Petrology of the Ashaway and Voluntown quadrangles, Connecticut-Rhode Island

by

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Abstract of Petrology of the Ashaway and Voluntown quadrangles, Connecticut - Rhode Island by Tomas Feininger, Ph.D., Brown University, June, 1964.

The Ashaway and Voluntown 7½' quadrangles lie astride the Conn. - R. I. border 35 miles southwest of Providence. Geologic mapping and laboratory work were supported by the U. S. Geological Survey in cooperation with the State of Connecticut, Geological and Natural History Survey, and the State of Rhode Island, Development Council.

The rocks are plutonic and fall into four groups. (1) Metamorphic rocks underlie about a quarter of the area. All are sillimanite grade. From oldest to youngest they are: Cambrian(?) Plainfield Formation (quartzite, and quartzose and feldspathic gneiss), Ordovician(?) metavolcanic rocks (mafic to felsic), and Ordovician(?) calc-silicate quartzite. Sparse inclusions of mafic metamorphic rock in granitic rocks are of unknown age. (2) Mississippian or older gneissic peraluminous granitic rocks underlie about three-quarters of the area. These rocks are genetically related to each other and to the bulk of the granitic rocks of western Rhode Island, here called the Rhode Island batholith. Batholith rocks here mapped are (oldest to youngest, gradational units hyphenated): augen gneiss, Escoheag Quartz Diorite Gneiss, porphyritic granite gneiss, Potter Hill Granite Gneiss - Hope Valley Alaskite Gneiss - Scituate Granite Gneiss - Ten Rod Granite Gneiss. (3) Late or post Pennsylvanian Narragansett Pier and Westerly Granites are confined to a stock and scattered dikes at Westerly. (4) Two thin Triassic(?) mafic dikes are exposed.

That the granitic rocks (2 and 3 above) were emplaced as magmas is shown by their field relationships, textures, mineral compositions, and uniformity over large areas. Magmas of the Rhode Island batholith were forcibly intruded as tabular sheets and as large dome-like bodies during and immediately following the regional metamorphism. The magmas of the granites at Westerly were emplaced at a distinctly later time and more passively at a higher level in the crust. The main stock of Narragansett Pier Granite grades upward into a swarm of steep sills. An exposure of the up-dip termination of a 22 meter-thick dike of Westerly Granite shows that the magma was emplaced as a thin sheet which was thickened uniformly during intrusion of additional magma.

Quartz-sillimanite nodules occur locally in Hope Valley Alaskite Gneiss, in Potter Hill Granite Gneiss, and in porphyritic granite gneiss. The nodules probably were produced by two mechanisms. (1) Layers of nodules in granite far from metamorphic rocks reflect especially aluminous domains within the magma that were drawn into sheets during intrusion. (2) Abundant nodules in sills of Hope Valley Alaskite Gneiss within sillimanitic gneiss of the Plainfield Formation were produced by escape of alkalis from the magma, with consequent conversion of sillimanite to feldspar in gneiss adjacent to the sills. The same process, on a large scale, probably caused extensive feldspathization of the Plainfield Formation in the Ashaway quadrangle.

The similarity and concordance of structures within the batholith to those of the metamorphic host rocks, and the regional uniformity of all structures show that the regional deformation was a single event and was related to the intrusion of the batholith magmas. Excluding the augen gneiss, the batholith rocks are free of mechanical strain. This and the rarity of both filled and unfilled cross joints show that the principal deformation was largely complete before the final crystallization of the batholith. Emplacement of the later Narragansett Pier and Westerly Granite magmas did not influence the regional structures.

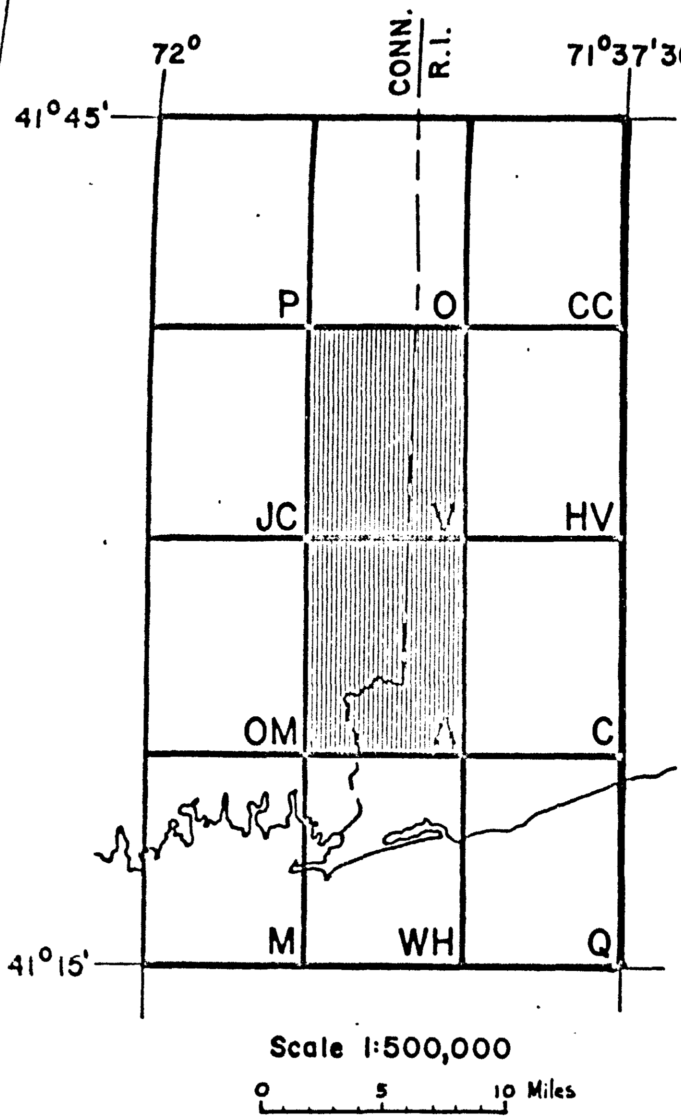
Evidence, partly from adjacent areas, shows that the principal orogenic episode was pre-Pennsylvanian, probably Acadian. A later (possibly Appalachian) event introduced the Narragansett Pier and Westerly Granite magmas, and probably affected the radiometric ages of the batholith rocks. Emplacement of the mafic dikes may have been contemporaneous with creation of a regional north-northeast joint set in part well expressed by topographic lineaments.

INTRODUCTION

The Ashaway and Voluntown 7 1/2 minute quadrangles lie astride most of the south half of the Connecticut-Rhode Island border (fig. 1). Together they constitute an area of 112 square miles, and are a little more than 17 miles north-south, and 6 1/2 miles east-west.

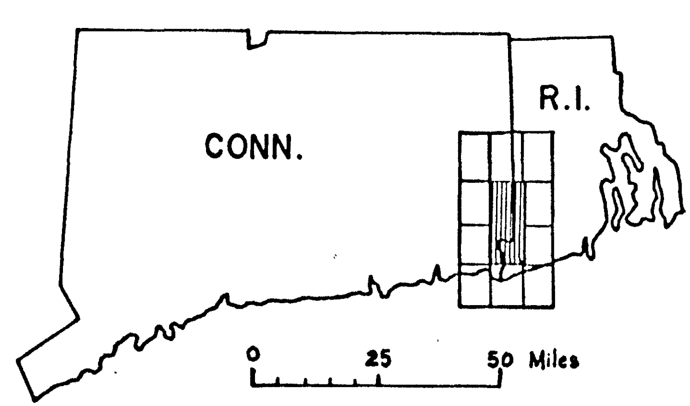
Greater Westerly, which includes adjacent Pawcatuck, Conn., is the only large town. The villages of Ashaway, Hopkinton, Potter Hill, and Rockville, R.I., and Voluntown, Conn. dot the remaining largely rural area. Manufacture is restricted to small mills and factories in and around Westerly. The rural land, especially north of New London Turnpike, is very sparsely populated. Considerable portions of the Voluntown quadrangle are uninhabited, and much of this land has been set aside as State Forest or Public Reservation. A few dairy farms are still operating, but little of the area is suited for modern agriculture. Hardwood, principally oak, is cut for railroad ties east of Beach Pond, and elsewhere is converted to charcoal on a small scale. The main use of the rural land is for recreation. Summer cottages and camps dot the shores of many of the ponds.

A network of paved or well-maintained gravelled roads covers both quadrangles and is the principal means of transportation and access. Hiking trails, many of which are not shown on the topographic map, criss-cross much of the Voluntown quadrangle. The trails are particularly useful as they have been blazed in areas farthest from roads. Public transportation is limited to the south part of the Ashaway quadrangle. Westerly is served by the New York, New Haven, and Hartford Railroad, and by a small State Airport 2 miles south in the Watch Hill quadrangle. Scheduled bus service



Key to quadrangles

A	Ashaway
C	Carolina
CC	Coventry Center
HV	Hope Valley
JC	Jewett City
M	Mystic
O	Oneco
OM	Old Mystic
P	Plainfield
Q	Quonochontaug
V	Voluntown
WH	Watch Hill



Location of index.

Figure 1. - Index map showing location of Ashaway, Voluntown, and adjacent quadrangles.

connects Westerly with Ashaway and Bradford as well as with most nearby cities and towns.

Nearly all quadrangles adjacent to the Ashaway and Voluntown quadrangles have been geologically mapped at large scales within the past decade. Unpublished maps and field sheets of some of the adjacent quadrangles were generously made available to me during the present study. Table I lists the present status of geologic mapping in these quadrangles.

TABLE I. - Geologic mapping in quadrangles bordering the Ashaway and Voluntown quadrangles (refer to fig. 1)

Quad-rangle	Published	Unpublished	Remarks
C,Q	Moore, 1959		
CC	Moore, 1963		
HV	Moore, 1958		
JC	Sclar, 1958		Southern 2/3 only
M			No modern work
O		R. Goldsmith, USGS	R.I. portion only
OM	Sclar, 1958		Northern 1/3 only
P		H.R. Dixon, USGS	
WH		G.E. Moore, Jr., USGS	

Regional setting and objective of study

Nearly all the rocks and structures of New England are part of the Appalachian System. Much of the discussion below is based on the excellent summary of the regional geologic relationships of the eastern United States and Canada given by King (1959, p.41-53, 57-66).

The Appalachian System and the structures within it roughly parallel the east coast of the North American continent from northwest Alabama to Newfoundland, a linear distance of approximately 2000 miles. The rocks are principally Paleozoic. Sedimentary and volcanic rocks range from Cambrian (possibly late Precambrian in places) to Permian. Plutonic intrusive rocks, which have a compositional range from ultramafic to felsic, are Ordovician to Jurassic. A general continuity of structure and pattern exists within the Appalachian System, and contrasts markedly with adjacent rocks; little disturbed Paleozoic sedimentary rocks to the west-northwest, and a cover of Mesozoic to Cenozoic clastic coastal plain rocks to the east-southeast southward from Massachusetts.

The Appalachian System is itself broadly divisible into two parallel belts; a western sedimentary belt, and an eastern crystalline belt. The two are physically different in all respects, yet are chronologically and genetically related.

The sedimentary belt constitutes the classical Appalachians: the folded and faulted chiefly carbonate-quartzite sequence of the middle Atlantic states. Rocks of similar lithology and structure border western New England, though they are quantitatively unimportant. Metamorphism and plutonic intrusive rocks are absent.

The crystalline belt constitutes the bulk of New England. To the south, the piedmont and some of the Blue Ridge belong to this same belt. The crystalline Appalachians are a metamorphic terrane. Premetamorphic sediments were feldspathic sandstone and graywacke and volcanic detritus. Thicknesses were very great. Clean sandstone and carbonate rock were areally sparse. These rocks have been regionally metamorphosed and extensively intruded by granitic plutons. Those fossils that were present in the sedimentary rocks were largely destroyed by the metamorphism. Organic remains are exceedingly scarce (none has been found in eastern Connecticut or Western Rhode Island), and the ages of individual units in the crystalline Appalachians, largely based on long-distance correlation, are somewhat uncertain.

Similarity of rocks in the crystalline Appalachians to the

Precambrian rocks of the Canadian shield led earlier geologists to correlate the terranes. Modern fieldwork has shown, however, that most of the New England terrane is Paleozoic, and that the few fossils that have been found are not preserved in chance younger inliers, but are integral parts of the local bedrock. Some Precambrian rock is exposed in anticlinal welts in the western crystalline Appalachians in the Green Mountain anticlinorium, the Berkshire and Hudson Highlands, the Reading Prong, and much of the Blue Ridge to the south. Some rocks in eastern Massachusetts have been assigned a Precambrian age, but confirmation awaits more detailed stratigraphic studies and radiometric age determinations.

The above synthesis is very sketchy and obviously greatly over-simplified. It serves, however, as a framework in which to discuss some of the problems encountered by geologists who have worked in the crystalline Appalachians, and particularly in New England.

The Ashaway and Voluntown quadrangles are underlain by three main rock suites; an old sequence of layered, largely deformed metasedimentary and metavolcanic rocks, a group of gneissic granitic rocks, and a small area of younger massive granitic rocks. The three suites are distinct in time and space.

The metamorphosed layered sedimentary and volcanic rocks underlie most of eastern Connecticut (Rodgers, 1959); those mapped in the present study are at the eastern fringe of this mass. The gneissic granitic rocks are at the western edge of a large volume of similar rocks which underlie the bulk of Rhode Island (Quinn, 1963), hereafter referred to as the "Rhode Island Batholith". The massive granitic rocks are abundant only along the southern coast of Rhode Island (ibid.).

Many questions about the structural geology and petrogenesis of New England crystalline Appalachian rocks are yet unanswered. A complete listing of these questions would be fruitless; however, the following are particularly pertinent to the area of this study: What is the origin of the large, commonly domical bodies of gneissic granitic rock? Are such bodies intrusive, or are they the products of in-situ transformation of pre-existing nongranitic rock? How, if at all, are structures within these bodies related to structures in adjacent metamorphic rocks? How is the metamorphism of the sedimentary and volcanic rocks related to the formation of the gneissic granitic rocks? Have the gneissic granitic rocks undergone a metamorphism subsequent to their formation? Has regional metamorphism been isochemical, or has large-scale metasomatism taken place? Has there been more than one period of regional metamorphism?

Probably none of the above questions can yet be answered conclusively and in its entirety, although features found in the rocks of the Ashaway and Voluntown quadrangles offer some preliminary answers. Several factors have made the area of the present study a suitable one. Outcrop is very abundant, somewhat more so than in adjacent areas, and surface rock is mostly fresh. The quadrangles are on the border between the very large Rhode Island Batholith and the metamorphic terrane to the west, and the relationship of these rock masses to one another is clearly discernable. Several distinct facies of the gneissic granitic rocks are mappable and, in many instances, the relationships between them allow firm statements on the origin of these rocks.

The objective of the present study has been to answer four questions as fully as possible: What is the origin of the rocks?

What was the course of plutonic events which formed them into their present state? What was the structural evolution which gave the rocks the relationships to each other that we now can see? How does this evolution relate to the geologic history of the northern crystalline Appalachians?

An answer to the last question was sought by another New England geologist a century and a quarter ago. In his "Report on the Geology of the State of Connecticut", Percival wrote this purpose (1842, p.12):

> "The exact determination of the Primary Geology of this State could therefore furnish a clue to the Primary Geology of Southern New York, as well as of Massachusetts and Rhode Island, and not only of those States, but of the whole Atlantic Primary of North America".

Although the above is archaic wording, it expresses a very modern objective.

Method of study

The backbone of this study is fieldwork. The types of rocks present and their abundant exposure particularly lend themselves to such an approach. In all, 18 months were spent in the field during the summers from 1958 through 1963, the fall of 1962, and the spring of 1962 and 1963. All outcrops in both quadrangles were sought, and probably more than 95 percent were found and are shown on the geologic map. Outcrops were located in the field by pace and compass traverses to and from known points, topographic position, and, in parts of the Voluntown quadrangle, by air photographs. Structural attitudes were measured by Brunton compass. Samples for comparison and study were taken from more than 2000 outcrops.

Petrographic study was in two parts; a description of the mineral composition and texture of thin sections from all the formations, and numerical modal analyses of thin sections of granitic rocks. Numerical modal analyses were made with a mechanical point counter. From 1000 to 2000 points were spaced so as to cover entirely the thin sections, which average 600 mm^2. More than 450 thin sections were studied, and approximately 150 numerical modal analyses prepared. Modes of metamorphic rocks were only estimated as the heterogeneity of these rocks, commonly within a single thin section, is very great. Plagioclase determinations in thin sections were made using the statistical method of Michel-Lévy. Untwinned and poorly twinned plagioclase was determined by refractive index measurement of crushed grains in oil. Excellent agreement, commonly with a percent or two An content, was found where both methods were used on the same sample.

Samples of six granitic rocks were chemically analyzed. The results are presented and discussed in this study.

Recent geophysical surveys of the area (aeromagnetic and aeroradioactivity) are correlated with the results of this report, and regional considerations are discussed.

Previous work

Geologists first made recorded observations in the Ashaway and Voluntown area more than a century and a quarter ago. The earliest published work is by Mather (1834), who included the Connecticut portion of the present report on his geologic map. The Rhode Island portion of the present report appeared on Jackson's geologic map (1840), which, like the above, is solely of historical interest. Two years later, the results of Percival's prodigious labors, a report on the geology of Connecticut, was published. Although rather dryly written, the keen observations and accurate map of Percival show exceptional geological insight. The next geologic map of Connecticut was that of Gregory and Robinson (1907), which was accompanied by a very wordy report (Rice and Gregory, 1906). Both proved less accurate and less useful than Percival's work. More detailed studies appeared shortly thereafter, notably those of Loughlin (1912), and Martin (1925). In the meantime, Rhode Island had been included on Emerson's geologic map (1917), though only at a scale of 1:250,000. The geology of eastern Connecticut was broadly summarized by Foye in 1949. A modern preliminary map of Connecticut appeared in 1956 (Rodgers et al.), and a geologic map of Rhode Island, compiled by A.W. Quinn and based on large scale quadrangle mapping, became available in 1963.

The most recent detailed work in the Ashaway-Voluntown area, a geologic map of the Voluntown quadrangle, has recently been published (Perhac, 1958), though its petrologic conclusions are challenged in the present report.

Acknowledgements

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cussions on a number of field trips. His provocative suggestions are gratefully acknowledged. J.P. Schafer, also of the U.S. Geological Survey, located several outcrops that I had missed in the Ashaway quadrangle. I was ably assisted by James T. McCoy during the summer of 1961 and part of the summer of 1962.

In addition, the following people were helpful during the field work; Mr. Angello M. Gencarelli, owner of the only operating quarry in the quadrangles, and Messrs. L. Bottinelli and E. Monti, owners and operators of the Crumb quarry in the adjacent Carolina quadrangle, for unlimited access, at times for large groups, to their properties; and H. Cushman "Gus" Anthony and the Yawgoog Boy Scout Camp for loan of a rowboat which made mapping of the shores of Yawgoog Pond easier, and mapping of the islands possible.

My advisers for this thesis have been Professors A.W. Quinn, B.J. Giletti, and T. A. Mutch of Brown University. I have been especially fortunate to have had Professor Quinn as my principal adviser. His familiarity with Rhode Island geology spans three decades, and his knowledge of regional geologic problems comes from first-hand experience in five New England states. Professor Quinn's greatly appreciated help has been manifold and continuing. Ultimately, however, the conclusions reached in this thesis are my own, and are not always the same as those of my counselors.

PHYSIOGRAPHY

Topography

Low relief and gentle slopes characterize the topography of the Ashaway and Voluntown quadrangles. Few hilltops are more than 200 feet higher than adjacent valley floors, and most are considerably less. Escoheag Hill, in the northeast corner of the Voluntown quadrangle, is the largest and highest hill. The summit is slightly more than 560 feet, and it stands 300 feet above adjacent Falls River. The lowest point in the quadrangles is sea level, on the Pawcatuck River at Westerly.

The boundary between the New England Upland physiographic province on the north and the Seaboard Lowland physiographic province on the south passes through the Voluntown quadrangle (Fenneman, 1938) from a point about 2 miles south of Voluntown village, approximately through the center of Beach Pond, and through the south end of Escoheag Hill. This boundary is not recognizable in the field, nor does the topographic map suggest its presence. The Ashaway and Voluntown quadrangles are broadly physiographically uniform, with an overall elevation increase northward.

Local topography, however, is rugged in places. The terrains at Wyassup Lake, northwest of Clarks Falls, and east of Pitcher Mountain in the Ashaway quadrangle, and the terrains around Ell and Long Ponds, and at Escoheag Hill in the Voluntown quadrangle, are characterized by the scarcity of level ground, by abrupt slopes, and by vertical cliffs of bedrock as much as 100 feet high. Other smaller areas of steep slopes and cliffs 50 feet high or less are common in both quadrangles.

Probably the dominant single topographic feature of the area is the valley of Green Fall River between Green Fall Pond and Laurel Glen. This four mile segment of the valley is steepsided, from 100 to 250 feet deep, and almost straight.

Geologic influence on topography

Topography in the Ashaway and Voluntown quadrangles is controlled primarily by bedrock. Glacial erosion and deposition have modified the topography principally through the removal of much overburden on hills and the deposition of thick glaciofluvial fill in the larger valleys.

Nearly all of the rocks in the area are physically resistant. Only mica-rich schists, quantitatively unimportant, are weak. Differences in relative resistance of adjacent rocks are generally small, although locally they are sufficiently great to have produced an accurate topographic reflection of the underlying rocks. Two examples of this relationship are particularly clear. East of Pitcher Mountain, at the west central margin of the Ashaway quadrangle, two parallel east-west ridges are supported by resistant Hope Valley Alaskite Gneiss and quartzite of the Plainfield Formation, whereas relatively lower areas north of, between, and south of the ridges are underlain by the weaker Potter Hill Granite Gneiss, amphibolite, and schist of the Plainfield Formation. In a similar situation near the southwest corner of the Voluntown quadrangle, augen gneiss forms a triangular highland north of Billings Lake that stands higher than adjacent, relatively weak metavolcanic rocks.

Most geologic contacts, however, are not topographically reflected. Factors other than lithology- principally rock structure and its orientation with respect to the direction of glacier movement, joint density, and depth of pre-glacial weathering- have been more influential than the relatively slight differences in bedrock resistance in shaping the present topography.

Strongly linear topography in the northwest corner of the Ashaway quadrangle, and between Beach and Deep Ponds in the Voluntown quadrangle, is coincident with the strike of foliation of the underlying rocks. In some places, as between Yawgoog Pond and Denison Hill Road, and 1.3 miles south of the center of Beach Pond, changes of strike of bedrock foliation are followed by slopes and valleys similarly arcuate in plan.

Striations, crescentric fractures, and abundant crescentric gouges (figs. 2,3) throughout the area show that the direction of last ice movement was between S10E and S20E. Overriding southward-moving ice has, in general, produced gentle north slopes, and steep to precipitous south slopes. Where bedrock "grain", especially strike of foliation or compositional layering, parallels or nearly parallels this direction, topography is relatively smooth with few cliffs or abrupt slopes. Where these bedrock structures are oriented athwart the direction of ice advance, topographic smoothness is minimal, and the landscape is irregular and characterized by steep to vertical south-facing slopes. The small-scale ruggedness of Ashaway quadrangle topography is in opposition to the general smoothness of that in the Voluntown quadrangle. This condition is produced by the prevailing east to northeast grain of the bedrock in the Ashaway quadrangle, and a north-northwest grain of all bedrock in the Voluntown quadrangle except that in the southwest corner.

Where steep to vertical parallel joints are closely spaced, glacial plucking has commonly removed rock selectively. The

Figure 2. - Glacial markings on bedrock. Crescentric fractures on Hope Valley Alaskite Gneiss midway between Deep Pond and Woody Hill, Exeter, R. I. Hammer Handle (38 cm long) parallels direction of ice movement, which was away from observer.

Figure 3. - Glacial markings on bedrock. Crescentric gouges on porphyritic granite gneiss 0.05 mile south of Ten Rod Road.0.55 mile east of State line, Exeter, R. I. Gouges are 1 meter tip-to-tip. Ice movement was toward Brunton compass.

topography thus developed, well seen on the hill north northeast of Chapman Pond (Ashaway quadrangle) and near Long Pond (Voluntown quadrangle), is a succession of cliff-bounded hillocks and valleys. Such topography exists only on a small scale in the area, but it is by far the most rugged.

A set of sub-parallel, straight lineaments strike north-northeast across the east half of the Voluntown quadrangle. The lineaments, shown on the geologic map, are conspicuous both in the field and on air photographs. The geologic nature of these landforms will be discussed later.

Location and nature of outcrops

Glaciation is directly responsible for the location and nature of nearly all outcrops in the Ashaway and Voluntown quadrangles.

Nearly all bedrock exposed at the surface is fresh and sound. Glacial erosion has swept off most weathered rock that mantled the area prior to the last ice advance, and post glacial time has been insufficient to allow much rock weathering. Some extensive areas of distintegrated and decomposed rock do occur in both quadrangles. These are discussed in the next section.

Bedrock is generally not exposed in the larger valleys owing to thick deposits of glaciofluvial sediment, but exposures on uplands are plentiful. Steep south slopes and irregular, hilly uplands bear the most abundant outcrops, whereas broad, smooth hills and north slopes are normally without outcrop. One notable exception is the smooth upland with negligible local relief east and north of Green Fall Pond on which outcrop is nearly continuous. An unusual combination of glacial erosion and non-deposition, absent elsewhere, must have prevailed here.

Outcrops exposed by natural post-glacial processes are rare. Som[illegible] exposures along the Pawcatuck River have been made or enlarg[illegible] erosion of overlying unconsolidated material by the river itself. Erosion by smaller streams since deglaciation has been slight, although the unnamed brook that flows into Beach Pond from the south 0.3 mile west of the State line has cut through a thin till mantle and exposed a large ledge of Hope Valley Alaskite Gneiss.

Many of the most informative bedrock exposures in the quadrangles are the work of man. Quarries have been opened in most of the units mapped, and are extremely numerous in the Westerly area. In addition, road cuts and railroad cuts have provided information unobtainable in natural exposures.

Glacial boulders are plentiful on uplands throughout nearly the entire area. Most are 1 meter or less in diameter, though some have largest diameters of as much as 10 meters. Some boulders are erratics, unrelated to local rocks, and have been carried great distances. For example, the southwest corner of the Ashaway quadrangle, west of Pawcatuck River, is strewn with boulders of Preston Gabbro which must have been carried 10 miles or more from the north northwest. Most boulders, however, are demonstrably of local derivation. In many places of sparse outcrop glacial boulders offer the only clue to the nature of the underlying lithology, and many of the geologic contacts in such areas have been mapped by "boulder surveys"; where the boulder lithology most prevalent is judged to be the most likely to constitute the underlying bedrock. Generally from 75 to 95 percent of the glacial boulders within a few tens of meters of a point of observation are of a single lithology.

Weathering

Most bedrock in the Ashaway and Voluntown quadrangles is fresh or nearly so. Surface weathering and staining rarely extends to depths greater than a few centimeters. Broad, unshaded whaleback outcrops of granitic rock have been sun bleached light gray to white. Some rock, however, is disintegrated to depths of several meters and, in places, chemically decomposed. Disintegration and decomposition processes were preglacial, as the resulting rock material is overlain by fresh till in several places.

Glacial erosion probably smoothed, polished, and striated bedrock throughout the area wherever the preglacial weathered mantle was swept off. This is supported by the abundance of such glaciated surfaces on fresh bedrock where glacial sediments have recently been stripped, as at the tops of roadcuts and at the edges of quarries. Natural outcrops, however, rarely show either polish or striations and have pitted or granular surfaces. Several processes contribute to the destruction of glacially polished surfaces. Freezing of water from rain and snow in minute intergrain selvages or intragrain cracks splits grains and breaks them free. Feldspar and mica hydration similarly produces a rupturing expansion. Chemical attack of rock by humic acid from roots, mosses, and lichens is probably considerable, and contributes greatly to rock pitting.

The nearly complete absence of glacial polish on naturally exposed rock surfaces suggests an appreciable rate of bedrock denudation. It is uncertain whether bedrock now exposed has been continuously exposed since deglaciation. Windthrown trees, forest fires, and slopewash all contribute considerably to the area of exposed bedrock. On the other hand, deposition of slopewash material and advancing vegetation tend to reduce bedrock exposure, and in many places, they entirely cover previously exposed rock. It is likely, however, that most of the large, relatively high-standing outcrops of both quadrangles have been free of cover nearly continuously since deglaciation, about 10,000 years ago.

Glacially polished bedrock is more resistant to mechanical and chemical attack than is roughened, granular bedrock which has a relatively larger specific surface. Denudation of bedrock is, therefore, not constant, but probably proceeds much more quickly once the initial polished surface is destroyed.

Several features on outcrops in the Ashaway and Voluntown quadrangles suggest the rate of local denudation of exposed granitic bedrock. Veins and knots of milky quartz, and quartz-sillimanite nodules commonly stand above the granular, pitted surface of granite gneiss outcrops (figs. 4, 41). Relief is as great as 6 cm, although in most places it is between 2 and 3 cm. Many of these features are mechanically delicate and could not have withstood overriding glacial ice; they clearly result from postglacial weathering. Some quartz knots west of Mason-Gray Pond (fig. 4)and quartz veins 0.27 mile south of the south tip of Beach Pond preserve glacial polish and represent the level of the initial glaciated surface of the outcrop. The magnitude of these features is consistent with a reasonable rate of denudation of exposed granitic bedrock in the area. Three assumptions are made in the following calculations; 1. the examples seen have been exposed since deglaciation; 2. the amount of denudation of exposed bedrock in the quadrangle is fairly represented by those places where the amount is measurable; and 3. approximately one half of the time of exposure (5000 years) was required to destroy the initial resistant polished

Figure 4. - Quartz knot with glacially polished surface 5 cm above granular surface of Hope Valley Alaskite Gneiss. Long axis of quartz knot is 20 cm. 0.73 mile S.80°W. of outlet of Mason-Gray Pond, Voluntown, Conn.

surface. About three dozen examples of measurable postglacial microrelief were noted. The average value is approximately 3 cm. Under the above assumptions, the rate of denudation of exposed granitic bedrock in the Ashaway and Voluntown quadrangles has been a little more than 1 cm per 2000 years, or 1 km per 200 million years.

The calculated denudation rate found for exposed granitic bedrock is not an average value for the entire area. Only a fraction, probably less than 10 percent of the quadrangles, is bare bedrock. Most bedrock is covered by glacial sediments and stable, vegetation-locked soil. Destruction of bedrock under such cover is negligible. Material denuded from high-standing bedrock outcrops is deposited in adjacent low areas; the total amount of material removed from the quadrangles by streams is probably small, and may have been nearly nil prior to Colonial occupation. Level forest floors and swampy swales are accumulating organic debris; thick, rich soils and peat on glacial sediments in these areas testify to appreciable aggradation since deglaciation. Finally, areally important rock types, particularly quartzite and mica schist, appear to be more resistant than granitic rock to currently operative destructive processes.

Two large areas, one in each quadrangle, are underlain by mantles of disintegrated and or decomposed granitic rock. Granular, disintegrated rock is locally known as "rottenstone".

A large area of rottenstone is developed on Scituate Granite Gneiss in the extreme northeast corner of the Voluntown quadrangle. principally northeast of Kelley Brook. The texture and structure of fresh gneiss is perfectly preserved even though the rock is entirely disaggregated and can be dug with hand tools. The thickness of the rottenstone mantle is unknown. Many cuts and small pits expose 2 meters or more, and a postglacial gulley 0.4 mile S66W of the northeast corner of the quadrangle is 6 meters deep and entirely in rottenstone. The rottenstone consists of relatively fresh felsic rock fragments stained red-brown to dark brown.

Much of the Potter Hill Granite Gneiss in a one mile radius semicircular area northeast, southeast, and southwest of the center of Bell Cedar Swamp is deeply disintegrated and locally decomposed. Although the Potter Hill is rarely fresh (p.78), the great depth of disintegration in this area and the occurrence of decomposed gneiss is not found elsewhere in this rock in the Ashaway quadrangle.

The transition from fresh rock to rottenstone can be seen in several outcrops and roadcuts. Figure 5 shows dark brown totally disaggregated rock along joints and selected foliation planes which grades through an intermediate zone of cohesive but strongly-stained orange-brown rock, into central areas of fresh, pinkish gray rock. Nearly all natural outcrops of Potter Hill Granite Gneiss are in the intermediate stage of the above sequence. Potter Hill rottenstone has a distinctive topography well shown by the hill south of Clarks Falls and much of the hill south of Bell Cedar Swamp. The land surface is irregular and dotted with small knolls. Glacial boulders are very scarce, and outcrops are very small and sparse. The soil is poor.

Disintegration of the Potter Hill is produced entirely by oxidation and hydration of accessory magnetite. The sole thin section difference between deeply stained, partly disaggregated gneiss and fresh rock, is the condition of this accessory which has been partly to wholly converted to brown hydrous iron oxides ("limonite") in the former rock. Thin but continuous limonite films coat all inter-

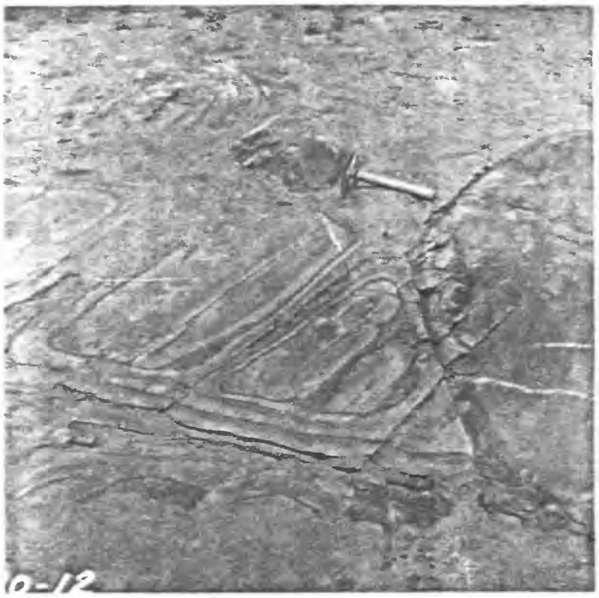


Figure 5. - Stain and disintegration of Potter Hill Granite Gneiss controlled by primary foliation (dips 35° left) and joints (dip 15° right). Corestones are largely unstained. Cut on Voluntown Road 0.07 mile south of New London Turnpike, North Stonington, Conn. View looking east.

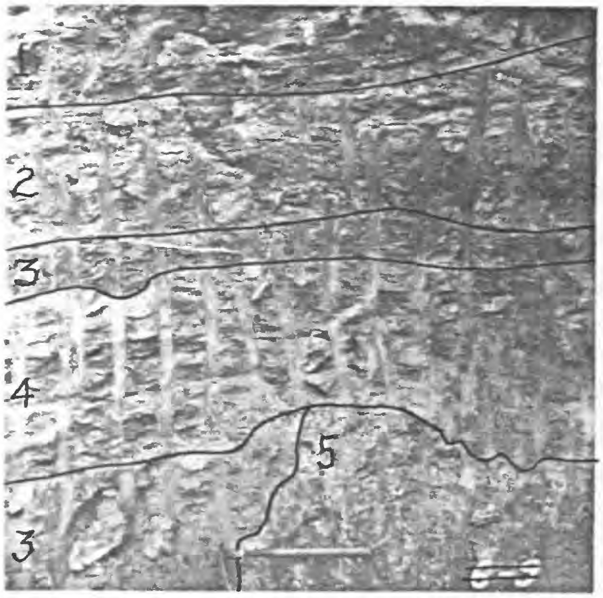


Figure 6. - Cut in saprolite of Potter Hill Granite Gneiss with schist and pegmatite, southwest corner of Voluntown Road and New London Turnpike, North Stonington, Conn. 1. Slightly decomposed biotite schist; 2. decomposed and iron-stained Potter Hill Granite Gneiss; 3. thoroughly decomposed biotite schist; 4. decomposed and bleached Potter Hill Granite Gneiss; 5. decomposed pegmatite. View looking south. Shovel handle approximately 50 cm long.

granular and some intragranular surfaces in rottenstone. The volume increase of the magnetite to limonite reaction is considerable. Initial partial conversion of small magnetite octahedra that stud Potter Hill Granite Gneiss caused stresses which produced myriads of fractures, principally intergranular, in adjacent rock. The fractures were subsequently enlarged by deposition of additional limonite derived by further oxidation and hydration, and the rock became disaggregated.

Scituate Granite Gneiss rottenstone was not studied in detail. A mechanism similar to that operative in the Potter Hill may have disaggregated the Scituate, although the relatively abundant biotite and hornblende in the latter may have played an unknown role.

Small areas of the Potter Hill rottenstone terrane are underlain by chemically decomposed rock. Whereas rottenstone consists chiefly of fresh mineral fragments, the chemically decomposed rock is a saprolite that consists of clay, quartz, and sparse unaltered rock fragments. The material is soft and plastic when wet. Most of the saprolite is stained brown to reddish brown, though in places it is a mixture of white clay and gray quartz granules. An exposure in saprolite of Potter Hill Granite Gneiss and associated schist and pegmatite is shown in figure 6. Rottenstone and saprolite are gradational in this and other exposures. Saprolite is extremely weak. Only two natural outcrops, both very small, were found, and the areal extent of this material is unknown.

Rottenstone and saprolite in the Ashaway and Voluntown quadrangles have been formed through surficial, weathering processes. In nearly all exposures, the material grades into fresher rock at depth.

DESCRIPTION OF THE ROCKS

Igneous rocks underlie about three quarters of the Ashaway and Voluntown quadrangles. The rest of the area is underlain by high-grade metamorphic rocks.

The metamorphic rocks consist of (oldest to youngest) mafic metamorphic rock, Plainfield Formation, metavolcanic rocks, and calc-silicate quartzite. Isolated lenses of mafic metamorphic rock within granitic rocks of the Voluntown quadrangle are probably older than the Plainfield Formation, but their exact relationship to other rocks is unknown. The Plainfield Formation is principally gneiss, schist, and quartzite. The oldest rocks are feldspathic biotite gneiss and schist and quartzose biotite gneiss and schist. The two are probably gradational. Lenses and layers of calc-silicate quartzite and calc-silicate granofels occur in feldspathic biotite gneiss and schist in the Ashaway quadrangle. The youngest rock in the Plainfield Formation is quartzite. Metavolcanic rocks overlie the Plainfield Formation. They range from mafic to felsic. Fine-grained mafic and felsic metavolcanic rocks at Wyassup and Billings Lakes are probably correlative with coarser-grained metavolcanic rocks farther south in the Ashaway quadrangle mapped as amphibolite, layered felsic gneiss, and calcareous felsic gneiss. A thin layer of calc-silicate quartzite discontinuously overlies metavolcanic rock east and northeast of Billings Lake. Metamorphic rocks are interlayered at all contacts.

The granitic rocks are magmatic and consist of a group of older largely gneissic rocks of the Rhode Island batholith, and two younger granites in the Westerly area. Cross-cutting relationships and other evidence suggests the following relative ages beginning with the oldest (gradational rocks hyphenated): augen gneiss, Escoheag Quartz Diorite Gneiss, porphyritic granite gneiss, Potter Hill Granite Gneiss-Hope Valley Alaskite Gneiss-Scituate Granite Gneiss-Ten Rod Granite Gneiss, Narragansett Pier Granite, and Westerly Granite.

As far as has been possible, the information given in this section is observational. Most genetic inferences have been omitted here in order to present them succinctly and in a unified manner in the following section.

Metamorphic rocks

The Plainfield Formation, metavolcanic rocks, calc-silicate quartzite, and mafic metamorphic rock are the product of recrystallization of a preexisting solid rock in response to high temperature and pressure. Considerable metasomatic chemical change accompanied the metamorphism of some of the rocks.

Plainfield Formation

The oldest rocks in the Ashaway and Voluntown quadrangles are a thick sequence of heterogeneous metasedimentary rocks here assigned to the Plainfield Formation following the usage of Lundgren (1963). In the Voluntown quadrangle the Plainfield Formation is in part equivalent to the Plainfield Quartz Schist of Gregory (Rice and Gregory, 1906, p. 114, 132-134; Gregory and Robinson, 1907), and in the Ashaway quadrangle it is in part continuous with rocks mapped as Blackstone Series in the Carolina quadrangle (Moore, 1959).

The name Plainfield Formation was chosen in the present report for several reasons. Much of the rock greatly resembles the Plainfield Quartz Schist described by Gregory (ibid.) The general designation "formation" is more appropriate than quartz schist, however, as considerable areas of the rock are neither quartz-rich nor schist. The type locality of the Plainfield has never been specified precisely, but it is presumably in the township of that name whose south border is only one mile north of the northeast corner of the Voluntown quadrangle. The name Blackstone Series is not appropriate as the Ashaway and Voluntown quadrangles are more than 30 miles from the type locality (Quinn, 1949) and correlation of the two rock units, separated by the bulk of the Rhode Island batholith, is yet uncertain.

Four general rock types have been mapped within the Plainfield Formation; (1) feldspathic biotite gneiss and schist, (2) quartzose biotite gneiss and schist, (3) calc-silicate quartzite and calc-silicate granofels, and (4) quartzite. Calc-silicate quartzite within the quartzite was not mapped separately.

Feldspathic biotite gneiss and schist

About 10 square miles of the Ashaway quadrangle ~~are~~ is underlain chiefly by dark feldspathic biotite gneiss and schist which occur principally in two large bodies; one between Canonchet and a point one mile northeast of Ashaway, and the other between Ashaway and Chase Hill. The rock is mostly medium to dark gray, medium-grained, equigranular, well-foliated gneiss and schistose gneiss composed predominantly of feldspar, quartz, and biotite. Compositional layering is pronounced. Layers, from 1 cm or less to 1 meter thick, differ principally in mafic-to-felsic mineral ratio. Granitic material, as sills (and less commonly as dikes) of pink aplite, granite, and pegmatite, has permeated the rocks and distorted the foliation of many outcrops (fig. 7). The contact between granitic material and host rock is in part sharp and in part diffuse. In places, as 0.55 mile east of the summit of Chase Hill, the rock is

Figure 7. - Plainfield Formation, feldspathic biotite gneiss intruded by sills and dikes of coarse pegmatite. Note sharp contacts, commonly with biotite selvages, as to right of hammer. Hammer handle is 38 cm long. Roadcut 0.64 mile N.68°E. of Hopkinton village, Hopkinton, R. I.

a migmatite. Porphyroblasts of pink to beige subhedral feldspar as much as 4 cm long constitute as much as 20 percent of the rock 0.38 mile east of McGowan Corners and at a few other places. Hornblende, commonly as black poikilitic grains 1 to 3 mm in diameter, is locally a conspicuous constituent, and in places exceeds biotite in abundance.

The gneiss in a broad arc from Canonchet to Laurel Glen is more uniform and has less compositional layering than rock of any comparable area within this part of the Plainfield Formation. The rock is a medium-grained, beige to light gray, well-foliated feldspar-quartz-biotite gneiss. Porphyroblasts of light gray to pink feldspar, as much as 8 by 25 mm, and small magnetite octahedra surrounded by mafic-free quartz-feldspar shells are common. The gneiss parts readily along planar, lustrous, biotite-rich foliation planes. On the State line, 1.2 miles northwest of Hopkinton village, the gneiss is highly contorted and the foliation has no single trend.

The base of the feldspathic biotite gneiss and schist is not exposed in the Ashaway quadrangle. The upper contact with quartzite is not sharp. The two rock types are intercalated in a zone several meters thick well exposed 0.6 mile southwest of South Hopkinton and around the periphery of the quartzite in the syncline east of Ashaway.

Amphibolite and quartzite are quantitatively unimportant, but, as will be shown later, they shed much light on the origin of the sequence.

Amphibolite constitutes the bulk of an outcrop on the south shore of Wyassup Lake. Here black, coarse-grained layers composed almost entirely of hornblende are intercalated with fine-grained dark gray plagioclase amphibolite, layers rich in biotite, and massive and thinly laminated quartzite. Veins of epidote and calcite cut parts of the outcrop. A 2-meter long lens of fine-grained amphibolite occurs in otherwise normal light gray feldspathic biotite gneiss, 0.73 mile S.55°W. of the outlet of Ashville Pond. Much of the irregular body in Potter Hill Granite Gneiss on the southeast slope of Mount Moriah is amphibolite and dark biotite schist.

Layers of pure to feldspathic and biotitic quartzite a few centimeters thick are common, as on Chase Hill just north of BM "Potter", and 0.32 mile S.61°W. of the outlet of Shingle Mill Pond.

Thin section study shows that most samples of feldspathic biotite gneiss and schist consist of quartz, two feldspars, biotite, and a sparse accessory suite. Hornblende occurs with, or in place of biotite in some samples.

Quartz is clean and slightly strained, although in samples between Shingle Mill Pond and Hopkinton village grains have strong strain shadows. Inequidimensional grains have long axes in the plane of the foliation. Where quartz is in two coexisting grain sizes, as southeast of McGowan Corners, only the large grains have strain shadows. Grain borders are involuted in quartz-rich samples.

Microcline, which is fresh and shows prominent grid twinning, exceeds plagioclase in most specimens except those rich in hornblende. Perthite is rare to absent. Plagioclase ranges from middle oligoclase in felsic gneiss to andesine or labradorite in dark gray hornblende-bearing gneiss. Most oligoclase is dusted with white mica or completely altered to a very fine white mica aggregate. Albite law twinning is moderately well developed in most samples, and myrmekite rims are locally prominent. Albite rims against adjacent microcline are characteristic of some plagioclase, especially in rock northeast of Laurel Glen.

Biotite is fresh, though the smallest flakes in many thin sections are chloritized. Zircon inclusions surrounded by radiohalos are ubiquitous. Pleochroism is quite uniform; X = straw yellow to yellow tan, and Z = dark brown to opaque. The Z color of some flakes has an olive cast. Where present, muscovite (rare in this group of rocks) occurs as leaves in, or appendages on biotite.

Hornblende, a common green variety, is present in about a tenth of the samples. Grains are fresh with X = pale yellow-green, Y = dark green to dark greenish brown, and Z = dark green; $X < Y \leq Z$. Hornblende in the coarse amphibolite on the south shore of Wyassup Lake has a bright blue-green Z color.

Apatite, magnetite, sphene, and zircon occur sparingly in most thin sections. Allanite is found in most hornblende-bearing gneiss, and commonly has a rim of epidote (or clinozoisite?). Sparse small scapolite porphyroblasts and epidote granules, visible only in thin section, occur in a feldspar-quartz-biotite-hornblende gneiss 0.17 mile north of Ashaway-Alton Road 0.5 mile west of the east border of the Ashaway quadrangle.

Quartzose biotite gneiss and schist

A 2.5-square mile crescent from a point one mile east of Pendleton Hill to a point one mile east of Mount Misery is underlain by quartzose biotite gneiss and schist. Conspicuous lenslike pods of clear gray quartz from 1 to 10 cm or more in diameter, extreme waviness of foliation (fig. 8), and well-developed compositional layering (fig. 9) characterize nearly all exposures. Principal rock types range from slightly biotitic light gray quartzite

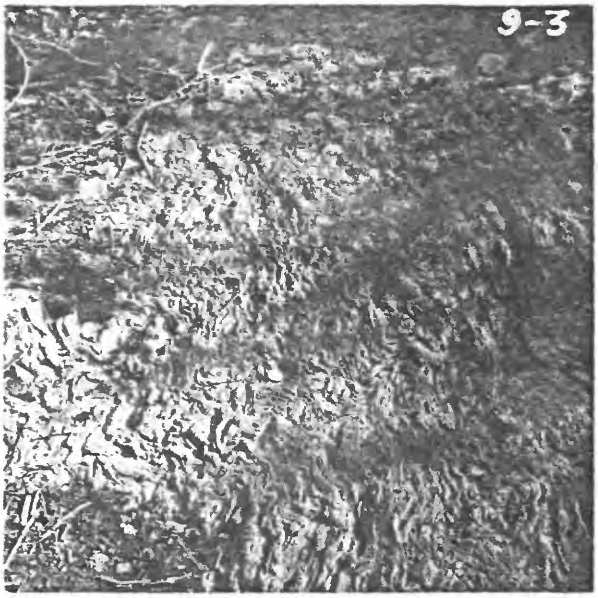


Figure 8. - Plainfield Formation, quartzose biotite gneiss, much crumpled. Quarter gives scale. West shore of Green Fall Pond 0.35 mile north of the dam, Voluntown, Conn.

Figure 9. - Plainfield Formation, quartzose biotite gneiss studded with lenslike pods of clear gray quartz. Note compositional layering. Gray layer near bottom is fine-grained, nearly pure quartz quartzite with thin micaceous partings. Hammer handle is 38 cm long. Green Fall Pond dam, Voluntown, Conn.

to dark gray quartz-plagioclase-biotite gneiss. Quartz-biotite-muscovite-sillimanite schist, biotite-sillimanite quartzite, and light-colored feldspathic gneiss are also present. Amphibolite and calc-silicate granofels constitute lenses and layers in some outcrops.

Medium-grained, light to medium gray, gnarly quartz-biotite gneiss with myriads of lenslike quartz pods is the most abundant single lithologic type and is well exposed at Green Fall Pond dam. Fine-to medium-grained, tan, feldspathic biotite gneiss constitutes much of the outcrops on the west slope of the Green Fall River valley one mile north of the south border of the Voluntown quadrangle. Thin amphibolite layers are present in some outcrops as at the head of Denison Brook. Soft, rusty-weathering biotite-muscovite-quartz-sillimanite schist is abundant immediately northwest of Green Fall Pond. Small resistant sillimanite-rich aggregates as much as 1.2 by 0.5 cm stand in relief on the surfaces of many of the schist outcrops.

Granitic material is far rarer than in the feldspathic biotite gneiss and schist, but pale pink aplite and less commonly pegmatite, principally as sills, are locally important. The largest sills are Hope Valley Alaskite Gneiss and are shown on the geologic map. Migmatite is uncommon.

Minerals in thin section are fresh. Quartz is generally the most abundant. In the lenslike pods it is as perfectly clear and unstrained interlocking grains commonly several millimeters in diameter. Coexisting matrix quartz grains are very much smaller, rarely more than 1 mm in diameter, slightly strained, and commonly show relic sutured intragrain boundaries.

Where two feldspars are present, plagioclase is generally considerably more abundant than microcline, and in many thin sections it is the only feldspar. The composition in most rocks is between calcic oligoclase and sodic andesine, and grains are generally very lightly dusted with white mica. Plagioclase in amphibolite layers ranges widely, from middle andesine (An_{37}) to bytownite (An_{73}). Microcline is fresh, non-perthitic, and ranges from very feebly to moderately well grid-twinned.

Biotite is strongly pleochroic with X = light yellow-tan, and Y = Z = dark golden brown. Biotite in sillimanite-bearing rocks is paler with X = colorless to light reddish tan, and Y = Z = medium red-brown. Zircon inclusions with radiohalos are common. Pale tan phlogopite is sparingly present in some calc-silicate quartzite layers.

Muscovite is abundant only in two-mica sillimanite schist where large flakes, commonly crowded with tiny needles of sillimanite, constitute as much as 20 percent of the rock. In other rock types muscovite occurs sparingly as leaves in biotite or as tiny plumose fronds. It is absent in amphibolite and calc-silicate quartzite.

Hornblende in amphibolite layers is similar to that in amphibolite layers in feldspathic biotite gneiss and schist described above. Allanite inclusions with radiohalos are prominent in some grains. Colorless to very pale green tremolite is present in most calc-silicate quartzite layers, many of which also bear colorless diopside.

Sillimanite is principally the variety fibrolite; hair-like needles 0.02 mm or less in diameter which occur separately or in bunches in rusty-weathering two-mica schist. The fibrolite is both interstitial and as inclusions in quartz and muscovite. Where sillimanite constitutes the bulk of a thin section, it occurs both as fibrolite and as stubby euhedral prisms as much as 0.7 mm in diameter. Trace quantities of fibrolite are present in some gray feldspathic gneiss layers. Quartz grains in sillimanite-bearing rocks generally bear scattered [illegible] ted fibrolite needles.

Scapolite is a major constituent [illegible] medium-grained hornblende-rich gneiss 0.56 mile N.21°W. of the Green Fall Pond. The scapolite, which occurs as poikilitic grains interlocked with green hornblende, is approximately $Ma_{30}Me_{70}$ by the data of Winchell (1951, p. 353); $n_\epsilon = 1.561 \pm 0.001$, $n_\omega = 1.585 \pm 0.001$, $n_\omega - n_\epsilon = 0.024 \pm 0.002$. The mineral is colorless in thin section and pale green in the hand specimen. Other minerals in this somewhat unusual gneiss are biotite (30 percent), labradorite (6 percent), and minor apatite, magnetite, and sphene.

Allanite, apatite, magnetite, and zircon are sparingly present in most thin sections. Calcite and epidote occur in calc-silicate quartzite, the latter only where tremolite and diopside are absent. Sparse tiny garnet anhedra are scattered through a gray plagioclase-quartz-biotite gneiss 0.34 mile S.70°E. of the outlet of Green Fall Pond.

Calc-silicate quartzite and calc-silicate granofels

Five areas of calc-silicate quartzite and calc-silicate granofels in the Ashaway quadrangle are large enough to show on the geologic map. Four are in feldspathic biotite gneiss and schist east and north of Maxon Hill, and the fifth is in Potter Hill Granite Gneiss 1.2 miles northwest of Bumpin Hill.

The rocks in this group range from pale green-gray to black.

Most are medium-grained and bear conspicuous chartreuse epidote or green diopside or tremolite or both. Nearly all outcrops show well-developed compositional layering and many have vuggy surfaces owing to preferential weathering of non-resistant calc-silicate minerals and calcite. Quartz-rich layers are gray to green-gray. Quartz-hornblende layers range from steel-gray to black, and locally bear stubby black poikilitic hornblende porphyroblasts as much as 3 cm in diameter. Abundant epidote, as 0.55 mile S.26°E. of Hopkinton village, colors some layers bright chartreuse. The rocks are generally exceedingly heterogeneous, especially where coarse-grained. Minerals occur in clots and streaks, and mineral abundances of many thin sections differ greatly from estimated megascopic modes of samples from which they were cut. Joint faces in some outcrops are coated with secondary epidote and calcite.

Common mineral assemblages are (quartz universally present): labradorite-epidote-hornblende-diopside, labradorite-epidote-actinolite-diopside, microcline-hornblende-epidote-scapolite, and bytownite-hornblende-diopside. Mineral pseudomorphism or replacement is not visible in thin section.

Quartzite

Thirteen bodies of quartzite occur in the Ashaway and Voluntown quadrangles. Although now separated by as much as several miles, many of the bodies were probably once continuous as a single stratigraphic unit. The quartzite is the most uniform metamorphic rock in the quadrangles.

Most outcrops reflect the strong layering of the quartzite (fig. 10). Individual layers range from less than 1 cm to more than a meter thick, although most are between 3 and 8 cm. Layers, which are typically planar, are separated by thin relatively biotite-rich selvages, Surfaces of some layers in the Voluntown quadrangle are deeply slickensided (fig. 11) as on the 520-foot hill on the west side of Gallup Road and 0.3 mile east of the church on Pendleton Hill. Layering in much of the quartzite between Wyassup Lake and Pendleton Hill is wavy, and individual layers are broadly lenslike. The large body a mile west of Ashaway is much deformed and its layers are tightly folded. In some exposures, as in the large abandoned quarry 1.5 miles west of Green Fall Pond, the quartzite is nearly massive. Here, the only layers are sparse, thin, and vague purplish horizons of quartzite containing a little biotite.

Frost action has extensively fractured most quartzite outcrops and many, especially in the Voluntown quadrangle, are completely reduced to a scree of angular blocks.

The quartzite ranges from a nearly pure quartz rock to biotite quartzite, and locally to calc-silicate quartzite. Typical fresh rock is fine- to medium-grained and light tan; weathered rock is light gray. Quartz constitutes more than 75 percent of most rock and only rarely is it less than 50 percent. Impurities (excluding calc-silicate minerals) are biotite and feldspar. The former is the more abundant; a quarter or more of the quartzite is a gray biotite quartzite, or less commonly, well-foliated dark gray quartz-biotite gneiss. Biotite is both evenly distributed through the rock as small alined pale brown flakes and concentrated in thin schistose layers. Feldspar is usually only visible on weathered surfaces as small chalky spots.

Calc-silicate quartzite, conglomerate, sillimanite quartzite, garnetiferous biotite schist, and amphibolite occur as lenses and

Figure 10. - Quartzite of the Plainfield Formation showing thick uniform layering. Hammer handle is 38 cm long. 0.47 mile east of intersection of Babcock and Voluntown Roads, North Stonington, Conn.

Figure 11. - Quartzite of the Plainfield Formation. Layer showing slickensides on surface. 0.2 mile southeast of abandoned quarry midway between Hodge and Palmer Ponds, Voluntown, Conn.

layers in quartzite and biotite quartzite. Only calc-silicate quartzite is common.

Calc-silicate quartzite is green and commonly somewhat coarser-grained than adjacent lime-free quartzite. It occurs in nearly all the quartzite bodies mapped, but individual layers are not laterally extensive and correlation from one body to another is not possible.

Calcite-bearing calc-silicate quartzite weathers readily. Layers of this rock on the west slope of Pendleton Hill are soft, partly disaggregated, and etched back as much as a meter from overlying and underlying clean quartzite.

Prominent outcrops of calc-silicate quartzite are north of Babcock Road on the 240-foot knob 0.4 mile west of Voluntown Road, and 0.3 mile east of the west border of the quadrangle. Veins and knots of quartz and pale green actinolite cut the latter outcrop.

A few quartzite outcrops in the Voluntown quadrangle contain conglomerate layers. The best exposures are on the 520-foot hill west of Gallup Road, and 0.32 mile S.46°W. of the intersection of Sand Hill and Wheeler Roads. Clasts are composed principally of quartz and minor megascopic muscovite, and are lenslike with their short axes normal to foliation and layering. Nearly all are 1.5 to 3 cm in diameter and 1 to 2 cm thick. The matrix ranges from clean tan quartzite to granular-weathering, slightly feldspathic brown quartzite. Clasts in the latter are conspicuous on weathered surfaces where they stand out in relief as white knots owing to their superior resistance. In the tan quartzite matrix the clasts are inconspicuous white spots on a light gray surface.

Megascopic sillimanite in quartzite is restricted to a few outcrops southwest of the intersection of Sand Hill and Wheeler

Roads. Amphibolite layers, uncommon except near the contact zone with overlying amphibolite, are present in some outcrops west of Gallup Road. Garnet-biotite schist crops out just north of Babcock Road a half mile east of the west border of the Ashaway quadrangle.

Contact between quartzite and overlying amphibolite, like that with underlying gneiss is by intercalation of the two rock types. This type of contact is especially well exposed north of Wyassup Lake.

Granitic material is not abundant in quartzite. Dikes and sills of pegmatitic Narragansett Pier Granite are locally plentiful south and southeast of Diamond Hill. Potter Hill Granite Gneiss has intruded quartzite a mile west of Ashaway, and the massive facies of the same granite constitutes much of the outcrops mapped as quartzite just north of the railroad 0.4 mile northeast of McGowan Brook.

Thin section study of the quartzite confirms the uniformity suggested by field study of outcrops. Quartz grains are slightly strained, and contain abundant unoriented inclusions of mica, feldspar, and smaller round quartz grains from 0.04 to 0.3 mm in diameter. These inclusions in the quartz are not common in other rock in the quadrangles. Although the megascopic texture of most of the quartzite appears to be fine- to medium-grained, thin section study shows that the component quartz grains of many specimens are very much larger, commonly 4 or 5 mm in diameter. Like all metamorphic quartzites, this rock breaks through grains rather than around them, and the apparent grain size on freshly broken surfaces of some specimens reflects the hackly fracture of the inclusion-bearing quartz grains, not the true grain size of the rock.

Potassium feldspar (microcline) and plagioclase occur in most specimens, but together they rarely constitute as much as 10 percent of the rock. The relative abundance of the two feldspars ranges widely, although plagioclase is normally predominent in biotite-rich quartzite. Microcline is moderately well grid-twinned. Plagioclase ranges from middle oligoclase to middle andesine. Weak twinning and extensive alteration to white mica aggregates make precise determinations impossible in some thin sections. Plagioclase in calc-silicate quartzite is fresh, well twinned, and ranges from middle andesine to calcic labradorite.

Nearly all the thin sections of the quartzite examined contain from 1 to 5 percent biotite, although it ranges up to 32 percent. Flakes are moderately pleochroic with X = light yellow-brown or light red-brown, and Y = Z = medium to dark brown or dark red-brown. Some are slightly chloritized. Zircon inclusions with radiohalos are ubiquitous. The mica in calc-silicate quartzite layers is a pale phlogopite.

Diopside and tremolite, the former generally considerably more abundant than the latter, are the characteristic minerals in layers of calc-silicate quartzite. Both are generally colorless, although some tremolite has a light gray-green Z color.

Scapolite is present in some outcrops along the east side of Koistenen Brook from 0.07 mile north to 0.3 mile south of Sand Hill Road in the Voluntown quadrangle.

Muscovite, nowhere as plentiful as biotite, is present in trace quantities in many thin sections as small shreddy flakes or as leaves in biotite crystals. Rarely it occurs as large subhedral flakes and constitutes 2 or 3 percent of the rock.

Apatite is the most common accessory mineral and occurs in more than half the thin sections studied. Magnetite, in part converted to limonite, is nearly as common. Calcite, epidote, sphene, and zircon are almost equally abundant and occur in about one third of the thin sections studied. Calcite and epidote occur principally in calc-silicate quartzite. Zircon is most common as inclusions in biotite. Allanite, clinozoisite, garnet, and sillimanite are rare accessories.

Metavolcanic rocks

Metavolcanic rocks underlie much of the area around Westerly and Pawcatuck, the southeast slope of Diamond Hill, a small area east of Pitcher Mountain, and an arc-shaped area from Wyassup Lake northward to a point 1.5 miles south of Voluntown. Five units are recognized. Two units, mafic and intermediate metavolcanic rocks, and felsic metavolcanic rocks, are mapped north of Wyassup Lake. These are not distinguished north of approximately the Voluntown-North Stonington town line owing to scarcity of outcrop. Three units, amphibolite, layered felsic gneiss, and calcareous felsic gneiss, have been mapped in other parts of the area.

The metavolcanic rocks everywhere overlie quartzite of the Plainfield Formation. Amphibolite is overlain by, and is thus older than layered felsic gneiss and calcareous felsic gneiss. The metavolcanic rocks north of Wyassup Lake are probably equivalent to the amphibolite and layered felsic gneiss to the south, but the correlation is uncertain.

Amphibolite

Gray medium-grained amphibolite constitutes much of the metavolcanic rock exposed around Westerly and Pawcatuck, the southeast slope of Diamond Hill, and east of Pitcher Mountain. Martin (1925, p. 19-20, map) was the first to recognize this rock, although she did not distinguish it from other metamorphic rocks on her geologic map.

The amphibolite ranges from very dark gray or black rock composed largely of hornblende, to light gray plagioclase-hornblende-biotite-quartz gneiss. Accessory calcite, garnet, and sphene are megascopically identifiable in some exposures.

Most of the rock is prominently foliated and layered; layers most commonly differ only in texture or in the relative abundance of minerals (fig. 12), and are a few centimeters thick. In some outcrops, however, Amphibolite bears intercalated layers of other rock types, particularly fine-grained light gray quartzite, pale green calc-silicate quartzite, feldspathic gneiss, and biotite schist. These range from a centimeter or less to several meters thick. Good examples can be seen in cuts on Westerly-Bradford Road just east of Pound Road, on the hill west of Nooseneck Hill Road just south of Pawcatuck River, and in much of the amphibolite southeast of Diamond Hill.

Sills, dikes, and irregular masses of Narragansett Pier Granite and related pegmatite are locally abundant in amphibolite as east of Chapman Pond and north of Nooseneck Hill Road between Stillmanville and Pawcatuck River. Some outcrops at the latter locality are migmatite. Other sills are in part fine-grained Potter Hill Granite Gneiss.

Foliation and layering are generally grossly planar but undulant on a small scale owing to pinch-and-swell of some layers. In addition, knots of pegmatite and spindles of fine-grained dark amphibolite (fig. 13) bow apart layers in some outcrops. Much of the

Figure 12. - Amphibolite showing layering. Layers differ principally in hornblende and plagioclase abundance. Coarse-grained white layers composed nearly exclusively of plagioclase have a pegmatitic texture, North Anguilla Road 0.17 mile north of Elm Ridge Road, Stonington, Conn.

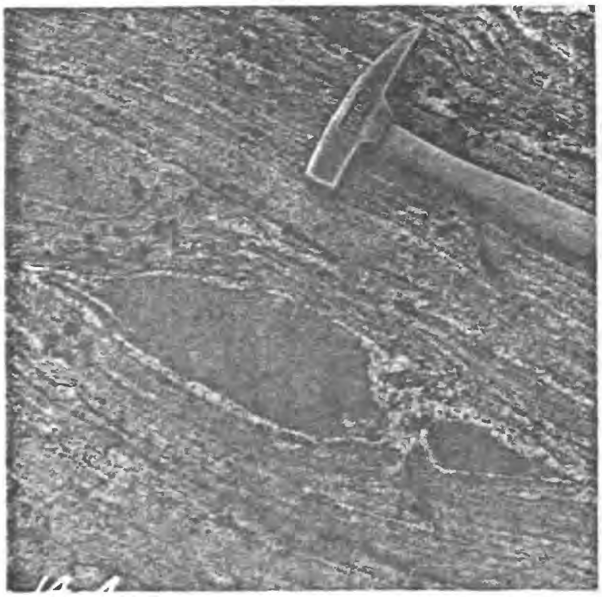


Figure 13. - Spindle of fine-grained dark amphibolite in normal medium-grained layered amphibolite. Fracture on right is filled with white oligoclase-hornblende pegmatite. Spindle is 40 cm long. 0.57 mile N.48°W. of the summit of Hinkley Hill, Stonington, Conn.

rock in the syncline southeast of Diamond Hill is tightly folded.

Contacts of amphibolite and layered felsic gneiss are mostly broad zones of intercalation of the two rock types. Much of the layered felsic gneiss in Pawcatuck contains layers of amphibolite, although only one is large enough to show on the geologic map. South of this layer amphibolite is very scarce.

The heterogeneity of amphibolite and of other intercalated rock types is very great. In general, minerals are fresh or only very slightly altered, and free of strain shadows. Individual grains lie with longest axes in the plane of rock foliation.

Typical medium to dark gray amphibolite is composed of 35 to 50 percent plagioclase, 25 to 55 percent hornblende, 0 to 18 percent quartz, 0 to 6 percent biotite, and 1 to 5 percent each of apatite, chlorite, magnetite, and sphene, and trace amounts of calcite, epidote, garnet, and zircon. Lighter-colored layers are richer in plagioclase, quartz, and biotite, and poorer in hornblende. Garnet in amphibolite ranges from red-brown almandite ($n = 1.825 \pm 0.005$) to pale pink garnet of $n = 1.795 \pm 0.005$ that is probably 75 percent almandite and 25 percent pyrope (Winchell, 1951, p. 487).

Plagioclase is andesine from An_{32} to An_{42}. Grains range from fresh to largely converted to white mica aggregates, commonly within a single thin section. Albite law twinning is prominent.

Hornblende is strongly pleochroic. Colors range widely, although X = light yellow-brown to light green-brown, Y = medium green-brown, and Z = medium to dark brown-green to blue-green are the most usual, and $X < Y \leqslant Z$ in all samples. In some thin sections hornblende occurs in two distinct habits; as large equant poikilitic anhedra, and as small alined subhedral prisms. Inclusions of bright green chlorite with sharp contacts are dispersed in some grains.

Biotite is slightly to extensively chloritized. Pleochroic colors range widely; in most X = light yellow-tan, and Y = Z = olive-brown to dark red-brown. The associated chlorite contains magnetite and is bright green with strong anomalous blue interference colors. Zircon with radiohalos is sparingly distributed in both biotite and chlorite.

Quartz is present in some amphibolite, but only rarely exceeds 15 percent. It occurs as small inclusion-free round to broadly sutured grains, which in some thin sections are grouped in small pods.

Microscopic calcite-epidote veins crosscut the foliation and layering in some amphibolite.

The mineral composition and texture of quartzite and calc-silicate quartzite layers in the amphibolite are like those of similar rock types in the underlying Plainfield Formation. Plagioclase (andesine) is the principal feldspar in quartzite which also contains minor biotite, chlorite, and muscovite. Calc-silicate quartzite mineral assemblages are diopside-tremolite-andesine-quartz (with and without calcite), and labradorite-epidote-diopside-quartz.

Layered felsic gneiss

Layered felsic gneiss underlies a strip along the south border of the Ashaway quadrangle westward from Westerly. Similar rock underlies much of the west half of the Watch Hill quadrangle to the south (George E. Moore, Jr., personal communication). The layered felsic gneiss and the granitic rocks have, at least in part, similar mineral and chemical compositions, but very dissimilar textures and structures. Some layers of light-colored feldspar-quartz-biotite gneiss of the Plainfield Formation, however, as west of Old Rockville Road 0.3 mile north of Hopkinton village, are indistinguishable from layered felsic gneiss exposed in Pawcatuck.

Martin (1925) was the first to distinguish the layered felsic gneiss of the present study from Sterling Granite Gneiss. She mapped this rock as "injection gneiss" and defined it as a composite of "ancient schist" and various granitic rocks including the Sterling.

The layered felsic gneiss is medium-grained, and ranges from light pink and light pinkish gray to medium gray. It is composed of feldspar, quartz, biotite, and hornblende in order of decreasing abundance. Hornblende exceeds biotite in places. Megascopic differences between quartz and feldspar, and between microcline and plagioclase are subtle, and discrimination of these minerals is difficult in most outcrops. Mafic minerals are generally less than 3 percent of the gneiss, and nowhere exceed 15 percent.

Prominent layering is the most obvious characteristic of the gneiss, and outcrops appear banded. Differences of color, texture, and mineral composition distinguish adjacent layers which generally have sharp contacts and range from less than a centimeter to a meter or more thick. Layers are persistent and can be traced across large outcrops.

Thin sills of pink to white pegmatite, generally only a centimeter or two thick, which constitute several percent of most outcrops tend to accent the layering. Similar pegmatite is also discordant.

Fine-grained, pink, predominantly aplitic granite, some with rotated inclusion of host gneiss (fig. 14) is common as discordant bodies, and in places constitutes the bulk of an outcrop.

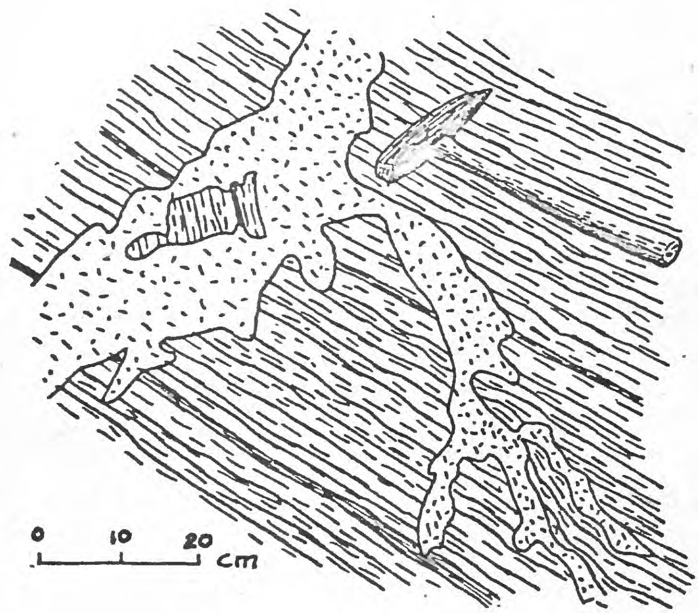


Figure 14. - Layered felsic gneiss cut by fine-grained aplitic pink granite containing rotated inclusion of host. Traced from a photograph. 0.4 mile S.68°E. of the summit of Hinkley Hill, Stonington, Conn.

Blocks of amphibolite as much as a meter in diameter are exposed in outcrops of layered felsic gneiss north of Norwich Road in Pawcatuck. Similar blocks, as well as lenses and layers of amphibolite and hornblende-biotite schist are widespread in the gneiss, but are nowhere abundant. Only the amphibolite layer on Hinkley Hill is of mappable size.

A few quartzite layers are intercalated in layered felsic gneiss on the south slope of Hinkley Hill in the Watch Hill quadrangle (George E. Moore, Jr., personal communication).

The top of the layered felsic gneiss is not exposed in the Ashaway quadrangle; the base is intercalated with amphibolite.

Thin sections of layered felsic gneiss show that the rock consists of from 25 to 35 percent quartz, 50 to 75 percent feldspar, and 0 to 15 percent mafic minerals. Accessory minerals are restricted to sparse apatite, magnetite, sphene, and zircon. Apatite constitutes as much as 2 percent of medium gray hornblende-bearing layers.

Quartz is unstrained to slightly strained. Grains have simple borders.

On the basis of the relative abundance of microcline and plagioclase, the gneiss has a composition ranging from granite to quartz diorite. The microcline is fresh and shows grid-twinning; plagioclase ranges from sodic oligoclase to sodic andesine. Commonly within a single thin section some plagioclase grains are fresh and others are extensively sericitized. Some grains have borders of myrmekite where in contact with microcline.

Biotite is strongly pleochroic with X = straw yellow, and Y = Z = dark brown to dark red-brown. Some flakes are partly chloritized and zircon inclusions with radiohalos are common. Hornblende is prominent only in medium gray layers, as 0.33 mile N.80°W. of the intersection of Norwich Road and Pequot Trail, where it constitutes as much as 10 percent of the rock.

Most of the fine-grained granite that cross cuts the layered felsic gneiss is aplitic and nearly free of mafic minerals. This granite is very potassic, with slightly perthitic microcline greatly in excess of plagioclase. The latter is sodic oligoclase with ubiquitous albite borders where in contact with microcline. Some of the fine-grained discordant granite, however, is unlike the potassic aplitic granite. It has a granitoid texture, a microcline-to-plagioclase ratio near unity, and contains from 1 to 3 percent biotite, commonly as acicular flakes as much as 2 mm long. This granite is probably Westerly Granite from which it is indistinguishable in thin section, and which it greatly resembles megascopically. Also, much of the Westerly that has been mapped, especially that in the smaller dikes, is characterized by sporadic acicular biotite (fig. 20), which is not present in other rocks of the area.

Good exposures of the aplitic potassic and Westerly granites in layered felsic gneiss are in a cut on Pequot Trail 0.15 mile S.25°E. of the summit of Hinkley Hill, and just south of Pequot Trail 0.65 mile east of Elm Ridge Road, respectively.

Calcareous felsic gneiss

A feldspathic gneiss grossly similar to the layered felsic gneiss described above, but which contains calcite and calc-silicate minerals, is exposed in a half dozen outcrops between Reuterman and Babcock Roads in the Ashaway quadrangle. The outcrops are small and the rock is poorly exposed.

The gneiss is beige to pink and medium-grained; Compositional layering is very prominent. Layers are generally thin, no more than a few centimeters thick, and the compositional contrast of adjacent layers is commonly great. Many layers are granitic and are either equigranular, or have porphyroblasts of pink microcline as much as 2 cm in diameter. Gray layers are quartz-rich. Some layers are composed principally of epidote, and others are hornblende-rich.

The solution of calcite has left many outcrop surfaces extensively pitted. Rust-lined cubic voids, probably once sites of pyrite crystals, dot the surfaces of some layers. Additional pyrite in this gneiss at depth is probably the source of the abundant iron in local ground water. Cobbles in the brook east of Pitcher Mountain are coated with limonite for several hundred meters downstream from this rock.

Only two thin sections of the calcareous felsic gneiss were examined, an inadequate number for a thorough description of such a heterogeneous rock. Calcite is an abundant accessory in both sections.

Granitic layers are composed of slightly strained quartz, fresh microcline with prominent grid-twinning, sericitized plagioclase (oligoclase?), and pale green biotite.

Calc-silicate mineral assemblages (calcite and quartz present in all) are: epidote-green biotite-bluish green hornblende-microcline-oligoclase (An_{28}), and epidote-garnet-diopside-scapolite-microcline-tremolite. The garnet ($n = 1.832 \pm 0.004$) is 60 percent andradite, and 40 percent grossularite based on the data of Winchell (1951, p. 491). Tremolite occurs as tiny anhedra in diopside.

Mafic and intermediate metavolcanic rocks

More than half the area of metavolcanic rocks from Wyassup Lake to a point 1.5 miles northeast of Billings Lake is underlain by mafic and intermediate varieties. Sparse outcrop suggests that most of the area mapped as undivided metavolcanic rocks is underlain by similar rock.

The metavolcanic rocks in the Wyassup Lake-Billings Lake area have not previously been described in detail. Loughlin (1912) mapped the rocks as "gray quartz-biotite schist" and did not distinguish them from the rocks farther east (quartzose biotite gneiss and schist of the Plainfield Formation in the present study).

Many rock types constitute this unit, but some distinctive characteristics are common to nearly all. The rocks range from gray to deep green-gray and black and are fine- to very fine-grained. Most are foliated and strikingly laminated. Individual laminae, which differ in mineral composition, in relative abundance of minerals, or in texture, are generally a millimeter or less thick. In some rocks more than 25 laminae per centimeter are megascopically discernable. Massive layers are mostly extremely fine-grained to aphanitic, and break with a subconchoidal fracture. The fine grain size of all rocks in this unit make quantitative field identification of component minerals uncertain, and renders the rocks darker-colored than coarser-grained rocks of identical mineral composition.

Amphibolite is the predominant rock type. Hornblende-rich amphibolite is black. Gray amphibolite is relatively richer in plagioclase, and much of it contains quartz and microcline. Biotite is present locally in all amphibolite, and is especially conspicuous on surfaces of biotite-rich laminae along which the rock preferentially parts. Foliation planes coated with granular white calcite are abundant in some outcrops. The bulk of the hornblende in plagioclase-rich gray amphibolite is as lenslike black porphyroblasts, 0.5 cm in diameter, that are encased in shells of plagioclase. Some amphibolite layers are "rubbly"; they are composed of irregular knots and fragments of hornblende and plagioclase generally less than a centimeter in diameter, but locally several times larger.

Quartzite, feldspar-quartz-biotite schist, feldspathic gneiss, and sillimanitic schist, in order of abundance, are intercalated with amphibolite. They nowhere constitute the bulk of an exposure.

Quartzite is in layers from a centimeter to several meters thick. Most is clean and tan to light gray, although in places it is biotitic and darker gray. Nearly all layers are characterized by alternating gray to white very fine-grained granular laminae and gray vitreous laminae, commonly several to the centimeter ("pin-stripe quartzite"). Feldspar-quartz-biotite schist is gradational with biotite amphibolite and amphibolite. Relative abundance of biotite and hornblende in these rocks cannot be accurately estimated in the field. Feldspathic gneiss layers are like the bulk of the felsic metavolcanic rocks described below. Sillimanitic schist is exposed in a single outcrop 0.67 mile N.53°W. of the summit of Pendleton Hill.

Lamination and layering are planar in approximately half the exposures. Elsewhere the rocks are in folds which range from broad and open with amplitudes as much as 20 meters, as in the cliff 0.19 mile S.57°E. of the northwest corner of the Ashaway quadrangle, to outcrops composed entirely of minutely crinkled rock as at the head of Dark Hollow Brook.

Thin sections are particularly valuable in the study of these rocks owing to their fine grain size. Thin section modes commonly differ greatly from estimated megascopic modes made during mapping, but they confirm the general correlation between rock color and hornblende content of amphibolite. Minerals are generally fresh, and the composition of the mafic and intermediate metavolcanic rocks is much like that of the amphibolite and intercalated rocks at Westerly and Pawcatuck, although the textures are entirely different.

Dark amphibolite is composed almost entirely of hornblende and andesine. The former, which constitutes from 60 to 75 percent of massive black layers, is strongly pleochroic; predominant colors are Z = very light yellow-tan, Y = medium yellowish green, and Z = medium blue-green, X < Y ≤ Z. Andesine is weakly twinned and is extensively sericitized in a few sections. Biotite and quartz are sparingly present in nearly all amphibolite, but exceed 2 and 5 percent respectively only in the lighter-colored rocks. Quartz grains are severely strained in many samples, and are composed of numerous sutured sub-grains. Accessory minerals are apatite, calcite, epidote, magnetite (rarely with pyrite cores), sphene, and zircon (only in biotite amphibolite). All occur only in trace quantities except magnetite and sphene which constitute as much as 3 percent each of some samples.

Gray granular laminae and gray vitreous laminae in "pinstripe" quartzite layers have unlike textures and compositions. The former are much like the clean quartzite of the Plainfield Formation. They are more than 95 percent quartz, as clean, slightly strained, sutured grains less than a half millimeter in diameter. Other minerals, as interstitial grains, are sericitized feldspar, small shreds of muscovite, magnetite, and rare zircon. Vitreous laminae, on the other hand, are composed only of quartz in large (1 by 5 mm), highly strained and sutured grains. Contacts between laminae are straight and sharp.

Mafic and intermediate metavolcanic rocks are intercalated with felsic metavolcanic rocks at contacts of the two. Unusually clean outcrops that show this relationship are 0.83 mile N.16°E. and 0.6 mile N.23° W. of the outlet of Wyassup Lake.

Felsic metavolcanic rocks

Felsic metavolcanic rocks of the present study were mapped as intrusive sheets of alaskite facies of Sterling Granite Gneiss by Loughlin (1912).

This unit is more uniform than the rocks that constitute the mafic and intermediate metavolcanic rocks. The bulk is felsic gneiss composed of quartz, feldspar, and little else. The gneiss is light pinkish gray to beige; most is fine-grained, although the range is from aphanitic to medium-grained. Very fine-grained rock has an aplitic texture; coarser rock is granitoid. Fine, very well-developed lamination and layering is pronounced in all outcrops, and causes much of the rock to break into thin slabs. Pink pegmatite and pegmatitic granite is ubiquitous in all but aphanitic rock, generally as abundant sills 2 cm or less thick which accent layering. In a few places pegmatite occurs as irregular dikes and contains broken black tourmaline crystals as much as 5 cm long and 1.5 cm in diameter. Refractive indices of tourmaline from three localities are within the range n_ϵ = 1.632 to 1.634, and n_ω = 1.654 to 1.658. Pleochroism is ϵ = pale pinkish tan, and ω = deep green-gray to opaque. The tourmaline is schorlite (Winchell, 1951, p. 465).

Locally the gneiss is gray and contains as much as 10 percent biotite, but it is without the hornblende prophyroblasts present in otherwise similar layers in the mafic and intermediate metavolcanic rocks.

Other rock types in felsic metavolcanic rocks are rare, although layers of gray schistose biotite gneiss and fine-grained amphibolite are sporadically intercalalated, especially near bodies of mafic and intermediate metavolcanic rocks. Quartzite is absent.

Layers and laminae are planar and undeformed in all but a few outcrops. Intense crumpling, characteristic of much of the mafic and intermediate metavolcanic unit, is present in only a single outcrop of felsic metavolcanic rock 1.1 miles N.45° E. of the southwest corner of the Voluntown quadrangle. At many places tightly folded layers of amphibolite are in contact with undeformed felsic gneiss. Surfaces of some layers of felsic gneiss, especially where veneered with milky quartz, are striated.

In thin section most minerals appear to be fresh, but nearly all show signs of considerable deformation. Grains have no preferred size, but range continuously from a maximum (generally 1 mm or less) to tiny individuals resolvable only under high magnification. Mineral abundances parallel those in layered felsic gneiss at Pawcatuck, and rock composition ranges from granite to quartz diorite.

Quartz grains are highly strained, and most are composed of intricately sutured sub-grains. Trains of tiny (0.01 mm) grains lie parallel to foliation in many sections, and surround larger quartz grains in others.

Potassium feldspar is microcline. Grid-twinning is only weakly developed, and commonly is much distorted. Some grains have been broken and spaces between offset fragments are filled with very finely comminuted microcline.

Plagioclase is oligoclase. Most grains are weakly twinned, and many have bent lamellae. Some grains are broken and have fractures filled with tiny blebby quartz grains. Oligoclase in some sections has myrmekite or albite rims where in contact with microcline.

Biotite, generally much chloritized, constitutes from 2 to 5 percent of most thin sections. Flakes are well alined and moderately pleochroic with X = straw yellow, and Y = Z = medium to dark yellow-brown. Radiohalos and bent flakes are rare.

Apatite, calcite, epidote, magnetite, muscovite, and pyrite are sparse accessories. Green hornblende constitutes several percent of two thin sections.

Calc-silicate quartzite

Three lenses of calc-silicate quartzite lie between augen gneiss and felsic metavolcanic rocks in the Voluntown quadrangle. Outcrops are abundant, and if the quartzite is continuous under augen gneiss, it must thin to practically nothing where not shown on the geologic map. This rock was first described by Loughlin (1912, p. 61-62).

Calc-silicate quartzite is fine- to medium-grained, light gray, and prominently layered. Bright green epidote is conspicuous in nearly all outcrops and is commonly concentrated in pods 2.5 by 0.8 cm. Layers rich in gray plagioclase contain dark green amphibole. Rock in some exposures, especially that in the middle lens, is medium gray feldspar-biotite quartzite with no calc-silicate minerals.

Layers range from undeformed and planar to intensely crumpled; the latter is well-developed in medium-grained two-mica quartzite at the east end of the west lens. Very fine-grained to aphanitic felsic metavolcanic rock is interlayered in much of the calc-silicate quartzite. Augen gneiss, however, is not intercalated with calc-silicate quartzite, and the contact, exposed in several places, is sharp and conformable. A few small, pink, schorl-bearing pegmatities cut calc-silicate quartzite 1.5 miles N.30°E. of the southwest corner of the Voluntown quadrangle.

Thin sections of calc-silicate quartzite all show much evidence of deformation. Mineral grains are strained and broken. Grain size within a single section ranges widely, and mortar structure is common. Composition is quite uniform; three sections have the following ranges (figures are percent): quartz 60, plagioclase 5 to 15, microcline 5 to 12, epidote 10 to 20, amphibole 2 to 5, and biotite 1 to 3. Apatite, calcite, magnetite, and sphene are ubiquitous accessories, and one section contains half a percent of scapolite. Other quartzite in this unit without calc-silicate minerals is similarly deformed. It is composed of 60 percent quartz, 15 to 35 percent feldspar, 5 to 25 percent mica, and accessory apatite, magnetite, and zircon.

Quartz grains are mosaics of highly strained and sutured subgrains. Many are crushed to grains 0.05 mm or less in diameter, and drawn out in trains parallel to rock layering.

Feldspar shows a weak twinning which is commonly bent. Mortar structure is especially well developed in microcline. Plagioclase is andesine in sections containing epidote, and oligoclase elsewhere. Grains range from fresh to much altered.

Biotite is partially chloritized in calc-silicate quartzite. It is fresh and flakes are bent around noses of microfolds with coexisting muscovite in crumpled two-mica quartzite.

Epidote is concentrated as large granules in altered plagioclase, but many grains and groups of grains are in quartz or microcline away from plagioclase. Grains are only faintly pleochroic, and middle first order interference colors are anomalous blue.

Amphibole is very pale green to colorless, and is probably actinolite.

Mafic metamorphic rock

About a dozen isolated lenslike bodies of mafic metamorphic rock have been mapped in the granitic rocks of the Voluntown quadrangle. All are very elongate. The largest, which extends northwestward from Deep Pond, is 1.6 miles long (with one small break), but is nowhere more than 0.07 mile wide. Some lenses in Escoheag Quartz Diorite Gneiss, too small to map, are only a few centimeters thick and a meter or two long. Foliation within all lenses is parallel with foliation in host granitic rock. Contacts are exposed at many places and all are concordant and sharp.

Rock ranges from fine- to coarse-grained, and from dark gray to black. Most is medium-grained and black, and all is well-foliated. Compositional and textural layering is rare. Texture is gneissic to schistose. Hornblende and biotite are the most conspicuous minerals and constitute the bulk of most rock. In coarse-grained rock, hornblende is commonly in porphyroblasts as much as 1.5 cm in diameter, whereas in fine-grained rock it is in tiny weakly-alined acicular crystals. Much of the rock in Hope Valley Alaskite Gneiss is permeated with thin, contorted, commonly aplitic-textured sills of the alaskite.

Thin sections show that the relative abundances of the ubiquitous minerals hornblende, plagioclase, and biotite range widely, and that each is the major constituent in some samples. Quartz and microcline are present in less than half the rock, and nowhere exceed 15 percent. Allanite, apatite, calcite, epidote, magnetite, pyrite, and sphene are accessory. Only epidote and magnetite exceed one percent in some samples. Minerals are fresh and unstrained.

Granitic rocks

The granitic rocks are separable into two groups: those of the Rhode Island batholith, and the younger granites. The granitic rocks of the Rhode Island batholith mapped here are augen gneiss, Escoheag Quartz Diorite Gneiss, porphyritic granite gneiss, Hope

Valley Alaskite Gneiss, Scituate Granite Gneiss, and Ten Rod Granite Gneiss. Nearly all are strongly foliated and lineated, and range from medium- to coarse-grained. Many are porphyritic. The younger granites- Narragansett Pier Granite and Westerly Granite- are largely confined to the Westerly area. Both granites are massive to weakly foliated.

All the granitic rocks are composed predominantly of feldspar and quartz. Other constituents rarely exceed 10 percent, and they exceed a quarter of the rock in only one of the more than two hundred thin sections examined.

Intrusive relationships and other evidence suggest that the relative ages are in the order in which the rocks are described in this section, beginning with the oldest.

Augen gneiss

Augen gneiss is confined to a single body, approximately 2.3 square miles, in the southwest corner of the Voluntown quadrangle. A small area has been mapped as a separate muscovitic facies. The augengneiss was mapped as part of the porphyritic facies of Sterling Granite Gneiss by Loughlin (1912). Although this facies of the Sterling includes some granitic rocks not mapped as augen gneiss in the present report, Loughlin's description (ibid., p. 120-122) clearly refers to the rock north of Billings Lake.

The augen gneiss is a resistant rock and outcrops are plentiful. Rock in the eastern part of the body has a normal, porphyritic, granitoid texture, whereas that along the quadrangle border to the west is a cataclastic gneiss with much smaller grain size, and intensely slickensided foliation surfaces. The two are distinguished on the geologic map. Glacial boulders of augen gneiss emphasize the textural difference between the "normal" and the cataclastic rock (fig. 15). Although the two types are sufficiently unlike to warrant separate descriptions, it should be kept in mind that they are gradational in the field, and intermediate textures are common.

The "normal" (eastern) rock is medium- to coarse-grained, porphyritic, well-foliated, light pinkish gray biotite granite gneiss. Pink microcline and gray quartz are the most conspicuous minerals. Much of the microcline is in phenocrysts that range from single, euhedral, unfractured crystals as much as 5 cm long that generally show Carlsbad twinning, through partially granulated crystals with fractures healed with gray quartz, to lenslike granular aggregates generally less than 3 by 1 cm. Whereas the granular aggregates all lie parallel to the foliation of the gneiss, many of the single crystal phenocrysts do not, but lie with their long axes at angles as great as 90 degrees to the foliation. White to cream oligoclase is visible as small grains in the ground mass. Biotite occurs as small alined flakes, slightly concentrated in darker layers, which produce the strong foliation of the gneiss. The foliation wraps around phenocrysts. Small magnetite octahedra, commonly in the centers of the phenocrysts, complete the list of megascopically identifiable minerals. Lineation is not well developed, though locally it is produced by weak phenocryst alinement or by streaming of biotite and quartz.

The gneiss in the west, along the quadrangle border, has a strong cataclastic texture, is fine- to medium-grained, extremely well foliated, and, in most outcrops, is platy. The rock is medium to dark gray and more equigranular than is the gneiss to the east. The microcline phenocrysts are relatively inconspicuous tan to brown

A.

B.

Figure 15. - Stone walls of glacial boulders of augen gneiss. Walls are about 1.2 meters high. Along the road one mile north of Billings Lake, Griswold, Conn.

A. Sub-equant boulders of "normal" augen gneiss.

B. Slabby boulders of slickensided and cataclastic augen gneiss.

lenslike aggregates of fine grains. Foliation planes are deeply slickensided, undulant surfaces that pass smoothly around flattened feldspar lenses. These surfaces, which are free of megascopic mica flakes, are dark gray-green, and have a waxy luster. Many are coated with a white, granular film of calcite. White to brown feldspar (microcline and oligoclase), gray quartz, shreds of dark green biotite, and trains of magnetite granules are megascopically identifiable.

Contacts between augen gneiss and underlying metamorphic rocks (quartzite and calc-silicate quartzite wherever exposed) are concordant. Some thin layers of fine-grained, weakly porphyritic to nonporphyritic augen gneiss are interlayered with normal augen gneiss immediately above the contact. No inclusions of other rocks in augen gneiss were seen.

Cataclastic texture is present in all the thin sections studied, and it increases in intensity toward the west. Quartz, microcline, and biotite show cataclastic effects especially well, although no minerals are entirely free of them.

In plain light, quartz grains are clear, free of inclusions, and much flattened in the plane of foliation. Under crossed nicols the same grains have an entirely different aspect; they are composed of myriads of complexly sutured and highly strained small grains. Where large flattened quartz grains pinch and swell along foliation, component grains are smallest (0.01 mm or less) at points of pinch, and are largest and show the least strain where the host grain is thickest.

Feldspars are generally less well twinned than in the other granitic rocks in the Ashaway and Voluntown quadrangles. Microcline is fresh and generally not perthitic. Large grains are typically broken into mechanically rounded fragments which themselves show strain effects by bent twin lamellae. Interstices between fragments are filled with finely crushed microcline; a typical mortar structure. The plagioclase is oligoclase, and ranges from An_{12} to An_{17}. Twinning is generally weakly developed, and a majority of the grains show none at all. Many of the twinned grains are twinned on the pericline as well as on the albite law; this is very uncommon in the other granitic rocks. Some grains show faint normal zoning. Sodic borders against adjacent microcline grains are fairly common, but generally are not well developed. Some of these borders are finely myrmekitic and some are granulated.

Fresh augen gneiss appears far more quartz-rich to the unaided eye than the rock actually is. Probably much of the plagioclase, which is mostly fresh and untwinned, and has a clear, almost vitreous aspect in thin section, is megascopically indistinguishable from quartz.

Biotite is more abundant than in most of the other granitic rocks, and occurs as myriads of small shreds, generally without parallel edges. Pleochroism is strong, with X = light yellow-tan, and Y = Z = deep yellow-brown to opaque. Bent flakes and interleaved chlorite are both very rare.

Two of the 11 thin sections studied contain a few hornblende grains. The hornblende has a very small 2V, strong dispersion, and is very strongly pleochroic with X = light olive-brown, and Y = Z = deep blue-green to opaque.

Muscovite is present in small amounts in nearly all thin sections as trains and smears of sericitic grains in planes of granulation. Nowhere does muscovite exceed 2 percent.

Accessory minerals in the augen gneiss include allanite, apatite, calcite, clinozoisite, epidote, sphene, and zircon. Allanite, apatite, sphene (commonly polysynthetically twinned), and zircon are present in nearly all thin section; the others are relatively rare.

Thin section modes (Table II) show that augen gneiss has the composition of granodiorite as oligoclase is more abundant than microcline. The accuracy of the modes of augen gneiss is probably not as great as that of the other granitic rocks because 1) the thin section cannot properly weigh the contribution of the phenocrysts, 2) the composition of the highly granulated parts of the thin section can, in many instances, only be guessed at, and 3) only in the best-stained sections could untwinned oligoclase and microcline grains be distinguished with surety. However, even with these handicaps, the modes are believed to be accurate to well within one standard deviation of each major constituent.

Muscovitic facies

A small area of augen gneiss near the junction of Kinney and Dark Hollow Brooks bears abundant muscovite and has been mapped as a separate muscovitic facies. The texture and mineral composition of this facies are somewhat more variable than are those of normal augen gneiss, but the gross aspect of the two rocks is very similar.

The muscovitic rock is light beige or gray, ranges from fine- to medium-grained and ranges from equigranular to porphyritic. The rock is ubiquitously well-foliated and is characterized by muscovite-coated foliation planes. Phenocrysts in porphyritic rock are partially to totally granulated pink microcline crystals, locally

TABLE II. - Modes of augen gneiss (volume percent)

	1	2	3
Number of samples	7	1	7
Quartz	28.0	37.5	4.8
Microcline	25.8	24.6	4.5
Plagioclase	37.0	19.8	4.5
Hornblende	tr		
Biotite	6.5	0.4	2.3
Muscovite	0.8	16.3	
Magnetite	0.7	1.3	
Allanite*	0-0.4		
Apatite	0-0.3		
Calcite	0-0.3		
Chlorite	0-0.4	tr	
Clinozoisite	0-tr		
Epidote	0-0.8		
Sphene	0-1.0		
Zircon	tr-0.1	0.1	
Composition of plagioclase (An)	12-17	10±3	

*Figures for accessory minerals allanite through zircon give ranges, tr = trace

1. Average of augen gneiss excluding muscovitic facies
2. One thin section of augen gneiss, muscovitic facies
3. Standard deviation of col. 1

as lenslike granular aggregates as much as 1.2 by 2.5 by 8 cm. None of the muscovitic rock is slickensided. Gray quartz, pink to beige microcline, beige plagioclase, muscovite flakes as much as 5 mm in diameter, biotite (absent in some outcrops), and magnetite octahedra are megascopically identifiable.

Thin sections of the muscovitic facies show the cataclastic texture characteristic of all the augen gneiss. The microscopic aspect of the minerals, with the exception of the abundant muscovite, is like that in normal augen gneiss described above. The muscovite occurs as large, well-alined, clean flakes with parallel edges. Some are slightly bent, and a few are broken and offset across cleavage. Smeared, sericitic muscovite, characteristic of normal augen gneiss, is absent. Modal analysis of one thin section of a porphyritic sample of the muscovitic facies (Table II) shows the rock to be richer in quartz and to have a higher microcline-to-plagioclase ratio than normal augen gneiss.

Escoheag Quartz Diorite Gneiss

A distinctive, coarse-grained, porphyritic quartz diorite gneiss is exposed in the northeast quarter of the Voluntown quadrangle. The gneiss, which underlies the settlement of Escoheag, R.I. and most of Escoheag Hill, is herein named Escoheag Quartz Diorite Gneiss. The type locality is the abundant exposure on Escoheag Hill centered a half mile southeast of the lookout tower. The gneiss is confined to a single northwest-trending belt about a half mile wide, which begins near Ten Rod Road at the south and passes into the Oneco quadrangle to the north. The rock is resistant and forms abundant outcrop. The best exposures are at the type locality where the rock was once quarried, and along Molasses

Hill Road 0.18 mile south of Shetucket Turnpike. Several elongate bodies of a fine-grained facies have been mapped elsewhere in the Voluntown quadrangle.

Much of northwestern Rhode Island is underlain by quartz diorite gneiss (Quinn, 1963). However, detailed mapping of this rock type outside the Voluntown quadrangle is not extensive. Quartz diorite gneiss has been mapped in the extreme northwest corner of the Coventry Center quadrangle (Moore, 1963) which abuts the Voluntown quadrangle on the northeast, and much of the Clayville quadrangle (north of the Coventry Center) is underlain by similar rock (Acker, 1950; Frost, 1950), Whether or not all quartz diorite gneiss in west central and northwestern Rhode Island is correlative is uncertain.

Escoheag Quartz, Diorite Gneiss is medium- to coarse-grained and strongly porphyritic. Color and structure are not uniform, but range from pink to very dark gray, and from massive to schistose respectively. Most of the rock is medium to dark gray and strongly foliated. Lineation is locally present, but generally absent.

Phenocrysts, which constitute 10 to 15 percent of most outcrops, are microcline, and range from euhedral blocky crystals that show prominent Carlsbad twinning, to pods and lenses of granules. Most are subhedral to euhedral and about 1.2 by 3.0 cm on outcrop surfaces, although lengths and breadths range from 1.0 to 8.0 cm and 0.5 to 3.0 cm respectively. In general, strongly foliated gneiss contains phenocrysts that are longer, narrower, and more granulated than are those in weakly foliated to massive rock. Granulated phenocrysts all lie with their long axes in the plane of foliation, whereas many subhedral to euhedral phenocrysts lie with long axes at large angles to foliation. Single crystal phenocrysts are predominantly beige, though some are pink, whereas granulated phenocrysts are light gray to white. Biotite foliation wraps around phenocrysts in all but rare outcrops of massive rock, and gives the rock a prominent gnarly aspect.

Matrix is fine- to medium-grained and is composed of gray quartz, anhedral beige feldspar, biotite or biotite and hornblende, and magnetite. The latter is commonly abundant as conspicuous euhedral octahedra as much as 0.6 cm in diameter; many outcrops have 200 or more per square meter of surface.

Textural layering is prevalent but subtle. Layers differ in abundance and size of phenocrysts, and in development of foliation. Contacts between layers are mostly gradational.

Part of the Escoheag is poorer in mafic minerals and richer in microcline than the typical gneiss. This granitic facies is not common, and as it is neither sharply demarcated from the normal quartz diorite gneiss, nor different in overall aspect, it has not been mapped separately.

Inclusions of other rocks in the Escoheag are restricted to a few amphibolite lenses. Aplite, pegmatite, and vein quartz are rare.

Coarse grain and porphyritic character complicate quantitative thin section study. Only thin sections with a phenocryst-to-matrix ratio similar to that in the outcrops from which they came were modally analyzed. Results are given in Table III. The large excess of plagioclase over microcline is found in no other granitic rock in the Ashaway or Voluntown quadrangle.

Quartz is in clean, unstrained to slightly strained grains.

Microcline is predominantly as phenocrysts and is rare in the matrix. It is fresh throughout. Phenocryst microcline has very prominent grid-twinning and is perthitic with patches and veins of albite. Matrix microcline is anhedral, non-perthitic grains,

TABLE III. - Modes of Escoheag Quartz Diorite Gneiss (volume percent)

	1	2	3	4
Number of samples	10	5	10	5
Quartz	21.5	19.9	5.6	2.5
Microcline	16.1	19.0	7.8	6.4
Plagioclase	46.4	43.4	9.0	3.4
Hornblende	1.4	2.4	1.8	3.0
Biotite	12.6	14.0	5.7	5.1
Magnetite	0.4	0.1	0.4	0.1
Allanite*	0-0.2	0-0.2		
Apatite	0-0.8	tr-0.4		
Chlorite	0-0.2	0-0.1		
Epidote	0-0.1			
Garnet	0-0.1			
Sphene	0-1.6	0.5-1.7		
Zircon	tr	0-0.1		
Composition of plagioclase (An)	16-36	25-32		

*Figures for accessory minerals allanite through zircon give ranges, tr = trace.

1. Average of Escoheag Quartz Diorite Gneiss
2. Average of Escoheag Quartz Diorite Gneiss, fine-grained facies
3. Standard deviation of col. 1
4. Standard deviation of col. 2

generally with very faint, inconspicuous grid-twinning. Inclusions of quartz, biotite, and plagioclase are abundant; the latter have albite rims.

Plagioclase constitutes the bulk of the matrix. Composition ranges from An_{16} to An_{36}, although in nearly all samples it is between An_{25} and An_{36}. Grains are fresh, not strongly twinned, and locally contain spherical inclusions of quartz. Many grains show vague normal zoning.

Biotite in large flakes is abundant in all samples, and constitutes more than 20 percent of some. Pleochroism is X = light yellow-tan, and Y = Z = dark olive brown to opaque. Zircon inclusions with radiohalos are conspicuous in most thin sections. Chlorite is very rare.

Strongly pleochroic hornblende is present in most samples, but nowhere exceeds 6 percent. The mineral has a very small 2V and strong dispersion. Colors are: X = light yellow-brown, Y = Z = deep olive-brown or deep blue-green. Allanite inclusions with radiohalos are widespread.

Most thin sections contain accessory apatite, allanite, epidote, sphene, and zircon. Muscovite and garnet are sparingly present in some hornblende-free samples.

Fine-grained facies

Three small bodies of medium to dark gray gneiss in the Voluntown quadrangle have been mapped as the fine-grained facies of Escoheag Quartz Diorite Gneiss. The largest body, west of Deep Pond, is 1.15 miles long and 0.12 mile wide.

The rock is fine- to rarely medium-grained, equigranular, and very prominently foliated. Biotite, and locally hornblende, are conspicuous; biotite is abundant enough to coat foliation surfaces completely. Layering is absent. No outcrops of the fine-grained facies are near roads or trails, and the best exposures, west of Deep Pond, are difficultly accessible.

Although the fine-grained facies differs megascopically from normal Escoheag Quartz Diorite Gneiss in nearly all respects, the two are correlated on the basis of similar occurrence and nearly identical mineral composition (Table III).

Many thin sections of the fine-grained facies show a moderately well-developed cataclastic texture. Quartz is much strained, and many grains are composed of sutured and strained sub-grains. Biotite on many foliation surfaces is in partly shredded to fine-grained but fresh aggregates, whereas in adjacent foliae it is as large undeformed flakes. No mortar structure is developed in feldspar, but twin lamellae of some plagioclase grains are bent.

All minerals are fresh. Feldspars are weakly twinned. The larger microcline grains commonly have slightly perthitic cores. Plagioclase ranges from An_{25} to An_{32} and the larger grains are vaguely zoned. Albite and myrmekite rims on plagioclase at contacts with microcline are developed locally. Biotite, hornblende, and accessory minerals are the same as those in the medium- to coarse-grained Escoheag Quartz Diorite Gneiss.

Porphyritic granite gneiss

Belts of porphyritic granite gneiss are well exposed in both the Ashaway and Voluntown quadrangles. The largest belt enters the Ashaway quadrangle from the west a little less than a mile south of Wyassup Lake and trends east northeast to a point half a mile west of Yawgoog Pond in the Voluntown quadrangle. Here the strike changes to northwest. The belt ends 1.5 miles east of Voluntown village, nearly 10 miles on strike from where it entered the Ashaway quadrangle. Other large belts are along Reuterman Road in the Ashaway quadrangle, and south of Yawgoog Pond, southeast of Beach Pond, northwest of Tippecansett Pond, and along the northeast slope of Escoheag Hill in the Voluntown quadrangle. Large clean exposures are abundant at the east end of Beach Pond and east of Green Fall Pond.

The porphyritic granite gneiss corresponds in part to the porphyritic facies and in part to the alaskite facies of Sterling Granite Gneiss mapped by Loughlin (1912).

Assigning a formal name to the porphyritic granite gneiss in the present report is unwarranted owing to the great megascopic heterogeneity of the rock, the uncertainty of correlation of widely-separated bodies, and the impossibility of selecting a single representative type locality.

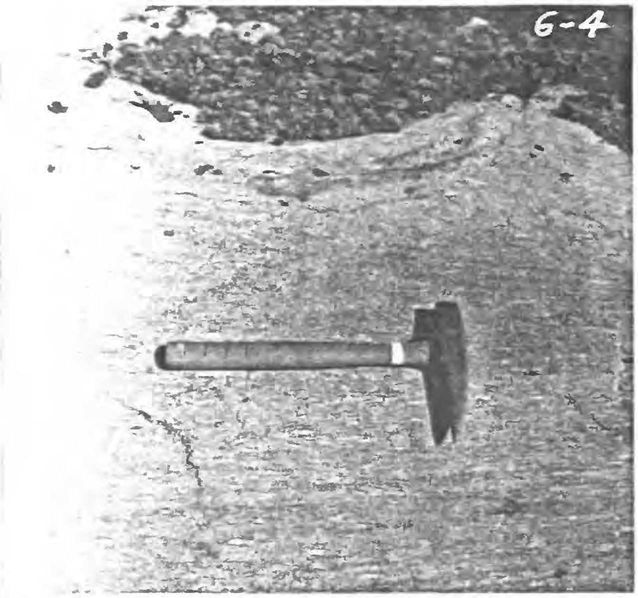
Porphyritic granite gneiss is the most heterogeneous granitic rock mapped in the two quadrangles. Outcrops are characteristically streaky, and layers of granite, predominantly of slightly different texture, are in conformable succession. In general, gneiss in the Ashaway quadrangle is less strongly layered and more biotitic than that in the Voluntown quadrangle.

Most of the rock is medium-grained, though some is fine. The rock ranges from gray in the Ashaway quadrangle to light grayish pink and pink to the north. Foliation is ubiquitous; where mica is sparse or absent, preferential parallelism of platy microcline phenocrysts, and probable parallelism of (010) faces of matrix feldspar produces foliation which, although subtle in fresh rock, is conspicuous on weathered surfaces.

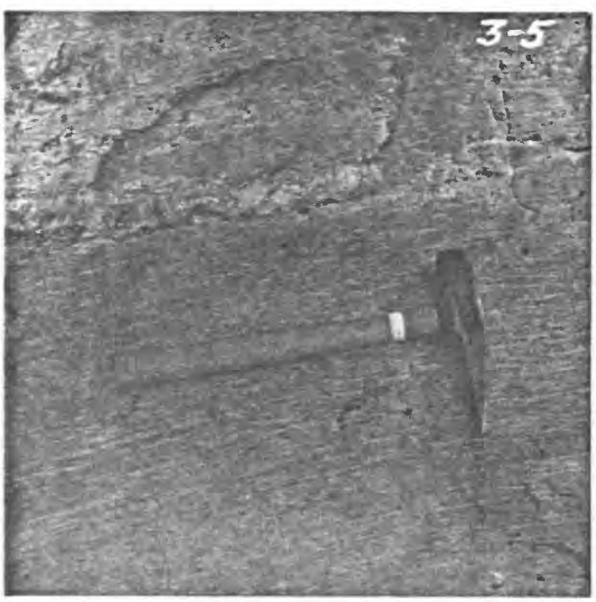
Porphyritic texture is nearly ubiquitous. Phenocrysts constitute from a trace to 20 percent of the gneiss, and are as much as 3 cm long. They range from euhedral pink microcline crystals with prominent Carlsbad twinning, to lenslike and rarely rodlike granular aggregates of microcline grains (fig. 16). Many of the former are at angles to the foliation of the gneiss. Linear parallelism of phenocrysts is restricted to two localities. In the belt north of Grindstone Hill Road, between Wyassup and Hetchel Swamp Brooks in the Ashaway quadrangle, phenocrysts are granulated and show slight down dip elongation. Similar phenocrysts in the same belt northeast of Green Fall Pond in the Voluntown quadrangle are rodlike and impart a striking lineation to the gneiss.

Textural layering of porphyritic granite gneiss is the most conspicuous feature of outcrops in the Voluntown quadrangle. Layers differ principally in abundance of phenocrysts; in many places gneiss with 10 to 20 percent phenocrysts is interlayered with equigranular gneiss or gneiss with only a percent or two phenocrysts. Less commonly, layers differ in grain size. Compositional layering is restricted to minor differences in biotite content of otherwise similar gneiss.

Layering is accentuated by abundant sills of Hope Valley Alaskite Gneiss, especially near contacts with that rock. Many outcrops in the body of porphyritic granite gneiss northwest of Tippecansett Pond, and just east of the east end of Beach Pond are as much as 50 percent such sills which range from a few centimeters to ten meters thick. Sills of Scituate Granite Gneiss have intruded porphyritic granite gneiss on the point of land in Beach Pond 0.23 mile N.40°W. of where Ten Rod Road crosses the State line.



A.



B.

Figure 16. - Porphyritic granite gneiss. A. Normal development of microcline phenocrysts as blocky subhedral crystals to lens-like aggregates. 0.15 mile north of the east end of Beach Pond, Exeter, R. I. B. Microcline phenocrysts as highly drawn out rodlike aggregates. Bed of Green Fall River 0.48 mile N.24°E. of the outlet of Green Fall Pond, Voluntown, Conn.

Pegmatite and aplite are scarce in porphyritic granite gneiss. Thin sills are widespread but nowhere abundant, and discordant bodies are extremely rare. A few thick aplite sills have been mapped separately.

Two outcrops on the east and northeast shore of Green Fall Pond contain small conspicuous quartz-sillimanite nodules.

Outcrops of the porphyritic granite gneiss are more similar to outcrops of layered felsic gneiss than to outcrops of any of the granitic rocks described in this section. Layered felsic gneiss, however, is equigranular, has pronounced compositional layering, contains very abundant pegmatite and aplitic granite as sills and discordant bodies of irregular outline, and nowhere contains quartz-sillimanite nodules.

Porphyritic granite gneiss with sparse phenocrysts greatly resembles Potter Hill Granite Gneiss, especially where the latter is slightly porphyritic.

Pink to tan feldspar, quartz, biotite, and minor magnetite can be distinguished in hand specimens. Megascopic discrimination between microcline and plagioclase is not possible in most rock. Muscovite, absent or inconspicuous in most outcrops, is conspicuous in gneiss on the northeast shore of Green Fall Pond, at the intersection of Shetucket Turnpike and Molasses Hill Road, and in some outcrops northwest of Tippecansett Pond. Garnet is a minor accessory at the latter locality.

In thin section the porphyritic granite gneiss is far more uniform than outcrops suggest. The gneiss has the composition of a quartz monzonite (Table IV); microcline is only slightly more abundant than plagioclase.

TABLE IV. - Modes of porphyritic granite gneiss (volume percent)

	1	2
Number of samples	31	31
Quartz	30.5	4.4
Microcline	34.5	6.0
Plagioclase	29.4	5.3
Biotite	3.4	1.7
Muscovite	1.2	2.3
Magnetite	0.5	0.5
Allanite*	0-0.2	
Apatite	0-0.2	
Calcite	0-0.4	
Chlorite	0-1.0	
Epidote	0-tr	
Garnet	0-0.1	
Sphene	0-0.7	
Zircon	0-0.1	
Composition of plagioclase (An)	10-17	

*Figures for accessory minerals allanite through zircon give ranges; tr = trace.

1. Average of porphyritic granite gneiss
2. Standard deviation of col. 1

Quartz is as clean, generally unstrained grains with simple borders. In samples from northeast of Green Fall Pond and east southeast of Wyassup Lake quartz is considerably strained and grains are complexly sutured.

Microcline is fresh and has prominent grid-twinning. Rare perthite is developed preferentially in phenocrysts.

Plagioclase is sodic oligoclase. Grains are generally dusted with white mica. Twinning ranges from well-developed to absent; most grains are weakly twinned. Albite rims fringe some grains where in contact with microcline. Albite lenses between large microcline grains are common. Some grains are broken, and many twin lamellae are bent in samples from east of Green Fall Pond.

Biotite is fresh and strongly pleochroic with X = light yellow-brown, and Y = Z = deep brown to opaque. Zircon inclusions with radiohalos are common. Chlorite is developed in biotite only southeast of Wyassup Lake and along Reuterman Road in the Ashaway quadrangle. Muscovite is rare.

Fresh magnetite is ubiquitous, and some grains have rims of sphene or leucoxene.

Small grains of allanite, apatite, sphene, and zircon are found in nearly all thin sections. Calcite, epidote, garnet, and dark blue-green hornblende are very sparse accessories.

Potter Hill Granite Gneiss

Nearly a third of the Ashaway quadrangle is underlain by a uniform, well-foliated, fine-grained granite gneiss. The name Potter Hill Granite Gneiss is herein proposed for this rock. The type locality is the Pawcatuck River village of Potter Hill, three miles northeast of Westerly, where exposures of the typical lithology are abundant. The uniformity of this gneiss, its areal extent, and its distinct structural position all warrant its naming. Earlier workers (Loughlin, 1912; Martin, 1925) did not map the Potter Hill as a separate unit, but regarded its area to be underlain by two or three facies of Sterling Granite Gneiss. This multiplicity of facies within the area of Potter Hill Granite Gneiss is in disagreement with field observations made during the present study.

The bulk of the Potter Hill is in a single body in the central and west-central part of the Ashaway quadrangle. Satellitic bodies, including a massive facies (see below), occur in adjacent rocks. The main body, which has an east-northeast axis, has a tri-lobed eastern termination in the Ashaway quadrangle, and passes westward into the Old Mystic quadrangle. No Potter Hill crops out in the Voluntown quadrangle.

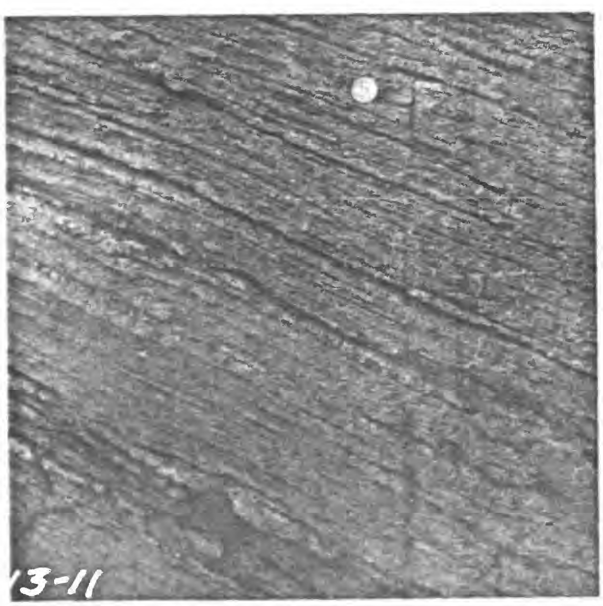
Typical Potter Hill Granite Gneiss is stained and somewhat crumbly. Fresh, sound, and unstained rock is exposed only in roadcuts and quarries. Stain somewhat hinders megascopic mineral identification, although quartz, feldspar, biotite, and accessory magnetite are ubiquitously recognizable. Potassium feldspar can be distinguished from plagioclase only in thin section. Although the megascopic difference between stained rock found in natural outcrops and the far less common fresh rock is very great, the difference in thin section is negligible (p. 21). Outcrop rock is pinkish orange to tan, to dark orange-brown where more thoroughly weathered. Fresh rock is light pinkish gray.

Very well-developed foliation characterizes the Potter Hill. The foliation, which is weak only east of Diamond Hill, is the product of parallelism of biotite flakes, and the segregation into layers, several to the centimeter, of rock alternately slightly enriched, and slightly impoverished in biotite. Thin pegmatite sills, generally a centimeter or two thick, are present in nearly all outcrops. Weathering accentuates foliation, and has made most outcrops slabby (fig. 17). Inasmuch as weathered outcrops of gneiss bearing little or no mica are as slabby as those of more micaceous rock, it is probable that (010) feldspar faces are preferentially parallel to foliation. Lineation is generally absent.

Some variation from the typical lithology does occur, although the overall aspect of a Potter Hill outcrop is constant throughout the map area. Somewhat porphyritic Potter Hill Granite Gneiss, bearing 5 to 20 percent lenslike phenocrysts of partially granulated pink to orange microcline, as large as 1.3 by 3.8 cm, occurs north of New London Turnpike at the west border of the quadrangle, 1.2 miles south of the same road along Voluntown Road, and a half mile west southwest of Maxon Hill. Alaskitic Potter Hill, essentially free of ferromagnesian minerals, occurs locally as west of Bell Cedar Swamp. This rock has a lineation produced by the aggregation of quartz into tiny pods much like that of the Hope Valley Alaskite Gneiss, although the latter rock is much coarser-grained. Hornblende-bearing Potter Hill is restricted to a single outcrop south of Norwich Road 0.2 mile east of the west border of the quadrangle. A line of outcrops immediately south of Clarks Falls Road bear elliptical, slightly flattened quartz-sillimanite nodules as much as 8 cm in diameter. The nodules are concentrated in layers which are parallel to foliation.

Potter Hill Granite Gneiss is gradational with Hope Valley Alaskite Gneiss just northeast of the intersection of Boom Bridge and Ashaway Roads, whereas on the south side of Grindstone Hill Road 0.18 mile east of Hangman Hill Road the two rocks are in sharp

A.



B.

Figure 17. - Potter Hill Granite Gneiss. Foliation etched by weathering. A. Horizontal outcrop with nearly vertical foliation 0.15 mile west of Norwich Road 0.8 mile north of junction with Voluntown Road, Stonington, Conn. Hammer handle is 38 cm long. B. Vertical, east-facing exposure 0.04 mile south of New London Turnpike 0.36 mile east of Voluntown Road, North Stonington, Conn. Notice abundant thin concordant pegmatites.

conformable contact. Dikes of Potter Hill Granite Gneiss cut quartzite of the Plainfield Formation one mile west of Ashaway.

Thin sections of Potter Hill Granite Gneiss show remarkable uniformity. Modal data is given in Table V.

Quartz is clean, and generally only weakly strained. Some sections show more strongly strained quartz, but no evidence of cataclasis.

Potassium feldspar is microcline which is fresh, generally very prominently grid-twinned, and it is slightly perthitic in about half of the thin sections examined.

Plagioclase ranges from An_5 to An_{20}, though most determinations fall between An_{11} and An_{16}. Grains are slightly to moderately dusted with alteration products. The more calcic plagioclases are commonly weakly zoned, and show albitic borders against microcline.

Biotite is usually fresh and strongly pleochroic with X = pale yellow-tan, and Y = Z = dark brown to opaque. Zircon inclusions with radiohalos are present in some grains; interleaved chlorite is very rare. Muscovite is present in minor amounts; its commonest occurrence as thin shells surrounding magnetite grains. Hornblende occurs only in one outcrop, cited above. A section from this exposure contains 2.7 percent strongly pleochroic dark green hornblende.

Accessory minerals are unusually scarce and half of the sections examined contain none. Although sparse grains of apatite, calcite, epidote, sphene, and zircon occur in a few thin sections, only epidote, as scattered, tiny granules, occurs in more than a quarter of those studied.

Potter Hill Granite Gneiss has the composition of granite, containing a considerable excess of microcline over plagioclase in a

TABLE V. - Modes of Potter Hill Granite Gneiss (volume percent)

	1	2	3
Number of samples	23	3	23
Quartz	33.0	33.5	3.0
Microcline	38.9	38.4	6.1
Plagioclase	23.7	25.2	5.5
Biotite	2.6	1.0	1.9
Muscovite	1.0	1.4	0.8
Magnetite	0.8	0.5	
Apatite*	0-0.1		
Calcite	0-tr		
Chlorite	0-0.2	0-1.5	
Epidote	0-tr	0-tr	
Sphene	0-0.9		
Zircon	0-0.1		
Composition of plagioclase (An)	5-20**		

*Figures for accessory minerals apatite through zircon give ranges, tr = trace.
**21 samples are 12-20, 2 samples are 5 and 8.

1. Average of Potter Hill Granite Gneiss excluding massive facies
2. Average of Potter Hill Granite Gneiss, massive facies
3. Standard deviation of col. 1

majority of the modes prepared.

Massive facies

Much of the area between Bradford and Chapman Pond in the Ashaway quadrangle is underlain by a massive facies of Potter Hill Granite Gneiss. Outcrops lack the slabbiness of the normal Potter Hill, but in hand specimen and in thin section the difference is slight.

The massive facies is pink to tan, fine-grained, and nearly massive. Locally lineation or foliation or both are weakly developed. Pegmatite, largely confined to thin sheets in Potter Hill Granite Gneiss, occurs in irregular bodies in the massive facies and locally, as south of Kedinker Island, constitutes the bulk of the outcrop. Abundant dikes of the massive facies crosscut quartzite just north of the railroad 0.4 mile northeast of McGowan Brook. Surface rock is characteristically stained and crumbly. Fresh rock, exposed only in abandoned quarries, is light pinkish gray and firm.

Under the microscope the massive facies is nearly identical with Potter Hill Granite Gneiss. Modal analyses (Table V) of the two are nearly indistinguishable, but do show significant dissimilarities between the massive facies and the Westerly Granite, which where fresh, megascopically resemble each other greatly.

Mixed facies

A narrow belt two miles north of Westerly that passes through Bumpin Hill, and three much smaller adjacent pods, consist of a mixture of rock types. The rocks are in part normal Potter Hill Granite Gneiss, but light to medium gray, fine-grained feldspar-quartz-biotite gneiss, in part porphyritic and locally layered, is the predominant lithology. Other rock types present are thin layers of dark medium-grained biotite schist, fine-grained light gray aplitic alaskite, massive tan to pink granite (probably phgm), and abundant coarse-grained simple pegmatite. The rock types are intimately mixed, and separation on the scale of the geologic map is impossible.

The fine-grained gray gneiss and the biotite schist were examined in thin section. Mineral proportions in the gray gneiss differ considerably from Potter Hill Granite Gneiss. Plagioclase (An_{24} to An_{30}) is in considerable excess over microcline, and constitutes as much as half the rock. Microcline does not exceed 25 percent of the rock, and normally is less than 10 percent. Quartz, which ranges from 15 to 30 percent, is severely strained and has complexly sutured boundaries. Biotite is abundant, as much as 17 percent in some sections, and commonly is extensively altered to bright green chlorite with strong anomalous blue interference colors. Green hornblende is a minor constituent of some sections. Accessory minerals are far more plentiful than in normal Potter Hill Granite Gneiss. Epidote, magnetite, and sphene are especially abundant; in some sections each constitutes as much as 2 percent of the rock. Apatite, calcite, and zircon are less common. The biotite schist is composed of two thirds moderately pleochroic, brown biotite, one third andesine (An_{35}), and accessory sphene.

Hope Valley Alaskite Gneiss

Hope Valley Alaskite Gneiss was named by Moore (1958) for exposures of strongly lineated, coarse-grained, mafic-poor granite gneiss well exposed on low knobs one mile north of the village of Hope Valley, Rhode Island. The type locality is 2.25 miles N.47°E. of the northeast corner of the Ashaway quadrangle. The Hope Valley

Alaskite Gneiss mapped in the present report is nearly entirely contiguous with, and both megascopically and microscopically indistinguishable from the rock at the type locality.

The term alaskite (orig. "alaskyte") was introduced by Spurr (1900) who defined the rock type as a quartz-alkali feldspar igneous rock "characterized by being exceptionally high in silica and low in iron and lime" (ibid., p. 230). Although this definition could include most pegmatites, they are presumably excluded. A dozen years later this term was first applied to some of the rocks of southeastern Connecticut and southwestern Rhode Island by Loughlin (1912) who mapped an alaskite facies of the Sterling Granite Gneiss. The alaskite described by Loughlin (ibid., p. 123-126) corresponds to the Hope Valley Alaskite Gneiss of the present report.

Hope Valley Alaskite Gneiss is areally the most abundant rock in the Ashaway and Voluntown quadrangles. The rock is resistant and outcrop is generally very plentiful, although some fairly extensive areas of the Hope Valley in the Voluntown quadrangle have very sparse exposure. The best outcrops are on the rocky shores of Yawgoog Pond in the Voluntown quadrangle, and near Laurel Glen and Clarks Falls and east of Pitcher Mountain in the Ashaway quadrangle.

The bulk of the Hope Valley Alaskite Gneiss is a pale pink, coarse-grained, equigranular, strongly lineated rock. Feldspar, quartz, minor biotite, and accessory magnetite are generally megascopically identifiable. Feldspar is pale pink, tan, or white, and occurs as subhedral crystals and granular aggregates. Potassium feldspar and plagioclase are normally not easily distinguishable megascopically. Gray to smoky quartz occurs almost exclusively in parallel rod-shaped aggregates which impart a pronounced lineation to the rock. The rods range from 2 to 8 cm long, with most between 3 and 4 cm. Rod length-to-width ratios are normally between 8:1 and 10:1. This ratio increases with rod length and reaches values as great as 20:1 or more (see fine-grained facies, below). Mafic minerals are exceedingly sparse in the Hope Valley. Magnetite is locally conspicuous as large slightly granulated octahedra as much as 2 cm in diameter which constitute as much as 3 percent of the rock, though more than a half percent is uncommon. Biotite is sparse to absent, and nowhere constitutes more than 4 percent of the rock. Poikilitic muscovite flakes are visible locally. A few exposures bear megascopic allanite, garnet, and sillimanite.

Quartz rod lineation is visible in nearly all outcrops. ~~Al-though~~ The attitude of lineation is generally very constant within a single exposure and from exposure to exposure. In some outcrops, however, as on the southwest slope of Chapman Hill, and 0.7 mile north of the outlet of Green Fall Pond, the lineation shows considerable swirl with a range of bearing of 30 degrees or more.

Weathered outcrops of the Hope Valley are platy, much like similar outcrops of Potter Hill Granite Gneiss, although the layers etched into relief are thicker in the Hope Valley. As platiness is developed in mica-free alaskite with no visible compositional layering, the platiness probably reflects strong parallelism of (010) feldspar faces. Mica foliation, where present, parallels platiness. At a few localities, as on the north shore of Yawgoog Pond, and just north of Laurel Glen west of Denison Hill Road, the foliation is in broad folds a few centimeters in amplitude.

Some outcrops of the Hope Valley depart somewhat from the typical lithology described above. The belt of alaskite that enters the Ashaway quadrangle from the west just south of Wyassup

Lake, passes southeast of Pendleton Hill, and terminates a quarter mile west of Green Fall Pond as thin sills of fine-grained saccharoidal alaskite, is less homogeneous than any other large body of the Hope Valley mapped in the present report. The rock ranges from typical strongly lineated, coarse-grained, pale pink alaskite well exposed between Green Fall Road and Wheeler Road, to alaskitic and granitic gneisses that range from beige to pink, from coarse- to fine-grained, and from equigranular granitoid to saccharoidal. The latter, more variant lithologies, compose many of the outcrops on Pendleton and Chapman Hills in the Ashaway quadrangle. Most of the rock of this belt is foliated, and much is characterized by thin lamination; an interlayering of quartz-rich and feldspar-rich layers from 2 to 4 mm thick. Lamination is not found in the Hope Valley elsewhere.

The Hope Valley in the vicinity of Deep Pond in the Voluntown quadrangle is porphyritic, with subhedral to anhedral phenocrysts of pink microcline generally less than 2 cm in diameter. The rock is medium-grained, and bears from 2 to 4 percent biotite which imparts a strong foliation. Quartz rod lineation is less well developed than in most Hope Valley.

In the northern part of the Voluntown quadrangle, as at the inlet to Mason-Gray Pond, the Hope Valley is light gray to tan, contains as much as 4 percent biotite, and locally bears pale pink microcline as granular aggregates as much as 3 cm in diameter. Quartz rod lineation is strong, but the structure is swirled. This gneiss is intermediate in color and texture between normal Hope Valley Alaskite Gneiss and the gray granitic gneiss of the type Sterling formerly quarried a mile west of Oneco in Sterling, Connecticut, 4.5 miles north of the Voluntown quadrangle. In general, the Hope Valley richest in biotite in the Ashaway and Voluntown quadrangles occurs in the northwest corner of the Voluntown quadrangle as along the road 0.8 mile west of Mason-Gray Pond where it contains 4 percent biotite as evenly distributed flakes. This gneiss is not easily distinguished from Scituate Granite Gneiss.

Isolated bodies of the Hope Valley, as small as the body north of Babcock Road in the Ashaway quadrangle, or smaller, are medium- or even fine-grained. Other scattered outcrops, as in the bed of Pachaug River at Voluntown, and 0.85 mile N.40°E. of the outlet of Beach Pond, are finer-grained than the surrounding gneiss of normal grain size.

A few outcrops of exceptionally muscovite-rich Hope Valley Alaskite Gneiss are indicated on the geologic map. Rock from these outcrops contains as much as 20 percent muscovite and grossly resembles feldspar-quartz-muscovite schist.

Sillimanite and layers of quartz-sillimanite nodules in the Hope Valley are exposed at several localities. All occurrences are shown on the geologic map.

A one-meter-thick layer of the Hope Valley on the south tip of Phillips Island in Yawgoog Pond bears a calc-silicate accessory mineral assemblage. The rock, which is strained and weathered, contains in approximate order of decreasing abundance, epidote, diopside, red-brown garnet, and orange heulandite (opt. (+), 2V c.60°, $n_x = 1.495 \pm 0.001$, $n_z = 1.505 \pm 0.001$). The layer parallels the platy foliation of the Hope Valley.

A thin layers of largely decomposed pyrite-bearing rock is exposed in a roadcut on New London Turnpike 0.9 mile northeast of

Hopkinton village. The exposure is within a few meters of the contact with a biotite gneiss of the Plainfield Formation to which the pyritiferous horizon is probably related.

Hope Valley Alaskite Gneiss dikes and irregularly shaped bodies crosscut Escoheag Quartz Diorite Gneiss 0.73 mile north of the intersection of Escoheag and Ten Rod Roads, and they similarly crosscut porphyritic granite gneiss just west of Deep Pond. Rotated inclusions of the latter occur in a glacial boulder of the Hope Valley several miles to the northwest (fig. 17). Hope Valley Alaskite Gneiss grades into Ten Rod Granite Gneiss west of Mason-Gray Pond

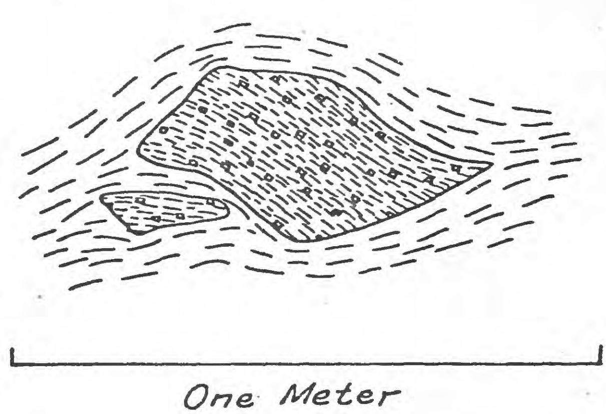


Figure 18. - Hope Valley Alaskite Gneiss containing rotated angular inclusions of porphyritic granite gneiss. Glacial boulder just south of Shetucket Turnpike 0.78 mile northeast of Wylie School Road, Voluntown, Conn. Traced from a photograph.

and east of Deep Pond, and it also grades into Scituate Granite Gneiss at all contacts with that rock. Amphibolite and quartzite southeast of Pitcher Mountain in the Ashaway quadrangle are crosscut by the Hope Valley, and the belt of Hope Valley south and east of Pendleton Hill ascends the stratigraphic section northward in a discordant manner.

In thin section, Hope Valley Alaskite Gneiss greatly resembles Potter Hill Granite Gneiss. In many respects the two are microscopically indistinguishable, although the Hope Valley is generally considerably coarser-grained and poorer in biotite. Only a brief summary of the microscopic characteristics of Hope Valley Alaskite Gneiss is given here; a detailed petrographic description would largely duplicate that given for the Potter Hill.

Quartz is clean and generally shows only weak strain shadows. Most grains have simple sweeping curved borders.

All potassium feldspar is microcline. Grains generally are prominently grid-twinned and fresh, and those in about half the sections studied are slightly perthitic with sparse hair-like laths of albite.

Plagioclase occurs as fresh to somewhat dusted grains moderately well twinned on the albite law. Composition ranges from An_7 to An_{17}. Sodic borders against adjacent microcline grains are common, especially on plagioclase An_{12} or more calcic. The sodic borders and thin plagioclase lenses between large microcline grains range from An_3 to An_{10}, though most are An_4 to An_5. Continuous normal zoning through a small composition range (1-3 percent An) is present in some plagioclase grains in about a third of the thin sections studied.

Biotite does not exceed 4 percent in any thin section, and is entirely absent in about one third. Pleochroism is strong with X = straw yellow, and Y = Z = deep golden brown to opaque. Chloritization is generally absent.

Muscovite occurs as sericitic smears or as sparse highly sieved flakes in most sections. Euhedral large crystals are very rare.

Three sections contain a few grains of strongly colored, strongly pleochroic hornblende; 2V = moderate, X = medium yellow-brown, Z = deep blue-green to opaque. The grains are too small and too sparse to allow more precise optical determinations.

Fresh magnetite subhedra are found in all sections. Rims of muscovite, sphene, or limonite partially or wholly enclose some. Other accessory minerals are very sparse in Hope Valley Alaskite Gneiss; allanite (largely metamict), apatite, garnet, sillimanite, sphene, and zircon are present locally in trace amounts. Only sphene occurs in more than half the sections examined. In addition, calcite, epidote, and zoisite are present in one section each.

Modal data on Hope Valley Alaskite Gneiss are given in Table VI. The mean composition is that of granite; the abundance of potassium feldspar is considerably greater than that of plagioclase.

Fine-grained facies

Part of the western margin of the main body of coarse-grained Hope Valley Alaskite Gneiss is bordered by a thin belt of finer-grained alaskite gneiss. This belt borders the Hope Valley from a point just south of the north border of the Ashaway quadrangle near Wheeler Road, northeastward to the State line west of Yawgoog Pond, thence northwestward to a point 2.4 miles S.55°E. of the village of Voluntown. The margin of the Hope Valley Alaskite Gneiss is generally poorly exposed elsewhere, and it is possible that the fine-grained facies is more extensive than that mapped. However, exposures of the Hope Valley-Plainfield Formation contact are abundant northeast of Laurel Glen where a fine-grained border facies of the alaskite is clearly absent. All the fine-grained facies shown on the geologic map is confined to a single body.

TABLE VI. - Modes of Hope Valley Alaskite Gneiss (volume percent)

	1	2	3	4	5
Number of samples	35	3	3	1	35
Quartz	33.8	32.3	35.4	34.4	4.6
Microcline	37.5	39.5	33.3	38.7	5.1
Plagioclase	26.3	25.8	29.2	24.7	5.8
Hornblende	**				
Biotite	1.0	0.6	0.2	1.1	1.2
Muscovite	0.7	0.5	1.4	0.5	1.1
Magnetite	0.6	1.2	0.5	0.6	
Allanite*	0-0.1				
Apatite	0-0.1	0-tr			
Calcite	0-tr				
Chlorite	0-0.7	0-0.1			
Epidote	0-0.1				
Garnet	0-tr				
Sphene	0-0.3				
Zircon	0-tr	tr			
Zoisite	0-tr				
Composition of plagioclase (An)	7-14	12-14		9	

*Figures for accessory minerals allanite through zoisite give ranges, tr = trace.

**0.3 percent in one thin section, absent in others

1. Average of Hope Valley Alaskite Gneiss
2. Average of Hope Valley Alaskite Gneiss, fine-grained facies
3. Average of Hope Valley Alaskite Gneiss, white facies
4. One thin section of Hope Valley Alaskite Gneiss, fine-grained granite
5. Standard deviation of col. 1

Individual or small areas of fine-grained alaskite within large bodies of Hope Valley Alaskite Gneiss are not mapped separately. The fine-grained facies is well exposed throughout much of its extent. Especially large and clean outcrops are located 0.8 mile east of the outlet of Green Fall Pond.

Moore (1958, 1959) mapped several small bodies of fine-grained Hope Valley Alaskite Gneiss in quadrangles to the east. The rocks mapped by Moore lack the quartz rod lineation characteristic of the fine-grained facies of the present report. Furthermore, the fine-grained facies in the Ashaway and Voluntown quadrangles is a border facies that occupies a distinct structural position, whereas the bodies mapped by Moore apparently have a random distribution.

The fine-grained facies is a fine- to medium-grained analog of normal Hope Valley Alaskite Gneiss. The rock is pink and strongly lineated by parallel alinement of gray to smoky quartz rods. Foliation is weak to absent. The quartz rods are longer and slimmer than those in normal Hope Valley Alaskite Gneiss, and some in outcrops northwest of Yawgoog Pond are 15 cm or more long. Generally the attitude of lineation is constant. Swirled structure is present, however, in some outcrops just east of the north tip of Green Fall Pond. Lamination of the fine-grained facies into thin quartz-rich and feldspar-rich layers is common. Weathering accentuates this texture.

Layers of quartz-sillimanite nodules occur in the fine-grained facies at two localities.

The contact between Hope Valley Alaskite Gneiss and the fine-grained facies is gradational and is based on quartz rod elongation ratios (which rarely exceed 10:1 in the normal gneiss, but reach values of 20:1 or more in the fine-grained facies), and grain size.

The contact between the fine-grained facies and porphyritic granite gneiss, especially near Green Fall Pond, is also inobvious. Similar structural history and mineral composition of the two rocks has made them difficultly distinguishable in the contact zone. The criteria used to separate the rocks and to locate the contact are given in Table VII. In some places characteristics of the two rocks overlap and precise location of the contact is impossible.

TABLE VII. - Distinctions between Hope Valley Alaskite Gneiss, fine-grained facies, and adjacent porphyritic granite gneiss

Fine-grained facies	Porphyritic granite gneiss
Biotite very sparse to absent.	Biotite generally conspicuous.
Equigranular.	Weakly to prominantly porphyritic with lenslike to rodlike aggregates of granular pink to beige microcline.
Conspicuous quartz rods.	No quartz rods.
Strong lineation, foliation weak to absent.	Foliation generally better developed than lineation.
Lamination into thin quartz-rich and feldspar-rich layers is common.	No lamination.

Thin sections of the fine-grained facies and normal Hope Valley Alaskite Gneiss are identical in all respects except the finer grain size of the former. The mineral composition of the fine-grained facies is virtually identical to that of Hope Valley Alaskite Gneiss (Table VI). The content of all constituents in the fine-grained facies is well within one standard deviation of the content of the same constituents in the Hope Valley.

White facies

Slightly more than one square mile of Hope Valley Alaskite

Gneiss in the Ashaway quadrangle has been mapped as a separate white facies. This lithology is confined to two bodies, one approximately 1.2 miles west of Laurel Glen, and the other approximately 1.8 miles west of Clarks Falls. Some layers occur elsewhere in otherwise normal Hope Valley Alaskite Gneiss, especially in the belt that underlies the south half of Chapman and Pendleton Hills, but the layers are too thin and too sparse to show on the geologic map. The best, most accessible outcrops of the white facies are along Grindstone Hill Road.

The white facies has not previously been mapped separately, although the rock was clearly described more than a century ago by Percival (1842, p. 185).

Outcrops of the white facies range from brilliantly snow-white to very light pink, beige, or gray. Like normal Hope Valley Alaskite Gneiss, the rock is medium- to coarse-grained, equigranular granitoid, and strongly lineated by parallelism of gray to smoky quartz rods. Much of the white facies is strongly foliated. However, even that rock which is inconspicuously foliated, non-layered, and mica-free, is very platy in weathered outcrops (fig. 19).

The white facies has been separated from normal Hope Valley Alaskite Gneiss solely on the basis of color. The contact between the two facies is gradational and somewhat arbitrary. Many outcrops of alaskite, as those on Mount Misery north of Voluntown, are intermediate, and could be mapped with either facies.

Gray to smoky quartz, white feldspar, and commonly, muscovite and magnetite are the megascopic constituents of the white facies. Potassium feldspar and plagioclase can be discriminated only microscopically. Sillimanite is a rare accessory, and minor garnet is present in one outcrop in the bed of Wyassup Brook 0.23 mile south

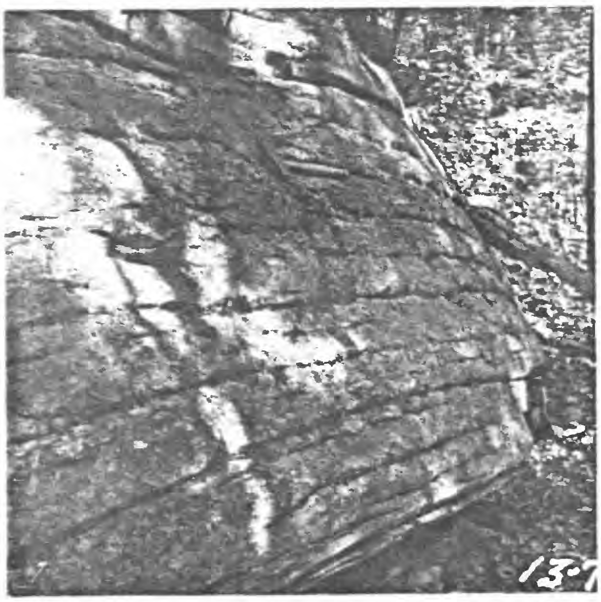


Figure 19. - Hope Valley Alaskite Gneiss, white facies. Weathered surface of mica-free, non-layered outcrop shows platiness not visible in fresh rock. Hammer handle is 38 cm long. 0.26 mile N.55°E. of intersection of Hangman Hill and Grindstone Hill Róads, North Stonington, Conn.

of Grindstone Hill Road. Quartz-sillimanite nodules occur in an outcrop 1.8 miles west of Clarks Falls.

Under the microscope the white facies differs from normal Hope Valley Alaskite Gneiss only by having more abundant muscovite, and by the complete absence of accessory minerals other than magnetite. Three modes were prepared and show a fairly wide range of composition, although the average is nearly identical with the normal Hope Valley (Table VI).

Fine-grained granite

Four outcrops in the bed of Lowden Brook near the northwest corner of the Voluntown quadrangle are of a leucogranite not exposed elsewhere in the Voluntown and Ashaway quadrangles. Bedrock exposures in the general area are very sparse, and the shapes and extent of the two bodies of this rock shown on the geologic map are conjectural. Fine-grained granite mapped to the east in the Hope Valley quadrangle by Moore (1958) is probably the same rock as that at Lowden Brook.

The fine-grained granite is fine- to very fine-grained, nearly massive, with a sub-saccharoidal texture. Fresh rock is pale tan, but exposed surfaces are stained light brown. Outcrops have a weak platy foliation barely perceptible in the hand specimen. Anhedral equant grains of beige feldspar and light smoky quartz, sparse small (0.3 mm) parallel flakes of black biotite, and even sparser smaller magnetite grains are the megascopic constituents of the rock. The abundance and microscopic aspect of the constituent minerals of the fine-grained granite are the same as in Hope Valley Alaskite Gneiss (Table VI).

The fine-grained granite was mapped as a facies distinct from the fine-grained facies of the Hope Valley because of the difference in texture of the two rocks. The composition of the fine-grained granite strongly suggests kinship with the Hope Valley group of alaskites.

Scituate Granite Gneiss

Scituate Granite Gneiss was named by Quinn (1951) for extensive exposures in Scituate township, about 20 miles northeast of the center of the Voluntown quadrangle. Previously, the Scituate had been considered part of the Sterling Granite Gneiss (Gregory, 1906, p. 134-136; Emerson, 1917, p. 229-230). Scituate Granite Gneiss mapped in the Voluntown quadrangle is not preceptibly different from the rock in the type area.

A little more than 10 percent of the Voluntown quadrangle is underlain by Scituate Granite Gneiss; that in the northeast corner is at the margin of a very extensive mass which underlies most of west and west central Rhode Island (Quinn, 1963) and is contiguous with the type area. Good accessible exposures of the Scituate are at Stepstone Falls, and in cuts on Rockville Road just west of the State line.

Scituate Granite Gneiss is a medium- to coarse-grained, strongly gneissic, pink, locally tan to light gray granite. Much of the rock is subporphyritic to porphyritic with pink microcline phenocrysts which range from slightly fractured subhedral single crystals to lenslike, or uncommonly, rodlike granular aggregates. Maximum phenocryst dimensions are generally between 1 and 3 cm, although rodlike aggregates in the rock at Stepstone Falls are 6 cm or more long.

Spear-shaped splotches of biotite flakes are the most distinctive feature of Scituate Granite Gneiss and serve to distinguish it from other granitic rocks in the area. The splotches are normally planar, 1 mm or less thick, and from 10 to 20 mm broad and 40 to 50 mm long. Long axes of the splotches are parallel and impart a very pronounced lineation to the rock; in fact, the Scituate has been called "linear granite" (Perhac, 1958, p. 12-14). Parallelism of platy surfaces of the splotches locally produces a weak to moderate foliation. Biotite splotch lineation is supplemented in most places by quartz rod alinement similar to that in Hope Valley Alaskite Gneiss, and, in porphyritic rock, by alinement of phenocryst major axes.

Pink postassium feldspar, white to cream plagioclase, gray to smoky quartz, black biotite, and rare small magnetite octahedra are readily discernable with the unaided eye. Black hornblende is megascopically visible in some specimens of the Scituate, but generally is visible either only with a hand lens or in thin section. Accessory allanite and sphene are visible only with a hand lens although allanite (?) is locally so abundant as to fleck the rock with red spots 1 to 3 mm in diameter, several thousand per square meter of outcrop surface. The most densely red-flecked rock occurs just south of Rockville Road just west of the State line.

Gray Scituate Granite Gneiss is rare in the Voluntown quadrangle, although it constitutes much of the rock in the type area (Quinn, 1951). The contact between gray and pink Scituate is sharp in the Voluntown quadrangle, and can be seen in cuts on Ted Rod Road 0.1 mile west of the State line.

Biotite content of Scituate Granite Gneiss ranges from less than 1 to more than 5 percent. Rock low in biotite is generally richer in hornblende than rock rich in biotite, although the Scituate

0.5 mile north and northwest of the outlet of Beach Pond is poor in both biotite and hornblende. Most Scituate contains between 3 and 5 percent biotite and 1 and 2 percent hornblende. Scituate low in both biotite and hornblende greatly resembles Hope Valley Alaskite Gneiss and the two rocks are clearly gradational (Moore, 1958). The contact between them is drawn with difficulty in many places. Simple field criteria were used in the Voluntown quadrangle to distinguish the two rocks. Splotches of biotite are the main diagnostic character of the Scituate. Some Hope Valley Alaskite Gneiss bears as much, or even more biotite than nearby Scituate Granite Gneiss, but the biotite in the alaskite is evenly distributed and not splotchy. Scituate Granite Gneiss breaks most easily in the plane of biotite foliation, whereas the Hope Valley tends to break normal to its quartz rod lineation. Magnetite is nearly everywhere very conspicuous in the Hope Valley, whereas it is scarce to absent in the Scituate. Rock with megascopic hornblende, even where biotite is low or absent, was mapped as Scituate Granite Gneiss. Layers of quartz-sillimanite nodules, fairly common in the Hope Valley, are absent from the Scituate. Gradation of the two rocks within a single outcrop can be seen immediately north of Beach Pond 0.64 mile west of the State line, 0.8 mile S.60°W. of BM "Beach", and several other less accessible places in the quadrangle.

Scituate Granite Gneiss is a resistant rock, although somewhat less so than Hope Valley Alaskite Gneiss. Outcrops are generally abundant. Surface rock is commonly incipiently disintegrated. Large areas of gneiss in the northeast corner of the quadrangle are deeply disintegrated, in places to depths of 6 meters or more (p.20, 23).

Under the microscope, quartz, the feldspars, biotite, and magnetite of the Scituate are the same as in Hope Valley Alaskite Gneiss and further description of them is unnecessary. Nearly all thin sections contain a strongly colored amphibole, probably common hornblende, either as small anhedral to subhedral grains, or as large poikilitic grains with abundant spherical inclusions of quartz and feldspar. The hornblende has a very small 2V (c. 15°), and is strongly pleochroic with X = light to medium greenish, or more commonly, yellowish brown, and Y = Z = deep blue-green to opaque. Amphibole cleavage is generally well developed.

Accessory minerals are very abundant and varied. Nearly all thin sections bear allanite, apatite, sphene (possible var. keilhauite of Young (1938)), and zircon. Radiohalos from allanite and zircon in hornblende and biotite are common. Very sparse garnet occurs in some thin sections, and smears of anhedral interstitial calcite are present in one.

Modal data on Scituate Granite Gneiss are given in Table VIII. The average composition of the Scituate, one of the most uniform granitic rocks in the area, is very similar to Hope Valley Alaskite Gneiss, and is that of granite.

Fine-grained facies

Three small areas in the northeast corner of the Voluntown Quadrangle are underlain by a fine-grained facies of the Scituate Granite Gneiss. The rock is best exposed in a small abandoned quarry west of Kelley Brook 0.1 mile south of the north border of the quadrangle.

A fine-grained facies of the Scituate has been mapped by Moore (1963) 3.5 miles north of the northeast corner of the Voluntown

TABLE VIII. - Modes of Scituate Granite Gneiss (volume percent)

	1	2	3
Number of samples	8	1	8
Quartz	31.4	28.8	2.4
Microcline	38.2	35.1	2.6
Plagioclase	25.5	30.4	2.5
Hornblende	1.4		1.3
Biotite	2.8	5.2	1.7
Muscovite	0.1	0.4	
Magnetite	0.3	tr	
Allanite*	0-0.2	0.1	
Apatite	0-0.1	tr	
Calcite	0-tr		
Chlorite	0-0.4		
Garnet	0-tr		
Sphene	0-0.6		
Zircon	0-tr	tr	
Composition of plagioclase (An)	8-17	13	

*Figures for accessory minerals allanite through zircon give ranges, tr = trace.

1. Average of Scituate Granite Gneiss excluding fine-grained facies
2. One thin section of Scituate Granite Gneiss, fine-grained facies
3. Standard deviation of col. 1

quadrangle, and much of the southeast part of the Oneco quadrangle is underlain by the same rock (R. Goldsmith, personal communication).

Both megascopically and microscopically the fine-grained facies differs from normal Scituate Granite Gneiss only in grain size. The modal composition of the two rocks is similar (Table VIII); the quantity of quartz and the feldspars in the fine-grained facies is within two standard deviations of the unusually uniform Scituate Granite Gneiss.

Ten Rod Granite Gneiss

Three small areas northeast of the village of Voluntown, and one area east of Deep Pond are underlain by the Ten Rod Granite Gneiss, a uniform medium-grained porphyritic granite gneiss. The rock is well exposed in a cut on Wylie School Road 0.44 mile west of Great Meadow Brook, and just north of Woody Hill Road where it leaves the Voluntown quadrangle east of Deep Pond. The rock has been mapped as Ten Rod Granite Gneiss as it is in part continuous with, and wholly similar to the Ten Rod Granite Gneiss originally defined by Moore (1958) in the adjacent Hope Valley quadrangle. The type locality of the rock is in cuts on Ten Rod Road 2.6 miles east of the east border of the Voluntown quadrangle. On older maps (Emerson, 1917) the Ten Rod was included in the Sterling Granite Gneiss.

Ten Rod Granite Gneiss in the Voluntown quadrangle is medium-grained, pink to light pinkish gray, and porphyritic. The rock northeast of Voluntown is weakly foliated, and in places has a swirly structure, whereas that east of Deep Pond is strongly foliated and lineated by quartz rods similar to those in adjacent Hope

Valley Alaskite Gneiss. The texture throughout is granitoid. Phenocrysts in the Ten Rod are predominantly partially granulated subhedral pink microcline crystals from 2 to 3 cm long, although some are lenslike aggregates of granular microcline 3 to 8 mm thick and from 8 to 20 mm in diameter. Phenocrysts constitute from 5 to 30 percent of the rock and are partially enveloped by the biotite-rich foliae of the gneiss which wrap around them.

In the hand specimen, two feldspars, quartz, biotite, and magnetite are visible. Pink microcline occurs in the ground mass as well as in the phenocrysts. Cream to white plagioclase is confined to the ground mass. The two feldspars are not distinguishable in all samples. Quartz is gray to smoky, and in the rock east of Deep Pond, is much concentrated in rods about 4 cm long and 0.5 cm in diameter. At the same locality euhedral magnetite octahedra, as much as 3 mm in diameter, are abundant.

Under the microscope, Ten Rod Granite Gneiss is similar to Hope Valley Alaskite Gneiss. Quartz is clean, but has strong strain shadows under crossed nicols, and in places bears sutured intragrain boundaries. Microcline is fresh and extremely finely grid-twinned. Phenocryst microcline is microperthitic with oriented thin plates of albite which constitute no more than a percent or two of the feldspar. Microcline in the ground mass is not perthitic. Plagioclase is middle oligoclase. Grains range from clear and fresh to extensively dusted with fine white mica. Twinning is not well developed. Sodic borders against adjacent microcline grains are common. Slender lenses of albite between two large microcline grains are common. Myrmekitic texture is rare but locally present. Biotite is strongly pleochroic with X = light yellow-tan, Y = Z = dark brown to opaque. Most biotite is fresh, although it is more than 20 percent chloritized in one sample from the northernmost body. Accessory minerals, which constitute less than 3 percent of the rock, are allanite, apatite, garnet, magnetite, sphene, and zircon. Only apatite, magnetite, and sphene exceed 0.1 percent each.

Ten Rod Granite Gneiss much resembles Hope Valley Alaskite Gneiss and Scituate Granite Gneiss. In the field, the Ten Rod can be distinguished from the Hope Valley by the relative abundance of biotite in the former, and from the Scituate by the lack of biotite splotches. The Ten Rod is generally more porphyritic than even the most porphyritic Hope Valley or Scituate.

Ten Rod Granite Gneiss has the composition of quartz monzonite or granodiorite (Table IX). Potassium feldspar-to-plagioclase is approximately 1:1.

Narragansett Pier Granite

Narragansett Pier Granite mapped in this study is confined to the Ashaway quadrangle. It and the Westerly Granite constitute the younger granites that crosscut nearly all the other rocks mapped. Nearly all the Narragansett Pier Granite is in a single stock near Westerly. Dozens of very much smaller bodies are present, of which only three are large enough to show on the geologic map. Good accessible exposures of fresh rock are plentiful in the abandoned quarries between the railroad and Nooseneck Hill Road northeast of Westerly.

Narragansett Pier Granite was named by Nichols (1956) for exposures along the shore south of Narragansett Pier (now Narragansett), about 17 miles east of Ashaway village. The rock at the type locality is identical to that described here. In the Westerly area, the granite was first mapped by Percival (1842, p. 179), who

TABLE IX. - Modes of Ten Rod Granite Gneiss (volume percent)

	1
Number of samples	2
Quartz	31.8
Microcline	29.8
Plagioclase	31.1
Biotite	4.7
Muscovite	0.5
Magnetite	1.1
Allanite*	0-tr
Apatite	0.1-0.2
Chlorite	0-1.1
Garnet	0-tr
Sphene	0-0.6
Zircon	tr
Composition of plagioclase (An)	15-20

*Figures for accessory minerals allanite through zircon give ranges, tr = trace.

1. Average of Ten Rod Granite Gneiss

noted its textural contrast with adjacent gneissic granites. Loughlin (1910) did not emphasize this difference, and mapped the granite as Sterling Granite which included all the granitic rocks described in the present report except Westerly Granite. In a later paper Loughlin (1912, p. 133-134) subdivided the Sterling, and included the granite (and much of the Potter Hill Granite Gneiss) in a "normal or even-grained" facies. Martin (1925, p. 36-39) mapped the granite separately ("Redstone Granite"), although she felt that it was a late facies of Sterling Granite.

Narragansett Pier Granite is a medium-grained, equigranular, granitoid, reddish pink, massive to weakly foliated rock. To the unaided eye the rock is composed of subhedral pink microcline, subhedral white plagioclase, and anhedral blebs of smoky quartz in subequal amounts, and minor biotite and magnetite. In sparse exposures the rock is tan or gray, Locally the granite has a pegmatitic texture; elsewhere it is weakly porphyritic and bears 1 or 2 percent pink microcline crystals 2 or 3 times the grain size of the normal rock. Pegmatitic and porphyritic rock accounts for less than one percent of the total Narragansett Pier Granite exposed.

The granite is faintly foliated but strong development of foliation is restricted to small bodies, and those areas of the large stock that are near the walls. Foliation is by parallel alinement of biotite flakes, with a very weak subsidiary development of discontinuous thin quartz-rich and feldspar-rich layers.

Narragansett Pier Granite is a resistant rock and commonly it underlies hills. The rock is almost invariably fresh within a few centimeters of the surface in natural exposures. Inclusions are locally abundant especially in the west end of the main stock. Maximum dimensions range from a few centimeters to 3 meters or more.

Minerals in thin sections of Narragansett Pier Granite are mostly fresh, and their abundances show that the rock has the composition of quartz monzonite or granodiorite, as microcline and plagioclase are subequal (Table X). No modes from the type locality are available, but mineral ranges given for the type rock (Nichols, 1956) are consistent with modes prepared from the granite in the Westerly area.

Quartz is unstrained to slightly strained. Grains have sweeping, simple boundaries, and are rarely involuted or sutured.

Microcline has prominent grid-twinning, and some grains are lightly dusted with white mica. Patch perthite is developed locally; the patches are albite, and are more dusted than the surrounding microcline.

Plagioclase is oligoclase. Polysynthetic twinning is generally fairly well developed, but is locally broad and weak, or even absent. Most grains are slightly to moderately dusted with white mica. Thin fresh albite rims are nearly ubiquitous at microcline contacts.

Biotite is fresh and strongly pleochroic with X = pale yellow-tan, and Y = Z = dark golden brown to opaque. Radiohalos from zircon spackle most flakes.

Muscovite occurs in large poikilitic crystals with amoeboid boundaries, and as small anhedral patches or rosettes in feldspar. In one section studied, large undeformed muscovite crystals enclose thin bent biotite flakes.

Chlorite occurs as leaves in some biotite flakes, but is more common as independent flakes, many of which are crowded with rutile (?) needles and opaque dust. Pleochroism is strong, with the X color almost indistinguishable from the X color of coexisting biotite, and a medium gray-green Y and Z color. Relic radiohalos

TABLE X. - Modes of Narragansett Pier Granite (volume percent)

	1	2	3
Number of samples	5	2	5
Quartz	28.1	25.3	4.0
Microcline	35.6	31.5	7.1
Plagioclase	31.2	40.0	5.9
Biotite	2.1	2.3	1.9
Muscovite	1.3		1.0
Magnetite	0.7	0.5	
Allanite*	0-tr	tr	
Apatite	0-0.2	tr-0.5	
Chlorite	0-0.8	0-tr	
Epidote	0-tr		
Monazite	0-0.3		
Sphene	0-tr	0-tr	
Zircon	0-0.1	tr	
Composition of plagioclase (An)	18-26	21	

*Figures for accessory minerals allanite through zircon give ranges, tr = trace.

1. Average of Narragansett Pier Granite excluding white facies
2. Average of Narragansett Pier Granite, white facies
3. Standard deviation of col. 1

are common. Most grains have strong anomalous blue interference colors.

Accessory magnetite is ubiquitous. Most thin sections contain allanite (commonly metamict), apatite, and zircon, and some contain epidote, monazite (commonly metamict), and sphene in addition.

White facies

The granite in the westernmost portion of the main stock of the main stock of the Narragansett Pier is white. The white granite grades into the reddish pink normal Narragansett Pier Granite, and many outcrops show pale pink intermediate granite. Outcrops on Hill 201 northwest of Pawcatuck afford good exposures of the white facies. Only Martin (1925, p. 38) previously recognized the white granite as a variation of the "Redstone", but she did not map it separately.

In the hand specimen, the white facies differs from normal Narragansett Pier Granite only in color. The rock is medium-grained equigranular, and generally weakly foliated. It is composed of subhedral to anhedral white feldspar, anhedral smoky quartz, and sparse biotite flakes. Tiny brown allanite crystals are generally visible with a hand lens. Amphibolite inclusions are abundant, some (probably roof pendants) are of mappable size. Surface rock of the white facies in natural exposures is usually fresh.

Thin sections of the white facies differ little from thin sections of normal Narragansett Pier Granite. The aspect of the quartz and feldspar is identical in the two rocks. Modal data on two samples of the white facies (Table X) suggests a higher plagioclase-to-microcline ratio than in pink Narragansett Pier Granite. Accessory minerals are abundant in the white facies.

Magnetite is ubiquitous, and allanite, both as fresh and as metamict grains, constitutes 1 to 2 percent of some thin sections. Apatite and zircon, the latter commonly as sharply terminated euhedra, are also common. Where allanite and zircon abut or are surrounded by biotite, strong radiohalos have been developed in the mica.

Westerly Granite

Westerly Granite is exclusively a dike rock in the Ashaway and Voluntown quadrangles, and is largely restricted to the south third of the Ashaway quadrangle. Only two dikes, both small, occur north of this. One is just north of New London Turnpike a mile northeast of Hopkinton village, and the other is on the north shore of Yawgoog Pond in the Voluntown quadrangle. The dikes in the Westerly area are from 3 meters to as much as 20.7 meters thick. Westerly Granite is best exposed in the active Gencarelli Quarry, northeast of Westerly, where geologic relationships are unusually clear.

Westerly Granite is almost certainly the world's most thoroughly analyzed rock (Fairbairn and others, 1951; Stevens and others, 1960). The single sample (G-1) that afforded the material for this study was quarried from a dike only 0.15 mile south of the Ashaway quadrangle. G-1 does not differ visibly from the Westerly Granite found in the larger dikes mapped in this area.

Descriptions of Westerly Granite have been in the geologic literature since the last century (Kemp, 1899, p. 367; Gregory, 1906, p. 154; Dale and Gregory, 1911, p. 103), but individual bodies of the granite in the Westerly area were not shown on a geologic map until 1925 (Martin).

Westerly Granite is a fine-grained, light gray, massive to rarely very feebly foliated, exceedingly uniform rock. Light gray to pinkish gray anhedral feldspar constitues the bulk of the rock in the hand specimen. Potassium feldspar and plagioclase are megascopically indistinguishable. Pale smoky to gray quartz occurs interstitially. The rock is flecked with vitreous black biotite flakes which impart a salt-and-pepper texture. Muscovite and rare allanite grains are visible with a hand lens, Locally, especially in small bodies, the granite is slightly porphyritic with phenocrysts of microcline and biotite. Many of the biotite phenocrysts have an unusual acicular habit, which in extreme cases has produced vanishingly thin basal plates as much as 30 mm long and 4 mm wide (fig. 20). Most of the acicular biotite flakes, however, are less than 2 mm long.

The normal gray granite is stained uniform pale pink in most surface exposures, and deep pink to reddish pink along most joints. In places thin planar zones, generally a centimeter or less thick, are stained pink although no joint surfaces that might have localized the stain are visible. These stains probably reflect early joints that are now healed, but remain as feebly permeable channelways for groundwater circulation. Inclusions of amphibolite and Narragansett Pier Granite in the Westerly can be seen in many of the quarries northeast of Westerly.

Thin sections show that the Westerly is as uniform and massive as the hand specimens suggest. Like Narragansett Pier Granite, the Westerly is a quartz monzonite or granodiorite. Modal data are given in Table XI.

Quartz is clean and has only weak strain shadows. Grain boundaries are generally simple and unsutured.

Microcline is fresh to lightly dusted with white mica. Some grains are prominently zoned with cores of dusted, finely grid-

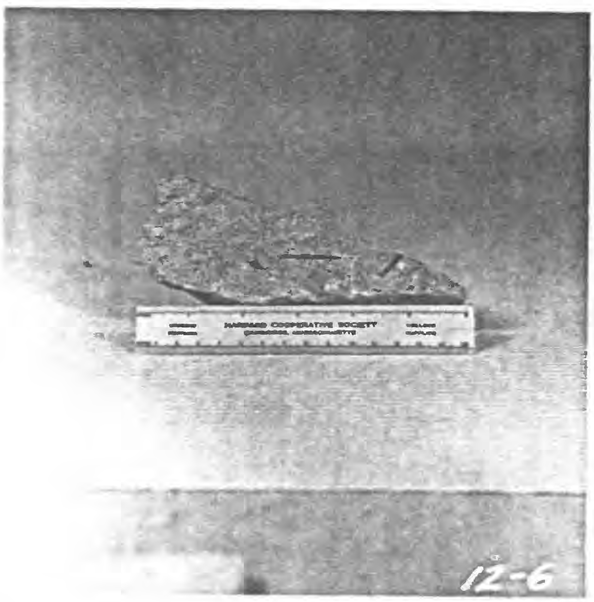


Figure 20. - Acicular biotite phenocrysts in Westerly Granite, Westerly, R. I.

TABLE XI. - Modes of Westerly Granite (volume percent)

	1	2
Number of samples	28**	28**
Quartz	27.5	1.4
Microcline	34.3	2.3
Plagioclase	32.3	2.1
Biotite	3.5	0.8
Muscovite	1.3	0.5
Magnetite	0.5	
Accessories*	1.1	
Allanite	tr-0.1	
Apatite	tr-0.2	
Calcite	0-tr	
Chlorite	tr-1.3	
Epidote	0-tr	
Sphene	0-0.5	
Zircon	tr	
Composition of plagioclase (An)***	17-23	

*Ranges of individual accessory minerals allanite through zircon based on 3 modes prepared for the present report; abundance of non-opaque accessory minerals given in other 25 modes are grouped as "Accessories" above.

**3 modes prepared for the present report. Others as follows: 16 by Chayes _in_ Fairbairn and others (1951, p.61), and 9 from an unpublished Honor's Thesis by L.W. Lundgren at Brown University, Providence, R.I.

***3 modes prepared for the present report only.

1. Average of Westerly Granite
2. Standard deviation of col. 1

twinned microcline surrounded by fresh, broadly grid-twinned shells. Other grains have cores of dusted patch perthite, or even cores of oligoclase.

Plagioclase is oligoclase, and is generally more dusted than coexisting microcline. Twinning on the albite law is moderately well developed. The majority of the grains have feeble normal zoning which is accentuated by the cores being slightly more dusted than the peripheries. The zoning is normal, and embraces no more than 2 or 3 percent An. Some thin sections contain subhedral to euhedral plagioclase phenocrysts 2 or 3 times the normal grain size. These grains are prominently zoned with as many as a dozen sharply bordered shells. The mean An content of these grains is the same as the An content of the matrix grains. Most plagioclase grains show sharply defined albite borders (locally myrmekitic) at contacts with microcline.

Biotite is fresh and strongly pleochroic with X = straw yellow to light tan, and Y = Z = deep golden brown to opaque. Some flakes contain as much as 5 percent interleaved chlorite which contains abundant very fine rutile (?) needles. Deformation of biotite is uncommon; some flakes are slightly bent in only two of the eleven thin sections studied.

Muscovite is less abundant than biotite, and occurs in two distinct habits. The commoner habit is as little whisps or finely divided flakes associated with feldspar or biotite. The other habit is as large, undeformed, poikilitic, optically continuous crystals that enclose smaller grains of all the other minerals.

Accessory minerals are allanite, apatite , calcite, epidote, magnetite, pyrite, sphene, and zircon. Only allanite, apatite, and magnetite commonly occur in more than trace amounts. Allanite is locally abundant, and occurs in grains as large as 1.2 by 0.4 mm. Much of the allanite is metamict, and has produced radiohalos in biotite and chlorite. Epidote, pyrite, and sphene are rare. All pyrite grains are rimmed with brown limonite. Zircon is ubiquitous. Crystals are euhedral and like allanite, have produced strong radiohalos in biotite and chlorite. Calcite occurs sparingly as anhedral films in oligoclase.

Aplite, pegmatite, and vein quartz

Sills, dikes, and irregular bodies of aplite, pegmatite, and vein quartz are in nearly all rocks in the Ashaway and Voluntown quadrangles. Most bodies are small, and only rarely do they constitute the bulk of an outcrop.

Aplite is massive, fine- to very fine-grained, and pink, tan, or less commonly white. Mafic minerals, except rare tiny magnetite grains, are absent. The texture is saccharoidal and all minerals are anhedral.

Pegmatite is simple and composed of pink microcline, white to cream albite or sodic oligoclase, and gray quartz. Thin books of biotite are common in those that cut Narragansett Pier and Westerly Granite, and magnetite octahedra as much as 3 cm in diameter are present in some in Hope Valley Alaskite Gneiss. Black tourmaline is abundant locally in small irregular bodies of pegmatite in felsic metavolcanic rock near Billings Lake. Tiny crystals of a strongly radioactive pale green mineral, probably autunite, occur with muscovite in a 30 cm-thick pegmatite in biotite schist on the west side of Tomaquaug Valley Road, 0.17 mile east of Burdickville Road in the Ashaway quadrangle.

Vein quartz is light gray to milky. Smears of pink to beige microcline constitute several percent of much of the vein quartz in Hope Valley Alaskite Gneiss.

Five small aplite sills have been mapped in the Voluntown quadrangle, and a few outcrops that are predominantly pegmatite are so indicated on the geologic map. No exposed quartz veins are more than a half meter thick. Large boulders on the south half of Diamond Hill, however, are of coarse vuggy vein quartz that contains euhedral terminated crystals of clear quartz with thin shells of milky quartz that are as much as 10 cm long and 2 cm in diameter. These boulders, for which Diamond Hill was named, must have come from a quartz vein, now buried under drift, many times larger than any now exposed.

Thin dikes of aplite, pegmatite, and vein quartz are especially abundant in the granitic rocks of the southeast quarter of the Voluntown quadrangle. These have been plotted separately (Plate V). The structural significance of these dikes in discussed later.

Mafic dikes

Two thin mafic dikes were mapped in the Ashaway and Voluntown quadrangles. The thicker dike is in the Westerly area. The exposure, now covered, was high on the south part of an east-facing headwall in an abandoned quarry 0.8 mile N.40°W. of the center of Chapman Pond. The dike is about 30 cm thick, and it divides at one point into two parallel 15 cm dikes separated by a septum of Narragansett Pier Granite. The other dike is in the Voluntown quadrangle, 0.8 mile due east of BM 487 ("Beach"), between Beach and Deep Ponds. This dike is very thin, generally between 4.5 and 5.0 cm, with extremes of 1.2 and 6.2 cm. The dike is exposed, with minor covered intervals, for a distance of 13 meters along strike.

The petrography of the two dikes differs considerably. Rock from the Westerly area dike is very fine-grained to aphanitic, and black. It bears stubby phenocrysts of pale yellowish green olivine, generally sparse and less than 3 mm long. In places, however, the phenocrysts are as much as 3.8 cm long, and constitute as much as 50 percent of the rock. Here the rock has weathered to a granular aggregate. Alinement of olivine phenocrysts is weak to absent. The dike from the Voluntown quadrangle is also very fine-grained to aphanitic, but less strikingly porphyritic. Tiny elongate laths of glassy plagioclase as much as 6.5 mm long, but generally considerably less, are the only mineral discernable with a hand lens. The laths are rigorously alined, and plunge directly down the dip of the dike. The dike, which is less resistant than the porphyritic granite gneiss host, weathers chocolate-brown.

Thin section study shows that the dike from the Westerly area is composed of phenocrysts of olivine (forsterite, Fo_{90-100}), set in a matrix of pigeonite (?), talc, antigorite, magnetite, amphibole, calcite, and chlorite. The pigeonite (?) is extremely abundant. It occurs as tiny laths of moderate relief ($n = c.1.65$) and moderate birefringence (0.015 ± 0.003). The laths are optically positive with a 2V of about 30°, are locally weakly zoned, and have a maximum extinction angle of 40°. The talc is pseudomorphic after olivine, and has replaced parts of euhedral olivine phenocrysts. Antigorite is intimately intergrown with the talc, and in addition forms veins and small irregular masses in the matrix. Magnetite occurs as abundant tiny granules scattered evenly through the matrix. Deep red-brown amphibole in small anhedral grains, small twinned calcite anhedra, and very pale green chlorite shreds are minor constituents. No feldspar or pseudomorphs of other minerals after feldspar are present. The rock is probably an altered feldspar-free lamprophyre (monchiquite?).

Tiny laths of labradorite (An_{69}) constitute approximately half the dike rock from the Voluntown quadrangle. The laths range from 7 by 0.2 mm down to the limits of microscopic resolution. Some of the crystals are feebly zoned. Rare patches of antigorite-talc-carbonate-magnetite, as much as 0.5 by 1.0 mm, exhibit regular outlines and clear zoning suggestive of pseudomorphism after a pyroxene. The matrix is finely granular, birefringent, and yellow-green in plane light. Only fine grains of magnetite are indentifiable. The rock is slightly altered, extremely fine-grained basalt.

PETROGENESIS

All rocks in the Ashaway and Voluntown quadrangles are plutonic. They were originally formed or were recrystallized deep in the crust under a thick cover. Subsequent erosion of this cover, probably accompanied by compensatory isostatic uplift, has exposed these once deep-seated rocks to view.

The origin and geologic evolution of the rocks described in the preceding section have been read from three parameters of the rocks themselves: their composition, their fabric, and their degree of uniformity. A few brief comments on the nature of these parameters will make clearer the discussion on the origin of individual rock units given below.

The minerals present in a rock and their relative abundances constitute the mineral composition of the rock. Determination of quantitative mineral compositions requires thin section modal analysis. Good qualitative estimates, however, can be made megascopically on all but the finest-grained rocks in the Ashaway and Voluntown quadrangles. The mineral assemblages of all the rocks reflect the plutonic temperature and pressure conditions under which they were formed.

Fabric is used in the broad sense suggested by Turner and Verhoogen (1960, p. 62), and refers to microscopic as well as to megascopic features. Grain size and shape, spatial relationships of grains, and orientation of non-equidimensional grains, as well as small folds and slickensides all are rock features treated as fabric in the present report.

Rock uniformity is of two types: uniformity of mineral composition, and uniformity of fabric. Non-uniform rocks here are nearly all so because of interlayering of rocks of unlike composition, unlike fabric, or both. On the other hand, rock changes along strike of layering or foliation are exceedingly rare. Layering in some rocks is subtle, discernible only in thin section, or by vague color differences, or through differential resistance to weathering. In other rocks layering is the most conspicuous feature of all outcrops.

Original nature of the metamorphic rocks

Compositional layering in nearly all metamorphic rock in the Ashaway and Voluntown quadrangles suggests pre-metamorphic sedimentary and volcanic bedding. Layers range from a centimeter or less, to ten meters or more thick, but probably only rarely do they have the original thickness of the bed from which they were formed. Where rocks have been stretched over domes of granitic rock, layers have been thinned, and where rocks have been squeezed between such domes, layers have been crumpled and thickened. Interbedding of metamorphic rock types at most contacts in the quadrangles suggests transitions of source or environment during sedimentation and makes unlikely the presence of unconformities.

Primary sedimentary structures other than bedding are nowhere unequivocally preserved. Sparse small-scale irregularities of layering and foliation could be interpreted as cross-bedding, cut-and-fill structures, or penecontemporaneous sedimentary deformation. However, as all examples are vague and commonly suggest contradictory geopetal directions, they have been interpreted as part of the metamorphic fabric.

Mafic metamorphic rock

Several masses of mafic metamorphic rock are enclosed within granitic rocks of the Voluntown quadrangle. The most likely interpretation is that these isolated masses are inclusions or screens of mafic metasediment (impure sandy dolomite?) or of metavolcanic rock (basalt or basaltic detritus?) from a lower stratigraphic unit not elsewhere exposed. Concordance of these inclusions with gneissic structure of the host granite is a natural consequence of the well-developed foliation of the inclusions and their tabular form.

Plainfield Formation

The composition and bedding of the bulk of the Plainfield Formation mapped in the present report indicates a sedimentary origin. Much of the feldspathic biotite gneiss and schist in the Ashaway quadrangle and some feldspar-rich zones in the quartzose biotite gneiss and schist of the Voluntown quadrangle, however, have compositions that range from granite to granodiorite. Although some of these feldspathic rocks, as northeast of Laurel Glen, may be in part early intrusive rocks related to the porphyritic granite gneiss, the bulk is probably metasedimentary. Bedding is widespread, and the rocks are interbedded in places with such clearly non-igneous rock types as quartzite and schist. Moore (1959) has given evidence that similar and contiguous rocks in the Carolina quadrangle have been extensively feldspathized. Feldspathization of the rocks in the Ashaway and Voluntown quadrangles is indicated by the development of large feldspar porphyroblasts in schist adjacent to Hope Valley Alaskite Gneiss east of McGowan Corners and elsewhere. The process of feldspathization is closely tied to the development of quartz-sillimanite nodules in adjacent granitic rocks, and will be discussed in detail in a later section. Prior to feldspathization, the feldspathic biotite gneiss and schist probably had a composition similar to the quartzose biotite gneiss and schist in the Voluntown quadrangle.

The quartzose biotite gneiss and schist is a metamorphosed shaly sandstone; layers rich in biotite and plagioclase may have been graywacke. Sillimanite-bearing schist was probably shale, and sillimanite gneiss may have been feldspathic sandstone with a clay matrix. Rare amphibolite layers and pods were either dolomitic sediments or, less likely, thin beds or lenses of mafic volcanic detritus. Calc-silicate quartzite was calcareous quartz sandstone.

Much of the quartzite must have been nearly pure quartz sandstone prior to metamorphism, as modes of some samples show more than 95 percent quartz. Less quartzose sandstone and other rock types must have constituted some of the protolith, however, as layers of biotitic and feldspathic quartzite, calc-silicate quartzite, and metaconglomerate are found locally. Wavy layering of quartzite between Wyassup Lake and Pendleton Hill probably reflects lenticular bedding of the parent sandstone, whereas the virtual absence of bedding in quartzite in the abandoned quarry 1.5 miles west of Green Fall Pond suggests a very massive protolith.

Metavolcanic rocks

The composition of the metavolcanic rocks ranges from rhyolitic to basaltic. As compositional layering is prominent in all these rocks and as individual layers are rarely more than a few meters thick, it is likely that thin ash falls and pyroclastic beds constituted the parent rock. No rock derived from thick flows or thick uniform pyroclastic beds is exposed. The lateral persistence of beds a few centimeters thick across outcrops 20 meters or more long suggests deposition in, and possible reworking by water.

intercalation of non-volcanic rock types, particularly quartzite, calc-silicate quartzite, and sillimanite schist, similarly implies subaqueous deposition. It is possible that some of the thin, pure quartzite layers in amphibolite are metachert. The common interbedding of mafic and felsic material implies very vigorous volcanic activity with many centers and with much intertonguing of ejecta from different sources.

The felsic metavolcanic rocks at Wyassup and Billings Lake were mapped as sheets of intrusive alaskite by Loughlin (1912), and the layered felsic gneiss at Westerly was attributed to composite injection by several magmas by Martin (1925, p. 26-31). Three lines of evidence strongly favor a metavolcanic rather than an intrusive origin for these rocks.

First, the prominent textural layering of nearly every outcrop is quite unlike intrusive granite. Although composite sills and dikes that are the product of two, three, or a dozen injections of magma have been described, a magmatic origin of the felsic metavolcanic rocks, especially those at Westerly, would require thousands of such injections to represent the thousands of distinct layers.

Second, the layers differ not only in texture, but in composition as well. Much of the compositional layering is obvious in the field by color contrasts caused largely by unlike mafic mineral abundances. Thin sections, however, reveal that megascopically identical layers commonly have very different microcline-to-plagioclase ratios, and that not just two or three types are present, but that the range is a continuous one. None of the known magmatic granitic rocks exhibits as great a compositional range.

Third, the contact between felsic and mafic metavolcanic rock is sedimentary. Rock types are interbedded. A particularly clear example is the amphibolite in layered felsic gneiss at Hinkley Hill, Pawcatuck, Conn. The north contact is a zone of interbedding about 10 meters broad, whereas the south contact is sharp. The totally dissimilar nature of the two contacts is compatible with a succession of volcanic-sedimentary events, and is not compatible with magmatic intrusion of layered felsic gneiss.

Calc-silicate quartzite

The parent material of the calc-silicate quartzite ranged from shaly sandstone to calcareous sandstone. The former was recrystallized to micaceous and feldspathic quartzite, whereas the latter became the epidote quartzite found in most exposures.

Loughlin (1912, p.43-44, 61-62) attributed the calc-silicate quartzite to "epidotization" of quartz-biotite schist by contact action during intrusion of the overlying granitic magma. Much of the quartzite, however, including all that in the middle body of the three mapped, is without epidote. Furthermore, the far higher lime content of much of the calc-silicate quartzite than of the augen gneiss makes lime metasomatism from augen gneiss magma unlikely. It is far more probable that the composition of the calc-silicate quartzite is primary.

The calc-silicate quartzite is not continuous beneath the augen gneiss. Whether the parent sandstone was deposited as a series of discontinuous lenses, or whether it was a continuous layer that has since been in part cut out by intrusive augen gneiss is not certain. The latter interpretation is favored as such a relationship is suggested at the south end of the northernmost body of the calc-silicate quartzite.

Metamorphism

As hornblende and a plagioclase more calcic than albite are present in metamorphic rocks of appropriate composition throughout the Ashaway and Voluntown quadrangles, the regional grade of metamorphism is in the almandine-amphibolite facies (Turner and Verhoogen, 1960, p. 544). Mineral assemblages diagnostic of subfacies are scarce. However, the coexistence of sillimanite and muscovite in aluminous schist in the Voluntown quadrangle and in most nodules in granitic rock in both quadrangles is compatible with the sillimanite-almandine-muscovite subfacies (ibid., p. 548-549). All metamorphic rocks of both quadrangles have been assigned to this subfacies.

In places, however, the granitic rocks within the batholith have a higher metamorphic grade than surrounding rocks. Small rosettes of sillimanite occur with microcline but without muscovite in some outcrops of Hope Valley Alaskite Gneiss and Potter Hill Granite Gneiss. This assemblage is diagnostic of the sillimanite-almandine-orthoclase subfacies, the highest within the almandine-amphibolite facies (Ibid., p. 549-550).

Evidence of retrograde metamorphism is restricted to partial conversion of some plagioclase to white mica, local chloritization of small biotite flakes, and sparse chlorite inclusions in the hornblende of some amphibolite in the Westerly area. Extensive chloritization or development of epidote in plagioclase is nowhere present. The minor retrograde effects are interpreted as products of the wane of the metamorphism that produced the present rocks, rather than the products of a later, distinct metamorphism.

The grade of metamorphism was high enough locally to generate anatectic granitic magma in rocks of appropriate compostion. The most prominent example is the abundant aplitic, potassic granite in layered felsic gneiss (fig.14). Field evidence is strong that this granite is anatectic and not intrusive from a distant source. Much of the granite is in replacement dikes which show no wall dilation. Many such dikes, where followed along strike, elsewhere show wall dilation and other intrusive relationships. Where the anatectic magma which formed the dikes did not migrate, but remained _in situ_ as plates and pockets in relatively solid gneiss, wall dilation is absent. Where the anatectic magma migrated, even slightly, walls are dilated and rotated inclusions (fig. 14) are abundant. Further evidence of the anatectic origin of the aplitic, potassic granite is its nearly perfect confinement to the layered felsic gneiss. It is nearly completely excluded from adjacent amphibolite. It is likely that much pegmatite in the Plainfield Formation distant from granitic rocks (fig. 7) had a similar origin.

Mineral veins and pods in other metamorphic rocks that reflect the composition of their host were probably derived by metamorphic differentiation. Examples are numerous. Most abundant and widespread are the clear gray quartz lenses in the quartzose biotite gneiss and schist of the Plainfield Formation. Elsewhere, outcrops of calc-silicate quartzite and calc-silicate granofels of the same formation are cut by epidote-calcite veins, and tremolite-phlogopite quartzite just north of Babcock Road 0.3 mile east of the west border of the Ashaway quadrangle is cut by coarse-grained quartz-actinolite veins. Probably much of the light-colored oligioclase-hornblende pegmatite in amphibolite north and west of Westerly was derived by the same process.

Evidence of metasomatism or large-scale allochemical metamorphism is nearly restricted to the extensive feldspathization of parts of the Plainfield Formation to be discussed in a later section. Some samples of gneiss, amphibolite, and calc-silicate quartzite contain from 1 to 30 percent scapolite which suggests chloride or possibly carbonate metasomatism. It is equally likely, however, that these materials were present in the parent rocks.

Contact metamorphic and metasomatic effects of Naragansett Pier Granite intrusion are locally pronounced. Biotite was the stable ferromagnesian phase in the Narragansett Pier Granite magma. The magma reacted with, and converted the hornblende in amphibolite wall rock and inclusions to biotite (cf. Bowen, 1928, p. 197-198). On the other hand, inclusions of layered felsic gneiss are mineralogically and texturally unchanged.

Metavolcanic rocks in the Wyassup-Billings Lakes area (hereafter referred to as the northern rocks) are almost certainly correlative with those exposed to the south at Babcock Road, at Westerly, and at Diamond Hill. At all places the rocks directly overlie quartzite of the Plainfield Formation. Gross mineral composition and distribution of rock types within the metavolcanic rocks is everywhere the same. On the other hand, the fabric of the northern rocks is completely unlike that of the correlative rocks to the south.

Two features of the northern rocks are unusual and warrant explanation: fine grain size, and lamination. Nearly all these rocks are fine- to very fine-grained. Some rock types, especially black amphibolite, contain no grains larger than 0.3 mm, yet all are of high metamorphic grade in which the normal grain size is medium or coarse (Turner and Verhoogen, 1960, p. 464). Fine lamination (laminae less than 1 mm thick) is present in half or more of the northern rocks. Mineral distributions in laminae, for example hornblende-rich vs. andesine-rich laminae in amphibolite, strongly suggest that the laminae were formed by metamorphic differentiation and that they do not reflect sedimentary bedding of the protolith.

The fine grain size of the northern rocks are here postulated to be due to extensive internal movements, principally differential transport parallel with layering (shear) during metamorphism. The metamorphic differentiation which produced the fine compositional lamination of the northern rocks was promoted by the shear movements. These movements, which prevented the growth of large grains, were produced by syn-metamorphic and syn-tectonic emplacement of porphyritic granite gneiss, Potter Hill Granite Gneiss, and Hope Valley Alaskite Gneiss magmas under and south of the northern rocks. Movements within the metavolcanic rocks were presumably tensional; a response to upward doming produced by the swelling granite mass to the south. This is corroborated by the coincidental orientation of linear structures in the granitic and in the metavolcanic rocks, and by the absence of down-dip crumpling in the latter. The axis of least compressive stress during deformation paralleled the linear structures which now have a north northwest bearing and a gentle northward plunge.

Correlative metavolcanic rocks at Westerly have a grain size compatible with their high grade of metamorphism. Internal movements in these rocks during metamorphism were far less extensive, and metamorphic minerals were able to grow to larger sizes than in the northern rocks.

That the differences in fabric of the northern rocks and those at Westerly were induced by syn-metamorphic movements, and were not inherited from the parent rock, is corroborated by a comparison of corresponding features of the two groups of rocks.

The rocks at Westerly show little evidence of strain in thin section. Unbroken blocky porphyroblasts of hornblende and locally porphyroblasts of calcite interrupt foliation. Metamorphic differentiation is only moderately well developed. The northern rocks, on the other hand, invariably show evidence of intense strain in thin section. Felsic metavolcanic rocks, as well as overlying calc-silicate quartzite, all are cataclastic, and mortar structure is common. Strain effects in interbedded amphibolite, however, are slight, and are restricted to a few offset plagioclase lamellae and the granulation of that quartz which is present. Apparently the mafic rocks are able to recrystallize more completely in response to stress than are the felsic rocks. Porphyroblasts are rare and nowhere large. Calcite porphyroblasts in amphibolite at Westerly are represented in the northern rocks by thin films of granular calcite that coats some foliation planes in fine-grained amphibolite southeast of Billings Lake.

Anatectic granite, which in layered felsic gneiss at Westerly is commonly discordant and in irregularly-shaped bodies (fig. 14), has been wholly drawn into concordant smears of aplite and pegmatite in the northern rocks and is almost nowhere discordant.

Quartzite beds in amphibolite in the northern rocks contain thin (1 mm or less), gray, vitreous laminae, which are continuous with unchanging thickness across large outcrops. They are not found in quartzite elsewhere in the quadrangles. It is unlikely that the vitreous laminae are inherited from primary sedimentary features as in several places the laminae double back within a single bed (fig. 21). Axes of these "folds" parallel regional lineation. The highly strained vitreous laminae, which differ

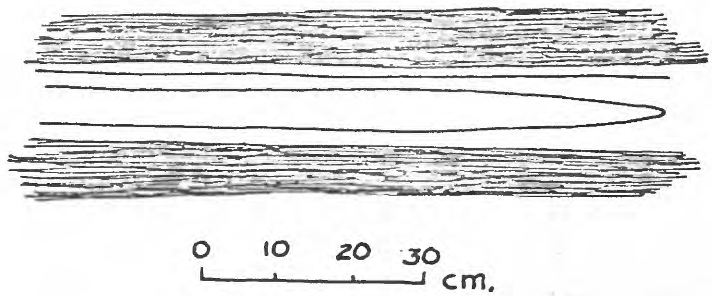


Figure 21. - Layer of quartzite (blank) in fine-grained, laminated amphibolite (ruled). Two gray vitreous laminae in the quartzite shown by lines; lower one doubles back. 0.6 mile N.48°W. of the summit of Pendleton Hill, North Stonington, Conn.

greatly from the normal granular quartzite in which they occur (see p. 53 for microscopic description) are here interpreted as surfaces along which preferential slippage occurred during metamorphism. The great purity of the gray vitreous laminae probably resulted from the continuous expulsion of impurities (largely feldspar and mica) during movement and recrystallization.

The absence of retrograde minerals in the rocks or in veins in the rocks, and the extreme deformation of the northern rocks is highly suggestive that the deformation of the rocks must have coincided with, and not continued beyond the period of maximum metamorphism. Evidence of pre-metamorphic cataclasis is lacking, but traces of any such episode would have been obscured or obliterated by the later metamorphism.

Whereas deformational movements and metamorphism appear to have been contemporaneous in the metavolcanic rocks and calc-silicate quartzite at Wyassup and Billings Lakes, a similar relationship between movements and metamorphism did not occur in all metamorphic rocks in the quadrangles. For examples, large quartz grains and groups of quartz grains are much strained in feldspathic biotite gneiss and schist of the Plainfield Formation east of McGowan Corners, whereas coexisting small quartz grains are unstrained. This implies metamorphic growth of the large grains either before or during at least some differential movement within the rock. On the other hand, pods and lenses of clear gray quartz common in the quartzose biotite gneiss and schist of the Plainfield Formation are unstrained whereas smaller quartz grains in the matrix are strained. Quartz in the pods and lenses crystallized after the cessation of movements in the rock, and may have been derived from the earlier matrix quartz.

Petrologic implications of the above discussion are considerable. The evidence summarized suggests that the contrasting fabric of the two groups of rocks is solely the product of differences in degree of internal movement of the rocks during their metamorphism; no differences of parent rock or of metamorphic grade are involved.

Regional metamorphism is commonly referred to as "dynamothermal" metamorphism, as rocks of regionally metamorphosed terranes universally show effects of both movement and heat. Modern experimental work has dealt in detail with the conditions of temperature and pressure of metamorphic reactions (see summary by Fyfe and Turner in Fyfe, Turner, and Verhoogen, 1958, p. 149-185). No quantitative studies have been made, however, on the effects of deformation on the fabric of systems undergoing metamorphism. The fabric contrasts within the metavolcanic rocks mapped in the present report show the need for considering syn-metamorphic deformation in addition to the temperature and the hydrostatic pressure of metamorphism and the nature of the parent rock.

Origin of the granitic rocks

The origin of many granitic rocks is controversial (Turner and Verhoogen, 1960, p. 329-330). Especially controversial is the origin of gneissic granitic rocks in high-grade metamorphic terranes. Few such granitic rocks show unequivocal criteria of their origin, and two genetic mechanisms are championed with nearly equal vigor: magmatic intrusion, and granitization. By the first mechanism granitic rocks crystallize from magma, generally intruded from a distant source. Granitic rocks formed by granitization are believed to develop in situ by chemical and textural reconstitution of a pre-existing, non-granitic rock. No liquid silicate phase partakes in this process.

The term magma used in the present report follows the usuage of Turner and Verhoogen (ibid., p. 50); "naturally occurring mobile rock matter that consists in noteworthy part of a liquid phase having the composition of a silicate melt". How much of the magma is actually liquid is not specified; it may be only a small fraction. The presence of a liquid silicate phase is important, however, as it separates those rocks considered to be magmatic from rocks which have behaved plastically, but in which no liquid silicate phase took part in deformation. That liquid silicate phases do exist in feldspathic rocks at geologically reasonable temperatures and pressures is abundantly demonstrated by experimental evidence. Particular evidence that relates to rocks of granitic composition is given by Tuttle and Bowen (1958). Mobility is an important part of the definition of magma. All granitic rocks in the Ashaway and Voluntown quadrangles which on other grounds are considered to have been magmatic, show evidence of having been far more mobile than the associated non-magmatic metamorphic rocks.

Probably much of the controversy on the origin of gneissic granitic rocks in high-grade metamorphic terranes stems from the non-definitive or ambiguous nature of contacts between the granitic and non-granitic rocks. Where magma is intruded into rocks during high-grade metamorphism, the mechanical difference between magma and host is small, and structures in the two rocks are similar and concordant. In high-level (and non-controversial) intrusions the mechanical contrast between magma and host is very great, and such intrusive relationships as discordant contacts and rotated inclusions are plentiful.

The granitic rocks in the Ashaway and Voluntown quadrangles are divisible into two groups which largely conform to the two situations cited above. One group of rocks, here called the Rhode Island batholith, includes augen gneiss, Escoheag Quartz Diorite Gneiss, prophyritic granite gneiss, Potter Hill Granite Gneiss, Hope Valley Alaskite Gneiss, Scituate Granite Gneiss, and Ten Rod Granite Gneiss. These rocks are largely concordant and have well-developed foliation and lineation quite similar to that in adjacent metamorphic rocks. The batholith rocks are believed to have been emplaced as magmas during the regional metamorphism. In contrast, the younger Narragansett Pier and Westerly Granites conform to the other situation. They are weakly foliated to massive and show abundant discordant relationships. They appear to have been emplaced as magmas under non-metamorphic conditions at a higher level in the crust than the batholith rocks.

relationships at or near their type localities (Moore, 1958), as does Scituate Granite Gneiss (Quinn, 1951). Although Escoheag Quartz Diorite Gneiss shows no intrusive relationships in the Voluntown quadrangle, correlative rock ("Ponaganset Quartz Diorite Gneiss") mapped by Moore in the Clayville quadrangle contains diversely oriented inclusions of metasedimentary gneiss (U.S. Geological Survey, 1963, p. A77). Most contacts between batholith rocks, and contacts of batholith rocks and metamorphic rocks are sharp. Units within the batholith that have gradational contacts, as between different facies of a single unit, or as between Hope Valley Alaskite Gneiss and Scituate Granite Gneiss, are believed to reflect composition gradients in the magma.

The general uniformity, and the absence of ghost structures in the batholith rocks, although in part negative evidence, strongly favors a magmatic origin. Some units, especially Escoheag Quartz Diorite Gneiss and porphyritic granite gneiss, are streaky or texturally heterogeneous owing to differential movement of the magma along preferred planes during intrusion. In many places the porphyritic granite gneiss has been made streaky by the intrusion of numerous sills of Hope Valley Alaskite Gneiss.

In places, the batholith magmas have intruded the metamorphic rocks on a small scale. Layers of fine-grained, pale pink to tan, saccharoidal alaskite, generally a meter or more thick, are locally abundant in the Plainfield Formation. Only layers near Green Fall Pond are thick enough to show on the geologic map. The layers appear to be intrusive sills of Hope Valley Alaskite Gneiss, as they have the mineral composition of the normal coarse-grained Hope Valley. Two lines of corroborative evidence were found. The belt of Hope Valley that trends northeastward from Wyassup Lake

No single criterion was found to be definitive in weighing possible origins of the granitic rocks in the Ashaway and Voluntown quadrangles. The preferred origin of these rocks, that of magmatic intrusion, was chosen on the weight of such evidence as their field relationships, their textures, their mineral uniformity over large areas, and their mineral compositions.

The ultimate origin of the magmas from which the granitic rocks of the Ashaway and Voluntown quadrangles crystallized remains unknown. Structural relationships make it clear that the magmas were introduced from depth. The three most likely magma sources are: differentiation from a parent basaltic magma, differentiation from the mantle, and partial fusion of deep-seated crustal rocks. The virtual absence of basaltic rocks from these quadrangles and from the surrounding area makes the first source unlikely. Very little is yet known about the role of the mantle in the genesis of granitic rocks, so the second source cannot be definitely accepted or rejected. The third source, favored by Turner and Verhoogen (1960, p. 388), is here considered the most likely. The generation of granitic magma by partial fusion, at least on a small scale, has been shown to be an actual process in layered felsic gneiss in the Ashaway and Voluntown quadrangles.

Field evidence

Although the granitic rocks of the Rhode Island batholith rarely show discordant relationships, most of the units somewhere show cross-cutting contacts or they contain rotated inclusions. Locations of several such outcrops in the present map area were cited with the descriptions of the rocks. In addition, Hope Valley Alaskite Gneiss and Ten Rod Granite Gneiss show intrusive terminates west of Green Fall Pond in a series of thin sills of identical aspect to those described above. Exposures at the termination show that normal medium- to coarse-grained Hope Valley Alaskite Gneiss grades laterally into fine-grained, saccharoidal alaskite with progressive thinning of the sills. In an exposure in another sill isolated from the larger body of Hope Valley Alaskite Gneiss, alinement of biotite flakes reflects the movement of magma (fig. 22). The flakes, probably remnants of an inclusion, are

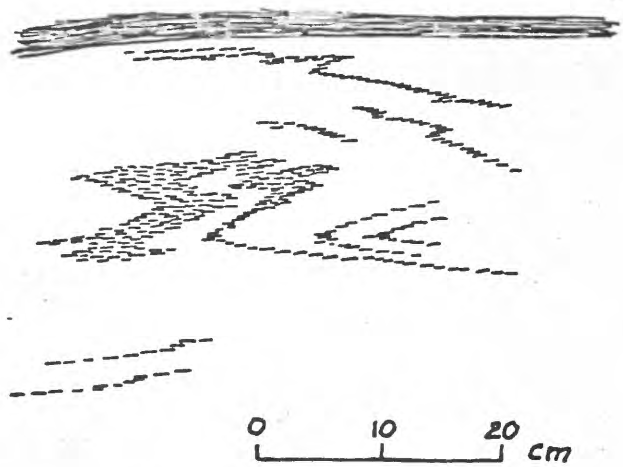


Figure 22. - Alined biotite flakes in sill of fine-grained saccharoidal Hope Valley Alaskite Gneiss in Plainfield Formation (dark ruled, top) 0.48 mile N.29°W. of the outlet of Green Fall Pond, Voluntown, Conn. Traced from a photograph.

alined parallel with the sill walls. The arrangement of the flakes into "folds" in the sill was produced by differential rates of magma flow during intrusion. The geometry of the "folds" is unlike that in any folds seen in the Plainfield Formation in which foliation everywhere parallels layering.

Small, fine-grained, light gray, biotite-feldspar-quartz schlieren occur singly and in groups in all the batholith rocks (fig. 23). They are concordant, lenslike, and range from a half

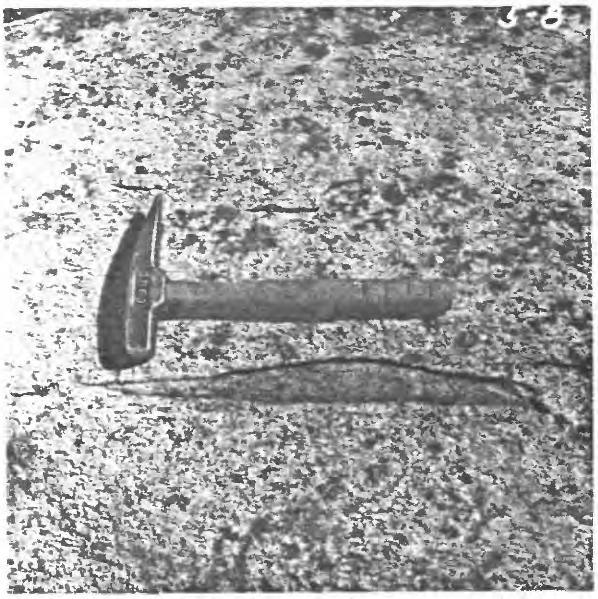


Figure 23. - Schlieren in Hope Valley Alaskite Gneiss 0.25 mile S.47°E. of the south tip of Deep Pond, Exeter, R. I.

meter by 5 cm, to 5 by 0.5 cm or less. The schlieren are composed of the same minerals as the host, but in different proportions, and probably are early-formed mineral aggregates. Schlieren in the massive granitic facies of Escoheag Quartz Diorite Gneiss (facies not mapped separately, see p. 68), are circular on outcrop surfaces, and are probably spherical. It is likely that the initial equilibrium form of all the schlieren was spherical, but that most have been drawn into lenslike or rodlike shapes by magma flow.

Bodies of aplite, simple pegmatite, and vein quartz occur in all rocks of the batholith, although they are sparse in augen gneiss, Escoheag Quartz Diorite Gneiss, and porphyritic granite gneiss. Bodies are predominantly discordant in Hope Valley Alaskite Gneiss and Scituate Granite Gneiss, and are predominantly concordant in Potter Hill Granite Gneiss. The structural significance of these bodies is discussed in a later section. The aplite, pegmatite, and vein quartz probably formed from residual liquids during the late stages of magmatic crystallization of their host. Many pegmatites reflect the mineral composition of their host. The mafic mineral in pegmatites in Hope Valley Alaskite Gneiss is commonly magnetite, in those in Potter Hill Granite Gneiss it is biotite, and in those in Scituate Granite Gneiss it is hornblende.

The intrusive, magmatic origin of Narragansett Pier Granite and Westerly Granite is demonstrable in many outcrops. Hornblende in amphibolite wall rock and inclusions has reacted with the magma and has been converted to biotite. Cross-cutting contacts and rotated inclusions, visible in dozens of exposures, are especially plentiful in quarries on the hills northeast of Westerly. Dikes of Narragansett Pier Granite too small to show on the geologic map crosscut most of the rocks mapped in the south half of the Ashaway quadrangle. The largest such dike, 25 cm thick, has cut Potter ill Granite Gneiss with a 90 degree discordance 0.1 mile N.27°W. f the dam at Clarks Falls.

Inclusions are more abundant in Narragansett Pier Granite than n Westerly Granite, and are especially profuse in the former on n Hill 201 in Stonington where many are of mappable size. Inclusions in the Narragansett Pier at the margins of the stock at esterly are locally sufficiently abundant to constitute an intruive broccia as at the small abandoned quarry 0.15 mile N.50°W. of ill 118 west of Chapman Pond.

Distribution of platy flow structure, indicated by biotite lake alinement, demonstrates the magmatic origin of both the arragansett Pier and the Westerly Granite. Platy flow structure s discernible in most Narragansett Pier Granite, and is everywhere onformable with contacts. The degree of development of platy flow tructure is markedly dependent upon the nearness of wallrocks, and ecomes more prominent with decreasing distance from them. This as produced during the intrusion of the Narragansett Pier Granite agma where differential movement was greater between layers undergoing laminar flow near the relatively stationary walls than in he central portions of the stock. The relationship is clearly seen in roadcuts along Norwich Road just north of Pawcatuck.

Many pegmatites in Narragansett Pier Granite contain cores of aplite. This relationship suggests sudden release of pressure during crystallization of residual water-rich pegmatite liquids as postulated by Jahns and Tuttle (1962).

Mineralogical evidence

Nearly all of the granitic rocks mapped in the present study can be approximately plotted on a quartz-albite-microcline triangular diagram, provided that oligoclase is allowed as a substitute for albite. Less than one tenth of the samples modally analyzed contain more than 10 percent of other minerals. However, Escoheag Quartz Diorite Gneiss generally contains more than 10 percent, and commonly more than 20 percent, of minerals other than quartz and feldspar, and the plagioclase is generally andesine.

Tuttle and Bowen (1958) have presented an elegant discussion on the origin of granite based on studies of the system quartz-albite-potassium feldspar-water. Although simplifications in this are obvious (and experimentally necessary), the results are compelling. That granitic rocks the world over have compositions that fall in the low-melting region of the "granite system" is very strong evidence of their derivation by crystallization from a liquid silicate melt.

One hundred and sixty seven modes of granitic rocks mapped in the present report have been plotted on a series of triangular diagrams (figs. 24-32), The apices chosen are quartz, microcline, and plagioclase. The last approximates albite in all but figure 25. Each plot, constructed by the method of Johannsen (1922), represents an individual modal analysis. Abundances of the apical minerals, recalculated to 100 percent, are given by the circle or square on the line. Actual modal abundances of the apical minerals are read from the plotted lines as follows. A horizontal line passed through the lower end of the plotted line will intercept the sides of the triangle at the actual abundance of quartz. Two lines passed through the upper end of the plotted line, one parallel to the quartz-plagioclase side of the triangle, the other parallel to the quartz-microcline side, will intercept the base of the triangle at points which indicate the actual abundance of microcline and the

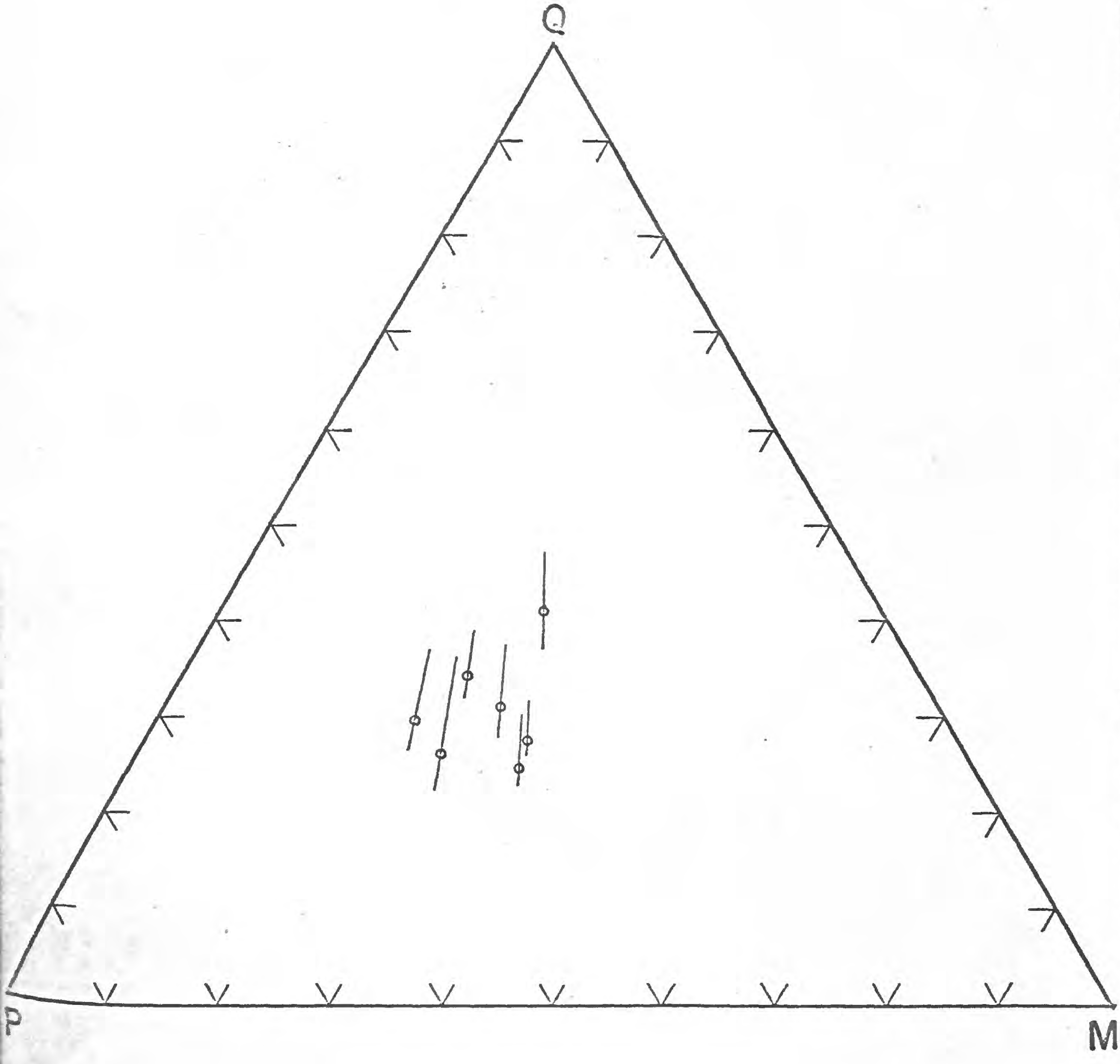


Figure 24.- Modal analyses of augen gneiss plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922).

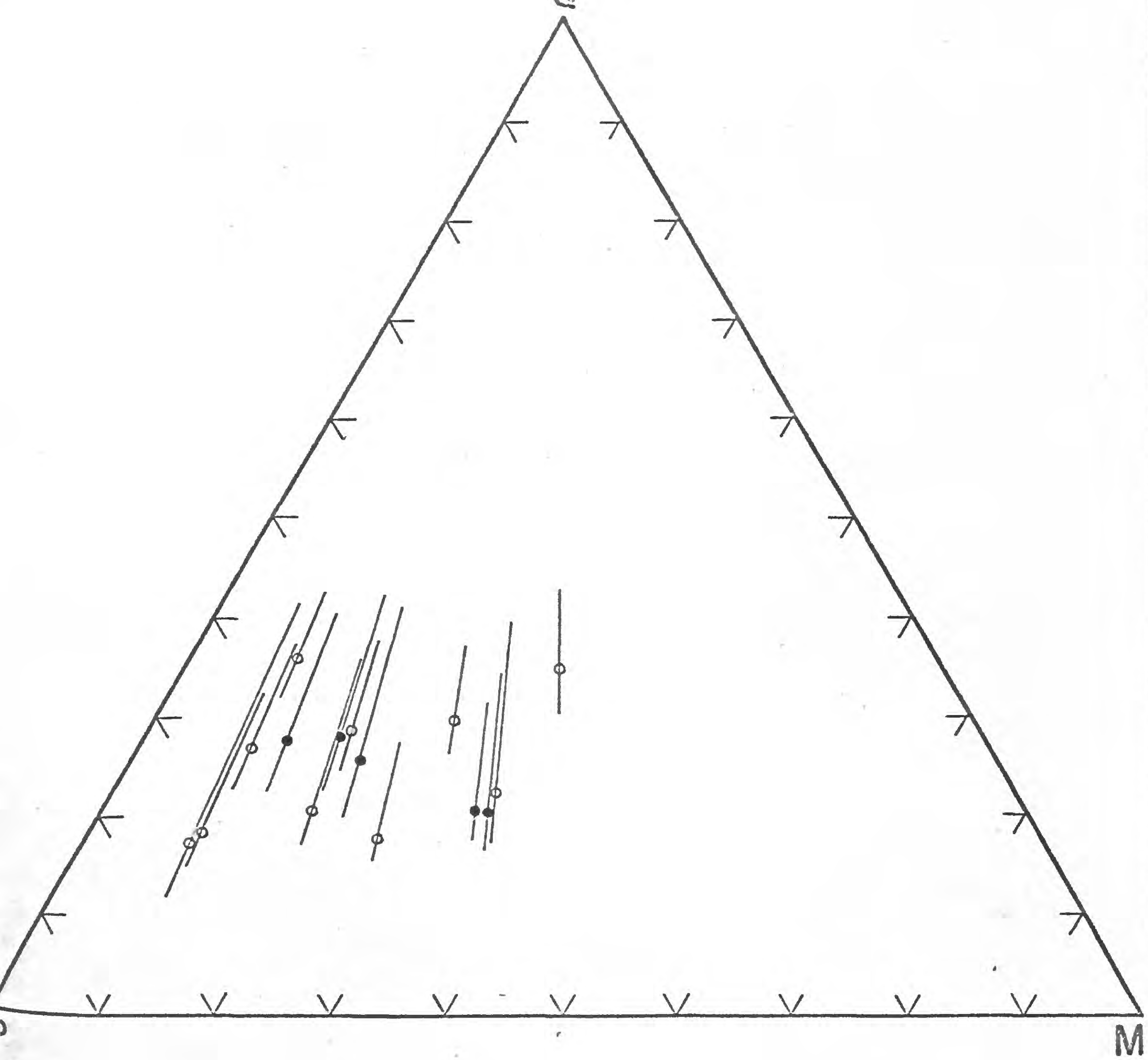


Figure 25.- Modal analyses of Escoheag Quartz Diorite Gneiss plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922). Solid circles, fine-grained facies.

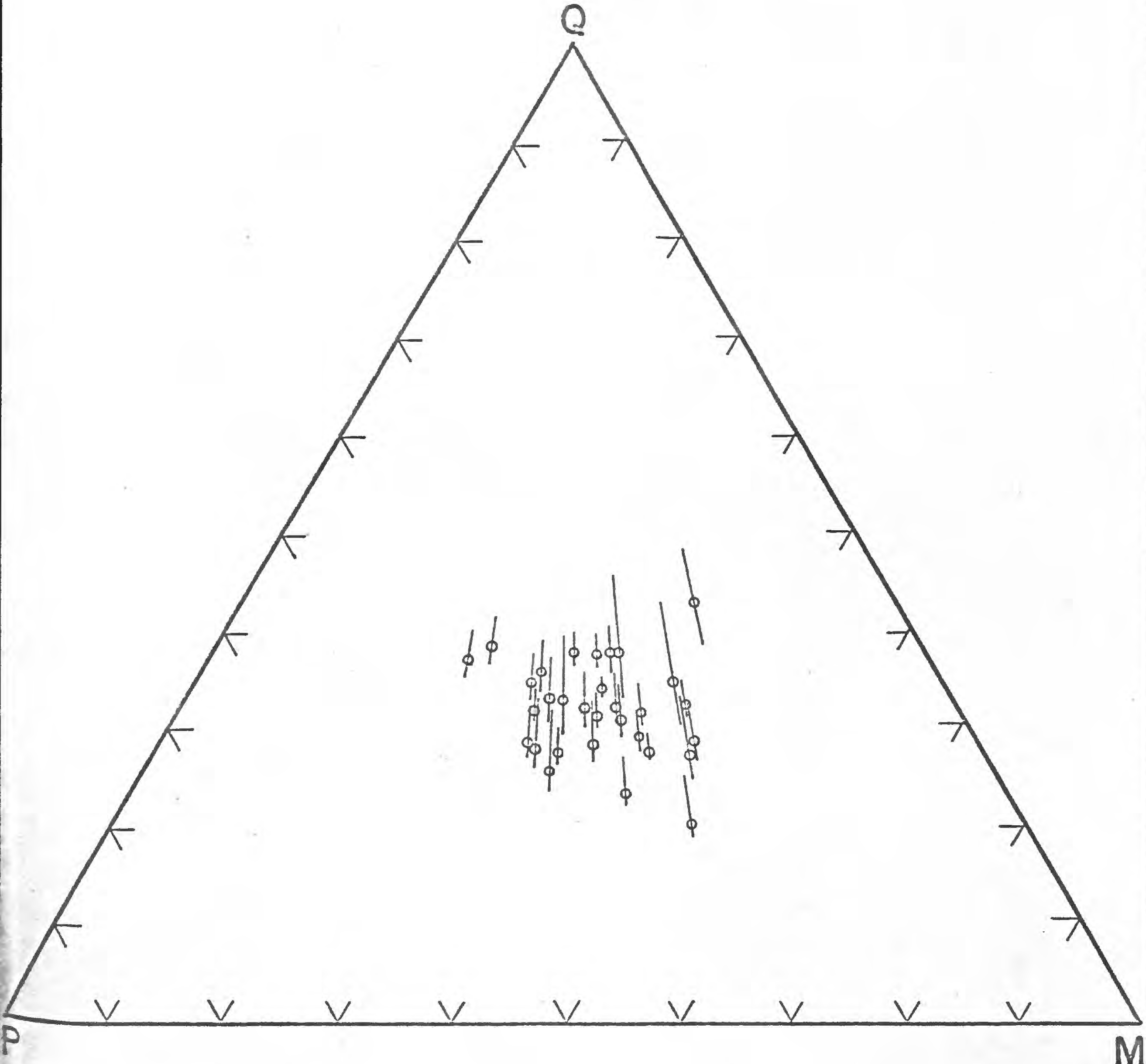


Figure 26.- Modal analyses of porphyritic granite gneiss plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922).

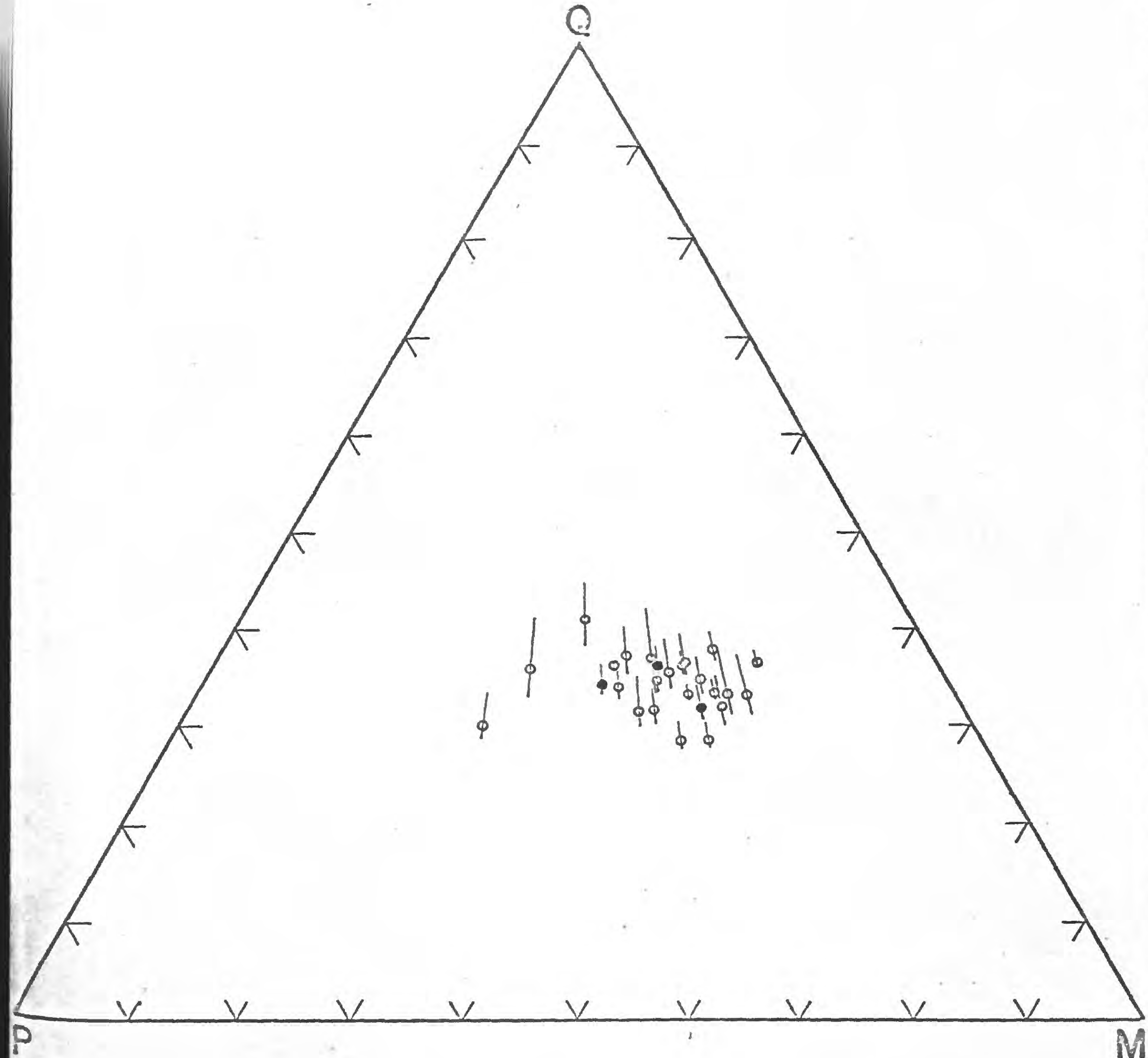


Figure 27.- Modal analyses of Potter Hill Granite Gneiss plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922). Solid circles, massive facies.

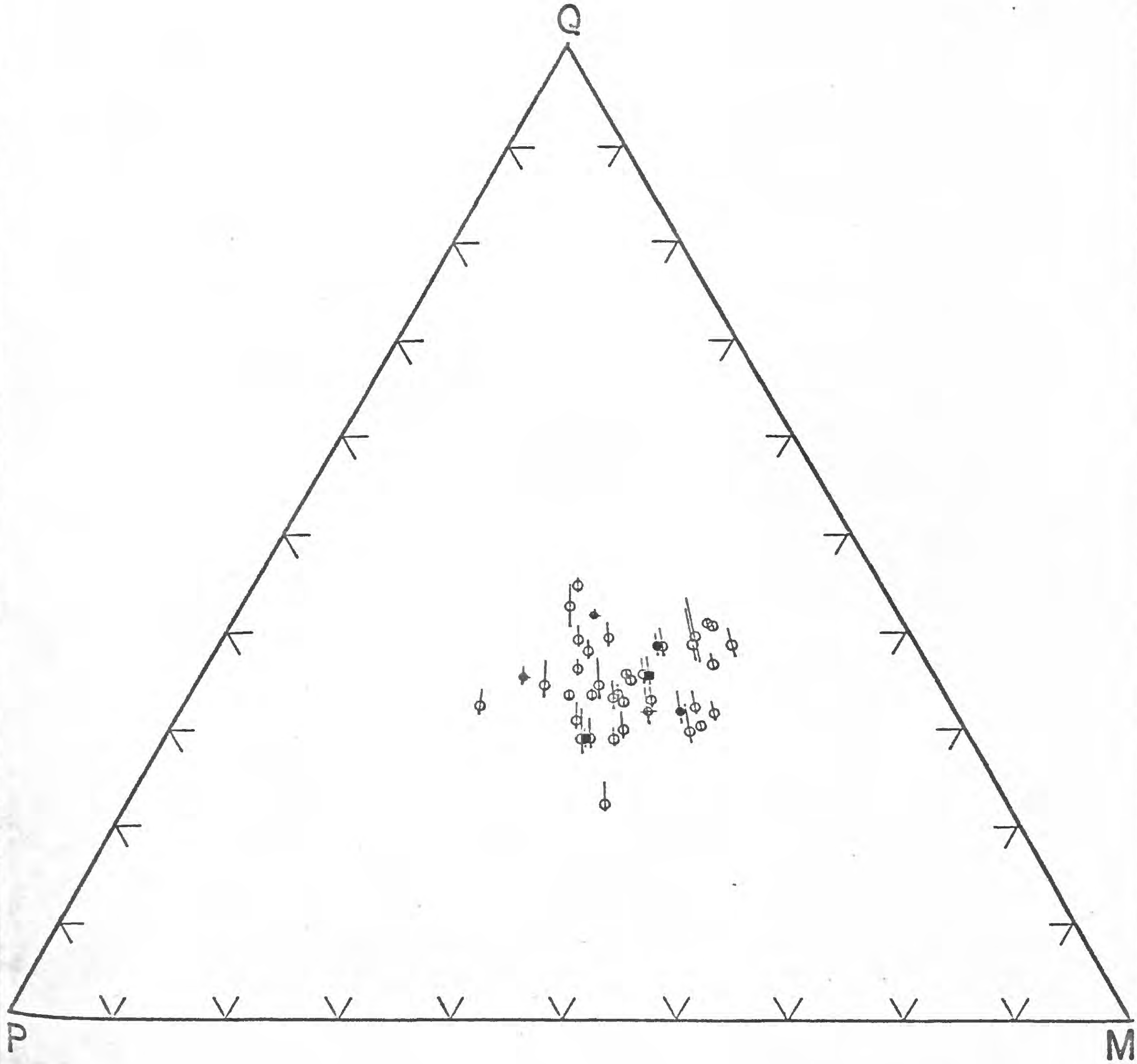


Figure 28.- Modal analyses of Hope Valley Alaskite Gneiss plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922). Solid circles, fine-grained facies; crossed circles, white facies; square, fine-grained granite.

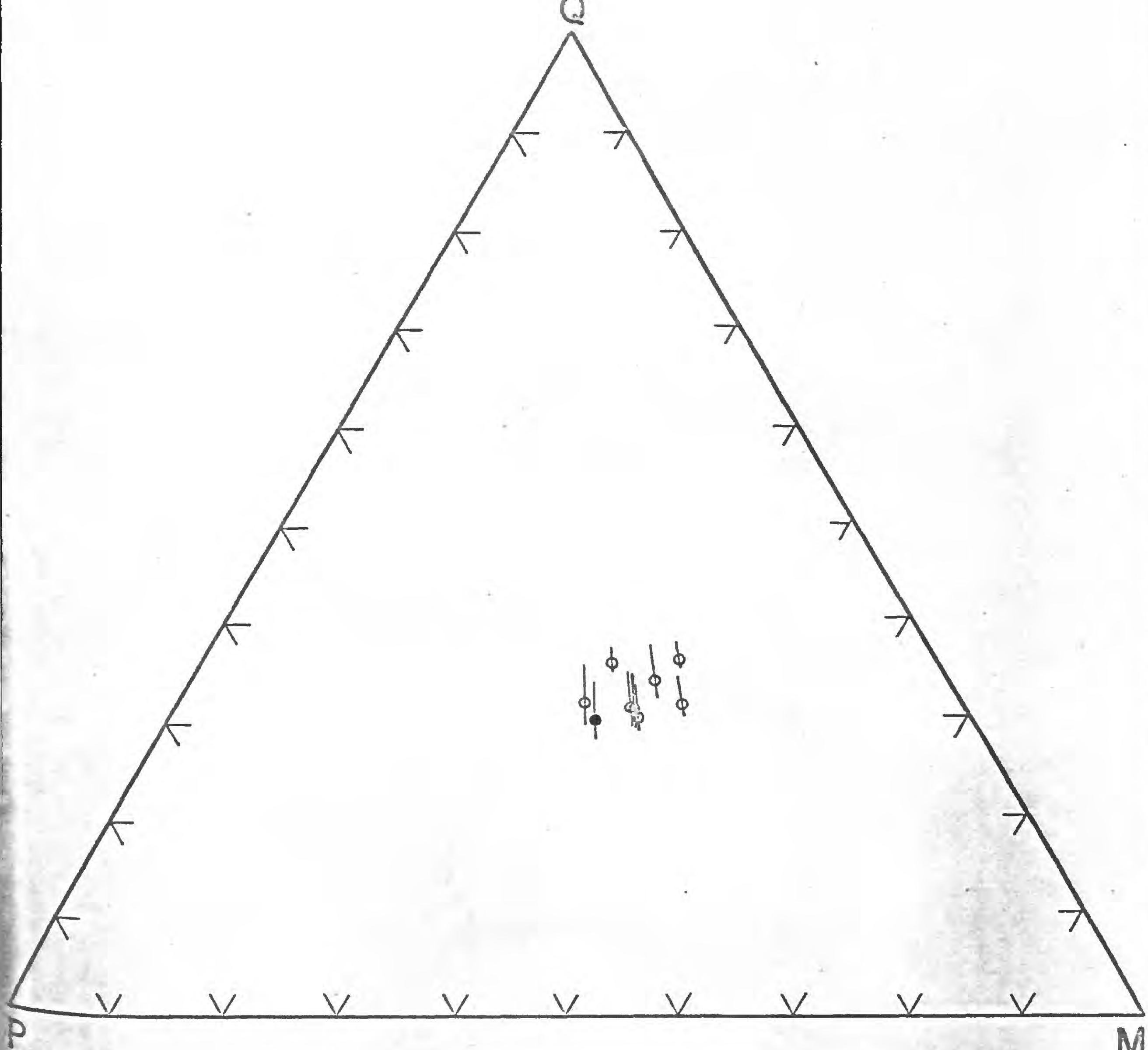


Figure 29.- Modal analyses of Scituate Granite Gneiss plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922). Solid circle, fine-grained facies.

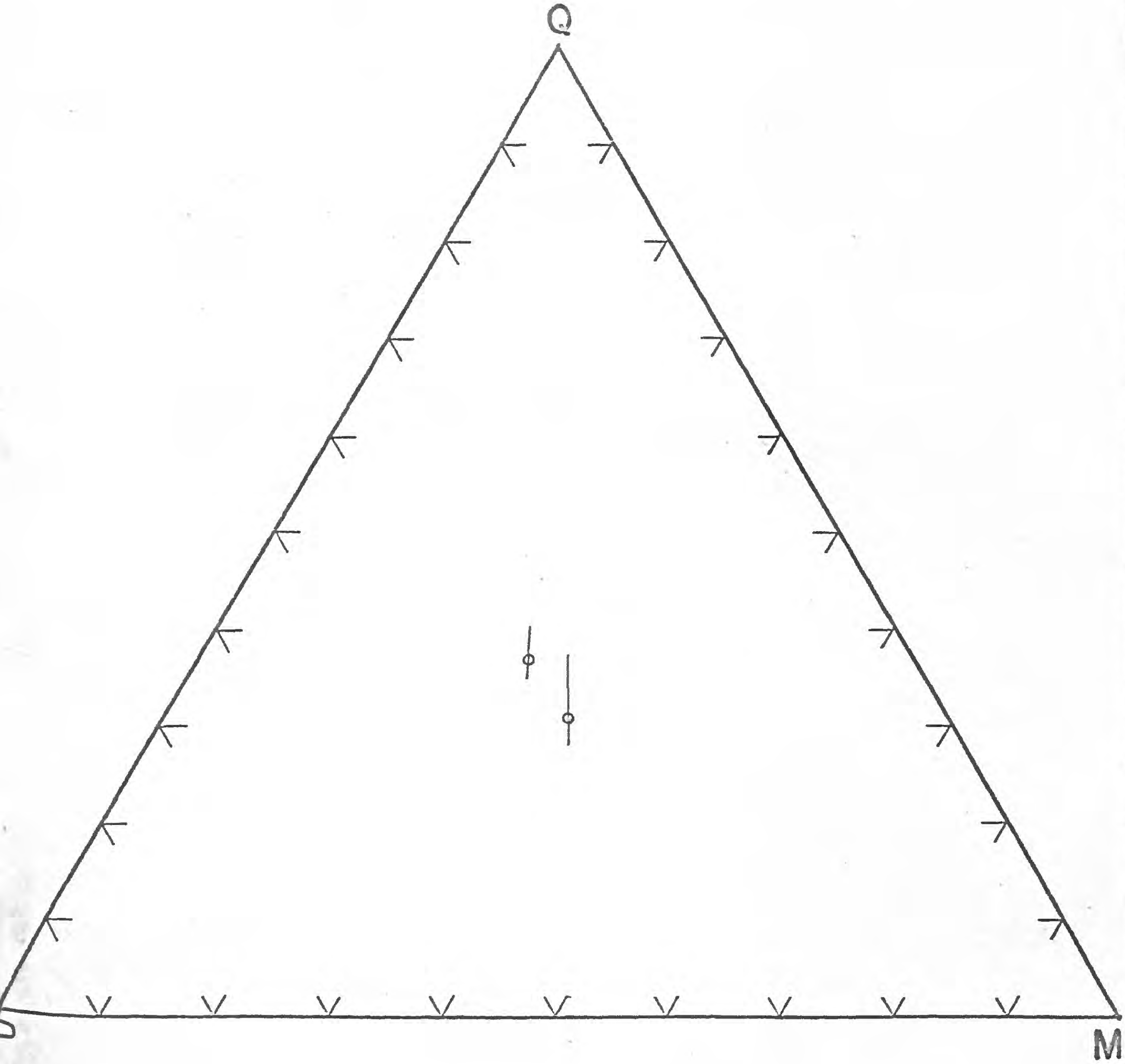


Figure 30.- Modal analyses of Ten Rod Granite Gneiss plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922).

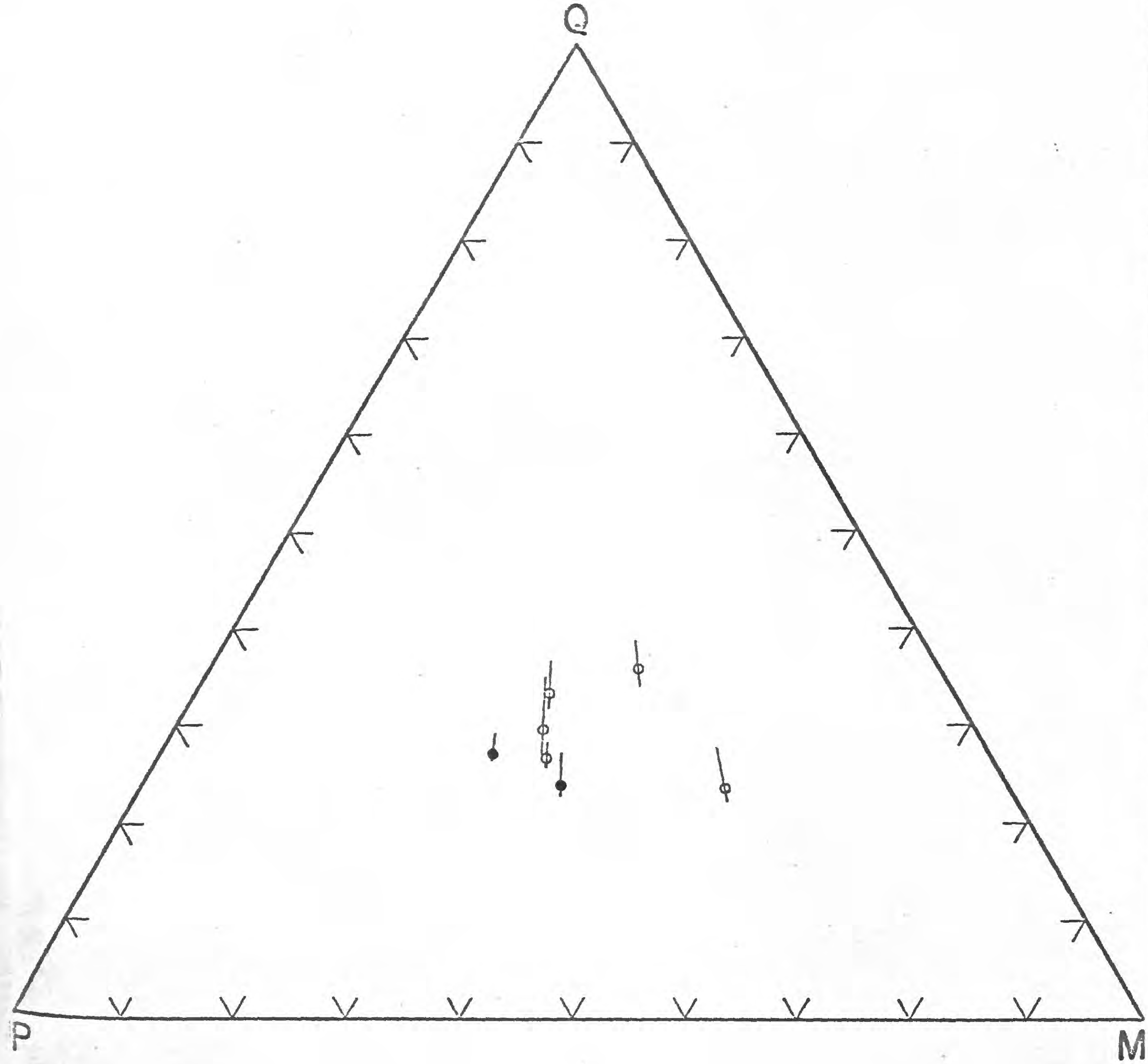


Figure 31.- Modal analyses of Narragansett Pier Granite plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922). Solid circles, white facies.

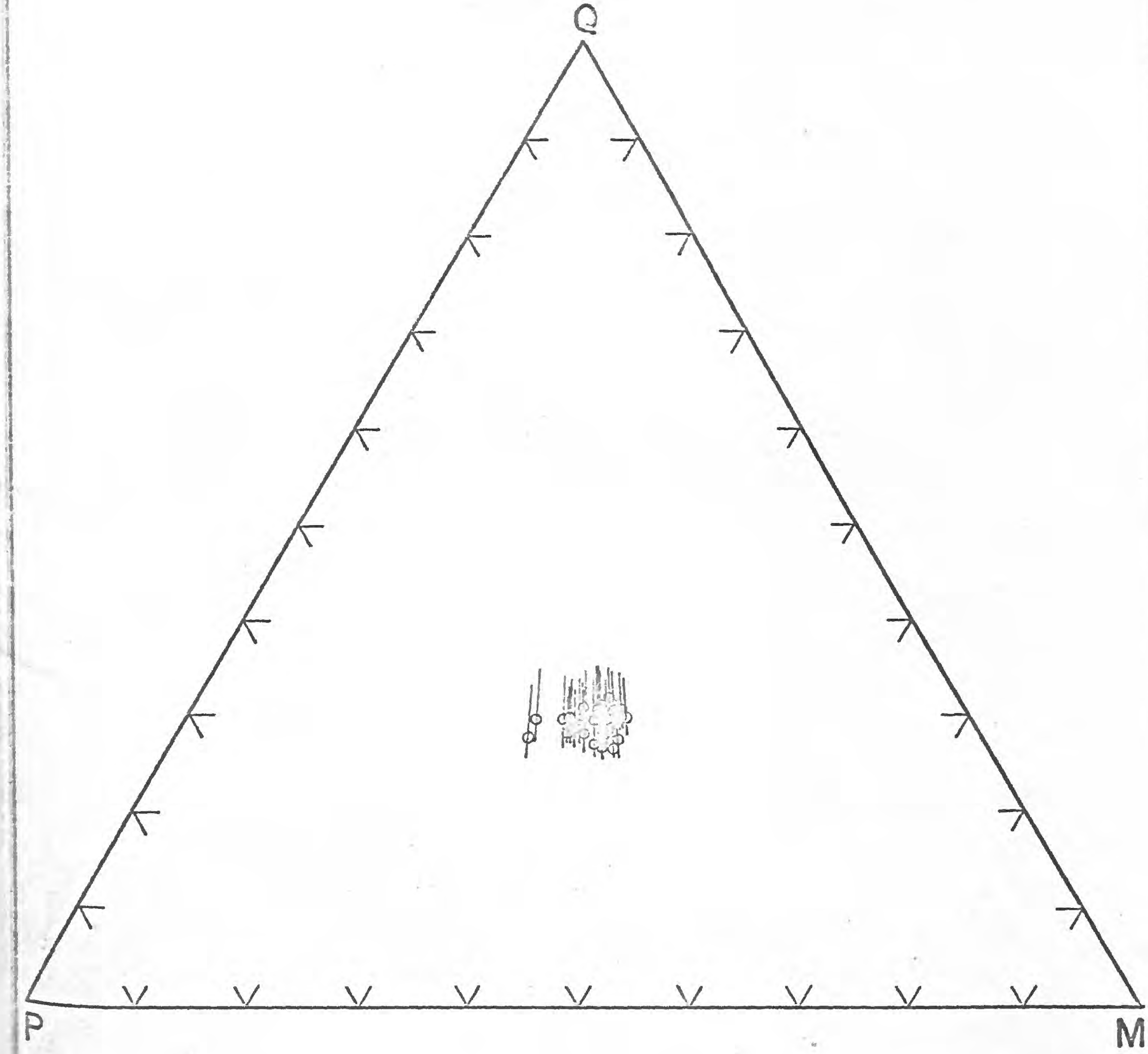


Figure 32.- Modal analyses of Westerly Granite plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922).

actual abundance of plagioclase respectively. For details of construction, see Johannsen (1922). Rocks composed entirely of quartz and feldspar would plot as points. Lengths of plotted lines are in direct proportion to abundance of minerals other than quartz and feldspar (i.e. compare figs. 25 and 28). Modal averages of the granitic rocks are summarized in figure 33.

Granitic rocks, which on the basis of field evidence are believed to be genetically related, have been grouped together, and their average modal compositions plotted in figure 34. Field boundaries in the system quartz-albite-potassium feldspar at two water vapor pressures (2000 and 5100 kg/cm^2) have been drawn (Tuttle and Bowen, 1958, p. 55; Luth, Jahns, and Tuttle, 1964, p. 765). The field boundaries mark the lowest-melting compositions in the system at the specified water vapor pressure; they are axes of "thermal valleys".

The uniformity of the granitic rocks is diagramatically presented in figure 35 which was constructed from the standard deviations given earlier with the modal compositions of the granitic rocks (Tables II-VI, VIII-XI).

Standard deviation is a numerical measure of uniformity. For example, the modal awerage of quartz in augen gneiss is 28.0 percent (Table II), and the standard deviation is 4.8 percent. This means that based on the data given (modal analysis of seven samples) approximately two thirds (64.8 percent) of the samples of augen gneiss analyzed will have a quartz content between 23.2 and 32.8 percent (28.0 $\pm$ 4.8). Eight of the granitic rocks are shown in figure 35. Abundances of quartz, plagioclase, and microcline of the average modal compositions of these rocks were recalculated to 100 percent and the points (not here shown) were plotted. The

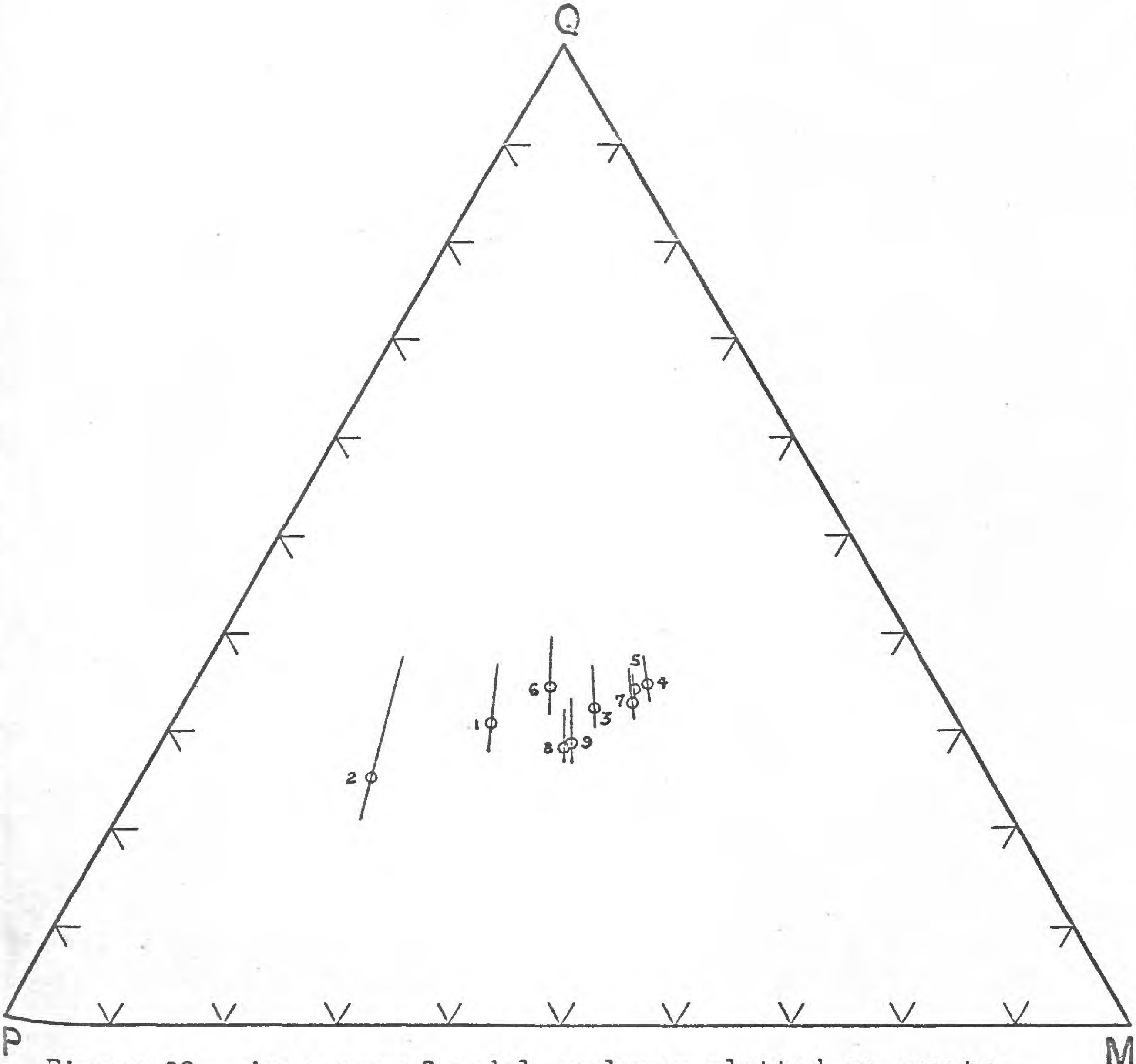


Figure 33.- Averages of modal analyses plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922).

1. Augen gneiss (7)*
2. Escoheag Quartz Diorite Gneiss and fine-grained facies (15)
3. Porphyritic granite gneiss (31)
4. Potter Hill Granite Gneiss and fine-grained facies (26)
5. Scituate Granite Gneiss and fine-grained facies (9)
6. Ten Rod Granite Gneiss (2)
7. Hope Valley Alaskite Gneiss and all facies (42)
8. Narragansett Pier Granite and white facies (7)
9. Westerly Granite (28)

* Figures give number of modes included in average

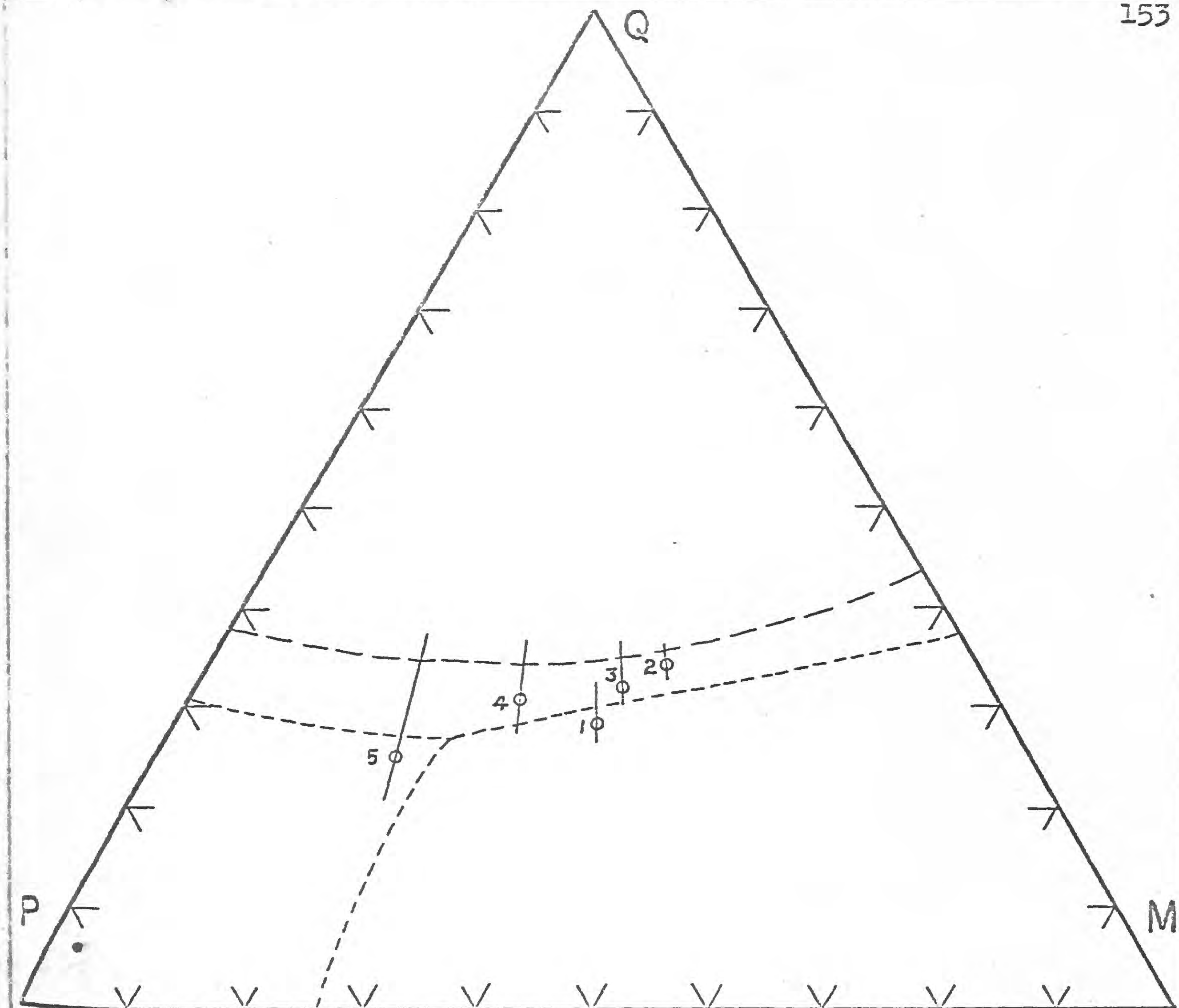


Figure 34.- Averages of modal analyses plotted on quartz-plagioclase-microcline (Q-P-M) triangle by the method of Johannsen (1922). Dashed lines give position of field boundaries and temperature minima; long dashed line, 2000 kg/cm^2 H_2O (Tuttle and Bowen, 1958, p. 55); short dashed line, 5100 kg/cm^2 H_2O (Luth et al, 1964).** Genetically related rocks are grouped as follows:

1. Narragansett Pier Granite and white facies, and Westerly Granite (35)*
2. Younger rocks of the R. I. Batholith; Potter Hill Granite Gneiss and massive facies, Hope Valley Alaskite Gneiss and all facies, Scituate Granite Gneiss and fine-grained facies, and Ten Rod Granite Gneiss (79)
3. Porphyritic granite gneiss (31)
4. Augen gneiss (7)
5. Escoheag Quartz Diorite Gneiss and fine-grained facies (15)

*Figures give number of modes included in average
**Both field boundaries for plagioclase = albite

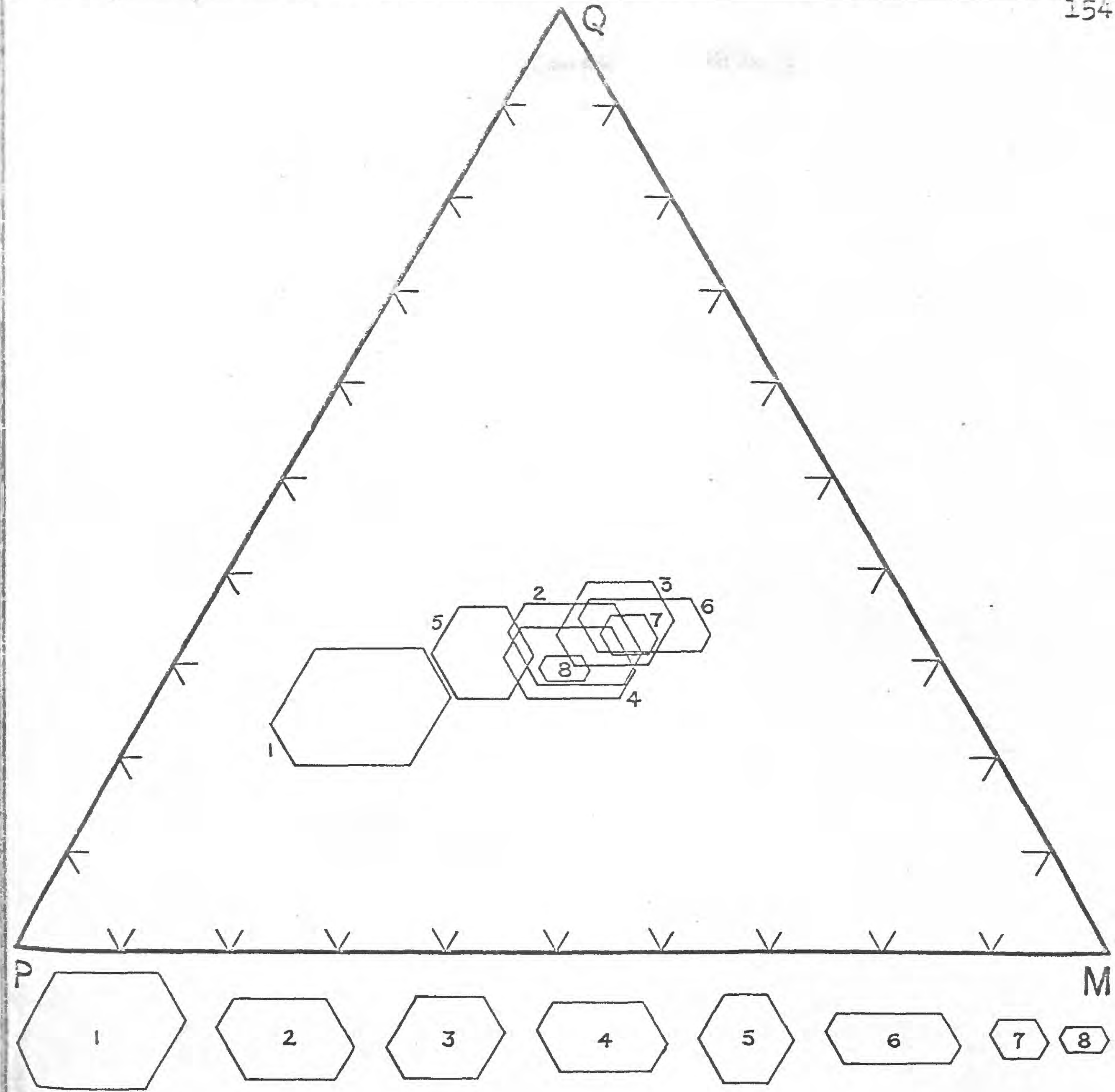


Figure 35.- Range of modal composition of the granitic rocks. See text for explanation.

1. Escoheag Quartz Diorite Gneiss (3.3)*
2. Porphyritic granite gneiss (1.9)
3. Hope Valley Alaskite Gneiss (1.6)
4. Narragansett Pier Granite (1.6)
5. Augen gneiss (1.5)
6. Potter Hill Granite Gneiss (1.2)
7. Scituate Granite Gneiss (0.4)
8. Westerly Granite (0.2)

* Figures give percent of area of triangle occupied

standard deviation of each apical mineral was represented as two lines parallel to the side of the triangle opposite that apical mineral at a distance of plus and minus the standard deviation from the point. The six lines that represent the standard deviations of the three apical minerals enclose a hexagon whose size is inversely proportional to rock uniformity. The hexagons within the triangle in figure 35 have been reproduced at the same scale beneath the triangle, and are arranged in order of decreasing size (and increasing uniformity) from left to right. The areas of the hexagons, expressed as percent of the area of the entire composition triangle, are also given. The usefulness of this graphical representation is three-fold.

First, it gives at a glance, a measure of the uniformity of each rock. A numerical measure of this is given by the area data. No suggestions are given here on the limits of a uniform rock vs. a non-uniform one, but it is interesting to notice that the area of the hexagon that represents the unusually uniform Westerly Granite, based on analyses of samples from many dikes, is only 0.2 percent.

Second, uniformity of the apical minerals relative to each other can be judged at a glance from the shape of the hexagon and the relative lengths of the three pairs of sides. A regular hexagon depicts identical uniformity of the apical minerals. Where the uniformity of apical minerals is not equal, the hexagon is elongated toward the apex of the mineral of least uniformity. The shortest pair of sides of the hexagon parallel the side of the triangle opposite the apex of the mineral of least uniformity. In figure 35, the hexagon that represents augen gneiss is nearly regular. The uniformity of the apical minerals is nearly equal (standard deviations from Table II: 4.8, 4.5, and 4.5 percent). Relative lengths of the three pairs of sides of hexagon 1 (Escoheag Quartz Diorite Gneiss) show that the uniformity of plagioclase is least and that of quartz is greatest (standard deviations from Table III: plagioclase 9.0, microcline 7.8, and quartz 5.6 percent).

Third, petrogenetic relationships are graphically suggested by relative positions of hexagons and the presence or absence of overlap. For example, the isolation of the hexagon that represents Escoheag Quartz Diorite Gneiss is supported by field observations; i.e. this rock is clearly older than and distinct from Hope Valley Alaskite Gneiss and those rocks that are gradational with the Hope Valley. Hexagons that represent the latter groups (nos. 3, 6, and 7) have unlike shapes but nearly coincident centers. Overlap of hexagons, however, does not everywhere imply consanguinity (i.e. hexagons 2 and 4, which represent unrelated granites).

The positions of the points that represent the average modal compositions of the granitic rocks (fig. 34), and the limited scatter of points that represent individual modes of each granitic rock (figs. 24-32) support the earlier evidence of a magmatic origin. Concentration of modal compositions at or near the thermal minimum (fig. 34) is strong evidence that the rocks crystallized from a melt. Modal compositions of each granitic rock, in places representing samples separated by as much as 20 miles, show great uniformity. Such uniformity (and textural uniformity as well) of the rocks over such great distances suggests derivation from very large volumes of very homogeneous magma.

Laboratory studies show that a single homogeneous alkali feldspar is the stable phase at magmatic temperatures under a variety of conditions (Tuttle and Bowen, 1958, p. 48-50; Orville, 1963). However, porphyritic hypabyssal granitic rocks that have phenocrysts of both potassium feldspar and plagioclase are common and show that two feldspars crystallize as separate phases from many magmas. All granitic rocks in the present report are two-feldspar rocks. Tuttle and Bowen (ibid., p. 49-50) suggest that the initial magmatic single homogeneous alkali feldspar has unmixed below the solidus to produce two feldspars in many granites. Unmixing is believed to be promoted by residual fluxes, especially water. The classification of salic rocks proposed by those authors (ibid., p. 126-130) is based on the final crystallization, which in two-feldspar rocks is held to have been sub-solidus.

The feldspars in none of the granitic rocks mapped in the present study show evidence of derivation from a single homogeneous phase. On the contrary; porphyritic texture, random grain relations seen in thin section, and sporadic zoned plagioclase crystals point to direct crystallization of two feldspars. Minor exsolution of albite from microcline, however, is recorded by sparse perthite, albite rims on plagioclase grains where to contact with microcline, and small lenses of albite between large microcline grains. In no rock does the exsolved albite constitute more than 1 or 2 percent of the total feldspar.

Three mechanisms have been proposed by which two alkali feldspars might crystallize simultaneously from a felsic magma: (1) depression of the solidus to where it intersects the solvus by the action of volatiles concentrated in the late stages of magma crystallization (Tuttle, 1952, p. 122); (2) depression of the solidus by high water vapor pressures (greater than 3.6 kilobars) to where it intersects the solvus (Luth, Jahns, and Tuttle, 1964, p. 765); (3) raising the solvus to where it intersects the solidus by addition of the anorthite molecule to albite (Tuttle, 1952,

p. 117-118; Yoder, Stewart, and Smith, 1956, p. 193).

It is unlikely that the first two mechanisms influenced feldspar crystallization from magmas that formed the granitic rocks of the Ashaway and Voluntown quadrangles. That excessive water vapor pressures never developed in the Rhode Island Batholith magmas is borne out by the presence of amphibole in many of the rocks (Tuttle and Bowen, 1958, p. 92-93), and by the presence of sillimanite rather than muscovite in others. Magma chambers in which the Narragansett Pier Granite and Westerly Granite crystallized were probably too high in the crust to allow much buildup of water vapor pressure without roof failure. The pressure required by the second mechanism is very high, and is attained only at a depth greater than 15 km and $P_{H_2O} = P_{load}$. Evidence of such deep crystallization of any of the granitic rocks is wanting.

The third mechanism, that the presence of anorthite in plagioclase causes the solvus to rise and intersect the solidus, is the most applicable to the rocks mapped in the present study. Nearly all the plagioclase in these rocks is more calcic than An_{10}. Plagioclase formed from sub-solidus exsolution from microcline cited above is quantitatively unimportant, but it is significantly more sodic (An_3 to An_8) than coexisting primary plagioclase. The nature of this exsolution suggests that the feldspar solvus was entirely below the solidus for plagioclase An_8 and more sodic, and was intersected by the solidus for plagioclase An_{10} and more calcic at the conditions under which the granitic rocks crystallized.

Chemical analyses

Chemical analyses of six samples of the granitic rocks were made by the Geochemistry and Petrology Branch, U.S. Geological

Survey. The results, calculated norms, and modes of the analyzed samples, are given in Table XII. All the rocks are peraluminous (Shand, 1947, p. 228), as corundum (C) appears in the norms.

The localities from which the chemically analyzed samples were taken are as follows:

CA-1 Potter Hill Granite Gneiss. Roadcut, 0.6 mile S.42°E. of the church on Voluntown Road south of New London Turnpike, North Stonington, Conn.

CA-2 Augen gneiss. Overhanging ledge 0.25 mile due north of the common point of the towns of Voluntown, North Stonington, and Griswold, Voluntown, Conn.

CA-3 Hope Valley Alaskite Gneiss. Roadcut, 1.5 miles N.55°E. of Hopkinton village, Hopkinton, R.I.

CA-4 Scituate Granite Gneiss. Roadcut, southwest side of Rockville Road, 0.11 mile northwest of the Rhode Island State line, Voluntown, Conn.

CA-5 Escoheag Quartz Diorite Gneiss. Abandoned stone prospect, south slope of Escoheag Hill, 0.38 mile S.48°E. of the lookout tower, West Greenwich, R.I.

CA-6 Porphyritic granite gneiss. Abandoned quarry, east side of Green Fall Pond, Voluntown, Conn.

Modal analyses of the chemically analyzed samples show that all but one approximate the average modal composition of the rock unit that they represent. The Potter Hill Granite Gneiss sample chemically analyzed is the most representative of the six, and closely approaches the modal average (Table V). The augen gneiss sample has a greater quartz-to-plagioclase ratio than the modal average (Table II). The Hope Valley Alaskite Gneiss sample has a higher microcline-to-plagioclase ratio and contains much less magnetite and biotite than the modal average (Table VI). The Scituate Granite Gneiss sample also has a higher microcline-to-plagioclase ratio then the modal average (Table VIII). The Escoheag Quartz Diorite Gneiss sample is richer in quartz and poorer in biotite, and has

TABLE XII. - Chemical analyses, calculated norms, and modes of six samples of granitic rock

Chemical analyses						
Chem. lab. no.	161986	161987	161988	161989	161990	161991
Field no.	CA-1	CA-2	CA-3	CA-4	CA-5	CA-6
SiO_2	73.16	73.48	75.71	74.13	72.58	73.66
Al_2O_3	13.88	13.32	12.93	13.10	14.90	12.93
Fe_2O_3	.70	1.44	1.10	.63	.74	1.44
FeO	.86	1.12	.39	1.63	.99	.80
CaO	1.35	1.75	.43	1.05	2.73	1.21
MgO	.25	.67	.01	.13	.20	.25
Na_2O*	2.6	2.7	2.5	3.0	3.5	3.6
K_2O*	6.3	4.7	6.3	5.6	3.5	3.4
H_2O^+	.32	.14	.14	.19	.20	.41
H_2O^-	.13	.05	.04	.05	.05	.13
TiO_2	.20	.36	.14	.21	.27	.22
MnO	.01	.06	.00	.03	.01	.05
Summ.	99.76	99.79	99.69	99.75	99.67	100.10
Sp. Gr. (bulk)	2.634	2.665	2.633	2.644	2.668	2.639
Calculated norms						
Q	30.30	34.80	36.36	31.86	32.52	38.94
C	0.31	0.61	1.22	0.10	0.41	1.12
or	37.25	27.80	37.25	33.36	20.57	20.02
ab	22.01	23.06	20.96	25.15	29.34	30.39
an	6.67	8.62	1.95	5.28	13.62	5.84
hy	1.39	1.96	.00	2.41	1.42	0.60
mt	0.93	2.09	0.93	0.93	1.16	1.86
il	0.46	0.76	0.30	0.46	0.46	0.46
hm	.00	.00	0.48	.00	.00	0,16
Summ.	99.32	99.70	99.45	99.55	99.50	99.39
C.I.P.W.	I.4.2.3	I.4.2.3	I.3.1.2	I.4.2.3	I.4.2.3	I.3.2.3
Modes						
Quartz	29.9	37.3	35.7	35.5	27.5	37.0
Microcline	44.8	25.6	44.2	40.4	23.0	22.2
Plagioclase	19.2	27.3	18.6	21.6	39.6	35.7
Hornblende	.0	.0	.0	1.5	.0	.0
Biotite**	2.2	6.4	0.2	1.0	9.0	2.8
Muscovite	1.5	1.0	1.0	.0	0.1	1.7
Magnetite	1.5	1.6	0.3	.0	0.1	0.4
Allanite	.0	0.1	.0	tr***	tr	.0
Apatite	.0	0.3	.0	tr	0.3	0.1
Calcite	tr	0.3	tr	tr	.0	.0
Garnet	.0	.0	.0	tr	.0	.0
Sphene	0.9	tr	.0	.0	0.4	.0
Zircon	.0	0.1	tr	tr	tr	0.1
Summ.	100.0	100.0	100.0	100.0	100.0	100.0
Comp. of plag. (An)	11	13	14	13	27	13

CA-1 Potter Hill Granite Gneiss — CA-4 Scituate Granite Gneiss
CA-2 Augen gneiss — CA-5 Escoheag Quartz Diorite Gneiss
CA-3 Hope Valley Alaskite Gneiss — CA-6 Porphyritic granite gneiss

* Analysis made in Rapid Methods lab using methods described in U. S. Geol. Survey Bull. 1144-A

** Includes chlorite. *** Trace.

a higher microcline-to-plagioclase ratio than the modal average (Table III). The porphyritic granite gneiss chemical analysis is the least representative and falls markedly out of line; the analyzed sample is far richer in quartz, and has a much greater plagioclase-to-microcline ratio than the modal average (Table IV).

Field evidence cited earlier suggests that Hope Valley Alaskite Gneiss, Scituate Granite Gneiss, and Potter Hill Granite Gneiss are gradational with one another. The rocks probably reflect compositional gradients in a single magma from which they all crystallized. It is not inferred, however, that this magma was intruded in a single pulse, as field evidence is abundant that emplacement was by many, probably dozens of pulses. The three gneisses, in the order listed above, show a progressive increase of Al_2O_3, CaO, MgO, and water, and a progressive decrease of SiO_2. Their crystallization, however, was probably most profoundly influenced by water vapor pressure in the magma. Where this was especially low, anhydrous Hope Valley Alaskite Gneiss crystallized. A slight increase of water vapor pressure caused the crystallization of Scituate Granite Gneiss with accessory biotite and hornblende in place of the magnetite characteristic of the Hope Valley. The hornblende-free Potter Hill Granite Gneiss with biotite represents crystallization at yet higher water vapor pressures at which hornblende is unstable (Tuttle and Bowen, 1958, p. 92-93). The fabric of the Potter Hill is unlike that of the other two gneisses and probably reflects crystallization under mechanical conditions different from those under which the Hope Valley and the Scituate crystallized.

Mechanism of intrustion

All granitic rocks in the Ashaway and Voluntown quadrangles are somewhere foliated and lineated, and many are invariably so. The structures are probably nearly everywhere primary. Secondary shear foliation is absent in all granitic rocks except augen gneiss. Lineation (quartz rods, alinement of biotite splotches, etc.) parallels the direction of magma movement during intrusion and crystallization. Foliation (principally parallelism of biotite flakes and of (010) feldspar faces) developed contemporaneously with lineation, and parallels wall rock contacts. Local intense development of these structures, commonly accompanied by finer grain size than in the same rock elsewhere, reflects concentrated zones of movement within the magma during intrusion and crystallization.

Careful mapping of structures in the granitic rocks in the Ashaway and Voluntown quadrangles has shown that magma emplacement was by forcible intrustion under three different conditions: (1) Sheetlike intrusion, under conditions of high shear stress, produced tabular bodies of well-foliated granitic rock exemplified by Escoheag Quartz Diorite Gneiss and by the porphyritic granite gneiss. Loughlin (1912, p. 38) believed that this mechanism was particularly important in the area. (2) Intrusion of magma on a large scale, probably under slightly lesser shear stress than (1), produced large domes and large elongate domes of lineated and foliated granitic rocks. The best examples are the Potter Hill Granite Gneiss, and the bulk of the Hope Valley Alaskite Gneiss and Scituate Granite Gneiss. (3) Intrusions of magma under conditions of low shear stress at relatively high levels in the crust produced the younger, nearly massive granites of the Westerly area.

Sheetlike bodies of (1) are characterized by abundant concordant schistose zones as described above. Phenocrysts in these zones are less abundant and more granulated than elsewhere. The concentration of movement during intrusion of the magma to these zones may have resulted from the large quantities of solid phenocrysts in the magma which prevented general, pervasive movement (Escoheag Quartz Diorite Gneiss and the porphyritic granite gneiss are, along with the augen gneiss, the most porphyritic granitic rocks in the quadrangles). Stresses that built up during intrusion caused failure along well-defined zones, which once begun, probably continued to be active until the cessation of intrusion. In Escoheag Quartz Diorite Gneiss much of the rock between schistose zones is massive and it probably moved as a unit without internal shear during intrusion. Sheetlike bodies of Escoheag Quartz Diorite Gneiss and of porphyritic granite gneiss now in Hope Valley Alaskite Gneiss and Scituate Granite Gneiss appear to have been initially

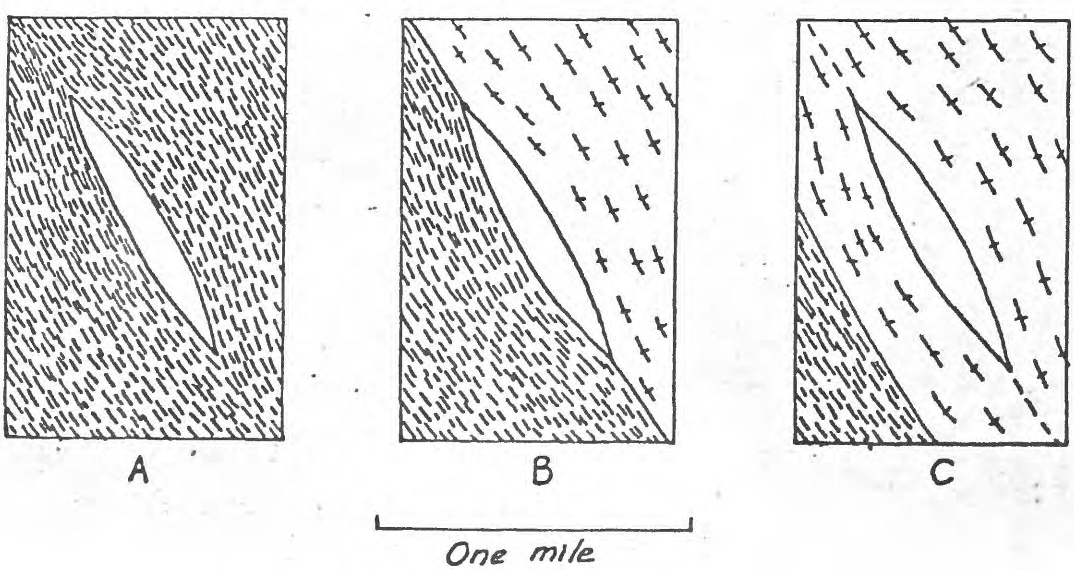


Figure 36. - Isolation of an older sheetlike body (blank) intrusive into metamorphic rock (ruled) by subsequent intrusions (crossed).

intruded into metamorphic host rock (of which, rocks mapped as mafic metamorphic rock (m) may be remnants), and subsequently to have been isolated by intrusion of the Hope Valley and the Scituate (fig. 36).

Of the large bodies intruded under conditions of shear (condition (2) above), the complex pluton of Potter Hill Granite Gneiss is by far the most instructive. Exposures are plentiful, and foliation is ubiquitous. The outline of the pluton with internal foliation generalized by form lines is given on Plate V. The pluton is tri-lobed. The north lobe, the least well exposed of the three, is a thick sheet that thins to the west. The central lobe, whose axis roughly parallels and lies just south of New London Turnpike, is a dome, overturned to the south. Gentle and horizontal dips of foliation are abundant at the crest. Discordance of form lines between Bell Cedar Swamp and Bumpin Hill strongly suggests that this part of the pluton was intruded by two pulses of magma. The later (western) intrusion, centered at the intersection of New London Turnpike and Norwich Road, was emplaced in the core of, and partly crosscuts the earlier (eastern) intrusion. The south lobe, which includes the type rock at Potter Hill, is, like the north lobe, an intrusive sheet. All foliation dips steeply.

Davis (1963) mapped a pluton in California that is structurally similar to the central lobe of the Potter Hill Pluton. He (ibid., p. 336) gives a form line map much like that given in the present report. The ubiquitous foliation of the California pluton was attributed to lateral extension of the magma parallel with foliation as a consequence of magma pressure normal to foliation (fig. 37). The diminution of foliation toward the core suggested by figure 37 was not observed in the Potter Hill.

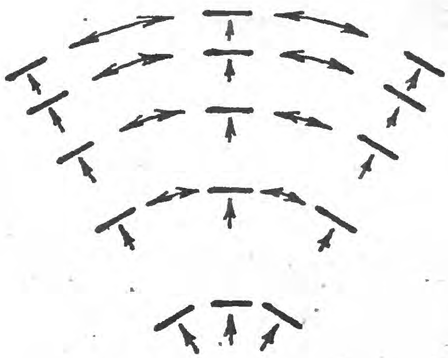


Figure 37. - Production of ubiquitous foliation by alinement of biotite flakes (heavy lines) in response to magma intrusion (single-ended arrows). From Davis (1963, p. 341).

The fine-grained border facies developed locally in Hope Valley Alaskite Gneiss shows that the greatest relative movement within the magma was along the walls, and that the walls remained relatively stationary during intrusion.

The younger granites of the Westerly area are feebly foliated to massive which suggests that the magma was very fluid or that shear stresses on the magma during intrusion were small, or both. That at least the Westerly Granite magma was fluid during intrusion is suggested by gravity settling of very small heavy mineral grains in a dike at Bradford (Quinn, 1943; Hall and Eckelmann, 1961, express a contrary view), and the near absence of flow structure.

The roof of the Narragansett Pier Granite stock at Westerly was probably not far above the present erosion surface. Inclusions in the granite are more abundant high in the quarries on the hills northeast of Westerly than low in the quarries. That the roof plunged to the west is suggested by the increasing abundance of inclusions in that direction. West of Norwich Road inclusions are very large and many are of mappable size. Few of the large inclusions are rotated; they are probably roof pendants.

Balk (1937, p. 86-87) postulated two possible upward terminations of steep-walled stocks: a blunt dome, and an upward gradation into steep dikes. Exposures on Hill 201 northwest of Pawtucket are probably within the lower roof zone of the Narragansett Pier Granite stock. Here the stock grades upward into a swarm of steep sills much as in Balk's second postulate. The dip of foliation and layering in the roof pendants is everywhere steep.

Two small bodies of Narragansett Pier Granite east of Ashaway could be offshoots of a much larger, yet unroofed stock that may underlie an area southeast of Diamond Hill. Vuggy quartz veins in boulders on the southwest slope of Diamond Hill (p. 122) also suggest an igneous body at depth.

Virtually all Westerly Granite mapped in the present report occurs in dikes that strike approximately N.90°E., and dip south from 12 to 42 degrees. Although dike contacts are nearly planar in most exposures, they are locally very irregular, and contact dips read from small exposures can be misleading. Only one dike, 0.45 mile west of Kedinker Island, is irregular. One quarry in this dike was being worked during 1958, and the owner, Mr. Larsen, reported a south dip of the granite.

The remarkable constancy of Westerly Granite dike attitudes in the Ashaway quadrangle and adjacent areas to the east (Moore, 1959), and the absence of correlation between dike attitude and structural attitudes in host rocks, suggest that the Westerly Granite magma was emplaced in fractures created by a regional, singly-directed stress system. Apophyses of the Westerly in host rocks, and relationships in the abandoned quarry described below, indicate emplacement by forcible intrusion. Scarcity of inclusions and smoothness of contacts show that stoping was not an active process during intrusion.

The 1.6 mile long dike of Westerly Granite northeast of Westerly is apparently continuous except for a single break 0.67 mile east of Nooseneck Hill Road. Bedrock exposure in this area is excellent, and the nature of the break is decipherable. Relationships are especially clear in the abandoned quarry at the east end of the west segment of the dike. The Westerly in this quarry is finer-grained, more jointed, and more strained than in adjacent quarries; factors which probably led to early abandonment of the quarry. The contact between the Westerly and the host Narragansett Pier Granite, which where exposed elsewhere in this dike is planar or grossly planar, is here highly amoeboid and irregular. Outcrop on the hilltop east of the quarry is entirely Narragansett Pier Granite with only rare pods of the Westerly, generally less than one meter across. The expected full development of the Westerly dike, which on the hills to the west and east has an outcrop width of more than 50 meters, is entirely absent.

The up-dip termination of the dike in the abandoned quarry cited above is unusual, and is one of the most interesting discoveries of the present study. The white line in the photograph (fig. 38) has been painted a few centimeters above the contact between Westerly Granite (below) and Narragansett Pier Granite (above). The large amphibolite inclusion (lower left) in the Narragansett Pier is truncated by both granites. The horizontal contact at the extreme right (apparent inclination is produced by perspective distortion in the photograph), at approximately the E. position, is the upper contact and strike of the dike. Two small Westerly bodies are exposed at the lower left. The right one is partially obscured by overburden; the left one is surrounded by Narragansett

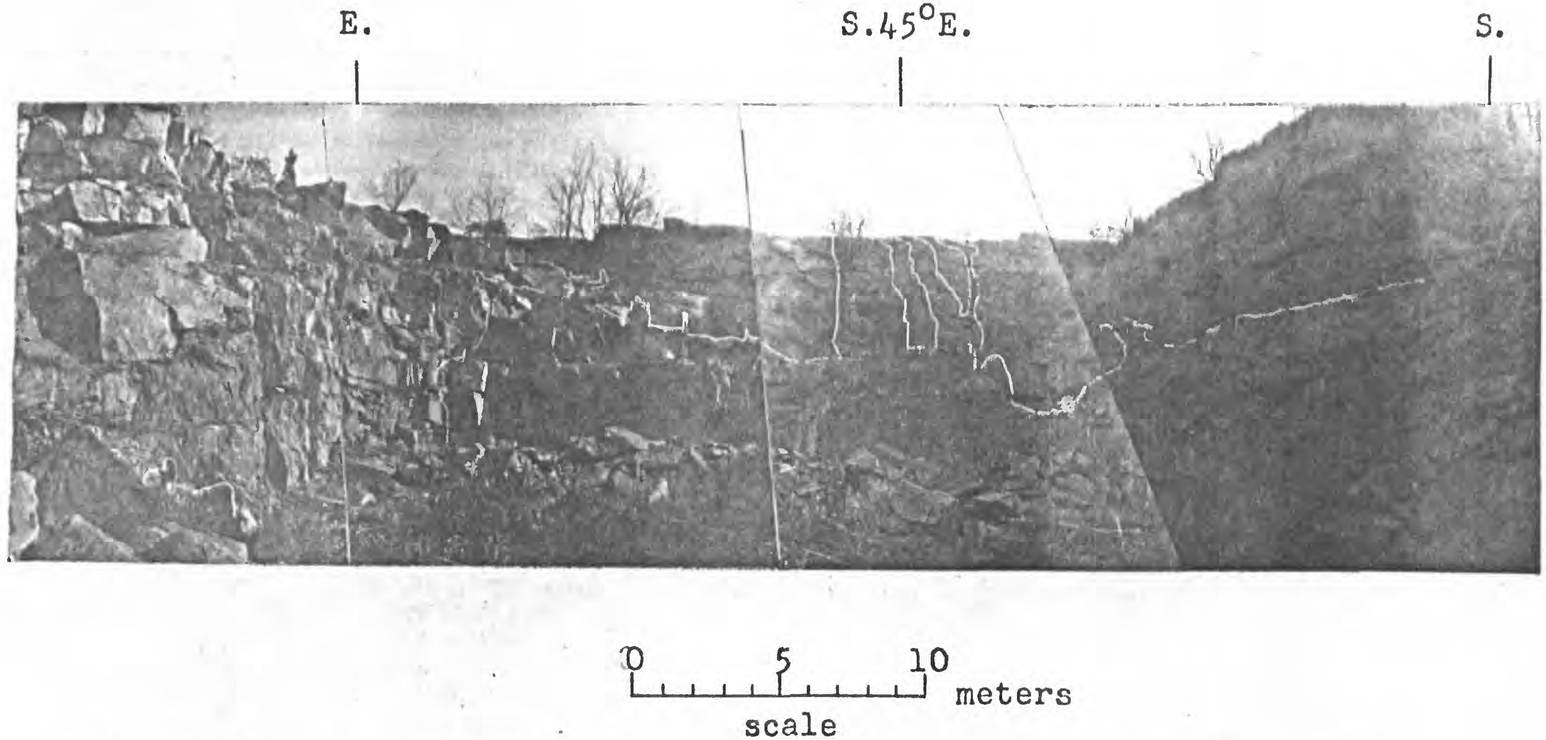


Figure 38. - Up-dip termination of Westerly Granite dike. Abandoned quarry northeast of Westerly, 0.61 mile N.9°W. of Hill 118, Westerly, R. I. Compass directions from observer shown. Scale true only in center background. See text for explanation.

Pier Granite on the exposed face.

The exposure suggests the mechanism of dike emplacement schematically shown in Figures 39 and 40. Prior to dike intrusion, the host Narragansett Pier Granite had a uniform east-striking primary platy flow structure which dipped steeply to the north. Everywhere except in the immediate vicinity of the present dike termination, the foliation has retained this attitude. The Westerly magma was intruded upward at a low angle from the south, probably in a plane normal to the prevailing direction of least compressing stress. It is significant that this plane is normal to the primary platy flow structure (foliation) of the Narragansett Pier Granite. Intrusion of the Westerly may have followed cross joints (Balk, 1937, p. 27-33) which were formed in and around the Narragansett Pier Granite stock during its intrusion, although absence of linear structures in the Narragansett Pier prevents positive identification of cross joints.

The geometrical relationships with the host suggest that the initial injection of Westerly magma reached the site of the present termination of the dike, but as a sheet much thinner than the present dike (A, fig. 39). Subsequent introduction of magma thickened the dike, but did not extend it further up dip. Stresses in the apical region were largely taken up by flowage during recrystallization of the host to a pegmatitic granite (blank in figs. 39B and 40) under the influence of volatiles escaping from the Westerly magma. The dike assumed its present form upon the cessation of magma introduction from below. The time relationship of the concordant offshoots (shown as late in fig. 40) to dike intrusion, is not known. The thickening of this initially thin wedge of magma which retained a relatively blunt end throughout, has caused some

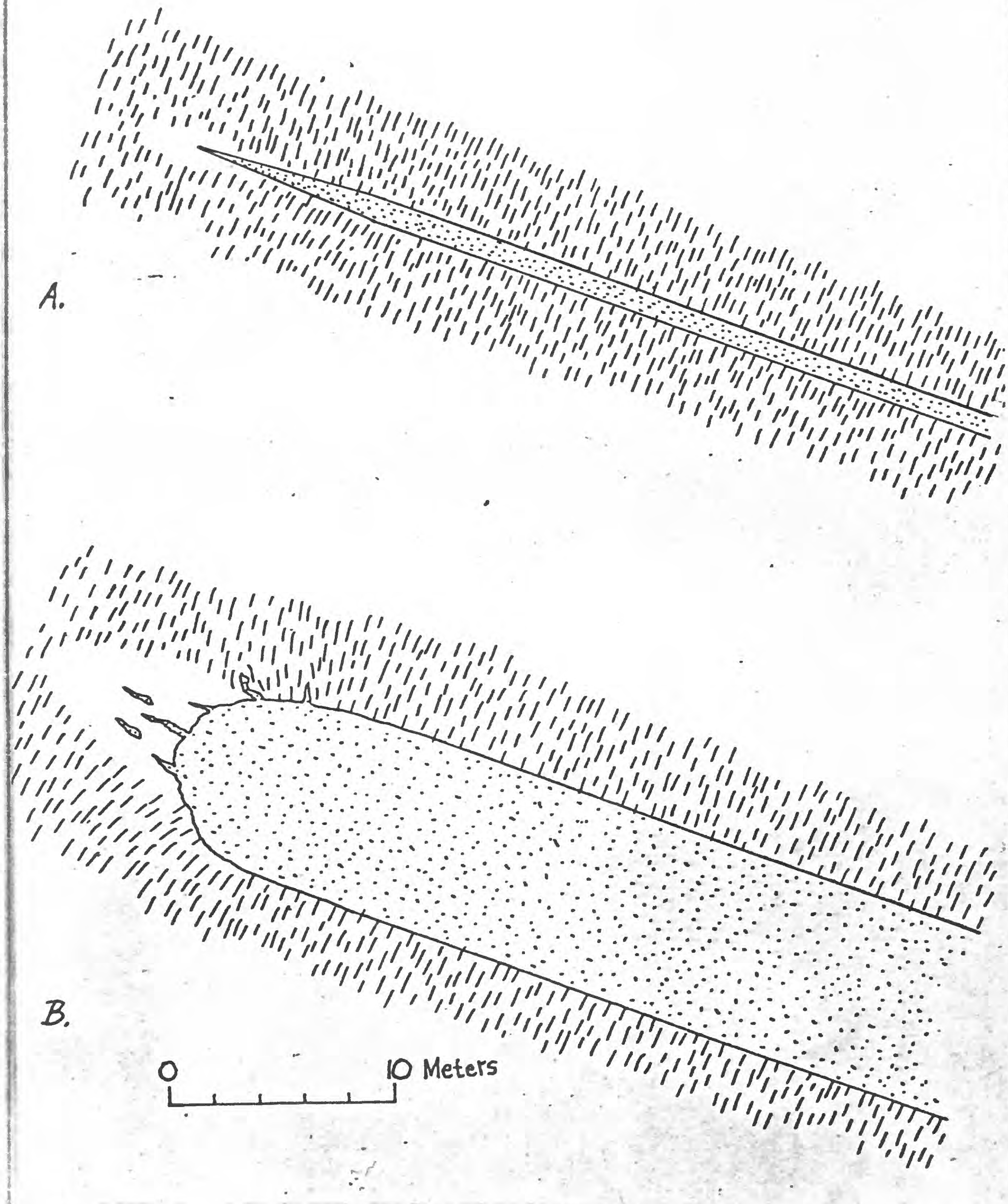


Figure 39. - First two stages of intrusion of Westerly Granite magma at site of up-dip termination of dike. View toward east. Apparently isolated pods of the Westerly in B are connected with the dike in the third dimension. See text for explanation.

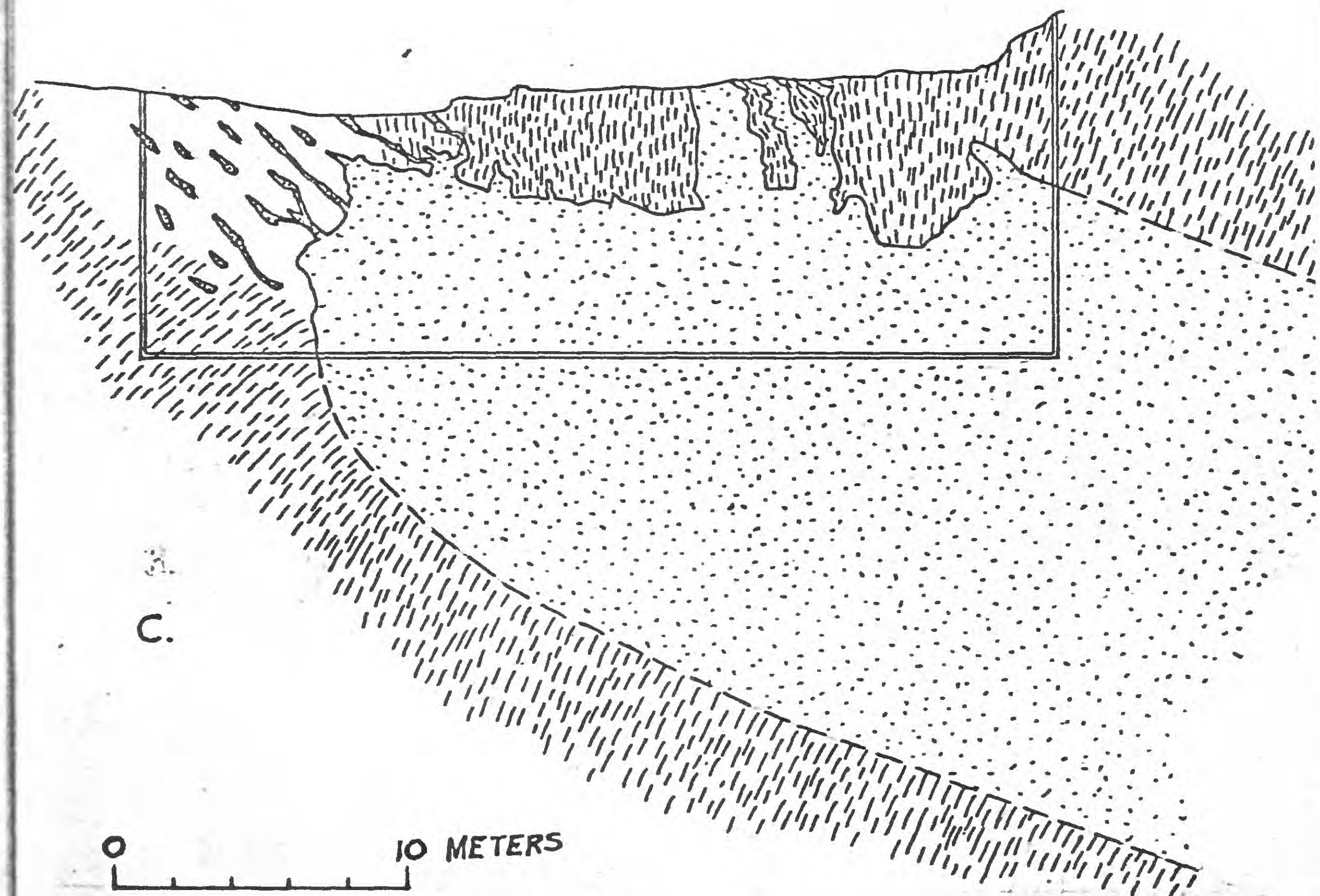


Figure 40. - Present relationships of Westerly Granite dike at site of the up-dip termination. View toward east. Quarry outlined by double lines. Apparently isolated pods of the Westerly are connected with the dike in the third dimension. See text for explanation.

rotation of the host which can be measured in the apical zone. The initial homoclinal steep north dip has been steepened (to vertical) above the wedge end, and has been shallowed considerably below it (fig. 40). Crumpling of foliation in the host is absent, and in fact, horizontal portions of the contact along the east wall of the quarry truncate undisturbed host foliation with a 90 degree discordance.

No inclusions are present in the Westerly in the apical zone. Thin sections from the termination of the dike show the rock to be finer-grained, but otherwise indistinguishable from other samples of Westerly Granite.

Quartz-sillimanite and quartz-sillimanite-muscovite nodules

About 20 outcrops of granitic rock contain white, medium- to coarse-grained quartz-sillimanite or quartz-sillimanite-muscovite nodules. The nodules occur in Hope Valley Alaskite Gneiss and in its fine and white facies, in Potter Hill Granite Gneiss, and in porphyritic granite gneiss. Contacts between nodules and host are sharp. Nodules constitute from less than one percent to as much as 30 percent of the rock. Most are sub-spherical and slightly flattened in the plane of foliation of the host rock. They range from 1 to 15 cm in diameter, and from 0.5 to 10 cm thick. Most are about 5 cm in diameter and 3 or 4 cm thick. Nodules are distributed in concordant layers from a few centimeters to several meters thick. The thickest layer is in Potter Hill Granite Gneiss north of Spalding Pond. In Hope Valley Alaskite Gneiss, nodules have a linear distribution on foliation surfaces that parallels quartz rod lineation in the gneiss. Nodules are particularly abundant in sills of fine-grained saccharoidal Hope Valley Alaskite Gneiss in Plainfield Formation northwest of Green Fall Pond. Several outcrops of otherwise normal Hope Valley Alaskite Gneiss and Potter Hill Granite Gneiss in the Ashaway quadrangle contain small rosettes of sillimanite or sillimanite-muscovite mixtures about 1 cm in diameter. In some outcrops, as on Hill 268 1.5 miles northeast of Hopkinton village, the rosettes grade into nodules. This suggests a transition from normal sillimanite-free granitic rock, to rock that contains one percent or less of sillimanite in rosettes, to nodular rock with several percent of sillimanite.

Thin sections show that nodules are predominantly unstrained quartz with as much as 25 percent sillimanite in tiny hair-like inclusions in quartz and in bundles of fibres that wrap around quartz grains. Other minerals, which are generally sparse, and which are entirely absent from some nodules, include magnetite, granular garnet (?), albite, microcline, and muscovite. The last, as large poikilitic flakes commonly with sillimanite inclusions, is abundant in some nodules. Feldspar was found in only one nodule.

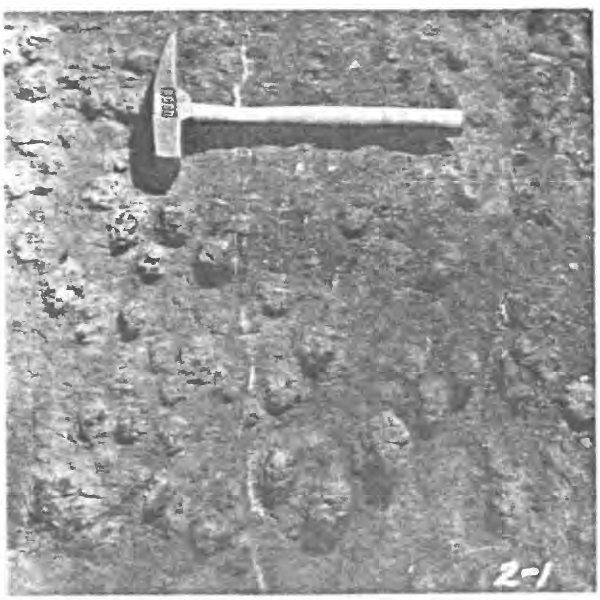
Matrix rock is generally more muscovitic and contains more microcline than the same rock more distant from nodules.

Greater resistance of the nodules than their matrix causes them to stand out on weathering, thereby making strikingly knobby outcrop surfaces. The nodules have not been previously described from the area, probably owing to the general inaccessibility of nodular outcrops. Typical exposures are shown in figure 41.

Genesis

The nodules are believed to be primary, and to have been produced during magmatic crystallization owing to an abnormally high Al_2O_3-to-(K_2O + Na_2O + CaO) ratio. Two mechanisms are postulated to have created this abnormal ratio; one is primary and the other

A.



B.

Figure 41. - Quartz-sillimanite nodules. A. In Potter Hill Granite Gneiss 0.55 mile S.80°W. of intersection of Voluntown and Clarks Falls Road, North Stonington, Conn. B. In Hope Valley Alaskite Gneiss on State line 0.92 mile north of the south border of the Voluntown quadrangle, Hopkinton, R. I. and Voluntown, Conn.

is secondary. Evidence is present that both mechanisms were operative.

About one outcrop per thousand of granitic rock distant from metamorphic rock contains nodules. These occurrences are believed to reflect the composition of the magma from which the rock crystallized. The data given in Table XIII is taken from Table XII. The rocks are all peraluminous. The molar excess of Al_2O_3 over that required to satisfy the available K_2O, Na_2O, and CaO in feldspar of each rock, expressed in percent of total Al_2O_3, is given in column 7 of Table XIII. It ranges from less than one percent to more than 10 percent. Modal mica of each rock, expressed in weight percent, is given in the last two columns. The micas are sinks for Al_2O_3; Al_2O_3-to-K_2O ratio in biotite ranges from 1.2 to 1.5 (Deer, Howie, and Zussman, 1962, vol.3, p. 58-60), and in ideal muscovite it is 2.0 Only two rocks in Table XIII have a large excess of Al_2O_3; porphyritic granite gneiss (9.6 percent) and Hope Valley Alaskite Gneiss (10.5 percent). Excess Al_2O_3in the former is taken up by the abundant modal mica. In the latter, however, very little mica is available to take up the large excess of Al_2O_3 and, in fact, the sample contains scattered sillimanite rosettes.

It is here postulated that certain domains within the magmas from which the rocks of the Rhode Island batholith crystallized were especially rich in Al_2O_3relative to K_2O, Na_2O, and CaO. These domains could have been the last remaining inhomogeneities, which had not been eliminated during the crustal melting proposed as the process that produced the magma. That such aluminous domains would be far more viscous than more normal magma is amply shown by experimental data (Schairer and Bowen, 1955; 1956). During intrusion, these viscous, aluminous domains were drawn out into thin sheets

TABLE XIII. - Some chemical and modal data relating to nodules in the granitic rocks.

Rock*	Molar quantities of oxides Al_2O_3	K_2O	Na_2O	CaO	Molar excess of Al_2O_3 over $(K_2O + Na_2O + CaO)$ expressed in percent Al_2O_3.	Modal biotite in analyzed sample, weight percent.	Modal muscovite in analyzed sample, weight percent.
phg	0.136	0.067	0.042	0.025	1.5	2.5	1.6
ag	0.130	0.050	0.044	0.032	3.2	7.1	1.1
hva	0.126	0.067	0.040	0.007	10.5	0.2	1.1
sgg	0.128	0.060	0.048	0.019	0.8	1.2	0.0
eqd	0.146	0.037	0.056	0.048	3.5	10.0	1.1
gg	0.126	0.036	0.058	0.021	9.6	3.2	1.9

* phg, Potter Hill Granite Gneiss
ag, augen gneiss
hva, Hope Valley Alaskite Gneiss
sgg, Scituate Granite Gneiss
eqd, Escoheag Quartz Diorite Gneiss
gg, porphyritic granite gneiss

enclosed in normal magma, and parallel to foliation. With further intrusion the sheets thinned, and ultimately separated. The separated pieces drew themselves into spheres, the shapes of least surface energy. Slight movements up to the point of complete crystallization kept the spheres slightly flattened. Striking evidence of the feasibility of this mechanism was offered by Adams (1898) who described a layer of quartz-sillimanite-muscovite rock in normal granite at Pine Lake, Ontario, that grades laterally into blocks, and ultimately into nodules indistinguishable from those described in the present report.

About one outcrop in ten of fine-grained saccharoidal Hope Valley Alaskite Gneiss in sills in the Plainfield Formation northwest of Green Fall Pond contains nodules. The abundance of nodules here, many times greater than that described above, suggests a different genetic mechanism. Nodules in the sills are believed to have been produced by alkali-depletion of the magma during intrusion by metasomatic loss to wall rocks. The host rocks in the area are quartz-biotite-sillimanite gneiss and schist. Within a few meters of the sills, however, the host contains feldspar in place of sillimanite. The complete absence of sillimanite in rock adjacent to the sills and its universal presence elsewhere in the area is not considered random chance, but is evidence of alkali metasomatism. Schematically the reaction can be written:

$$5SiO_2 + Al_2SiO_5 + K_2O \rightarrow 2KAlSi_3O_8.$$

The sills were emplaced in the roof zone of the batholith where water vapor, expelled upward during crystallization of the batholith, was more plentiful than at depth. This water greatly aided metasomatism.

The abundant sillimanite in the host rock provided a sink for the volatile alkalis expelled by the magma. As long as sillimanite remained exposed to alkali-rich solutions from the magma, and as long as the concentration of alkalis in the magma exceeded the concentration of alkalis in the host, a chemical gradient was maintained, and alkali extraction from the magma continued. In no samples studied does the feldspar content of the host equal or exceed the feldspar content of the adjacent granite. That such a mechanism has been operative elsewhere on a large scale has been demonstrated (Billings, 1938). What makes the Voluntown quadrangle occurrence unusual is that the imprint of metasomatism is present not only on the metasomatized rock, but on the rock which produced the metasomatism as well. The sillimanite in nodules precipitated from aluminous domains within the batholith magma was not converted to feldspar owing to lack of surplus alkalis beyond that required to form feldspar in the magma that surrounded the domains.

Regional significance

Much of the metasomatized Plainfield Formation adjacent to the nodular sills described above greatly resembles the feldspathic biotite gneiss and schist mapped in the Ashaway quadrangle. It seems probable that the feldspathic composition of the feldspathic biotite gneiss and schist results not from an original sedimentary composition, but from wholesale metasomatism (feldspathization) of a rock whose pre-metasomatic composition approximated that of the present non-metasomatized quartzose and sillimanitic gneisses northwest of Green Fall Pond. Probably these latter rocks were spared extensive metasomatism by the protective layer of porphyritic granite gneiss between them and Hope Valley Alaskite Gneiss.

Apparently metasomatic effects by porphyritic granite gneiss magma were slight. Corroborative evidence is given by Moore (1959) who reports only a single occurrence of sillimanite in correlative feldspathic rocks in the Carolina quadrangle. This occurrence, 0.2 mile north of the railroad crossing at Kenyon, is at the center of the largest area of these rocks in southern Rhode Island, and therefore farthest from Hope Valley Alaskite Gneiss and its metasomatic effects.

STRUCTURAL GEOLOGY

Regional setting

The generally northerly trend of rocks and structures in the Ashaway and Voluntown quadrangles is parallel to the regional trend of rocks and structures of the Appalachian mountain system in southern New England (Emerson, 1917, map; Rodgers et al., 1959, map). The east-striking rocks at Westerly, which depart markedly from the regional trend, are part of an area of east-striking rocks which underlies coastal Rhode Island and southeastern Connecticut. Whereas farther to the west a major fault separates these rocks from rocks with the prevailing northerly trend (Lundgren et al., 1958), the transition from easterly to northerly trends in the area of the present study is a gradual one. The area between the trends, north of Westerly, is occupied by the main body of the Potter Hill Granite Gneiss, and structural discordance is absent.

The granitic rocks which underlie most of the Ashaway and Voluntown quadrangles are part of a large anticlinal mass of granitic rocks, here called the Rhode Island batholith, that underlies more than 500 square miles of western Rhode Island. This batholith is bounded on the west by metamorphic rocks approximately at the Connecticut State line, and on the south by the younger Narragansett Pier Granite. The eastern margin of the batholith is obscured by a cover of Pennsylvanian sedimentary and metamorphic rocks in the Narragansett basin. The batholith extends northward into Massachusetts, but its boundaries there are imperfectly known. The batholith in Rhode Island and adjacent Connecticut is composed of many units, of which six have been mapped and described here (augen gneiss, Escoheag Quartz Diorite Gneiss, porphyritic granite gneiss, Potter Hill Granite Gneiss, Hope Valley Alaskite Gneiss, Scituate Granite Gneiss, and Ten Rod Granite Gneiss). Of the six, only the main body of the Potter Hill Granite Gneiss departs from the regional northerly trend.

The Ashaway and Voluntown quadrangles lie astride the western margin of the batholith, which here is a belt of intermixed batholith rocks and older metamorphic rocks. Most of the structures within the quadrangles, which have been generalized in figure 42, were produced by the folding and metamorphism of the metamorphic rocks, in part accompanied by, and in part closely followed by the intrusion of the Rhode Island batholith; this was all included within one orogenic episode. The general contemporaneity of deformation and intrusion is shown by the concordance of structures in the batholith with those in the host metamorphic rocks, and by the regional uniformity of all structures. Only the younger Narragansett Pier and Westerly Granites, largely confined to the Westerly area, are sharply discordant. These were emplaced at a later date, and did not influence the regional structures.

Minor folds and their significance

Compositional layering and foliation of the metamorphic rocks are generally planar and everywhere are parallel. The major trends indicate broad and open folds. In some places, however, layering and foliation have been deformed into tight minor folds. This deformation is especially well developed in the Plainfield Formation and the amphibolite southeast of Diamond Hill, in the Plainfield Formation near Green Fall Pond, and in the large quartzite body west of Ashaway.

The Plainfield Formation and the amphibolite southeast of

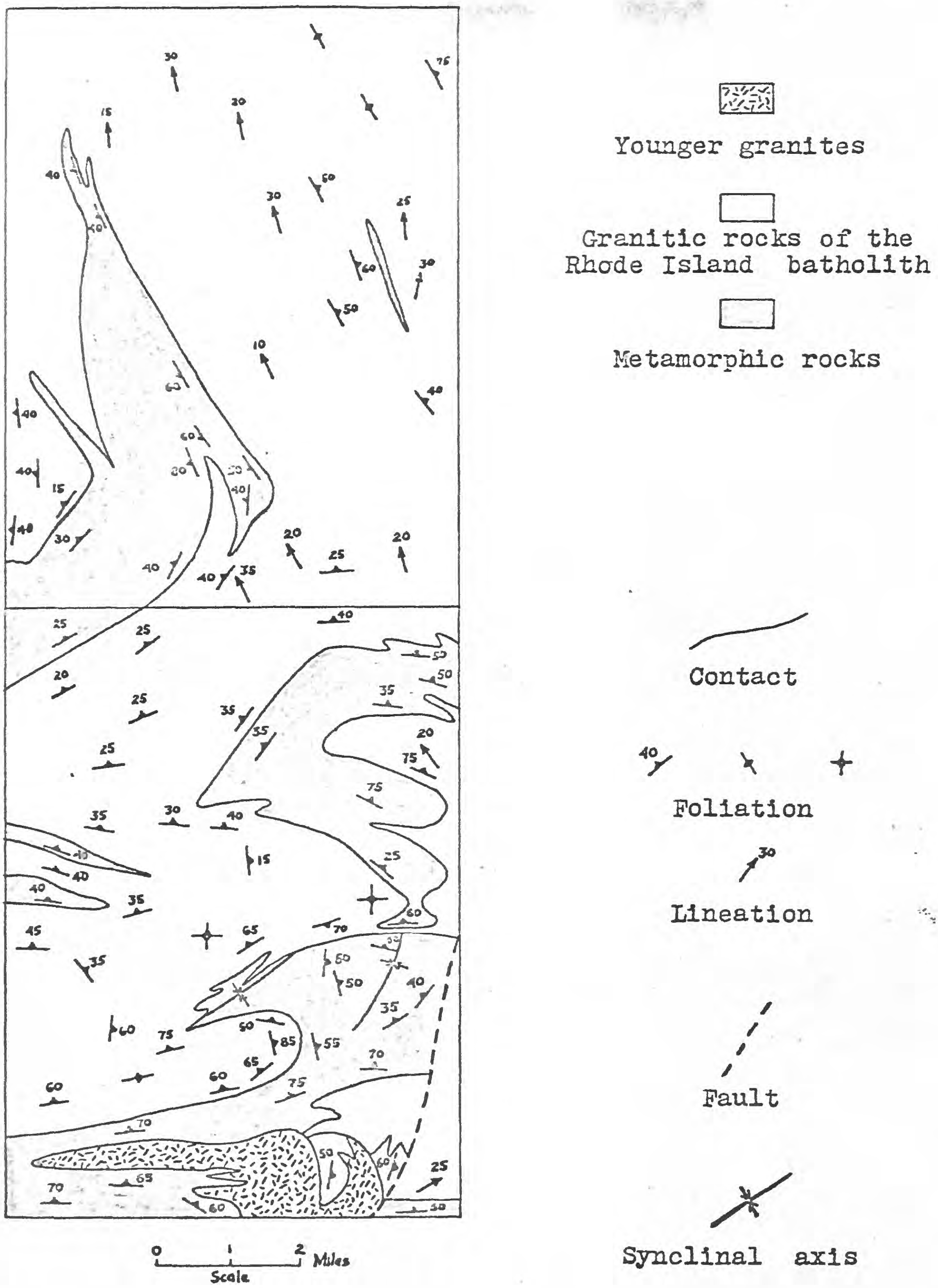


Figure 42. - Generalized structure map of the Ashaway and Voluntown quadrangles.

Diamond Hill are in a syncline whose axis bears and plunges north-northeastward. The rocks there are intensely crumpled, and the axes of minor folds parallel the axis of the syncline. The Plainfield Formation near Green Fall Pond is also in a syncline. This syncline, which has a northwest plunge, has been much disrupted by granite. The limb northwest of Green Fall Pond dips steeply to the west, and the limb southwest of Green Fall Pond dips gently to the northwest. Rocks within the syncline near Green Fall Pond are highly deformed (fig. 8). The axes of minor folds and the attitudes of slickensides on bedding surfaces in quartzite (fig. 11) parallel the axis of the syncline.

The form of the minor folds described above shows that they were produced in a stress field where the maximum compressive stress was perpendicular to the fold axes. Abundant joints perpendicular to minor fold axes, and the presence of slickensides coincident with fold axes on some bedding planes show that extension parallel to fold axes occurred during folding, and that the least compressive stress was parallel to minor fold axes.

Two of the three areas of most abundant minor folds are demonstrably the result of the squeezing of the rocks in troughs of synclines. By analogy with the areas cited above, the highly crumpled quartzite that constitutes the large body west of Ashaway is probably in the keel of a syncline, although Potter Hill Granite Gneiss obscures structural and stratigraphic relationships in the area. The quartzite was probably folded by the intrusion of Potter Hill Granite Gneiss magma to the north and to the south. The northeast plunges of the minor folds in the quartzite indicate that the syncline plunges in that direction, and that the keel rises above the present erosion surface toward the southwest. The east end of the syncline has been disrupted by the Potter Hill Granite Gneiss, although it may at one time have been continuous with the syncline southeast of Diamond Hill. Similar sinuous folds, although less disrupted by granite, have been mapped in similar rocks a few miles to the west (Goldsmith, 1961).

Joints, veins, and dikes and their significance in the Rhode Island batholith and adjacent rocks

The rocks of the Rhode Island batholith in the southeast quarter of the Voluntown quadrangle, principally Hope Valley Alaskite Gneiss and Scituate Granite Gneiss, are much fractured and contain abundant veins of quartz and dikes of pegmatite and aplite. These features and their orientation with respect to primary flow lineation and flow foliation of the granitic rocks show the orientation of extensional stresses during and following the late stages of magma intrusion.

The veins of quartz and the dikes of pegmatite and aplite formed throughout the late stages of crystallization of the magmas. Some formed while the magma was still fluid and moving. These have gradational contacts and irregular shapes (fig. 43), and many have in part or wholly been drawn into concordant veins and sills by magma movement (fig. 44). Slightly later veins and dikes have sharp and generally planar contacts, but the presence of deformed flow structure in adjacent granite shows that the granitic magma was not fully crystallized when the veins and dikes formed (fig. 45). Late veins and dikes are planar and have sharp contacts (fig. 46). The great lateral extent of the late veins and dikes (commonly 10 meters or more), and the absence of deformation of flow structure in adjacent granite, show that these were emplaced in fractures in

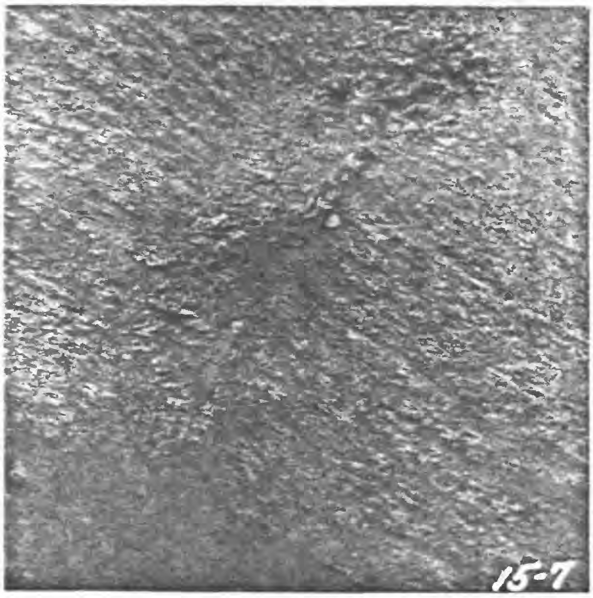


Figure 43. - Pegmatite dike in Hope Valley Alaskite Gneiss. Dike formed early in the crystallization of the gneiss. Notice diffuse contact, irregular shape of dike, and deformed flow structure in adjacent gneiss. 0.36 mile west of the west end of Ashville Pond, Hopkinton, R. I.

Figure 44. - Veins of quartz in Hope Valley Alaskite Gneiss. Veins formed early in the crystallization of the gneiss and were deformed by late movements of the magma. Notice transverse shear from upper right to lower left. Shore of Yawgoog Pond 0.53 mile N.48°W. of the outlet, Hopkinton, R. I.

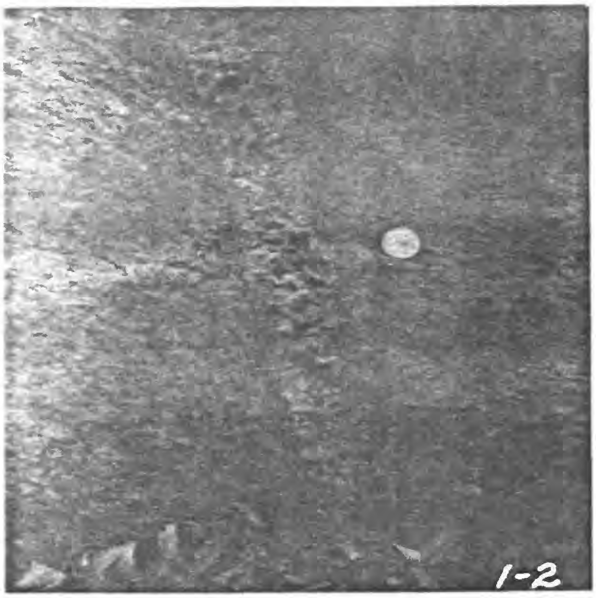


Figure 45. - Pegmatite dike in Scituate Granite Gneiss. Dike formed late in the crystallization of the gneiss. Notice sharp, straight contacts, but flow structure in adjacent gneiss is deformed. North shore of Wincheck Pond 0.5 mile west of intersection of Old Rockville and Canonchet Roads, Hopkinton, R. I.

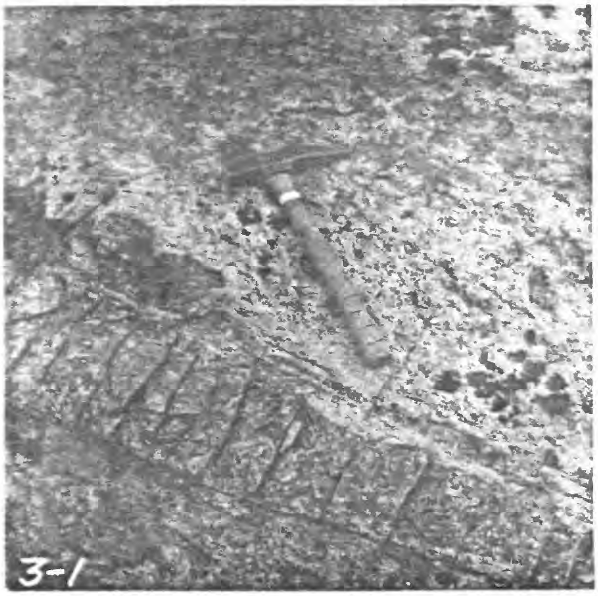
Figure 46. - Late vein of quartz in Hope Valley Alaskite Gneiss. Notice sharp, straight contacts, great lateral extent. Flow structure in adjacent gneiss is undeformed. 0.93 mile N.55°E. of the outlet of Green Fall Pond, Voluntown, Conn.

completely crystallized granite. The quartz, pegmatite, and aplite of these veins and dikes probably was tapped from residual magma and solutions at depth. Late veins and dikes are shown in Plate V, A, and joints in the same area are shown in Plate V, B.

Nearly all veins, dikes, and irregular masses of quartz and aplite in the southeast quarter of the Voluntown quadrangle are prominently fractured. The attitudes of the fractures (strikes are N.20° ± 5°E.) are remarkably constant throughout the area, and are independent of the shape of the quartz or aplite body in which they are developed (fig. 47). Some fractures extend a short distance into the host granite, but with diminished prominence (fig. 48). The attitudes of many of these fractures are shown in Plate V, C.

The late veins and dikes fill cross joints as they are normal to, or nearly normal to primary flow lineation in the granite (Balk, 1937, p. 27-33). This shows that the stresses which intruded the magma and extended it in the direction of flow lineation continued to the last stages of crystallization of the granite. The scarcity of cross joints and late veins and dikes in Hope Valley Alaskite Gneiss and Scituate Granite Gneiss outside the southeast quarter of the Voluntown quadrangle suggests that elsewhere intrusive stresses were relaxed earlier in the crystallization history of the same magmas.

Some of the joints in the southeast quarter of the Voluntown quadrangle are cross joints and have attitudes similar to those of the late veins and dikes (strikes are east northeast) (Plate V, B). These unfilled cross joints probably formed at a time when no liquid remained in the granite, and they are later than those filled with quartz, pegmatite, or aplite. The prevalent strike of joints,



A.

B.

Figure 47. - Quartz veins with prominent, uniform fractures.
A. In Hope Valley Alaskite Gneiss. Same locality as fig. 45.
B. In porphyritic granite gneiss 0.72 mile S.80°E. of BM "Beach", Exeter, R. I.

Figure 48. - Quartz knot and vein with fractures that in part extend into host porphyritic granite gneiss. 1.06 miles S.82°E. of BM "Beach", Exeter, R. I.

however, is north or northeast, and has no relationship to primary structures in the granites.

The fractures in quartz and aplite parallel the prevalent joint attitudes. The smaller range of strike of the fractures than of the joints reflects the mechanical isotropy of the quartz and aplite masses as opposed to the marked mechanical anisotropy of the lineated and foliated granites.

In the same area, 11 prominent topographic lineaments have trends parallel to the strike of the prevalent joints. The lineaments, shown on the geologic map, range from rock-walled, soil-floored valleys 10 to 20 meters wide and as much as 20 meters deep, to lines of outcrops with vertical faces that form a discontinuous scarp. Lineaments shown in areas of no outcrop were mapped on air photographs where they are reflected by linear swamps, or by a linear arrangement of swamps.

The lineaments are either zones of closely-spaced joints which have been topographically accentuated by glacial plucking, or they are faults. No lateral offset of rock units across the lineaments is measurable, but where the lineaments are rock-walled valleys, the east wall is higher, and where rock is exposed on only one side, it is generally the east side. Joints parallel to and adjacent to lineaments have steep westerly dips, and unweathered joint faces in places have slickensides which plunge directly down dip. The "grain" of the slickensides indicates a normal sense of movement. The lineaments are therefore probably zones of closely-spaced normal faults of small displacement. Glacial plucking of fractured rock in these zones has produced the prominent topographic expression.

The distribution of the north- to northeast-striking joints and associated lineaments shows that they are not genetically related to the intrusion of the Rhode Island batholith. The joints are regional and occur in all rocks. They are especially well developed in the younger Narragansett Pier Granite where they have prominent topographic expression just north and east of Chapman Pond. Both mafic dikes, the youngest rocks in the quadrangles, were intruded along north northeast-striking joints. The joints, therefore, post-date the intrusion of both the Rhode Island batholith and the Narragansett Pier and Westerly Granites, but predate, or are contemporaneous with the mafic dikes.

Structural evolution of the rocks

The structural evolution of the rocks has been guided by the syntectonic forcible intrusion of enormous quantities of magma of the Rhode Island batholith in several pulses through a relatively short timespan. Relatively little of the older metamorphic host rocks is preserved at the present erosion surface. The general concordance of structures over large areas, the coincidence of structures within the batholith with those in the metamorphic rocks, and the absence of later, superimposed structures are strong evidence that the present spatial relationships of the rocks were produced by this single event. If the metamorphic rocks were deformed by an earlier event, the imprint of it has been obliterated.

Movements of the magmas during intrusion are recorded by lineation and foliation in the crystallized granitic rock. The magmas made room for themselves by shouldering aside or by pushing upward the metamorphic rocks. The generally small differences in the mechanical properties of magma and host rock at the plutonic conditions during intrusion favored concordant contacts between the two. That the intruding magma deformed host rock is shown on a small scale by minor folds near some contacts, as in the quartzite along Babcock Road. The abundance of joints perpendicular to axes of such folds shows that folding was accompanied by tensional elongation in the metamorphic rocks parallel to the direction of magma movement, as the fold axes parallel the flow lineation in adjacent granite. Metamorphic rocks were much crumpled where caught between adjacent rising magma masses, as west of Ashaway, or were otherwise squeezed in synclines produced by magma intrusion, as at Green Fall Pond.

The Narragansett Pier and Westerly Granites are post tectonic. Although the east strikes of these intrusives at Westerly are broadly concordant, small-scale discordant relationships between Narragansett Pier Granite and host rocks are plentiful, and the south-dipping Westerly dikes cross cut all local structures. The emplacement of these magmas had only a local effect on the older structures.

AGES OF THE ROCKS

The relative ages of the rocks in the Ashaway and Voluntown quadrangles have been established by field relationships and by petrographic study. On the basis of these relationships the rocks can be gathered into four main groups, from oldest to youngest: (1) the Plainfield Formation and other metamorphic rocks, (2) the granitic rocks of the Rhode Island batholith, (3) the Narragansett Pier Granite and the Westerly Granite, and (4) mafic dikes. Relative ages within these groups are discussed below. Absolute ages of many of the rocks are uncertain.

The Plainfield Formation is the oldest rock as it underlies all the other metamorphic rocks, and it has been intruded by all the granitic rocks. Only the mafic metamorphic rock that occurs as xenoliths within the granitic rocks of the Voluntown quadrangle may be older, but its stratigraphic position is unknown. The metavolcanic rocks at Wyassup and Billings Lakes are considered correlative with amphibolite, layered felsic gneiss, and calcareous felsic gneiss as the rock types are similar and occupy similar stratigraphic positions. These overlie the Plainfield Formation. The youngest metamorphic rock is the calc-silicate quartzite that overlies the metavolcanic rocks east and northeast of Billings Lake.

The oldest granitic rock is probably the augen gneiss as this rock shows evidence of cataclastic deformation not present in any of the other granitic rocks. However, no contacts of augen gneiss and other granitic rocks are exposed. Escoheag Quartz Diorite Gneiss and the porphyritic granite gneiss have been intruded by, and are therefore older than Hope Valley Alaskite Gneiss. The relative ages of the Escoheag Quartz Diorite Gneiss and the porphyritic granite gneiss are not known; but the two are here considered closely related owing to the great structural similarity of the fine-grained facies of the Escoheag and the porphyritic granite gneiss. The youngest granitic rocks of the Rhode Island batholith- Potter Hill Granite Gneiss, Hope Valley Alaskite Gneiss, Scituate Granite Gneiss, and Ten Rod Granite Gneiss- are gradational and, therefore, roughly contemporaneous. Potter Hill Granite Gneiss and Hope Valley Alaskite Gneiss are locally in sharp contact, but are without cross-cutting relationships.

The youngest granites- Narragansett Pier Granite and Westerly Granite- crosscut the youngest rocks of the Rhode Island batholith. Dikes of Westerly Granite in Narragansett Pier Granite north of

Westerly show that the Westerly is the youngest granite.

The mafic dike at Westerly cuts Narragansett Pier Granite, and as a similar dike cuts Westerly Granite to the south in the Watch Hill quadrangle (A.W. Quinn, personal communication), the mafic rock is the youngest rock.

The absolute ages of the rocks are not well established, and definite assignment to geologic periods is not possible. No fossils were found in the metamorphic rocks, and in nearby, correlative rocks fossils are similarly lacking. Radiometric ages of many of the granitic rocks have been determined, but results conflict, and some are geologically unreasonable. The best and only non-ambiguous data are the geologic relationships of some of the granitic rocks with known Pennsylvanian sedimentary and metamorphic rocks of the Rhode Island Formation in the Narragansett and smaller, subsidiary basins.

In the North Scituate quadrangle, about 20 miles northeast of the present area, the Rhode Island Formation unconformably overlies Scituate Granite Gneiss (Quinn, 1951). In the Narragansett Pier quadrangle, about 17 miles east of Ashaway, the Rhode Island Formation is intruded by Narragansett Pier Granite (Nichols, 1956). These relationships place an upper limit on the Scituate Granite Gneiss, and a lower limit on the Narragansett Pier Granite. In the Ashaway and Voluntown quadrangles, the rocks of the Rhode Island batholith are probably closely related to each other and are nearly contemporaneous. Local cross cutting relationships, however, show that some spacing of magmas in time occured. The Scituate Granite Gneiss, although part of the youngest group of batholith granites, is probably not very much younger than the oldest, and the geologic age of the Scituate established in the North Scituate quadrangle, has been extended to include all the batholith granites here mapped. Similarly, the petrographic similarity and field association of Narragansett Pier Granite and Westerly Granite strongly suggests that these two are closely related.

Lead-alpha ages on monazite and zircon from several of the granitic rocks have been reported (Quinn et al., 1957). Six ages on Narragansett Pier Granite and Westerly Granite range from 208 to 274 M.Y., and one age each on Ten Rod Granite Gneiss, Scituate Granite Gneiss, and Hope Valley Alaskite Gneiss are 289, 299, and 303 M.Y. respectively. More recently, Hurley and colleagues have obtained a considerable range of age determinations on the Westerly Granite; biotite K-Ar, 240 ± 12 M.Y. (Hurley et al., 1960); biotite Rb-Sr, 274 ± 10 M.Y., and whole rock Rb-Sr, 315 ± 40 M.Y. (Pinson et al., 1962). K-Ar ages on Scituate Granite Gneiss reported this year range from 200 to 250 M.Y. (Harakal, 1964).

The lead-alpha zircon ages of the batholith rocks are Pennsylvanian according to Kulp's revision of the geologic time scale (1961). Excluding the anomalously old whole rock Rb-Sr age of the Westerly Granite, the ages of the Narragansett Pier and Westerly Granites, as well as the K-Ar ages of Scituate Granite Gneiss, are Permian or Triassic on the same time scale. Some of these ages are inconsistent with the geologic relationships and thus require clarification.

The geologic evidence shows that the rocks of the Rhode Island batholith were intruded and crystallized at depth. Relationships in the North Scituate quadrangle (Quinn, 1951) show that between the crystallization of these rocks and the deposition of the Pennsylvanian sediments, the roof rocks of the batholith and considerable quantities of the batholith rocks themselves were eroded.

The K-Ar ages of Scituate Granite Gneiss are in part inconsistent with this, and the lead-alpha zircon ages of the batholith rocks allow an unreasonably short timespan.

Most of the Pennsylvanian rocks in Rhode Island have been metamorphosed (Quinn, 1958, p. 567-569). Foliated inclusions of the Pennsylvanian Rhode Island Formation in massive Narragansett Pier Granite show that this metamorphism largely preceded intrusion (Nichols, 1956). The absence of chilled contacts between granite and host (ibid.), however, suggests that the intrusion closely followed the metamorphism. Effects of this metamorphism are not apparent in the rocks or structures in the Ashaway and Voluntown quadrangles. The anomalously young radiometric ages of the batholith rocks, however, may be due to the influence of this metamorphism which may have been more widespread than heretofore realized.

Collectively, the radiometric ages and the regional geologic relationships suggest that the principal episode of metamorphism and intrusion in the Ashaway and Voluntown quadrangles was pre-Pennsylvanian, possibly Acadian. The later episode of metamorphism and intrusion in the Narragansett Bay area was late or post-Pennsylvanian, possibly Appalachian. Recognized evidence of the later episode is restricted to the Narragansett Pier and Westerly Granites in the present study area.

The ages of the metamorphic rocks are less well known. The most conspicuous, and possibly the most abundant rock type in the Plainfield Formation is quartzite. Clasts of quartzite similar to the quartzite of the Plainfield Formation are abundant in conglomerate in the Narragansett basin. Many of these clasts contain Cambro-Ordovician fossils, It is here suggested that the source of the quartzite clasts was the Plainfield Formation. As a Cambrian rather than an Ordovician age has been suggested for the Plainfield Formation elsewhere (Lundgren, 1963, p. 38), this assignment is followed here. The uncertainty is large, however, and the age is open to question. The only other extensive quartzite in Rhode Island is the Westboro Quartzite of the Blackstone Series in the northeastern part of the state (Quinn, 1949). Although the Westboro was given a Precambrian (?) age, a lower Paleozoic age is possible (ibid.).

The metavolcanic rocks overlie the Plainfield Formation, and have here been given an Ordovician (?) age. This is based partly on their stratigraphic position, and partly on their lithologic similarity to the extensive Ammonoosuc Volcanics of New Hampshire (L.R. Page, personal communication).

The calc-silicate quartzite is probably Ordovician (?) as thin beds of similar rock are intercalated in amphibolite northeast of Westerly.

The mafic dikes may be related to extensive shallow intrusives and flows of diabase of Triassic age in the Connecticut Valley, 40 miles west of the study area. The unusual composition of the mafic dike at Westerly (monchiquite?), however, emphasizes the uncertainty of this correlation.

REGIONAL SUMMARY

The present detailed study of the rocks and structures of the Ashaway and Voluntown quadrangles has brought out the following. (1) Large volumes of gneissic granitic rock were intruded as magmas and are not the product of in situ granitization of preexisting rock. (2) Intrusion of the Rhode Island batholith magmas is closely related to the regional metamorphism. (3) The structures in the quadrangles are directly related to the intrusion of the batholith rocks. (4) The principal orogenic episode in the quadrangles was pre-Pennsylvanian, and therefore pre-Appalachian. Later events-the intrusion of Narragansett Pier Granite and Westerly Granite magmas, formation of regional joints, and mafic dike emplacement-were relatively mild events and did not blur the clarity of the structures of the earlier major episode.

The Rhode Island batholith, however, was not everywhere emplaced under the same conditions. The Pawtucket quardrangle (Quinn, 1949) lies near the northeastern border of the batholith, although the border zone is partly covered by Pennsylvanian sedimentary rocks of the Narragansett basin. Several interesting comparisons can be made between that area and the Ashaway and Voluntown quadrangles. In the area of the present study, the metamorphic rocks are in the almandine-amphibolite facies of regional metamorphism. Contacts between granitic and metamorphic rocks are mostly concordant. In the Pawtucket quadrangle, on the other hand, the metamorphic rocks are in the greenschist facies of regional metamorphism (Turner and Verhoogen, 1960, p. 533-541), and contacts between granitic and metamorphic rocks are mostly discordant.

In the Ashaway and Voluntown quadrangles, the high metamorphic grade of the host rocks, the absence of chilled zones and the well-developed foliation and lineation in the intrusive rocks, the prevalent concordance of contacts between intrusive and host rocks, the numerous examples of country rock that has been pulled apart, and the domical forms of some of the intrusives are all criteria of intrusion deep in the crust, the catazone of Buddington (1959, p. 714-715). In the Pawtucket quadrangle, on the other hand, the low to intermediate metamorphic grade of the host rocks, the weak to moderate development of foliation in the intrusive rocks, and the generally discordant contacts between intrusive and host rocks are all criteria of somewhat shallower intrusion, the mesozone of Buddington (1959, p. 695-697).

The greater degree of discordance of the granitic rocks in the Pawtucket quadrangle than in the Ashaway quadrangle shows that in the two areas, the mechanical contrast of magma and host rock was larger in the Pawtucket quadrangle. This is in accord with the contemporaneity of metamorphism and intrusion of the batholith suggested in this study, as the host rocks would be more brittle at the lower temperature of the greenschist facies than at the high, near-magmatic temperature of the upper almandine-amphibolite facies. The differences between the two areas may be due to a southwestward-deepening level of erosion in the Rhode Island batholith.

ECONOMIC GEOLOGY

Granite

The most valuable bedrock mineral resource is the Westerly Granite. This granite is much prized for statuary and architectural use owing to its homogeneity, its fine grain size, its light color, and its susceptibility to polish. It has been quarried intensively for more than a century, but reduced demand in recent years has left only one quarry presently operating. Nearly all of the good rock near the surface in the larger dikes has been quarried out.

Narragansett Pier Granite and Potter Hill Granite Gneiss are the only other granitic rocks once quarried on a large scale, although abandoned quarries and small stone prospects show that all but the augen gneiss at some time have been quarried.

Mineral deposits

A small area on the north shore of Blue Pond in the Voluntown quadrangle is strewn with boulders of Hope Valley Alaskite Gneiss and associated pegmatite containing large masses of ilmenite. The ilmenite constitutes as much as 10 percent of the rock in plates from 1 to 10 cm in diameter. The boulders are concentrated on a steep slope, and probably were derived from immediately underlying bedrock. Smaller and less abundant ilmenite plates occur in schist and Hope Valley Alaskite Gneiss in an outcrop 1.5 miles to the southwest. It is doubtful that either occurrence is of economic interest.

Surficial deposits

Glaciofluvial sand and gravel deposits and ground water are the most valuable mineral resources of the quadrangles. A discussion of the origin and extent of these resources, however, is beyond the scope of this study.

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APPENDIX

Modes of the granitic rocks based on 1000 or more point counts per sample.

Explanation: Q, quadrangle; A, Ashaway; V, Voluntown. Location; col. 1, miles north or miles south of the common border of the Ashaway and Voluntown quadrangles; col. 2, miles east of the west border of the quadrangles. Qu, quartz; M, microcline; P, plagioclase; H, hornblende; B, biotite and chlorite; Mu, muscovite; O, opaque accessories; N, non-opaque accessories.

Sample number	Q	Location 1	Location 2	Qu	M	P	H	B	Mu	O	N
Augen gneiss											
CA-2	V	1.30	0.57	37.3	25.6	27.3		6.4	1.0	1.6	0.8
9-26-A	V	2.66	0.00	26.3	20.0	42.5		8.9	0.8	0.5	1.0
9-34-H	V	2.17	0.49	32.1	22.8	38.0		5.2	0.8	0.2	0.9
13-3-P	V	1.96	0.99	25.6	31.9	36.3		4.5		1.2	0.5
13-9-C	V	1.61	0.15	28.8	26.4	35.8		5.6	2.0	0.8	0.6
13-16-C	V	1.16	0.15	22.8	22.4	40.9	0.2	11.2		0.7	1.8
13-20-H	V	0.90	0.45	23.4	31.7	38.2		5.4	1.0	0.2	0.1
Augen gneiss, muscovitic facies											
13-5-N	V	1.81	0.87	37.5	24.6	19.8		0.4	16.3	1.3	0.1
Escoheag Quartz Diorite Gneiss											
CA-5	V	7.11	5.55	27.5	23.0	39.6		8.9	0.1	0.1	0.8
3-1-W	V	8.58	4.61	30.3	28.4	28.8		6.8	5.3	0.1	0.3
3-2-V	V	8.52	4.57	24.9	15.9	46.7		11.7		0.8	
3-5-Y	V	8.31	4.74	11.8	6.5	51.9		27.8	1.6		0.4
3-10-W	V	7.98	4.64	17.9	14.3	49.4	3.0	13.3		1.4	0.7
4-27-K	V	6.93	5.54	17.7	26.0	34.4	5.8	14.2		0.1	1.8
4-28-L	V	6.84	5.62	32.0	9.3	48.5	0.9	8.0		0.4	0.9
8-2-L	V	6.37	5.59	14.9	7.5	59.6	3.0	13.9		0.7	0.4
8-10-W	V	5.85	6.27	15.4	21.8	50.9	1.1	8.6		0.6	1.6
8-18-Y	V	5.34	6.43	22.4	8.4	54.6	0.1	12.7		0.2	1.6
Escoheag Quartz Diorite Gneiss, fine-grained facies											
3-24-S	V	7.14	4.39	22.6	13.2	44.5		18.4			1.3
8-35-J	V	4.32	5.44	18.2	27.9	40.6	7.0	4.4		0.4	1.5
12-2-K	V	4.18	5.53	19.9	15.7	43.7	14.8	13.7			2.2
12-7-O	V	3.86	5.78	22.7	10.1	49.4	0.1	16.8			0.9
12-10-R	V	3.72	5.97	16.2	27.9	38.6		16.7			0.6
Porphyritic granite gneiss											
CA-6	V	2.28	3.57	37.0	22.2	35.7		2.8	1.7	0.4	0.2
283-A	A	3.65	0.76	30.5	39.0	26.5		2.0	1.5	0.5	
314-D	A	1.44	0.94	34.2	28.1	32.3		5.0		0.4	
315-A	A	1.93	0.53	34.0	35.0	29.6		0.3	0.7	0.4	

Sample number	Q	Location 1	Location 2	Qu	M	P	H	B	Mu	O	N
Porphyritic granite gneiss (cont'd.)											
318-C	A	0.93	1.96	36.1	32.1	27.7	1.1	2.1		0.7	0.2
321-C	A	1.57	0.58	28.8	40.6	27.4		2.8	0.1	0.3	
3-1-W	V	8.57	4.62	30.4	36.8	20.4		4.4	7.9		0.1
3-1-Z	V	8.59	4.83	27.6	30.6	37.1		3.6		0.9	0.2
3-2-W	V	8.52	4.67	33.7	31.1	23.8		4.7	6.6		0.1
3-16-O	V	7.62	4.14	30.9	30.0	35.8		2.7		0.5	0.1
3-26-V	V	7.02	4.59	29.7	37.2	27.6		4.1	0.3	1.0	0.1
4-16-P	V	7.61	5.84	30.8	37.0	27.5		3.8	0.1	0.1	0.7
7-14-T	V	5.58	4.49	30.3	35.9	30.7		2.8		0.1	0.2
8-4-X	V	6.25	6.28	27.4	42.0	27.8		2.1		0.2	0.5
8-7-X	V	6.03	6.30	27.7	44.3	23.8		2.2	0.2	1.7	0.1
8-16-C	V	5.48	5.03	30.4	33.5	30.2		5.3		0.2	0.4
8-22-F	V	5.10	5.23	25.2	42.4	23.9		7.7		0.5	0.3
8-26-C	V	4.83	5.04	27.1	35.7	31.0		5.8	0.2	0.2	
8-32-H	V	4.42	5.31	31.0	29.7	32.1		5.0		1.9	0.3
8-34-G	V	4.35	5.25	27.0	30.6	36.6		4.7		0.3	0.8
10-1-I	V	4.27	2.14	31.3	42.1	22.3		2.2	1.9	0.2	
11-30-D	V	2.42	3.45	39.2	35.4	15.3		0.1	9.2	0.7	0.1
11-33-I	V	2.24	3.78	29.8	29.7	30.7		5.6	2.8	1.4	
12-11-Q	V	3.62	5.91	19.2	47.6	27.0		5.0	0.2	0.6	0.4
12-12-R	V	3.55	5.96	27.2	34.6	35.2		1.9		1.0	0.1
12-20-V	V	3.09	6.21	22.8	41.1	31.4		4.5			0.2
12-23-X	V	2.87	6.36	24.0	31.8	35.7	2.7	5.5		0.1	0.2
15-1-H	V	2.12	3.71	36.4	30.1	29.6		3.3	0.3	0.3	
15-8-I	V	1.67	3.78	35.6	33.5	25.5		3.5	1.2	0.7	
15-14-O	V	1.30	4.14	35.3	21.3	38.3		2.7	1.9	0.2	0.3
15-27-D	V	0.48	3.47	33.6	27.8	34.2		2.2	1.5	0.3	0.4
Potter Hill Granite Gneiss											
CA-1	A	5.51	1.64	29.9	44.8	19.2		2.2	1.5	1.5	0.9
Canal St	A	6.99	2.44	29.5	38.0	25.3		6.1	0.1	1.0	
PH	A	6.06	3.86	34.0	38.4	22.5		3.8	0.4	0.8	0.1
49-1	A	4.77	1.39	35.6	39.1	21.2		1.8	1.4	0.9	
202	A	5.90	3.50	36.1	34.3	28.2		0.8	0.3	0.3	
254	A	7.06	3.31	28.7	25.6	41.1		3.2	1.1	0.3	
270-D	A	5.65	2.53	36.3	46.8	15.2		0.7	0.7	0.3	
272-A	A	4.57	2.06	31.4	45.5	16.8		5.4	0.2	0.7	
276-B	A	4.80	3.55	33.4	25.7	33.5		3.1	3.5	0.8	
277-A	A	5.31	0.03	31.3	43.7	18.9		5.3	0.4	0.3	0.1
278-C	A	4.65	0.99	34.4	38.0	24.5			0.7	2.4	
279-D	A	4.46	1.48	33.2	44.8	20.1			1.2	0.7	
279-J	A	4.12	1.86	35.9	41.4	20.6			1.6	0.5	
286-A	A	4.16	2.59	28.2	47.0	23.1		0.5	0.5	0.7	
287-B	A	3.37	2.23	37.5	41.5	18.0		2.5	0.5		
290-A	A	3.87	4.47	34.0	35.0	22.5		6.5	0.5	1.5	
292-E	A	3.77	5.70	32.5	42.5	22.5		2.0	0.5		
293-A	A	4.46	5.39	32.0	35.5	28.5		2.5		1.5	
302-C	A	2.90	2.78	38.6	28.4	27.2		2.6	2.0	1.2	

Sample number	Q	Location 1	2	Qu	M	P	H	B	Mu	O	N
Potter Hill Granite Gneiss (cont'd.)											
309-B	A	2.34	1.00	27.8	43.9	25.7		1.6	0.7	0.3	
313-A	A	1.50	1.50	33.8	41.8	20.6		2.3	0.6	0.9	
314-A	A	1.61	0.80	35.8	34.1	25.1		4.0	0.7	0.3	
328-B	A	2.08	3.30	30.2	39.9	25.5		3.2	0.3	0.8	0.1
Potter Hill Granite Gneiss, fine-grained facies											
fg	A	8.57	5.88	35.5	37.5	24.0		1.5	1.5		
100	A	7.05	5.00	30.9	43.1	21.7		2.4	1.0	0.9	
104	A	7.14	4.77	33.9	33.8	29.7		0.4	1.5	0.7	
Hope Valley Alaskite Gneiss											
CA-3	A	1.74	6.29	35.7	44.2	18.6		0.2	1.0	0.3	
19	A	8.14	6.44	28.0	36.5	31.4		3.1		1.0	
245.1	A	0.06	6.21	27.9	35.4	32.5		3.8		0.4	
246.5	A	0.22	5.54	36.6	39.6	18.5		2.9	0.2	2.1	0.1
275-B	A	5.09	3.19	37.5	44.5	15.5			1.5	1.0	
281-D	A	3.90	0.85	35.0	38.0	26.5				0.5	
282-C	A	3.77	0.37	32.5	39.0	28.5					
285-C	A	4.74	3.92	40.6	42.7	16.4				0.3	
306-A	A	2.59	2.62	28.1	39.5	30.9		0.1	0.7	0.6	0.1
306-B	A	2.67	2.42	29.0	39.1	29.4		0.3	1.1	1.1	
311-B	A	2.64	1.80	33.3	33.1	32.0			1.2	0.4	
315-D	A	1.48	0.02	44.4	28.5	26.1		0.1	0.2	0.7	
319-C	A	0.35	1.36	32.8	37.8	28.2			0.5	0.7	
319-H	A	0.61	1.66	37.7	32.2	28.4		1.7			
321-D	A	0.88	0.54	34.7	38.3	24.8			1.4	0.7	0.1
322-D	A	0.22	1.35	38.5	33.7	25.8		0.1	0.8	1.1	
325-B	A	0.88	3.42	31.4	44.7	21.1		1.0	1.3	0.4	0.1
326-A	A	1.36	3.65	32.5	40.2	25.5	0.3	1.1		0.1	0.3
329-C	A	0.04	4.30	35.8	32.7	30.1		1.0	0.2	0.2	
331-Z	A	1.95	5.68	40.5	41.8	16.1		1.0	0.5	0.1	
333-A	A	0.90	6.18	33.1	35.5	30.3		0.5	0.2	0.4	
1-23-U	V	7.19	1.32	40.1	28.9	26.5		4.0		0.2	0.2
3-4-Z	V	8.42	4.86	32.1	36.7	27.7		2.6		0.8	0.1
3-26-O	V	6.98	4.16	30.8	46.3	20.8			1.4	0.7	
4-9-H	V	8.10	5.35	29.9	34.9	32.1		2.7			0.4
5-6-B	V	6.12	0.09	34.8	37.8	26.8				0.6	
5-25-A	V	4.92	0.01	37.6	37.7	21.3			3.2	0.2	
7-10-L	V	5.82	3.99	36.8	39.0	17.6		0.2	5.9	0.5	
8-8-U	V	6.00	6.15	29.9	46.7	22.5		0.5		0.2	0.2
10-28-H	V	2.53	2.08	33.7	30.3	33.0		1.9	0.3	0.7	0.1
10-32-Y	V	2.54	3.14	28.8	44.6	22.9		1.9	0.1	1.4	0.3
11-24-K	V	2.32	3.90	33.5	34.4	28.8	0.3	2.0	0.4	0.2	0.4
12-1-U	V	4.29	6.19	21.2	41.3	34.2		3.1		0.1	0.1
14-7-X	V	1.66	3.09	38.5	30.8	29.0		0.3	0.6	0.8	
15-17-V	V	1.51	4.60	31.3	25.6	40.4		0.1	0.2	2.4	

Sample number	Q	Location 1	Location 2	Qu	M	P	H	B	Mu	O	N
Hope Valley Alaskite Gneiss, fine-grained facies											
AHVAF	A	0.06	3.07	28.7	37.0	33.0		0.1	0.2	1.0	
10-10-M	V	3.67	2.40	30.4	42.5	22.8		1.2	1.3	1.8	
11-32-K	V	2.33	3.88	37.9	38.9	21.7		0.6		0.9	
Hope Valley Alaskite Gneiss, white facies											
310-E	A	1.98	1.59	34.8	28.4	35.4			1.2	0.2	
313-B	A	1.67	1.37	30.3	40.1	25.9		0.3	2.3	1.1	
323-D	A	1.59	2.22	41.0	31.4	26.4		0.3	0.6	0.3	
Hope Valley Alaskite Gneiss, fine-grained granite											
1-5-R	V	8.31	1.08	34.4	38.7	24.7		1.1	0.5	0.6	
Scituate Granite Gneiss											
CA-4	V	3.76	4.24	35.5	40.4	21.6	1.5	1.0			
4-15-R	V	7.70	5.95	29.2	39.1	27.0	0.9	3.5		-	0.3
6-6-R	V	6.10	2.72	35.1	35.1	26.5	0.6	2.4	0.3		
7-4-S	V	6.17	4.41	29.7	38.0	26.1		5.5		0.6	0.1
7-23-M	V	5.02	4.09	32.4	38.6	23.8	3.4	1.3		0.2	0.3
7-23-Y	V	5.02	4.82	29.8	38.9	26.2	3.6	0.5		0.5	0.5
11-10-R	V	3.76	4.24	30.6	42.3	22.7	0.5	3.9			
16-15-A	V	1.19	4.91	29.2	33.3	30.1	0.6	4.9	0.4	0.9	0.6
Scituate Granite Gneiss, fine-grained facies											
3-12-M	V	7.86	3.99	28.8	35.1	30.4		5.2	0.4		0.1
Ten Rod Granite Gneiss											
2-12-M	V	7.86	2.41	28.6	32.3	30.4		6.0	1.0	0.9	0.8
2-21-A	V	7.30	1.69	35.0	27.2	31.8		4.6		1.3	0.1
Narragansett Pier Granite											
49	A	8.07	4.53	22.5	49.0	23.5		3.5	0.5	0.5	
160	A	8.13	2.84	27.0	30.0	35.0		5.5	0.5	1.0	
171	A	5.57	5.91	34.0	36.0	25.0			3.0	1.0	
237.4	A	7.84	1.71	31.3	29.7	34.1		2.8	0.6	0.9	0.6
298-B	A	4.88	6.20	25.8	33.4	38.6		0.1	2.1		
Narragansett Pier Granite, white facies											
259-G	A	7.75	0.78	23.5	35.0	38.0		2.0		1.0	
259-H	A	7.75	0.70	27.0	28.0	42.0		2.5			
Westerly Granite											
52	A	8.37	4.47	25.5	29.0	38.5		5.5	0.5	1.0	

Sample number	Q	Location 1	2	Qu	M	P	H	B	Mu	O	N
Westerly Granite (cont'd.)											
169	A	5.37	6.35	28.5	34.0	30.5		4.0	2.0	1.0	
15-10-W	V	1.54	4.66	26.3	33.4	33.7		4.2	1.5	0.1	0.8