms of low birefringence and length fast character. Sphene and zircon occur as somewhat larger grains, the former as anhedral granules and subhedral to euhedral wedge shaped crystals which are weakly pleochroic from pale brown to colorless, and the latter as subhedral squarish crystals of uniaxial positive character. Opaques are found as anhedral grains and subhedral crystals of cubic shape, and are probably mainly magnetite or pyrite. They are very uncommon in these rocks.

The quartz monzonite of the North Mountain intrusion is medium to coarse-grained and is pink in color. It commonly has a very weak foliation.

Its composition averages 39 per cent plagioclase, 27 per cent K feldspar, 27 per cent quartz, 1 to 2 per cent hornblende, 2 per cent biotite, 1 to 2 per cent chlorite and less than 1 per cent of epidote, allanite, sericite, apatite zircon, sphene and opaques.

In thin section plagioclase is commonly euhedral or subhedral but may occur in myrmekites as anhedral grains containing vermicular quartz. It is commonly in larger grains than the other minerals. Quartz is anhedral and interstitial.

K feldspar is found in large subhedral or anhedral grains with fringes of myrmekite. Biotite and hornblende are found as small subhedral grains. An extremely weak lineation is present due to a weak sub-parallel orientation of biotite and hornblende. Quartz commonly has undulatory extinction and the feldspars may be fractured, but the extensive granulation common in the quartz diorite-diorite is lacking. Despite the weak foliation and some deformation the texture is essentially hypidiomorphic granular.

Plagioclase has a composition of An_{30} to An_{32}. Complex twins are common, including a few of the Carlsbad-albite type. Zoning is apparently absent.

The K feldspar present usually has weakly developed grid twinning and so is microcline in part at least. No Carlsbad twins were noted.

Hornblende and biotite are the same types as those found in the diorite-quartz diorite. They are both rimmed and replaced by a chlorite with dark purplish anomalous interference colors.

Apatite, sphene, zircon and the opaques present are also the same types as those found in the diorite-quartz diorite rocks. The sphene, however, is usually euhedral and may be in extremely large grains. It commonly encloses opaque cores which may be ilmenite.

The epidote group minerals are particularly interesting in these rocks. They consist of pistacite and allanite.

The allanite may form the centre of the grain and have a margin of pistacite, or occur as irregular patches in the pistacite or as separate grains. Pistacite is biaxial negative, strongly birefringent, and may be intensely pleochroic from bright yellow to colorless, or weakly pleochroic. Allanite is always strongly pleochroic from dark brown to light brown. Epidote may occur in anhedral, subhedral, or euhedral grains.

Sericite is much more common in these rocks than in the diorite-quartz diorite. It occurs not only as felty masses throughout the feldspar grains but also occasionally in fractures in these grains.

The Danva pluton has a wide variation in composition. Of the four thin sections studied two are monzonite, one is quartz monzonite and one is granodiorite. In addition a very narrow border phase, similar to the quartz diorite-diorite of the North Mountain intrusion, is present. In both hand specimen and thin section these rocks are texturally and mineralogically, except for a difference in proportions, almost identical to the North Mountain quart monzonite.

The monzonite has the following average composition: plagioclase 55 per cent, K feldspar 35 per cent, quartz 5 per cent and less than 1 per cent each of chlorite, sericite, biotite, hornblende, epidote, allanite, sphene, apatite, zircon and opaques. The plagioclase is An_{32} to An_{34}, determined by measuring $X' \wedge 010$ for sections $\perp a$. Complex twins are rather uncommon and no zoning is present. The quartz monzonite has 50 per cent plagioclase, 30 per cent microcline, 15 per cent quartz, and the same minor minerals as the monzonite. Its plagioclase has a composition of An_{32} determined by measuring $X' \wedge 010$ for sections $\perp$ a. Apart from these features this rock is identical with the monzonite. The granodiorite has 55 per cent plagioclase, 15 per cent microcline and 25 per cent quartz and the same minor minerals as the above rocks. The plagioclase present is An_{30}, determined for a Carlsbad-albite twin.

The Beaver Lake pluton has not been studied in detail. In outcrop, in hand specimen, and in thin section, this rock is very similar to the rocks of the Danva pluton and to the North Mountain intrusion quartz monzonite. The only thin section studied is quartz monzonite with 40 per cent plagioclase, 38 per cent microcline, 20 per cent quartz and less than 1 per cent of each of biotite, apatite, chlorite, and sericite. No sphene, zircon, opaques, or epidote group minerals are present. The texture is hypidiomorphic granular with little evidence of deformation. The minerals present all have the same properties as those in the quartz monzonite of the North Mountain intrusion. Composition of the plagioclase is An_{30}, based on measuring N_x' for cleavage fragments.

The Sidebacon Lake pluton is also inadequately studied. It seems to be composed of rock similar to the granodiorite-quartz monzonite-monzonite of the other large masses. The only thin section examined contains 45 per cent plagioclase, 20 per cent microcline, 25 per cent quartz, 5 per cent biotite, 2 per cent epidote and less than 1 per cent of each of hornblende, apatite, zircon, sphene, opaques, chlorite and sericite. This is a quartz monzonite but is very close to the composition boundary between granodiorite and quartz monzonite. The rock is essentially hypidiormorphic granular without any directional textures. Quartz commonly has undulatory extinction and the feldspars may be fractured and biotite bent, but deformation is quite minor.

The plagioclase of this rock has a composition of An_{33} based on determinations of N_x' for cleavage fragments. It is not zoned. Biotite is pleochroic from greenish brown to colorless. The epidote is not quite as strongly pleochroic as that of the North Mountain quartz monzonite but does show distinct yellow to colorless pleochroism. The other minerals present all have the same properties as those in the North Mountain quartz monzonite.

The dykes belonging to the Coast Intrusions are very similar to the larger bodies, although they tend to be finer grained. Many are aplites. Their texture is commonly hypidiomorphic granular. They commonly lack foliation but may be strongly granulated, probably indicating intrusion in partly crystalline form. Their composition ranges from granodiorite to quartz monzonite. The same major and minor minerals are present as those in the plutons. An interesting feature of these dykes is that most of them contain numerous inclus-

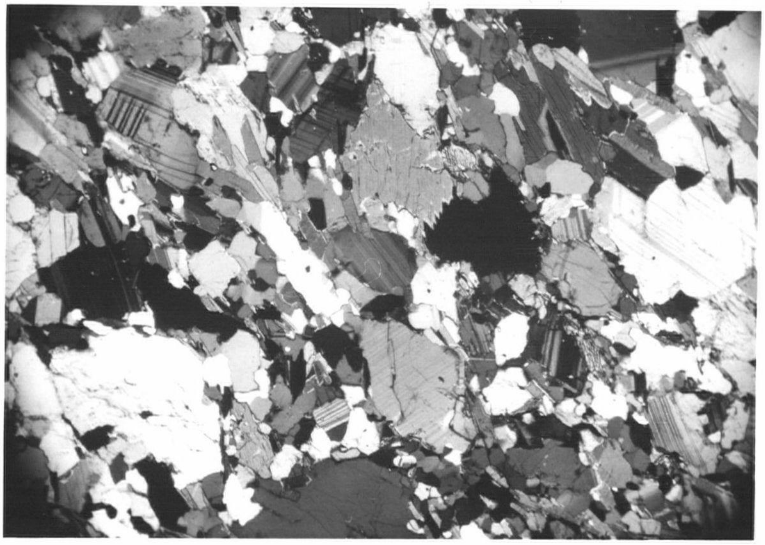

Figure 38. Photomicrograph of quartz diorite from the North Mountain intrusion. Plain light X24. The ragged biotite, hornblende and minor epidote are probably due to assimilation of country rock.

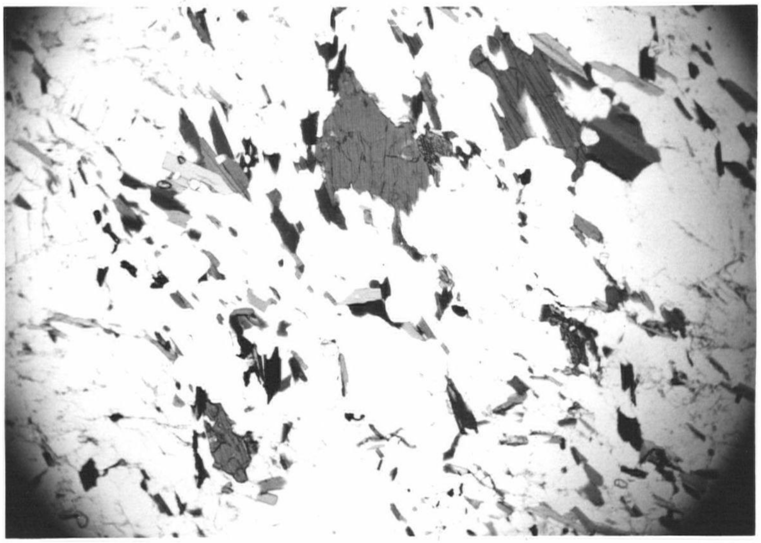

Figure 39. Photomicrograph of quartz diorite from the North Mountain intrusion. Polarized light X24. As Figure 29.

Figure 40. Photomicrograph of monzonite from the Danva pluton. Polarized light X24. Microcline, plagioclase, quartz and myrmekite are present.

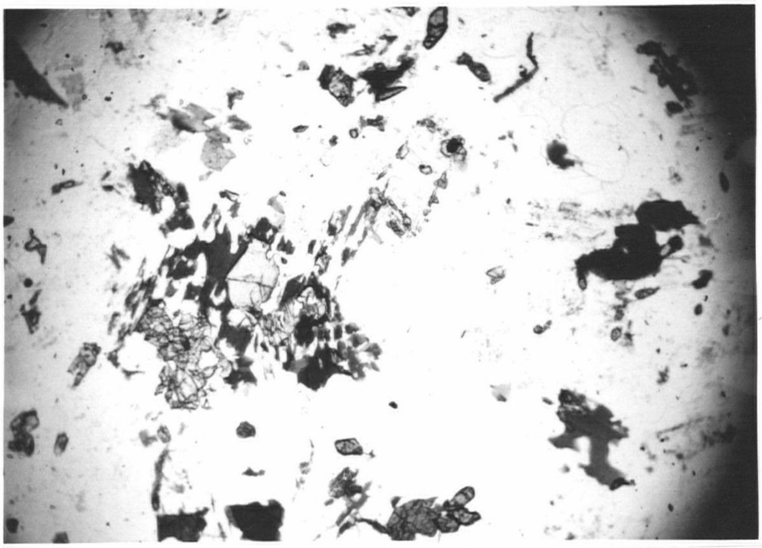

Figure 41. Photomicrograph of granodiorite. Plain light X24. A contaminated dyke containing biotite, hornblende, epidote and sphene.

ions of country rock in various stages of digestion, and in consequence thin sections may be crowded with such minerals as hornblende, biotite and epidote, and contain some almandine, all of which have resisted digestion.

The pegmatites consist of quartz, K feldspar and in some cases biotite or pale greenish muscovite. Small euhedral garnets were found in one pegmatite. The quartz and K feldspar are commonly found in graphic intergrowths. The K feldspar is usually white and the quartz glassy and colorless. Biotite and muscovite are found as small scattered flakes. Occasionally muscovite occurs as "books" of mica up to 2 inches thick and 4 inches across. The garnet is a deep red type similar in appearance to the garnets of the metamorphic rocks. It may have been formed from material assimilated from the wall rock.

ORIGIN AND NATURE OF THE COAST INTRUSIONS

The granitic rocks of Hawkesbury Island occur in mainly discordant bodies. The boundaries of the plutons are in some places nearly perpendicular to the foliation of the metamorphic rocks. The dykes and pegmatites are generally of random orientation and intrude the plutons, so that they cannot be regarded as evidence of partial granitization of the country rock. The boundaries of the plutons and dykes are quite sharp and not diffuse in nature. There are many xenoliths in the marginal parts of the plutons and in the dykes.

These xenoliths appear to have the same orientation as the same rock type outside the plutons and dykes. These features apart from the xenoliths, indicate that the Coast Intrusions of this area are truly intrusive in character and are not products of granitization in situ. However, the xenoliths show they have assimilated a good deal of country rock without displacing it to any great extent. This assimilation is marginal in the case of the plutons and may be considered to be a contact effect.

The two main modes of origin currently favored for granitic rocks of definitely intrusive character are (1) selective fusion of previously solidified rocks carried to depth and intrusion of the fused fraction and (2) the formation of a granitic magma by differentiation of a basaltic magma. The products of either of these processes would probably be indistinguishable. At any rate, the writer has found no evidence in the map area supporting one of these views against the other and will not discuss this point any further.

OTHER INTRUSIONS

(1) Carbonatized Andesitic (?) Rocks

This rock type was noted only in West Trench brook, at elevation 390 feet. Here it occurs as a boudin and has a total known extent of some 10 feet by 3 feet. Although the brook flows along strike no other boudins were noted.

In hand specimen this is a pale brownish grey aphanitic rock veined by numerous calcite-filled fractures. It weathers to a pale brownish color.

In thin section it is found to consist of a very fine-grained groundmass composed mainly of plagioclase with minor opaques, isotropic material (glass?) and alteration products. No quartz or K feldspar was noted. A few large phenocrysts completely replaced by calcite and/or a fine aggregate of unidentified material also occur. Numerous veins of calcite and minor quartz are present. One apatite crystal was seen in a calcite vein.

The plagioclase of the groundmass occurs as lath-like grains interwoven into a felty, non-directional aggregate. Two or three (albite?) twin lamellae can be seen under high power in some laths. The composition of the plagioclase is An_{18}, (oligoclase) determined by measuring N_x' for cleavage fragments. It probably forms at least 90 per cent of the groundmass.

The opaque material is found as very small anhedral and subhedral grains and occasionally as euhedral grains with cubic or octahedral outlines. It is probably magnetite. It appears to be scattered at random throughout the rock, of which it forms perhaps 1 per cent.

The material between the feldspar laths is mainly isotropic and has the same relief as balsam. It is probably glass. It may form 5 per cent of the groundmass.

The commonest alteration product is a brownish substance which looks opaque under medium power but is seen to be transparent under high power. It occurs in extremely small rounded grains and is so fine that birefringence and other properties could not be determined. This material is scattered throughout the section but is particularly common in, and along the margins of, the altered phenocrysts. Its presence along their margins makes the phenocrysts quite conspicuous in ordinary light. Another alteration product, confined to the phenocrysts, is a fine-grained, colorless, anisotropic aggregate with low relief and maximum interference colors of first order white. It may be composed of secondary feldspars.

The shape of the phenocrysts suggests they may have been pyroxenes, amphiboles, and feldspars. Most of them have a short rhombic outline (pyroxene or amphiboles?) but a few are square or nearly so (feldspar?).

The vein material is mainly subhedral calcite. Quartz occurs as a few large lens-shaped masses in, and associated with, calcite. The single apatite crystal noted is an elongate prismatic grain with several cross fractures.

On a compositional basis it seems likely this rock was an andesite or a similar rock. It seems essentially concordent and may be an intrusive (sill) or extrusive (flow).

The age of this rock type is in doubt. It may be older than, younger than or introduced during the main period of metamorphism. The third possibility may be dismissed, as the grade of metamorphism is such that it implies deep burial and high temperature during metamorphism. Any rock intruded under these conditions would not have the glassy matrix and

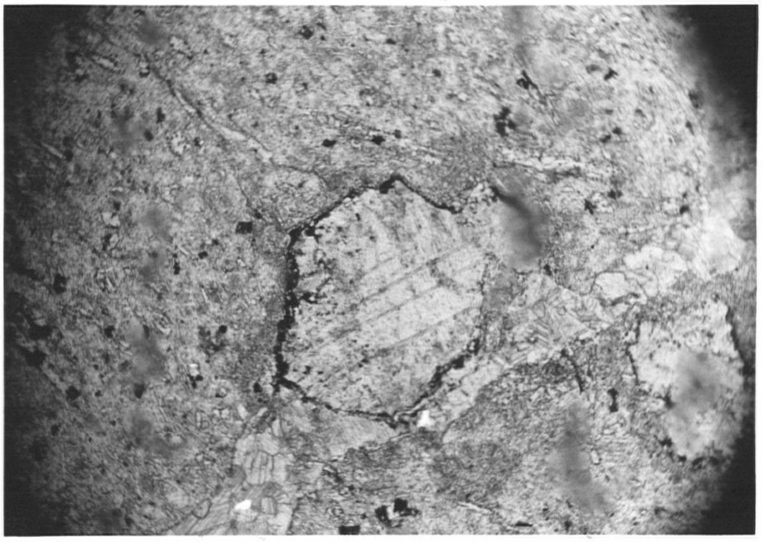

Figure 42. Photomicrograph of (?) andesitic rock. Plain light X64. A phenocryst replaced by calcite and rimmed by extremely fine-grained brownish material in a groundmass of feldspar laths, glass (?), opaques, etc. A vein of calcite is also present.

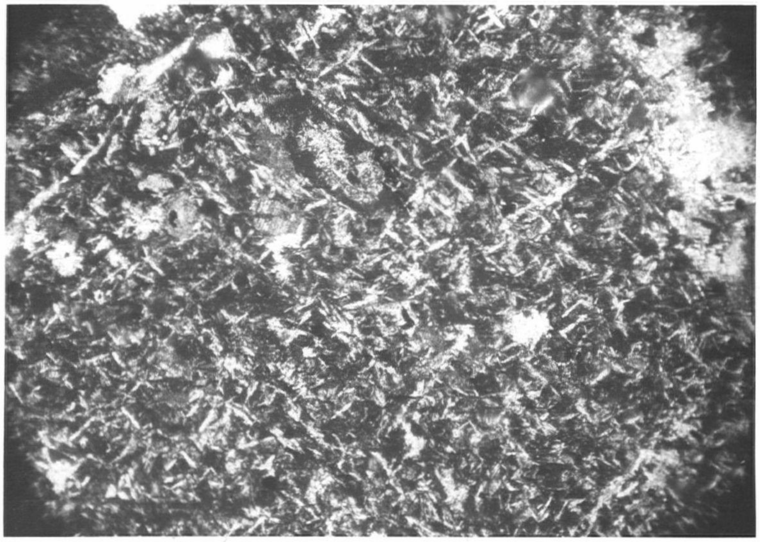

Figure 43. Photomicrograph of (?) andesitic rock. Polarized light X64. Similar to figure 42. A small phenocryst is present in the upper centre replaced by a fine-grained aggregate of secondary feldspar(?)

texture this rock has. It is difficult to see how this rock would retain its texture if intruded prior to metamorphism. The temperature would probably not be high enough to seriously affect the main minerals in this rock but the glass should recrystallize. If the andesite (?) is later than the main period of metamorphism, it must have been involved in some later deformation. The presence in this area of slickensides in a graphitic bed and of minor sericite schists, common in shear zones elsewhere, suggests this may have been the case. Due to serious doubts as to whether this rock could have survived, with its present assemblage, through the period of regional metamorphism, the writer believes it is most likely this is an intrusion which is younger than this metamorphism. In this case it would of necessity be a sill or dyke.

(2) Lamprophyre Dykes:

Lamprophyre dykes are not abundant on Hawkesbury Island, but are found here and there cutting through the Ecstall series. In one locality they were observed cutting through granitic dykes belonging to the Coast Intrusions. Individual dykes are generally only about 1 to 20 feet wide, but one dyke was seen that is about 150 feet wide. Most dykes are quite straight and of fairly constant width, but several were noted which pinched and swelled and the occasional dyke splits into two or more branches which may or may not rejoin.

The lamprophyre is dark green to grey-black in color.

It commonly weathers to a rusty brown shade. It consists of numerous black hornblende phenocrysts up to 1/3 of an inch in length set in an aphanitic groundmass. The hornblende phenocrysts are commonly long, prismatic, rod-like crystals, but may be in part short and stubby. They commonly make up some 15 per cent to 20 per cent of the rock but may reach 40 per cent.

In thin section the hornblende phenocrysts are seen to be embedded in a groundmass composed of plagioclase laths, smaller hornblende crystals, and generally subhedral grains of magnetite. A few elongate apatite laths are also present. The magnetite grains may make up as much as 5 per cent of the rock and the plagioclase and alteration products up to 75 per cent. Secondary minerals, comprising calcite, chlorite, epidote and sericite, are always present.

The hornblende is commonly in euhedral crystals. These are occasionally fractured and cemented by plagioclase or various alteration products. The hornblende is a deep brown variety which has well developed rhythmic zoning in some thin sections. It commonly has simple twins on (100).

The plagioclase, generally in euhedral elongate laths, has a composition of An_{30} to An_{34} in various thin sections, determined by measuring N_x' for cleavage flakes.

Of the secondary minerals; calcite, epidote and sericite are found replacing plagioclase and chlorite and calcite occurs replacing hornblende. These minerals vary greatly in

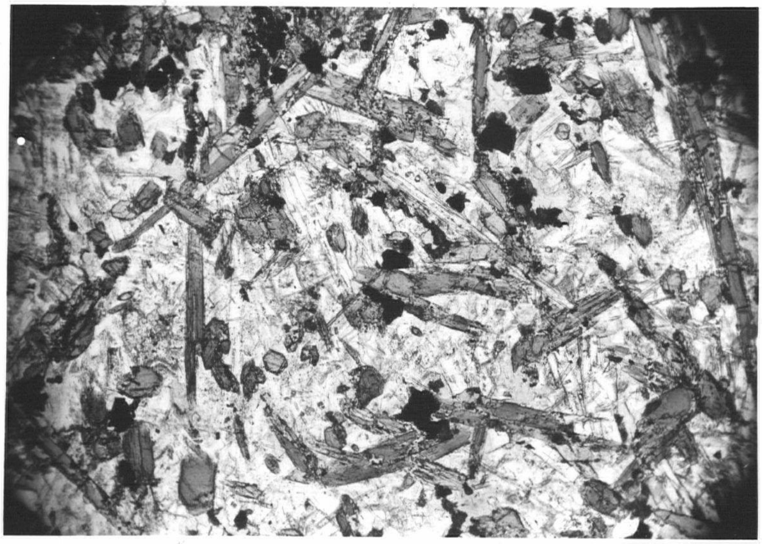

Figure 44. Photomicrograph of lamprophyre. Plain light X64. Elongate hornblende phenocrysts in a groundmass of feldspar, epidote, chlorite, apatite and opaques.

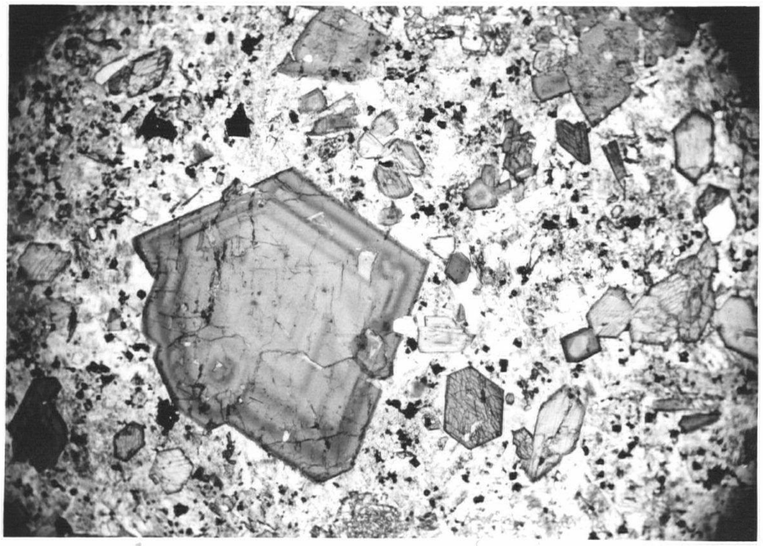

Figure 45. Photomicrograph of lamprophyre Plain light X24. Stubby zoned hornblende phenocrysts of various sizes in a groundmass of feldspar, epidote, apatite, chlorite, calcite and opaques.

amount, at a maximum comprising some 40 per cent of the thin section. They are all generally anhedral, except that in cases of complete replacement they may form euhedral or subhedral pseudomorphs. Epidote is a faintly pleochroic pistacite. Chlorite has anomalous greyish yellow to greyish green interference colors, parallel or nearly parallel extinction, and is weakly pleochroic from pale green to colorless. Calcite and sericite have the usual properties of these minerals.

CHAPTER V

STRUCTURAL GEOLOGY

GENERAL STRUCTURE OF THE NORTHERN PART OF THE COAST MOUNTAINS

The northern part of the Coast Intrusions of British Columbia have a general trend of a little west of north. This trend is paralleled by numerous roof pendants, septa, etc., which generally strike between north and north 15° west. The Ecstall septum or roof pendant has a general strike of north 15° west in the Douglas Channel-Skeena River area and probably a similar strike north of the Skeena and south of Gardner Canal. However, across Hawkesbury Island the general strike of the septum is north 60° west.

The trend of the Coast Mountains geological province and of the structures within it are reflections of the forces and conditions which have affected and are probably still affecting this region. The general north to north-west trend of the Coast Mountains probably reflects the effects of strong compressive forces which have acted in a direction approximately at right angles to this trend. The bend or warp of the Ecstall septum across Hawkesbury Island finds parallels in the Kootenay Arch composite fold system, in a similar system in the Skeena Mountains between latitude 55° and 57° N, and in warps in other septa and/or roof pendants of the Coast Range, as pointed out by White.[1] These features are all convex eastward,

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1 W.H.White, "Cordilleran Tectonics in British Columbia" A.A.P.G. Bull., Jan, 1959, p. 60, <u>et seq</u>.

and, according to White

> "resemble drag folds orientated to conform with a counter-clockwise rotation of the entire continental margin around the North Pacific basin."[2]

MAJOR STRUCTURAL FEATURES OF THE MAP AREA

The general trend of the foliation of the Ecstall series rocks on Hawkesbury Island is north 60° west to north 70° west north of a line running approximately from Backbacon Lake to Evelyn Lake. South of this line there is considerable variation in strike and dip but strikes of about north 45° east are predominant. There is a change in strike from north 60° to 70° west to north 45° east over a narrow transitional zone. The variation in strike probably is due to folding as there is no evidence of major faulting and the rocks which have the different trends are very similar in lithology.

In order to determine what deformation or deformations have affected the metamorphic rocks of this area figures 46 to 52 have been constructed. If these rocks have been affected by one period of deformation, the intersections of the planes of foliation, shown in figures 47 to 51, should have one strong maxima. The position of this maxima should indicate the strike and plunge of the fold axes. A scattering of the points of intersection and the production of two or more maxima indicate that the area has undergone more than one period of deformation. Examination of figures 47 to 52 shows that part of the area, at least, has undergone more than one period of

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White, *Ibid*, p. 60.

deformation. The amount of scattering of points of intersection decreases from west to east in the southern part of the area. There appears to be little or no scattering in the northern part of the map area, which can be interpreted as indicating either (1) that the northern area was involved in only one period of deformation or (2) that in this area the effect of the last strong period of deformation is so strong as to obliterate traces of any earlier deformation. The maxima in figures 50 and 51 indicate that the azimuth of the fold axes formed during this last strong deformation is north 50° west to north 55° north west. This steep plunge probably indicates re-folding of already folded strata as it is unlikely such steeply plunging fold axes could develop during one period of folding. Most of the traces of earlier deformation have been obliterated, however, particularly in the northern part of the island.

The azimuths and plunges of drag folds (figure 52) although quite variable, are also indicative of an azimuth of approximately north 50 west to north 55° west and a plunge of 50° to 55° northwest for the major fold axes. However, an insufficient number of drag folds were measured to put any interpretation based on them on a sound statistical basis. When the azimuth and plunge of the major fold axes derived from the data on the intersections of planes of foliation is plotted on figure 46, and a great circle is drawn at 90° to this pole it is found to pass through the centre of the strongest maxima on this figure. This indicates that an azimuth of north 50 west north 55° west and plunge of 50° to 65° northwest for the fold axes resulting from the dominant period of deformation is substantially correct. The failure of this great circle, or any other great circle based on the intersection of planes of foliation, to pass through the second maxima of figure 46 is probably due to the effects of the two or more periods of deformation which have affected this area. To summarize, the metamorphic rocks of Hawkesbury Island have probably undergone two or more periods of deformation. The fold axes resulting from the strongest (? and latest) period of deformation have an azimuth of north 50 west to north 55° west and plunge of 50° to 65° north west approximately.

If the folding is due to compression alone this probably indicates a northeast - south west direction of greatest compression i.e. the direction indicated by the general trend of the Coast Intrusions. The presence of a shear component would modify the picture somewhat.

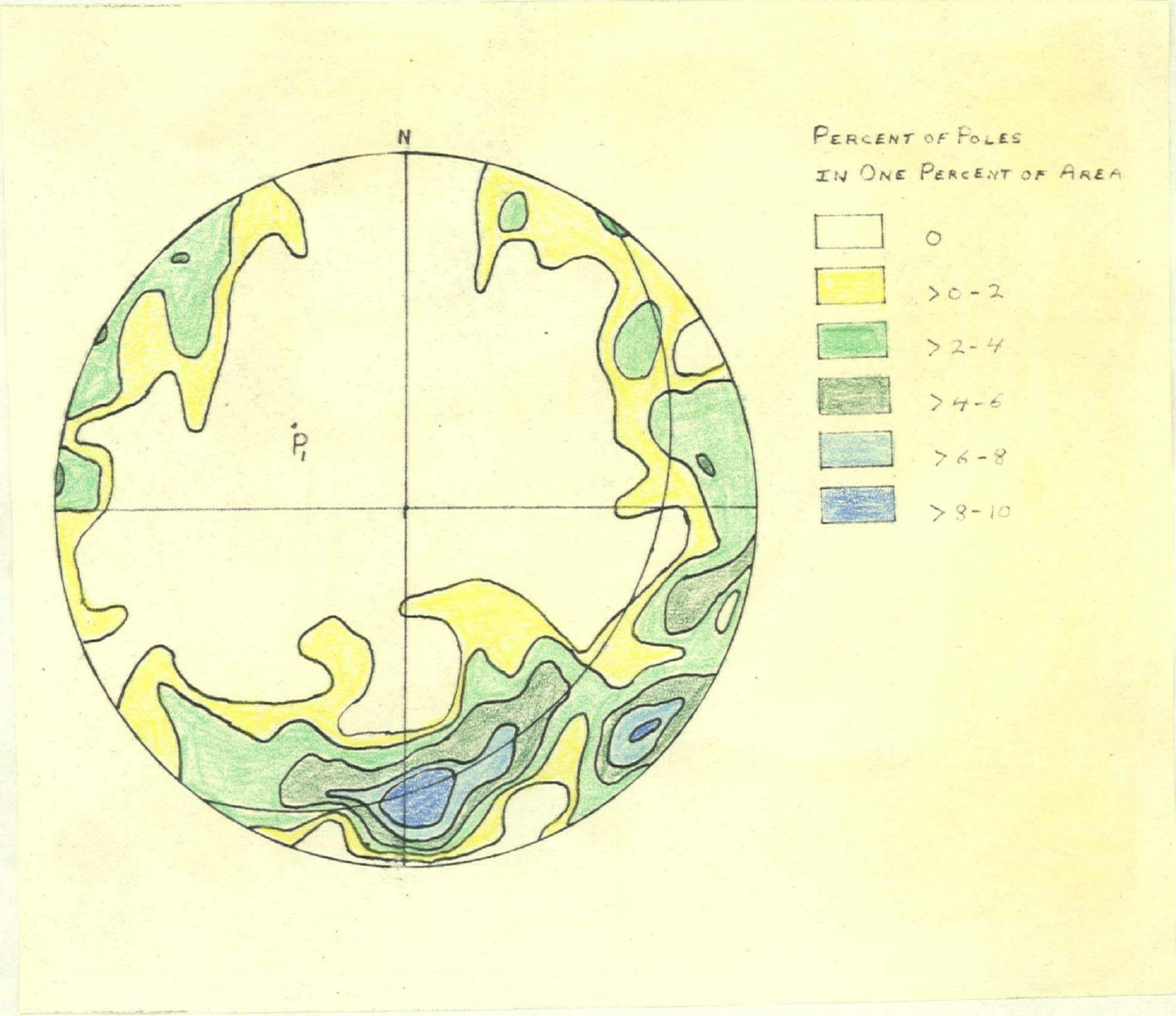

Figure 46. Poles of Foliation of the Metamorphic Rocks of Hawkesbury Island

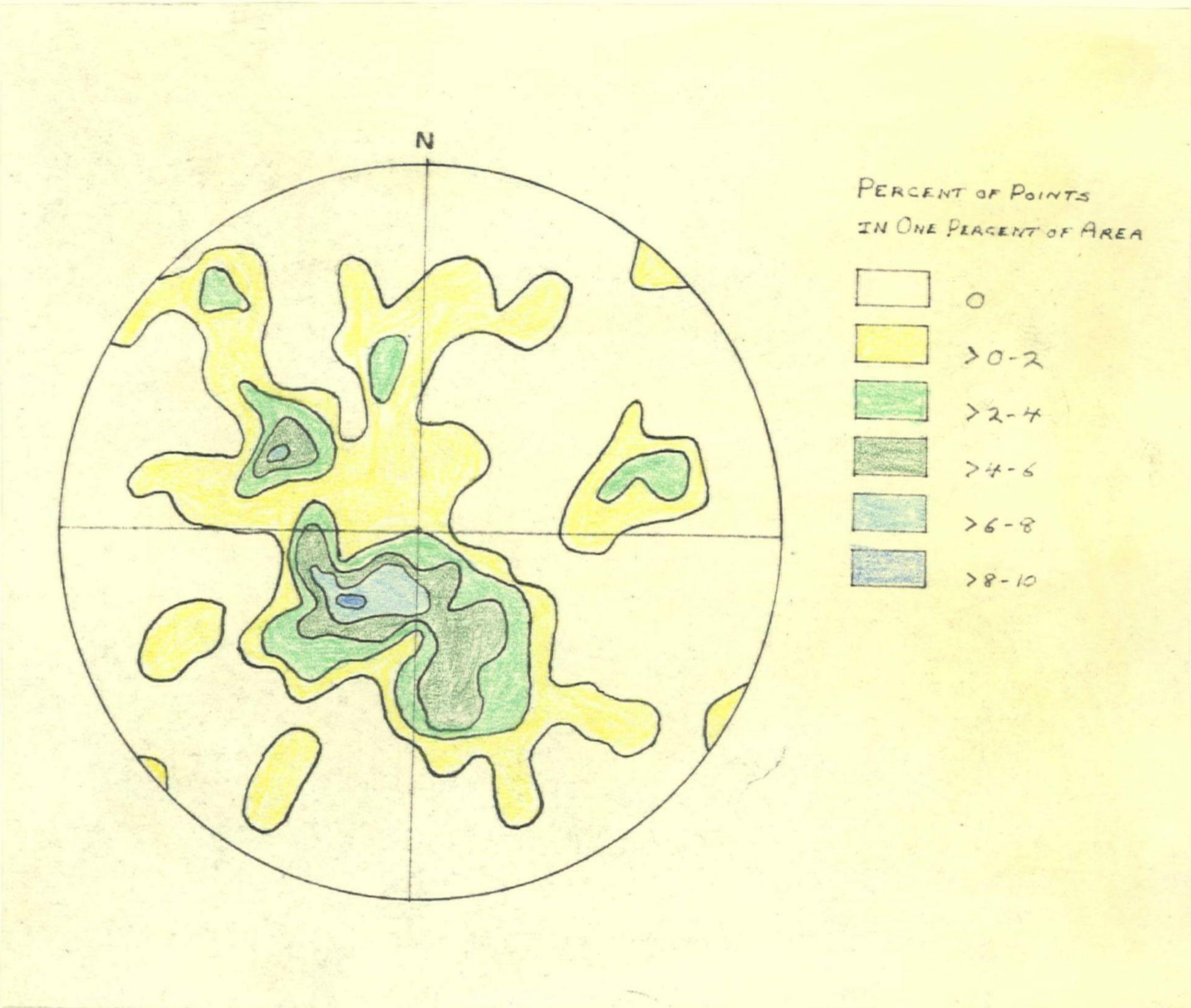

Figure 47. Intersection of the Planes of Foliation of the Metamorphic Rocks in Area I (bounded by the limit of mapping on the south, upper Angle Valley on the east, Ice Cake Lake to Backbacon Lake on the north and Douglas Channel on the west.)

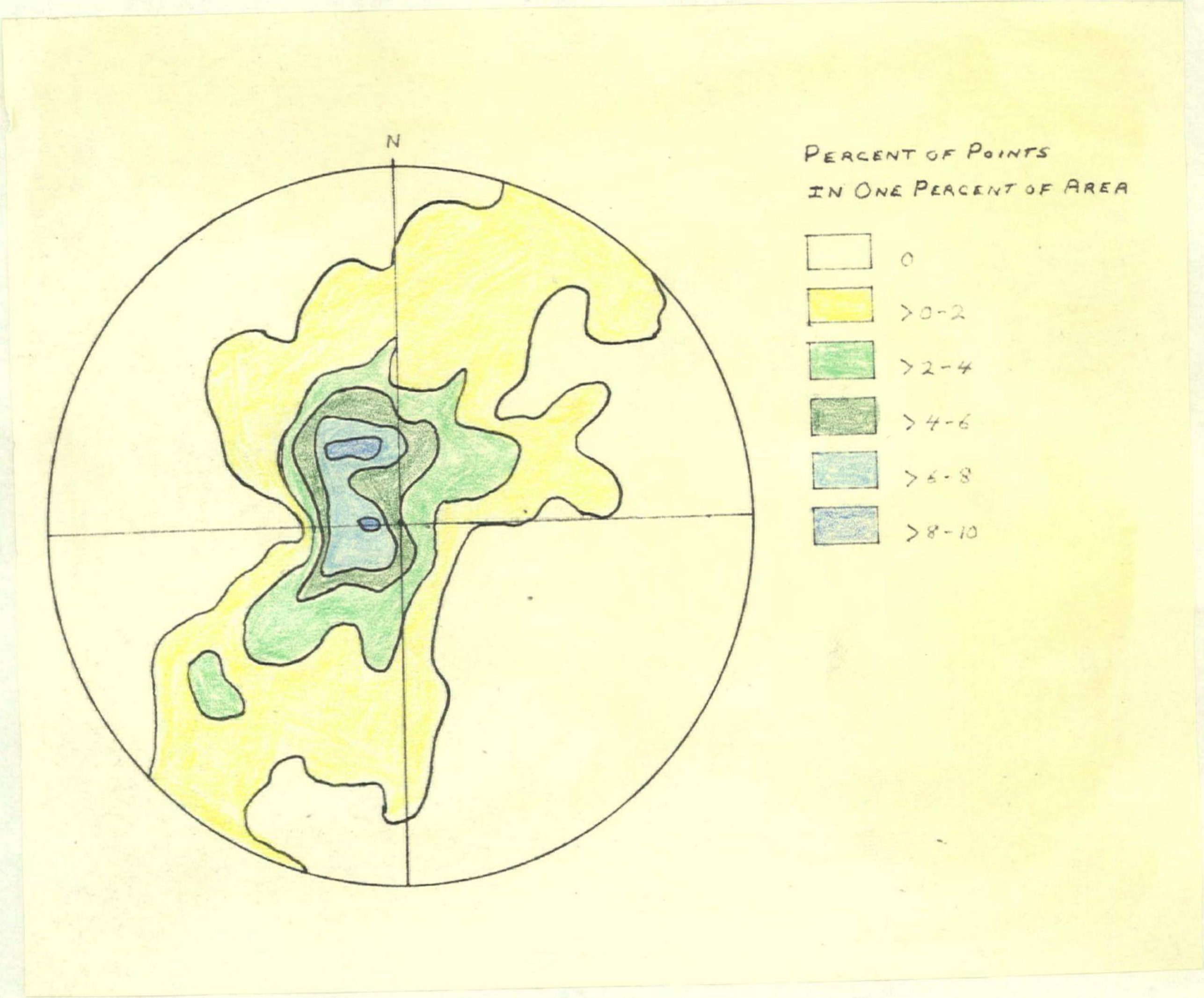

Figure 48. Intersection of the Planes of Foliation of the Metamorphic Rocks in Area II (bounded by the limit of mapping on the south, Verney Passage on the east, lower Angle Valley on the north, and upper Angle Valley on the west).

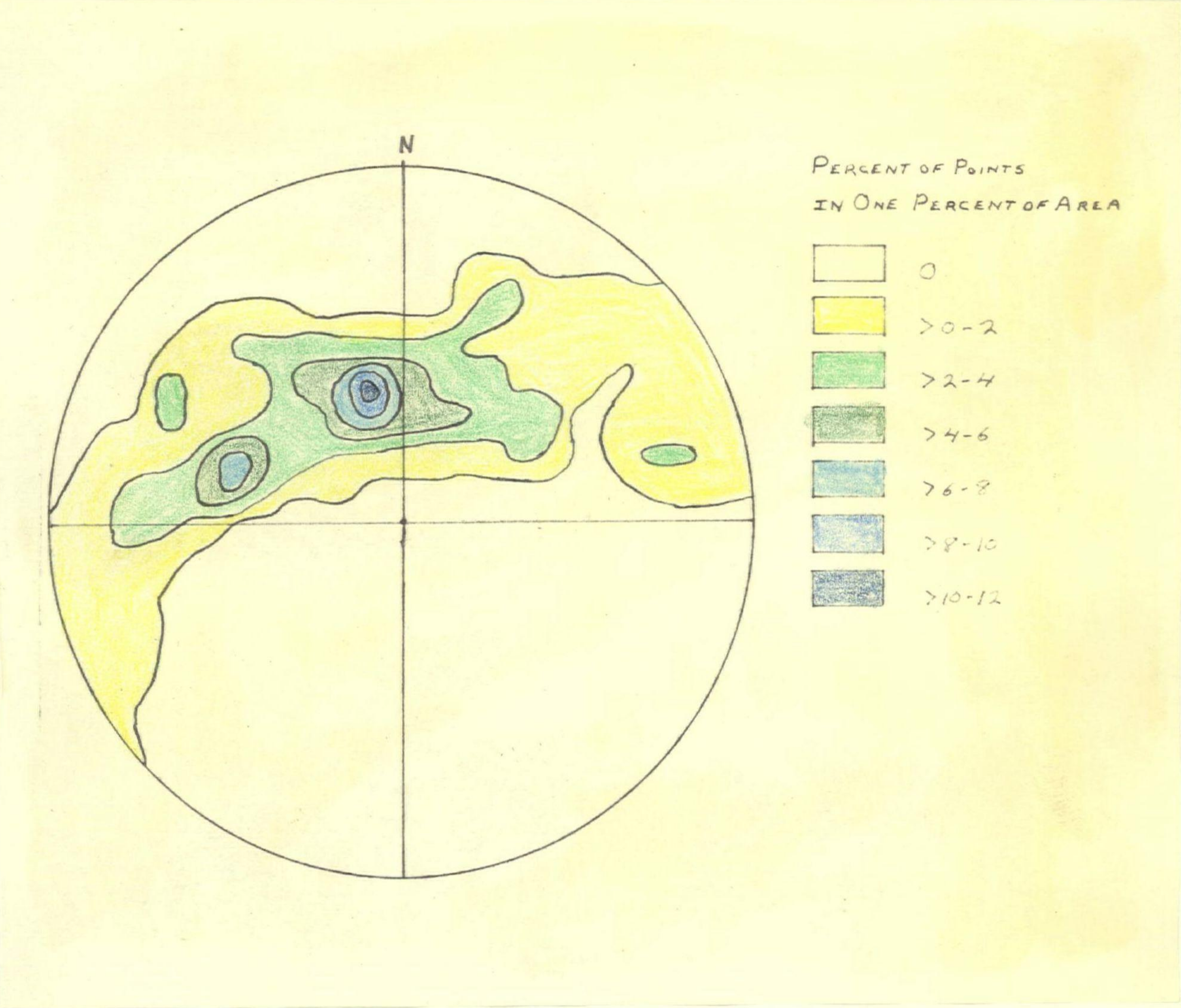

Figure 49. Intersection of the Planes of Foliation of the Metamorphic Rocks in Area III (bounded by Verney Passage on the south, Evelyn Creek on the east, Evelyn Lake to Ice Cake Lake on the north and lower Angle Valley on the west.)

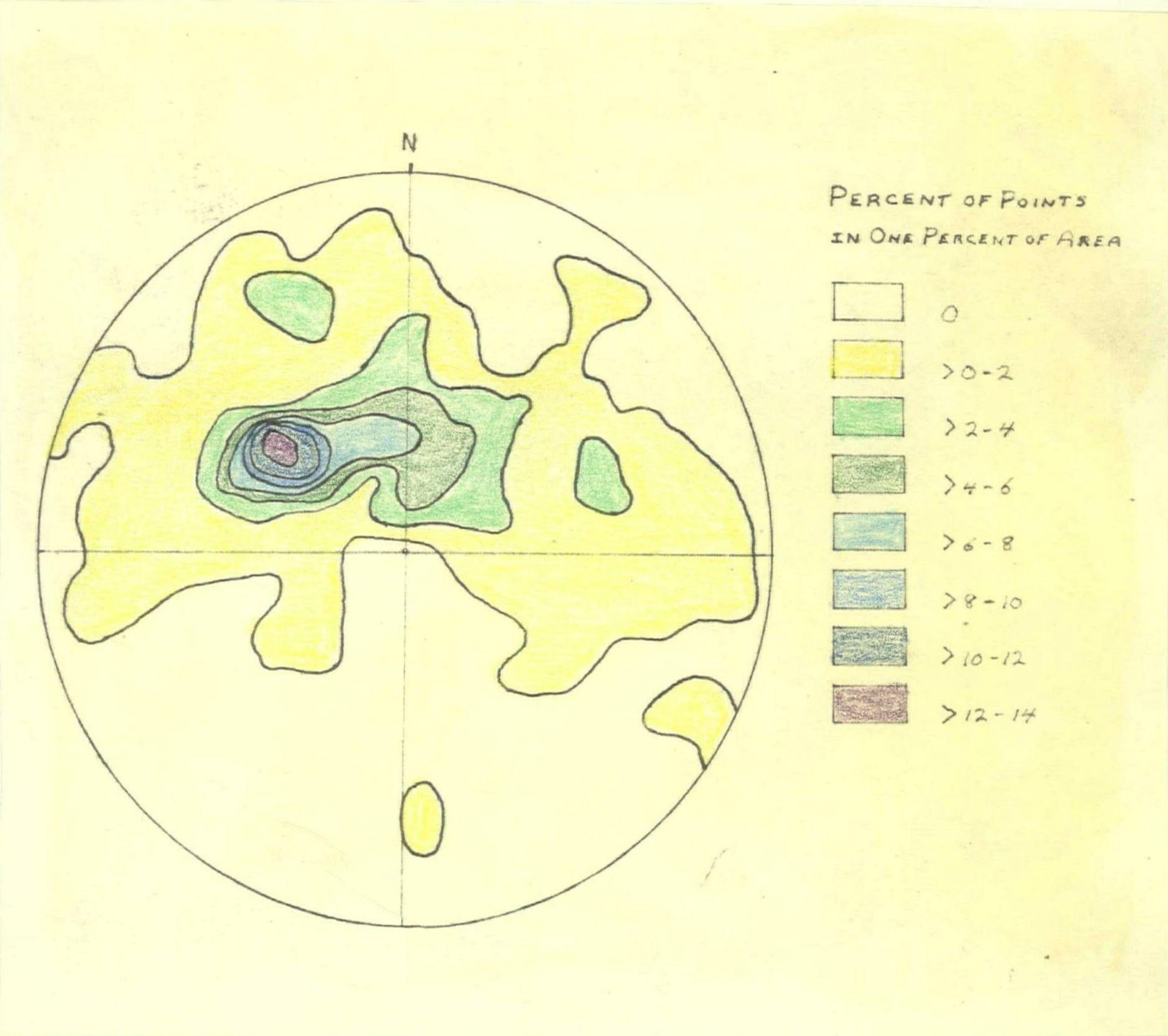

Figure 50. Intersection of the Planes of Foliation of the Metamorphic Rocks in Area IV (bounded by the sea on the south and east, Roy Lake to Evelyn Lake on the north, and Evelyn Creek on the west).

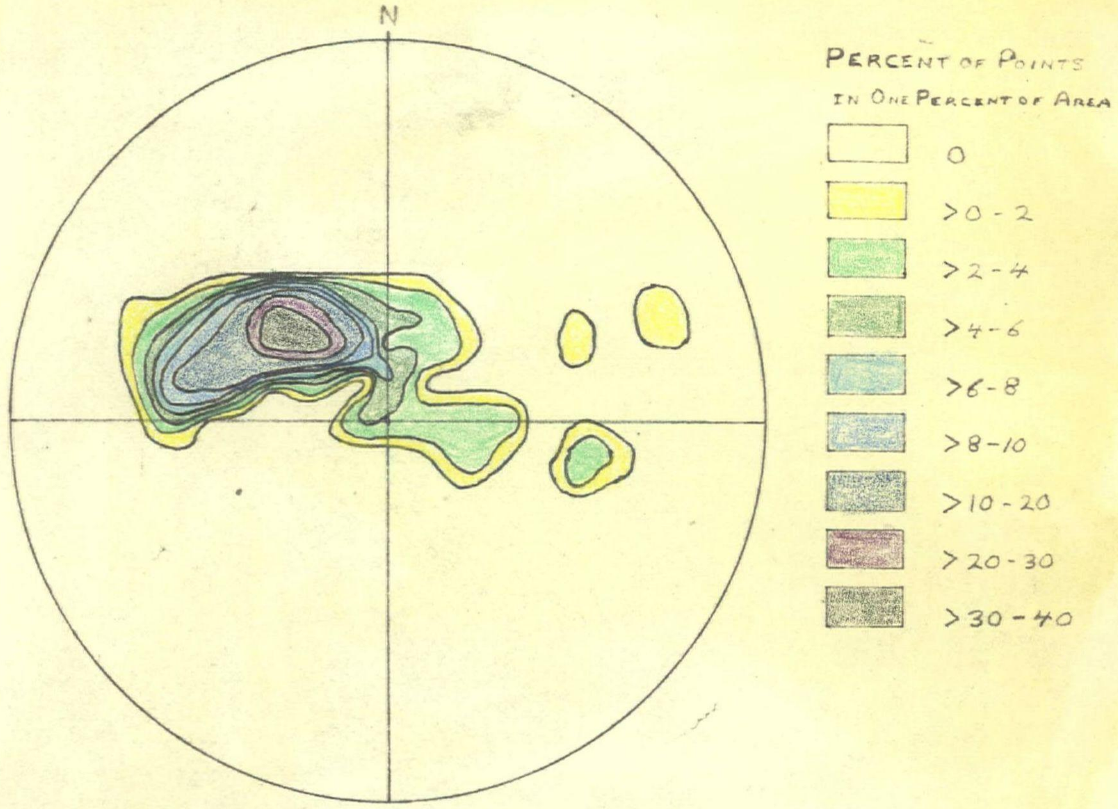

Figure 51. Intersection of the Planes of Foliation of the Metamorphic Rocks in Area V (comprising all the metamorphic rocks north of areas I to IV inclusive)

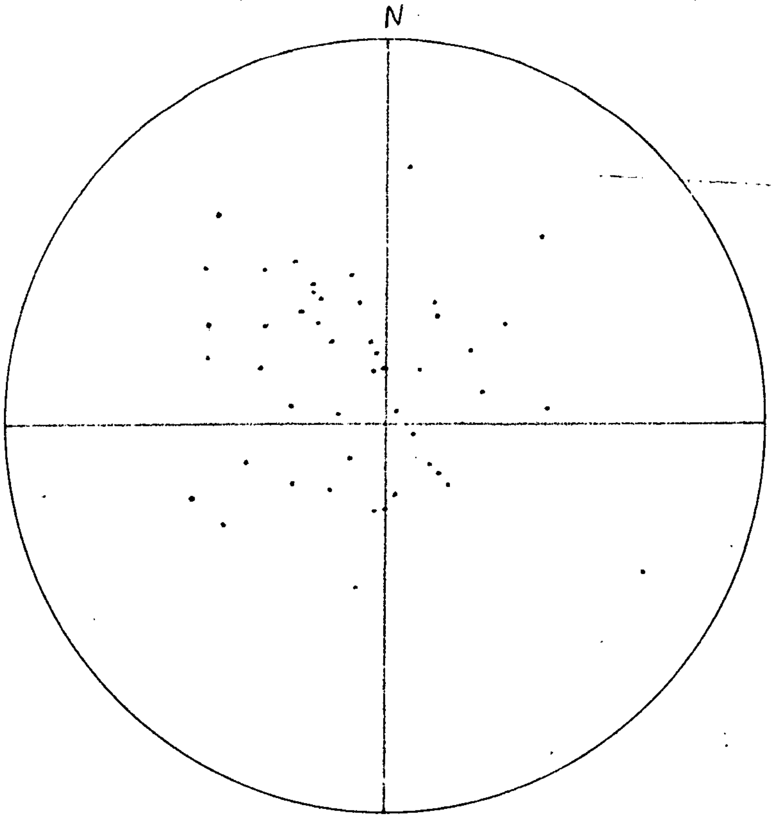

Figure 52. The Azimuth and Plunge of Drag Folds in the Metamorphic Rocks of Hawkesbury Island.

Owing to the nature of the mapping probably many small faults and shear zones escaped detection. The following are the only faults seen that extend more than a few feet:

1. A shear zone at least 5000 feet long in lower Angle Valley with a strike of north 50° east, a vertical dip (±10°) and drag folding which indicates an upward and southward movement of the west side of the shear relative to the east side.

2. A number of faults in the vicinity of Ice Cake Lake, the longest of which is some 5000 feet long, with strikes varying from north 10° east to north 40° east and steep dips. Most of these have displaced the kyanite-staurolite-almandine mica schist bands a few feet. One very long fault west of Ice Cake lake has offset the kyanite bands some hundreds of feet. In all cases there has been left hand separation. As the map units so displaced moved have nearly vertical dips, this probably indicates left lateral strike-slip movement. Some of the faults have resulted from movement along the axial plane of large drag folds which involve the whole of the kyanite band.

3. A single fault just to the west of the above series with a known length of some 300 feet. This strikes north 50° west, dips vertically and had an unknown amount of vertical movement, as indicated by slickensides.

4. A shear zone, and/or fault zone in and near West Trench Brook with a known length of some 4000 feet. This strikes north 60° west and dips very steeply. Slickensides indicate vertical movement.

5. A fault or narrow shear zone of unknown length (greater than 200 feet) cutting the North Mountain quartz monzonite at elevation 600 feet above Gaudin Point. This has a strike of due north, a dip of 85° west and an unknown direction of movement.

The strike and dip of the Angle Valley shear zone and the Ice-Cake Lake area faults indicates that the intermediate stress axis was nearly vertical. Assuming an angle of 30° between the direction of faulting or shearing and the greatest stress axis, and that all the movement noted is sinistral, these faults would have been formed during a period during which the axis of greatest stress varied between north 20^{o} west and north 20^{o} east. The variation in direction of maximum stress may be less than is indicated, as part of the variation in strike of the faults may be due simply to the inhomogeneous character of the rocks involved.

The north 50^{o} west to north 60^{o} west faults ((3) and (4)) have vertical or nearly vertical movement and are parallel or sub-parallel to the foliation planes in the metamorphic rocks. As these faults probably occur on foliation planes the direction of faulting, although to some degree indicative of the stress environment, is probably considerably modified by the weakness of these rocks parallel to this plane. A direction of greatest stress fairly close to vertical is indicated, however. These faults do not seem to fit the overall regional pattern. They may perhaps simply be the result of minor slippage along foliation planes.

SMALL-SCALE STRUCTURES

(1) In the metamorphic rocks

Small-scale structural features observed in the metamorphic rocks include schistosity or foliation, lineation, drag folds, segregation banding, minor crenulations of foliation, cataclastic structures, and pseudocataclastic structures of textures.

Segregation banding, cataclastic structures and pseudocataclastic structures have been discussed previously and will not be considered further.

Most of the rocks of the Ecstall series have a well developed foliation, as has been previously mentioned. A notable feature of this foliation is that it is parallel or nearly parallel to relict sedimentary bedding in all the localities in which the latter was seen. This may be due to ease of recrystallization parallel to original bedding. Lineation was noted in a few places in the amphibolites and is very prominent in the kyanite-staurolite-almandine mica schists. The lineation in the amphibolites is expressed by an alignment of hornblende prisms within the plane of foliation. It was noted in specimens of particularly coarse-grained amphibolites, especially from the Evelyn Lake area. One very coarse-grained amphibolite has two distinct lineations, one with a vertical dip and the other with a dip of about 50° East within a foliation plane that strikes north 65° west and dips steeply north. The lineation in the kyanite-staurolite-almandine mica schists is expressed by a parallel alignment of elongate kyanite crystals. This lineation is generally about horizontal.

Drag folds and minor crenulations are common and the attitudes of a number were measured. Unfortunately many outcrops were flat and no good idea of plunge could be obtained, so that only 49 readings were made which could be plotted accurately on the stereo-net. The great variation in azimuth and plunge is indicated by figure 6. There are usually one or two directions of major drag folding in a given exposure, but smaller crenulations in several directions also occur. In the northern part of the Ecstall series, the great majority of the major drag folds were found to have azimuths of south 85° west to north 50° west and steep westerly plunges. This indicates that the beds to the north have moved east relative to the beds to the south.

(2) The igneous rocks

Of the area of igneous rocks examined, only the North Mountain intrusion has well developed foliation and/or lineation. Weak lineations were noted in other plutons.

The foliation of the diorite and quartz diorite of the North Mountain intrusion is expressed by a sub-parallel alignment of individual hornblende crystals, biotite flakes, clots of mafics and inclusions of mafic-rich rocks. This foliation strikes north 50° west to north 65° west and dips from north 70° north to vertically. This foliation, as previously noted, may be due to injection of a partially crystalline magma or of granitization of part of the Ecstall series rocks, as it is sub-parallel to both the foliation in the Ecstall series rocks and the contact of the North Mountain intrusion. In the quartz monzonite a much weaker foliation probably some form of flow banding, is common. This is parallel to the foliation in the diorite and quartz diorite.

In the Danva pluton the attitude of the foliation varies from a strike of north 15° west and vertical dip to a strike of north 45° east and dip of 80° north-west. This foliation is probably not caused by flow but rather by assimilation *in situ* of the metamorphic rocks. It is due to alignment of clots of mafic minerals and in some places occurs nearly perpendicular to the nearest margin of the pluton. The foliation usually parallels the strike of the metamorphic rocks immediately outside the pluton.

The Beaver Lake pluton rarely has any noticeable lineation or foliation. These are confined to the margins of the pluton and are marked principally by a parallel alignment of mafic minerals. All the lineation and foliation noted had strikes parallel to the foliation of the adjacent metamorphic rocks and are probably also a result of assimilation *in situ* of these rocks.

The Sidebacon Lake pluton appears to lack lineation or foliation. However, most of its contact with the metamorphic rocks was not examined and it may have the same marginal type of lineation or foliation as the other plutons.

CHAPTER VI

CONCLUSIONS

The metamorphosed sedimentary and pyroclastic (?) rocks of the Ecstall series were laid down in a eugeosynclinal trough. The quartzites of the Quaal River-Ecstall River area may be an exception as they may have been laid down in a stable environment prior to the formation of the eugeosyncline. The source area for the sediments was probably one or more island arcs, which must have been the site of considerable local volcanic activity. The age of these sediments is somewhat doubtful but they are most likely to be Ordovician to Devonian.

The metamorphosed igneous rocks of the Ecstall series may have been in part flows associated with the volcanic activity of the island arcs. In part, however, they are intrusive bodies, probably originally gabbroic in composition, which may have been associated with the above mentioned volcanic activity or perhaps have been intruded during the orogeny which resulted in the metamorphism of the Ecstall series rocks.

The main metamorphism of the Ecstall series is regional in type. It took place under strong compression and probably at temperatures in the range of 400° C to 700° C. It preceded the intrusion of the Coast Intrusions. The grade of metamorphism generally reached is the almandine amphibolite facies, staurolite-quartz and possibly kyanite-muscovite-quartz subfacies, indicative of quite a high grade of regional metamorphism. Small amounts of late sericite, chlorite and epidote are common throughout the Ecstall series. These are due to retrogressive metamorphism. Retrogressive metamorphism is very intense in shear zones where sericite-epidote assemblages are developed which in composition approach the greenschist facies. The sericitized rocks of the shear zones may be due to hydrothermal solutions which used the shear zones as passageways.

The Coast Intrusions and related rocks in this area have reached their present positions by intrusion with some assimilation of the country rock. Although not responsible for most of the metamorphism of the Ecstall series rocks, they may have caused an increase in metamorphic grade within 300 feet or less of their contacts which has resulted in the formation of rocks belonging to and approaching the sillimanite-almandine subfacies of the almandine amphibolite facies.

The metamorphic rocks of the Ecstall series in the map area have undergone at least two periods of deformation. The direction of compression during the deformation which appears to have had the strongest effect on them was probably northeast-southwest.

Some time after (or before?) the intrusion of the Coast Intrusions erosion began in this area and has continued to the present time. The feature that has had the most effect in shaping the present topography is Pleistocene glaciation. The glaciers of this period, at one stage, completely covered the island. There was limited deposition of marine clays in the valleys shortly after retreat of the glaciers and deposition of talus, etc., is continuing and is gradually filling the glacial valleys. The position of the marine clays at altitude 330 feet probably indicates an isostatic recovery of this amount since their deposition.

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