# Geology of the Andover Granite and surrounding rocks, Massachusetts

By Robert Oliver Castle

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ABSTRACT OF THE DISSERTATION

Geology of the Andover Granite and surrounding rocks, Massachusetts

by

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Field and petrographic studies of the Andover Granite and surrounding rocks have afforded an opportunity for an explanation of its emplacement and crystallization. The investigation has contributed secondarily to an understanding of the geologic history of southeastern New England, particularly as it is revealed in the Lawrence, Wilmington, South Groveland, and Reading quadrangles of Massachusetts.

The Andover Granite and Sharpners Pond Tonalite together comprise up to 90 percent of the Acadian(?) subalkaline intrusive series cropping out within the area of study. The subalkaline series locally invades a sequence of early to middle Paleozoic and possibly Precambrian metasedimentary and metavolcanic rocks. Much of the subalkaline series and most of the Andover Granite is confined between two prominent east-northeast trending faults or fault systems. The northern fault separates the mildly metamorphosed Middle Silurian(?) Merrimack Group on the north from

a highly metamorphosed and thoroughly intruded Ordovician(?) sequence on the south. The southern "boundary" fault is a major structural discontinuity characterized by penetrative, diffuse shearing over a zone one-half mile or more in width.

The magmatic nature of the Andover Granite is demonstrated by: (1) sharply crosscutting relationships with surrounding rocks; (2) the occurrence of tabular-shaped xenoliths whose long directions parallel the foliation within the granite and whose internal foliation trends at a high angle to that of the granite; (3) continuity with the clearly intrusive Sharpners Pond Tonalite; (4) the compositional uniformity of the granite as contrasted with the compositional diversity of the rocks it invades; (5) its modal and normative correspondence with (a) calculated norms of salic extrusives and (b) that of the ternary ("granite") minimum for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$.

Orogenic granites, as represented by the Andover, contrast with post-orogenic granites, represented locally by the Peabody Granite, in their phase composition and texture. Unlike the Peabody, the Andover Granite is thought to have been thoroughly recrystallized through the unmixing of initially homogeneous phases with the concomitant development of extremely intricate, allotriomorphic textures. Textural relationships between potassium and plagioclase feldspars and among quartz and the two feldspars, suggest that the Andover Granite has evolved through exsolution of a single hypersolvus feldspar (or two coexisting subsolvus feldspars of only slightly disparate compositions) into discrete grains of plagioclase and potassium feldspar, much along the lines proposed by Tuttle (1952).

A hypothesis is proposed for the origin of myrmekite whereby it is evolved indirectly through exsolution of a homogeneous, hypersolvus, calcalkali feldspar in the presence of a silica reservoir. Where the An "molecule" is contained in the primary mix crystal, exsolution into potassium and plagioclase feldspar phases normally requires a paired exchange between Ca-Al and K-Si. Should the silicon requirements of the developing potassium feldspar be met by the matrix silica reservoir, the concomitantly evolving plagioclase may become stoichiometrically enriched in silicon and ultimately develop into myrmekite. Discrete unmixing of pure alkali feldspar proceeds through simple alkali ion exchange; ternary compositions high in An are more apt to fall initially in the two-feldspar field, thereby reducing the unmixing potential. General restriction of myrmekite to plagioclase of calcic albite to oligoclase composition is explained accordingly.

## Introduction

### Scope, geographic situation, field work and acknowledgments

The Andover Granite, which crops out over 90 to 95 square miles of northeastern Massachusetts, is typical of many of the two-feldspar granites associated with orogenic belts throughout the world. Although of moderate size, the Andover pluton is small enough to be examined in relative detail by a single investigator and is thus a suitable subject for the study of the general aspects of formation of orogenic granites. Accordingly, the major objective of this report is a complete description of the granite together with a detailed account of its proposed evolution from primordial to present state.

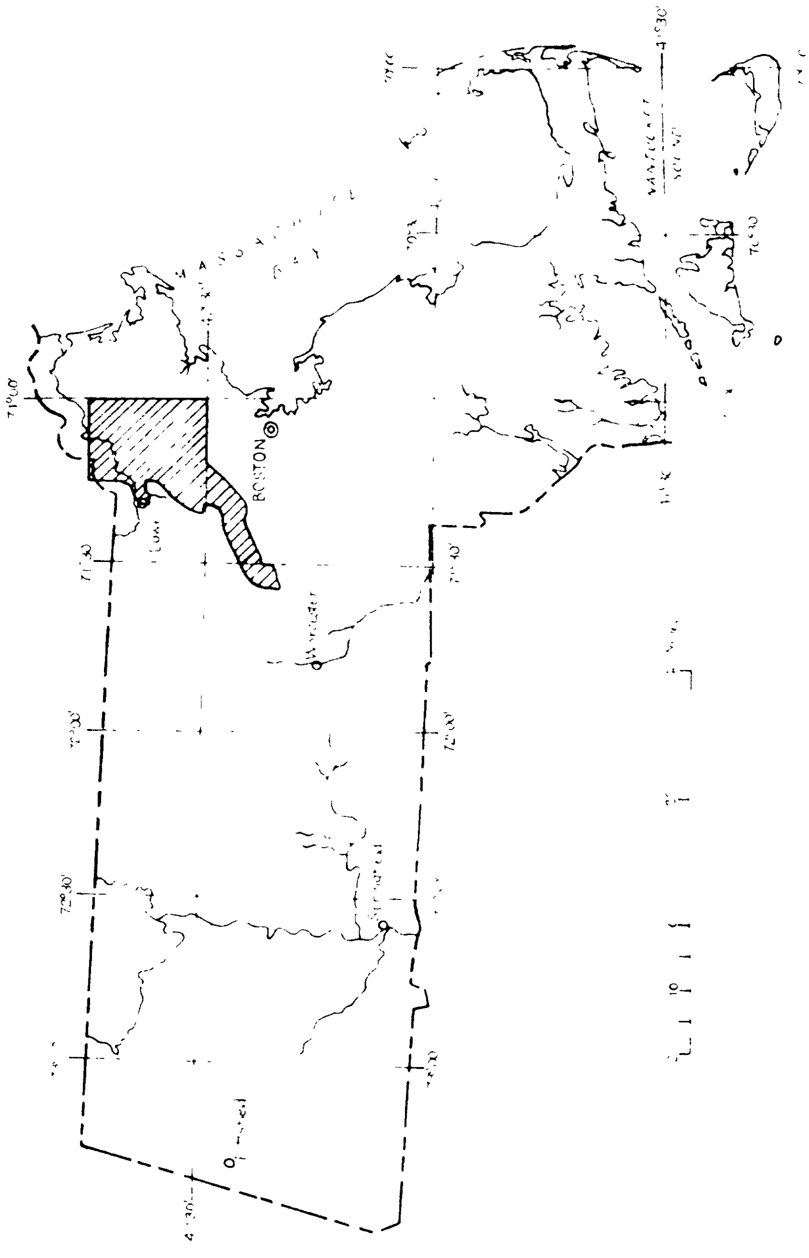
The scope of the report has been extended beyond this main objective, however, to consider the bedrock geology of the Lawrence, Wilmington, South Groveland, and Reading quadrangles (see index map, plate 1) in its entirety. Approximately 60 square miles of the outcrop area of the Andover Granite and about 50 square miles of the outcrop area of rocks believed to belong to the same plutonic series as the Andover, are contained within these quadrangles. For this reason the bedrock geology of these quadrangles has been described fully; in adjacent areas only the Andover and its contact rocks have been considered. As this paper accordingly contains both topical and regional aspects, the following presentation has been designed arbitrarily to conform with that normally adopted in purely areal investigations. The individual bedrock formations are described and discussed in an order that is thought to reflect their relative ages, regardless of their temporal position with respect to the Andover; broader structural features and geometric relationships among the separate bedrock units are considered subsequent to any discussion of the evolution of the rocks themselves.

The investigated area (see figure 1) includes approximately 270 square miles of northeastern Massachusetts and about 2 square miles of southeastern New Hampshire. The northeastern half of the Massachusetts part of the map area is in Essex County, and the remainder is in Middlesex County. The small, mapped section of New Hampshire is split between Rockingham and Hillsboro Counties. Major concentrations of population are found in and around the cities of Lawrence and Lowell and the towns of Reading, Wakefield, and Maynard. The population in general increases progressively toward the south and east (*i.e.*, toward metropolitan Boston). Accessibility is excellent owing to a closely spaced network of roads and railroads. Foot travel, however, is inhibited locally by a dense growth of junglelike scrub brush.

Field work by the writer has been confined chiefly to the Lawrence, Wilmington, South Groveland, and Reading

Figure 1

Index map of Massachusetts showing the area described in this report.


BOSTON

quadrangles and was carried out intermittently between 1951 and 1960. Field work in the remainder of the map area has been carried on by a number of individuals beginning before 1917 and continuing through 1961. Areas of the Andover Granite and surrounding rocks mapped by other workers are detailed on the index map accompanying plate 1.

The described investigation was undertaken as part of a continuing cooperative program between the Massachusetts Department of Public Works and the U. S. Geological Survey. The writer is indebted to M. E. Willard, R. H. Jahns, Priestley Toulmin, III, R. F. Novotny, N. P. Cuppels, J. L. Rosenfeld, W. G. Ernst, K. D. Watson and many other colleagues within and outside the Geological Survey, who have contributed immeasurably to the preparation of this report through discussion and suggestion. The writer is indebted further to R. V. Castle for able assistance in the field.

## Previous work

The rocks of northeastern Massachusetts, particularly those of Essex County, have been studied by several geologists beginning as early as 1833. Hitchcock (1841) described the several major rock types and structural belts of this area, but in only the most general terms. The first more or less comprehensive survey of Essex County was made by Sears (1905). This survey subsequently was complemented in Middlesex County by the work of Laurence LaForge which has been incorporated in Bulletin 597 of the Geological Survey (Emerson, 1917, p. 14). C. H. Clapp (1921) reviewed and refined much of Sears' work in the course of his investigation of the igneous rocks of Essex County. Although thorough for its time, Clapp's study focused primarily on the "alkalic" rocks along the coast and contributed little information on the rocks elsewhere in the county. LaForge (1932) has investigated the geology of metropolitan Boston in some detail, and Bell (1948) has remapped the same area in still greater detail. W. R. Hansen (1956) has studied the geology of the Hudson and Maynard quadrangles in western Middlesex County, and parts of his work have been incorporated directly in this report.

## Physiographic setting

The physiography of this part of New England is characterized by moderate to low relief. Within the map area a maximum relief of about 580 feet exists between the highest point at an elevation of about 590 feet in the town of Marlboro, and the lowest point at less than 10 feet in the town of Haverhill. The average relief, however, generally does not exceed 200 feet. One-half to two-thirds of the area is within the drainage basin of the Merrimack River which flows generally northeastward; remaining drainage is divided among the basins of the Ipswich, Saugus, and Aberjona Rivers. A large part of the flow of these smaller rivers is through swamp, and the major streams are little more than channels of very low gradient connecting individual swamps.

The pre-Pleistocene drainage pattern, controlled by the generally northeast-trending bedrock structure, was modified in Pleistocene time by continental glaciers that scoured and removed much weathered bedrock and subsequently redeposited this material as glacial drift. Advance of the ice sheet from the north-northwest produced a topographic "grain" that, together with irregular deposition of melt water deposits, now obscures the previously developed subsequent drainage pattern. The drift cover averages 15 to 20 feet in thickness and locally exceeds 100 feet. The mantle of glacial debris is relatively thick and continuous in the northern part of the area, and bedrock exposures here are sparse. Bedrock exposure in the area as a whole probably is less than one-half percent.

## General features of the bedrock geology

The bedrock of northeastern Massachusetts and southeastern New Hampshire consists of a complex group of metasedimentary, metavolcanic, and igneous rocks. The metasedimentary and metavolcanic formations are characterized by considerable compositional heterogeneity, whereas the igneous rock units commonly manifest profoundly contrasting fabrics, but tend to be more uniform in composition. Metamorphism ranges from chlorite through sillimanite grade, and it is likely that it has been complicated locally by metasomatism. Deformation of the metasedimentary and metavolcanic rocks, and to a lesser degree the igneous rocks, has been moderate to intense.

Owing in part to metamorphism few fossils have been found in the stratified rocks of this section of New England, and the ages of the rocks are poorly known. Relative ages among the several broad groups of stratified rocks are known, but those between individual formations or members generally have been obscured by deformation, extensive igneous invasion, or the locally thick drift mantle. The metavolcanic and metasedimentary units may range from Precambrian to Carboniferous in age. On the other hand, this range in age may be bracketed between Ordovician and Lower Devonian. There are no thoroughly satisfactory ties as yet with most of the local metasedimentary rocks and Upper

Silurian rocks to the east or Carboniferous(?) rocks to the west.

Radiometric age determinations coupled with a few definitive field relationships, suggest that all the igneous rocks, except for a few diabase dikes and a small mass of serpentinite, are of middle to late Paleozoic age. Geologic mapping indicates that these same plutonic rocks belong to at least two and perhaps four or five magmatic series. Relative ages among the several magmatic series and their individual members have been established chiefly on the basis of field relationships existing among themselves, and doubt remains regarding the chronology of their emplacement.

## Gneisses of undetermined origin and age

### Fish Brook Gneiss

The Fish Brook Geniss is here named for an irregularly shaped gneiss body cropping out along Fish Brook, Boxford in the southeast quarter of the South Groveland quadrangle (Castle, in review). It is well exposed west of the quadrangle boundary where it occupies about 4 or 5 square miles of the map area. At least part of the Fish Brook Gneiss is shown on Emerson's map of Massachusetts and Rhode Island (see plate 2) as Andover Granite, and the remainder appears as either Marlboro Formation or Salem Gabbro-Diorite.

The typical Fish Brook Geniss is a pearly-white to very light-gray, distinctly foliated, but generally unlayered biotite-quartz-plagioclase gneiss. The apparent foliation is gently undulate to crenulate and is manifested chiefly by oriented biotite flakes. The internal structure is only locally conformable with that of the adjacent Boxford Formation, and the foliation is at an angle of 50-60$^{o}$ with the long axis of the gneiss body itself. The texture is fine to medium grained and granoblastic to hypidioblastic.

Plagioclase composes up to 55 percent of the gneiss. It ranges in composition from $An_6$ to $An_{32}$ and averages about $An_{25}$. Quartz is the other major mineral present and composes up to at least 40 percent of the rock. Biotite or its chloritic derivative is most prominently developed in the northern half of the formation, where it composes up to 10 percent of the gneiss. Biotite becomes progressively less conspicuous toward the south and in some exposures makes up less than 1 or 2 percent of the rock. As a consequence of this southerly diminution of biotite the foliation locally is almost unrecognizable. Still other varietal and accessory minerals in the gneiss are hornblende, epidote, muscovite, apatite, zircon, magnetite, and, locally, microcline. Modal analyses are given in table 1; a chemical analysis and norm are presented in table 2.

Blocks of amphibolite and thinly layered biotite gneiss commonly are included in the Fish Brook Gneiss, particularly along its northern edge. All of the inclusions contained within the gneiss are rock types common to the adjacent Boxford Formation. Most of the inclusions measure from a few inches to several feet in length and are generally irregularly shaped; a few occur as small rectangular blocks (fig. 2A). The foliation in the surrounding gneiss is characteristically continuous with that of the inclusions, but locally, as in figure 2A, it gently wraps around the edges of the blocks. Contacts between the inclusions and the surrounding gneiss are generally sharp. In several places, however, the gneiss contains abundant, small

Table 1. Modal analyses of rocks from the Fish Brook Gneiss 1/

| | A. | B. | C. |
|---|---|---|---|
| Quartz | 32.9 | 39.6 | 39.7 |
| Plagioclase | 54.0 | 53.0 | 54.1 |
| Microcline | | 5.8 | tr. |
| Hornblende | 1.6 | | .7 |
| Biotite | 9.8 | | 4.1 |
| Chlorite | .2 | 1.0 | .1 |
| White mica | .7 | | |
| Epidote | .2 | .1 | .4 |
| Apatite | .3 | | .1 |
| Opaque | .3 | .2 | .8 |

A(C-9). Biotite gneiss 300 ft. S60°E of Towne Rd.-Main Street intersection, Boxford. Points counted: 1000. Plagioclase composition $An_{33 \pm 4}$

B(G-668). Quartz-plagioclase gneiss 3300 ft. N54°W of intersection of Boxford-Middleton-North Andover town lines, North Andover. Points counted: 500. Plagioclase composition undetermined

C(G-321). Biotite gneiss 1700 ft. N29°E of Lawrence Rd.-Main Street intersection, Boxford. Points counted: 1000. Plagioclase composition $An_{23 \pm 4}$

1/ All figures volume percent

Table 2. Chemical analysis, norm, and modal analysis of biotite gneiss from the Fish Brook Gneiss[1/]

Chemical analysis [2/] [3/]

| | |
|---|---|
| $SiO_2$ | 70.6 |
| $Al_2O_3$ | 14.3 |
| $Fe_2O_3$ | 1.2 |
| FeO | 3.0 |
| MgO | .78 |
| CaO | 3.8 |
| $Na_2O$ | 3.8 |
| $K_2O$ | .99 |
| $TiO_2$ | .32 |
| $P_2O_5$ | .08 |
| MnO | .08 |
| $H_2O$ | .76 |
| $CO_2$ | .06 |
| Sum | 100 |

Table 2. (cont.)

Norm[3/]

| | |
|---|---|
| Quartz | 34.62 |
| Corundum | .92 |
| Orthoclase | 6.11 |
| Albite | 32.50 |
| Anorthite | 16.41 |
| Enstatite | 2.01 |
| Ferrosilite | 4.09 |
| Magnetite | 1.85 |
| Ilmenite | .61 |
| Apatite | .34 |
| Calcite | .10 |
| Sum | 99.56 |

Table 2. (cont.)

Modal analysis4/

| | |
|---|---|
| Quartz | 32.9 |
| Plagioclase | 54.0 |
| Hornblende | 1.6 |
| Biotite | 9.8 |
| Chlorite | .2 |
| White mica | .7 |
| Epidote | .2 |
| Apatite | .3 |
| Opaque | .3 |

1/ (C-9). Biotite gneiss 300 ft. S60°E of Towne Rd.-Main Street intersection, Boxford. Points counted: 1000. Plagioclase composition $An_{33\pm4}$

2/ U. S. Geological Survey Rapid Rock Analysis Laboratory

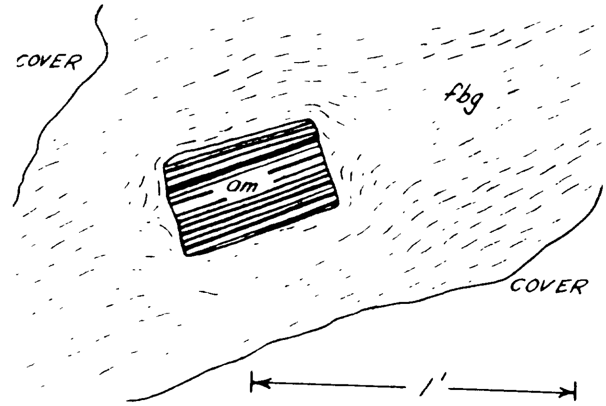
3/ All figures weight percent

4/ All figures volume percent

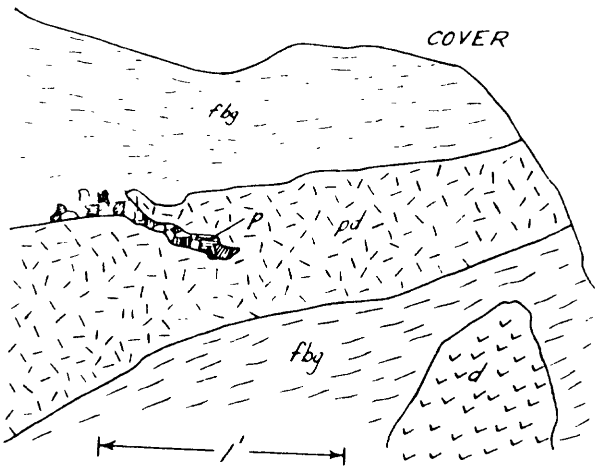
Figure 2

A. Diagrammatic sketch of exposure of the Fish Brook Gneiss (fbg) approximately .4 mile south of Towne Rd.-Main St. intersection, Boxford. Note that the foliation in the gneiss apparently "flows" around the included block of amphibolitic gneiss (am).

B. Diagrammatic sketch of exposure of the Fish Brook Gneiss (fbg) about 4000 feet north-northeast of the summit of Bald Hill, Boxford. The gneiss apparently is intruded by both a fine-grained diorite(?) porphyry (pd) and a medium-grained diorite (d), both of which presumably are related to the Sharpners Pond Tonalite. Note also the small, fine-grained pegmatite (p) apophysis apparently intruding the diorite porphyry.




A




B

schlierenlike plates of amphibolite in gradational contact with the gneiss.

As is true of most of the older units of this area, the Fish Brook Gneiss has been extensively invaded by later igneous rocks. Pegmatite veins or dikes are common and several small, fine-grained, porphyritic, relatively mafic dikes were seen locally. Diorite and tonalite of the Sharpners Pond Tonalite intrude the surrounding area and presumably intrude the Fish Brook Gneiss, but rocks typical of this igneous unit rarely were seen crosscutting the gneiss in individual outcrops. It is probable, however, that the porphyritic dikes alluded to above may represent a border facies of the Sharpners Pond.

A diffuse, unmapped zone of very coarse-grained biotite granite(?) and pegmatite occurs along the northern edge of the Fish Brook Gneiss, near its contact with the Boxford Formation. Rocks from this zone were not studied microscopically, but they appear to be compositionally similar to those occurring elsewhere in the Fish Brook Gneiss. Both granite and pegmatite, however, may contain notably higher proportions of potassium feldspar. The granite is generally massive, but here and there a faint lamellar structure is detectable, and uniformly oriented fragments of the Fish Brook Gneiss are included locally. Toward the south and east the granite is transitional with and merges imperceptibly into the typical Fish Brook. This same phenomenon has been observed elsewhere on a smaller scale. Figure 2B shows a small pegmatite apophysis in sharp contact with an adjacent diorite porphyry, but in apparently transitional contact with the Fish Brook Gneiss from which it appears to have developed.

The origin of the Fish Brook Gneiss remains an enigma. It is either (1) an intrusive igneous rock or (2) a highly metamorphosed, partially fused and metasomatized "core" or "dome" gneiss of either sedimentary or (less likely) igneous ancestry.

Although the gross chemical and mineralogical composition of the gneiss corresponds with that of known intrusive rocks that occur to the south (specifically, the biotite tonalite facies of the Sharpners Pond Tonalite; see tables 1, 2, 18 and 19), a simple intrusive origin is considered unlikely for the following reasons: (1) the foliation is extremely well developed and transects rather than conforms with the outer margin of the gneiss body, as would be more likely were it an intrusive; (2) the body itself is elongated at a high angle to the foliation; (3) the quartz content in some of the specimens examined is abnormally high for an igneous rock. It is possible, however, as suggested by L. R. Page (1962, written communication), that the foliation at least may be attributable to post-intrusion tectonism. If this is the proper interpretation there should be a general correspondence between the pattern of foliation developed in the Fish Brook Gneiss and that developed in adjacent and presumably older metamorphic rocks. There is a vague structural conformity between parts of the Fish Brook and the adjacent Boxford Formation, but toward the intersection of Brookview Road and Lawrence Road in Boxford, the foliation in the separate formations is almost at right angles.

A second general hypothesis would explain the Fish Brook Gneiss as a "core" or "dome" gneiss, similar to those of western New England. According to this interpretation the Fish Brook is a unit of considerable antiquity, subjected perhaps to a pre-Boxford metamorphism, and unconformably overlain by the onlapped Boxford Formation. This hypothesis could account for the partly discordant relationships between the Fish Brook and its boundary, and by the same token explain the crude conformity between the Fish Brook-Boxford contact and the internal structure of adjacent parts of the Boxford Formation. Moreover, the locally conspicuous foliation might then be dismissed as a palimpsest feature. Needless to say, this theory would not provide in itself an explanation for the amphibolitic inclusions of the type illustrated in figure 2A. However, the pervasive presence of diffuse patches of pegmatitic and granitic rocks within the Fish Brook suggests that the gneiss was subjected to local palingenesis. Thus the inclusions might prove boudin-like features infolded and retained in a host that was at one time highly plastic if not actually molten.

If the Fish Brook Gneiss is an intrusive rock it is probably no older than Taconic (late Ordovician), for the Boxford Formation is probably Ordovician or somewhat older (see section on correlation and age of the Boxford Formation, this report). As it in turn is intruded by the Sharpners Pond Tonalite of probable Devonian or Carboniferous age, it should be no younger than Devonian or Early Carboniferous. Should the Fish Brook prove to be a dome gneiss it is probably at least pre-Taconic. Thus it may be correlative with the Northbridge Granite-Gneiss or Sterling Gneiss of Precambrian or early Paleozoic age (see Emerson, 1917, p. 155-156; Rodgers _et al._, 1956, p. 57-58; Moorbath _et al._, 1962, p. 7).

## Unnamed gneiss in the Reading quadrangle

An irregularly shaped gneiss body, completely surrounded by igneous rocks, occurs along the northern edge of the Reading quadrangle. This gneissic unit trends roughly east-west, is just short of 2 miles in length and is approximately 1 mile in width. The gneiss has been intruded extensively by a variety of igneous rocks including diorite, tonalite, granite, and pegmatite, and scarcely an exposure was seen in which there was no evidence of intrusion or replacement. The unnamed gneiss exposed along Forrest Street, Middleton and near Stearns Pond, North Andover is similar to the Fish Brook Gneiss, and the two are probably correlative. However, owing to its isolated situation the unnamed gneiss is considered separately here.

### Amphibolite

Amphibolite or plagioclase amphibolite composes from 10 to 15 percent of the unnamed gneiss; it has been delineated separately where it is the most conspicuous rock over a mappable area. The amphibolites are prominently foliated, commonly thinly layered, and generally possess a fine- to medium-grained hypidioblastic texture. Those exposed near the military police camp in Andover are very fine grained and almost perfectly foliated. They are, moreover, identical in appearance to many of the amphibolites that occur in the upper member of the adjacent Boxford Formation, and may prove to be infolded correlatives of this unit. Elsewhere the amphibolites are somewhat coarser grained than those characteristic of the upper member of the Boxford. Common hornblende is the most prominent constituent of the amphibolite; it is accompanied by varying amounts of plagioclase, quartz, and biotite.

### Undifferentiated gneiss

The undifferentiated facies of the unnamed gneiss is composed chiefly of foliated and locally layered biotite-plagioclase-quartz gneiss. The foliation is almost everywhere moderately undulate to crenulate, and in some outcrops it is highly contorted (pl. 3). The texture of the biotite gneiss is typically medium grained and granoblastic to porphyroblastic. Quartz is one of the two major phases present and composes up to 50 percent of the rock. It occurs as discrete grains and as porphyroblastic inclusions in plagioclase. The plagioclase in the two specimens of the biotite gneiss examined petrographically was median oligoclase in composition and composed from 40 to 45 percent of the sample. Biotite, which is the only mineral present possessing an apparent preferred orientation, composes from 6 to 10 percent of the gneiss. The gneiss contains in addition accessory amounts of apatite, magnetite, and zircon.

The origin and age of the unnamed gneiss are presumably comparable with the origin and age of the Fish Brook Gneiss. However, there is a remote possibility suggested by the pervasive intrusion and lithologic heterogeneity of the gneiss, that it was derived through profound metasomatism of the nearby Boxford Formation.

## Rocks of pre-Late Silurian age

### Ordovician(?) rocks

Most of the metasedimentary and metavolcanic rocks exposed southeast of a line projecting through the cities of Lowell and Lawrence are thought to be Ordovician.

Plate 3

ighly contorted unnamed gneiss cropping out approximately 600 feet east of Forrest t.-Marblehead St. intersection, Middleton.

Establishment of the geologic age of these rocks is based chiefly on their tentative correlation with rocks of Ordovician age in New Hampshire and the probable Silurian age of the overlying Merrimack Group. Elsewhere the series described below is believed to form a continuous sequence, but faulting may have destroyed the continuity and removed part of the section in this area. Stratigraphic relationships among the several formations included in this series are obscure, but the separate units probably are in part transitional along the strike. All of the presumably Ordovician rocks have been intensely folded and deformed. Metamorphism ranges from the greenschist to the amphibolite facies and the entire series has been extensively intruded by both mafic and felsic igneous rocks.

At least one formation within the Ordovician(?) series has been intruded by a serpentinite. The age of the serpentinite body is unknown, but it is provisionally assigned to the Ordovician, for ultramafics are unknown in Silurian or younger rocks in New England.

### Westboro-type quartzite

The name Westboro Quartzite was first applied by Perry and Emerson (1903, p. 155) to a band of quartzite extending through the towns of Webster, Oxford, Sutton, Grafton and Westboro, Massachusetts. Emerson (1917, p. 30) subsequently suggested that the term Westboro Quartzite be employed for "all areas in which quartzite was sufficiently preponderant to give character and a name to the mass as a whole." Emerson was not specific, but he apparently intended that this usage be restricted to those belts he believed to be composed of Precambrian rocks. Following Emerson's usage, the unit described below should be regarded at least as Westboro-type, even though it is a questionable stratigraphic correlative of the type formation.

In this area the Westboro-type quartzite occurs entirely within the Reading quadrangle where it forms a lenslike band up to one-half mile in width and approximately 2 miles in length. The quartzite here has been extensively intruded by several generations of igneous rocks, and exposures are very poor. However, within the area shown as Westboro-type quartzite, quartzite is the only non-igneous rock exposed.

In hand specimen the quartzite is almost white to very light greenish gray. Most of the formation consists of fine- to very fine-grained granoblastic material that shows a massive to faintly foliated structure; it is one of the very few units within the map area in which bedding may be unambiguously recognized.

The bulk of the Westboro-type quartzite is relatively pure and generally contains in excess of 90 percent quartz. Albitic plagioclase, chlorite, and tremolite-actinolite are present in small amounts. The formation locally consists of less pure quartzite that contains up to 10 percent micaceous minerals, including both chlorite and sericite. It is in the relatively mica-rich zones that the quartzite loses its massive character and becomes thinly but faintly laminated. An approximate mode of a specimen from the more micaceous facies is presented in table 3.

Emerson (1917, p. 24) concluded that the Westboro Quartzite represents a shoreward sedimentary facies, a view with which the writer is inclined to concur. But whether or not a shoreward facies is indicated, the purity of the quartzite exposed here suggests that it was a mature sediment derived from a surface of low relief or considerably removed from its source.

The Westboro-type quartzite obviously has been thoroughly recrystallized, but it is difficult to estimate the maximum metamorphic grade attained owing to the purity of the rock. The coexistence of albite, chlorite and tremolite-actinolite suggests that all or most of the formation has been subjected to regional metamorphism at least as high as the quartz-albite-muscovite-chlorite subfacies of the greenschist facies (Fyfe, Turner, and Verhoogen, 1958, p. 219-222).

The correlation and age of the Westboro-type quartzite are discussed in a subsequent section.

Table 3. Estimated mode of rock from the Westboro-type quartzite[1/]

| | |
|---|---|
| Quartz | 85 |
| Plagioclase | 4 |
| Tremolite-actinolite | 4 |
| Chlorite | 5 |
| Epidote | 1 |
| Opaque | 1 |

1/ (R-172). Quartzite 1100 ft. northwest of Chestnut St.-Main St. intersection, Lynnfield

## Marlboro Formation

A wide band of dull-black biotite schist and hornblende schist, prominently developed in the town of Marlboro, has been named the Marlboro Formation by Emerson (1917, p. 25). Hansen (1956, p. 8) has described the Marlboro Formation immediately northeast of Marlboro as "predominantly a fine-grained medium gray to dull-olive-gray amphibolite schist", with locally developed "brownish arenaceous beds, intercalated with amphibolite, and containing small amounts of biotite and muscovite, and beds of white or cream-colored quartzite." The Marlboro Formation cropping out in the area described here includes most of the above rock types plus several others apparently unexposed at or near the type locality.

Within the map area (pl. 1) the Marlboro Formation occurs: (1) in contact with much of the Andover Granite along the south side of its southwestern extension; (2) as a broad, east-northeast trending belt extending from the southern border of the Wilmington quadrangle through the south-central part of the Reading quadrangle. The formation is well exposed in the towns of Marlboro, Maynard, Concord, Burlington, and Wilmington, and in the area north of Reading center. Elsewhere, particularly in the area from Cedar Swamp to the eastern border of the Reading quadrangle, it is poorly exposed.

The Marlboro Formation is differentiated here into the following units: (1) the B member of the Marlboro Formation; (2) the porphyroblastic gneiss member; (3) the A member of the Marlboro Formation embracing amphibolite, quartzite, and undifferentiated facies. The A and B members locally grade into each other transitionally across (and perhaps along) the strike; the porphyroblastic gneiss member may be intercalated more or less between the A and B members. Particular facies of the A member have been delineated only where they form conspicuous lithologies; these separately mapped facies grade irregularly in and out along the strike and do not necessarily have stratigraphic significance. Delineation of units within the Marlboro Formation has been based chiefly on field observation, and the positions of boundaries between units are highly inferential.

The outcrop belt of the Marlboro Formation within the map area has a maximum width of about 2.5 miles. This figure has little significance in terms of original stratigraphic thickness, however, owing to structural complexities and the fact that the outcrop belt here is bounded on both sides by broad expanses of igneous rocks.

B member

The B member of the Marlboro Formation is most conspicuously exposed in the towns of Woburn and Burlington in the Wilmington quadrangle, where its outcrop area is wedge-shaped and pinches out to the northeast. It is characterized by the prominence of fine- to coarse-grained, distinctly laminated, quartzo-feldspathic gneiss (see plate 4A). Quartzite and amphibolite also are exposed within the B member, but they are apparently subordinate to the gneiss. The entire unit is transitional with the rest of the Marlboro Formation and the precise division between A and B members is arbitrary.

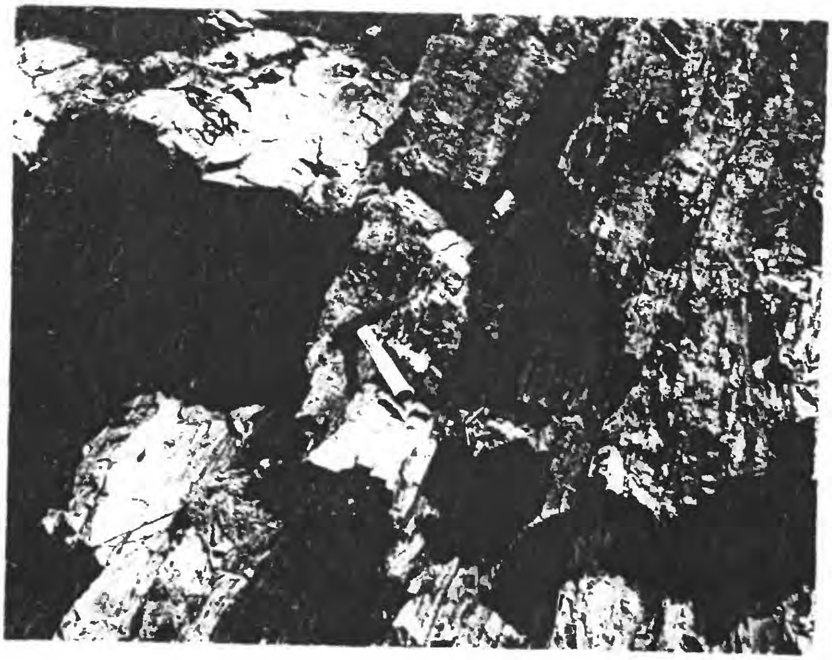
The color of the gneiss ranges from very light gray to almost black; light- to medium-gray varieties predominate. White and pink layers of granitic composition, texturally similar to the other gneissic rocks, occur locally. Individual gneissic layers range in thickness from a small fraction of an inch to many feet and, in the case of the thicker layers, commonly continue along the strike at least tens of feet. The very thin layers generally are discontinuous and persist over a distance of only a few inches. The thicker layers commonly comprise a sequence of regularly alternating thinner layers that serve to define the coarser units. In general the layering and foliation are almost perfectly conformable with the foliation in the rocks of the adjacent A member.

The textures of the B member of the Marlboro Formation are very distinctive and provide one of the bases for distinguishing these rocks in the field. They are characterized by a fine- to medium-grained xenoblastic mosaic within

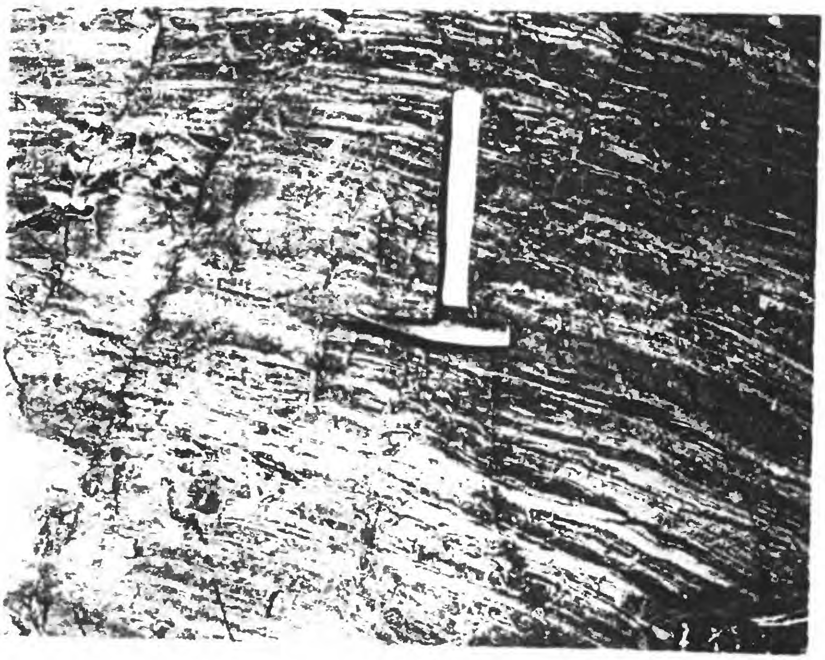
Plate 4

A. Quartz-feldspar gneiss exposed in the transition zone between the A and B members of the Marlboro Formation along Main St., near Woburn-Wilmington town line, Wilmington. Rocks exposed here are typical of the B member, although they actually occur in an area mapped with the A member. Small, white, pea-size lenses are rounded feldspar grains enclosed in a fine-grained groundmass of quartz, feldspar, and mica.

B. Outcrop of the undifferentiated A member of the Marlboro Formation approximately 2500 feet north-northwest of northern tip of Mishawum Lake, Woburn. The Marlboro Formation here is composed chiefly of plagioclase amphibolite in which the plagioclase-hornblende ratio ranges widely from layer to layer.



A



B

which there commonly occur rounded or elliptical feldspar grains up to about 1 cm. in length. The larger feldspar crystals commonly are fractured and locally manifest strong strain shadows. Quartz grains tend to be flat, average 0.05 to 0.10 mm. in length, and are nowhere longer than about 1 mm. The quartz grains also commonly show a pronounced preferred orientation of their c-axes, and where they are large enough for clear definition under the microscope they are relatively free from apparent strain. Grain boundaries, particularly quartz-quartz boundaries, are moderately to intricately convoluted, and mortar structure is prominent. Lenticles of fine-grained mica or quartz characteristically wrap around the generally coarser feldspar grains, imparting an undulatory appearance to the rock. A megascopic aspect of these textures is illustrated by the photograph in plate 4A, whereas textural details are best shown by reference to the photomicrographs in plates 9, 10, 11A, and 16. An interpretation of these textures is integrated with a discussion of the textures in the Marlboro Formation as a whole.

The gneissic rocks of the B member are composed primarily of quartz and feldspar, but there is a wide compositional range within these limits (see table 4). Quartz is common to virtually all the gneiss, but its content ranges widely from 15 to more than 50 percent. The potassium feldspar-plagioclase feldspar ratio is another prominent

Table 4. Estimated modes of rocks from the Marlboro Formation.

| | B member | Transition zone | | | A member | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I |
| Quartz | 15 | 40 | 50 | 8 | 5 | 2 | | 40 | 25 |
| Plagioclase | 55 | 10 | 10 | 38 | 20 | 39 | 35 | 15 | 48 |
| Microcline | | 37 | 10 | | | | | | |
| Hornblende | 8 | | | 38 | 40 | 55 | 52 | | |
| Actinolite | | | 3 | | | | | | |
| Biotite | 7 | | 10 | | 15 | | | | |
| Chlorite | | | | 2 | 5 | | 2 | 23 | 10 |
| White mica | 4 | 7 | 10 | 4 | 5 | | 3 | 8 | |
| Epidote | 4 | 5 | 3 | 3 | | | 2 | 7 | 10 |
| Apatite | 2 | | | | | tr. | | | |
| Sphene | 2 | | 2 | | 6 | 3 | 4 | | |
| Carbonate | | | 1 | 7 | | | | 1 | 7 |
| Opaque | 3 | 1 | | | 4 | 1 | 2 | 6 | 2 |

A(W-1237). Gneiss of tonalitic composition from B member of the Marlboro Formation 2800 ft. east of St. Marys Mission, Burlington

B(W-1233). Quartz-feldspar gneiss from transition zone between A and B members of the Marlboro Formation, 1200 ft. west-northwest of summit of Peach Orchard Hill, Burlington. Specimen taken from outcrop within what is mapped as A member

Table 4. (cont.)

C(W-488). Mica-feldspar-quartz gneiss or schist from transition zone between A and B members of the Marlboro Formation, along Main St., Wilmington, 450 ft. north of Woburn-Wilmington town line. Specimen taken from outcrop within what is mapped as A member

D(W-488). Plagioclase amphibolite from transition zone between A and B members of the Marlboro Formation along Main St., Wilmington, 450 ft. north of Woburn-Wilmington town line. Specimen taken from outcrop within what is mapped as A member

E(W-1213). Biotite-plagioclase-hornblende schist from amphibolite unit of the A member of the Marlboro Formation, 1500 ft. north of Mill Pond in Wilmington

F(W-1228). Amphibolite from amphibolite unit of the A member of the Marlboro Formation, 2400 ft. northwest of summit of Peach Orchard Hill, Burlington

G(W-1221). Amphibolite from amphibolite unit of the A member of the Marlboro Formation, 2500 ft. north-northwest of intersection of Woburn-Wilmington-Burlington town lines

H(R-134). Thinly layered, aphanitic, chloritic-quartzose rock from the A member of the Marlboro Formation, one-half mile northeast of Uptons Hill, Peabody

Table 4. (cont.)

I(R-315). Thinly layered, aphanitic, chloritic-feldspathic rock from the A member of the Marlboro Formation, 1800 ft. southwest of Franklin St.-Main St. intersection, Reading variable, ranging from 0 to more than 1. Biotite, muscovite, actinolite, sphene, and calcite are common accessory minerals, and garnet and apatite are less common accessories. Many layers within the B member have the mineral composition of granite or adamellite and consist of quartz, microcline, relatively sodic plagioclase ($An_{10}$-$An_{25}$), and accessory amounts of biotite, muscovite, and epidote. Other gneissic layers are essentially tonalitic in composition (see table 1) and are composed chiefly of quartz, plagioclase (sodic andesine), hornblende, and biotite, with little if any potassium feldspar.

The compositions of the gneissic rocks of the B member indicate that they were derived from a series of impure arenaceous sediments, locally admixed, perhaps, with igneous rocks ranging from rhyolite or granite to dacite or tonalite. The quartz-plagioclase-microcline-muscovite-biotite assemblages characteristic of the quartzo-feldspathic gneisses suggest a maximum metamorphic grade compatible with the staurolite-quartz subfacies of the almandine amphibolite facies (Fyfe, Turner, and Verhoogen, 1958, p. 228-229). Retrogressive effects include the development of chlorite in and around biotite, sericitization and saussuritization of feldspar, and the development of actinolite.

The quartzites and amphibolites exposed within the B member are indistinguishable from and are described with those of the A member.

## Porphyroblastic gneiss member

The presence of the porphyroblastic gneiss member in this area is inferred from its distribution in the Salem quadrangle (Toulmin, 1958, written communication) and the discovery by Toulmin of a single exposure of this unit in the Reading quadrangle. Owing to its limited exposure in this area Toulmin has supplied the writer with the following description of the porphyroblastic gneiss member as it occurs in the Salem quadrangle.

"This series of rock crops out in a northeast trending belt about one mile wide. Foliation and compositional banding strike northeast and dip northwest generally more steeply than 45°. The series consists of interbanded plagioclase amphibolite and feldspar-quartz-biotite gneiss with porphyroblasts of microcline and more rarely of plagioclase. Bands of contrasting lithology are even and regular in many outcrops; alternate bands may be of plagioclase amphibolites and gneiss, or may be gneisses with different proportions of minerals. The proportions of porphyroblasts in the gneiss vary widely. Bands are from 1 or 2 inches to several feet thick.

"The porphyroblasts in the gneiss range from about 3 mm to a centimeter or more in greatest dimension; they are characteristically subhedral or euhedral, though some are of approximately elliptical cross section. Visible foliation results principally from parallel orientation of biotite crystals and is parallel to compositional banding where both features are present.

"The plagioclase amphibolite is a medium-grained rock composed of approximately equal amounts of hornblende and plagioclase. Some outcrops show a well-developed foliation, but many are apparently without oriented fabric; the non-foliated rocks are not easily distinguished in hand specimen from diorite."

The single exposure of the porphyroblastic gneiss in this area occurs along Norris Brook, approximately one-half mile north of Crystal Pond. This exposure consists of prominently, though irregularly foliated amphibolitic schist in conformable contact with a massive plagioclase-hornblende rock, indistinguishable from locally occurring diorite, but within which Toulmin has discovered a band of porphyroblastic gneiss.

Toulmin (1961, written communication) has concluded that the "distinctly bedded structure of the (porphyroblastic) gneiss indicates a sedimentary or pyroclastic origin." He favors a pyroclastic origin "because of the relatively small amount of quartz and the association with plagioclase amphibolite believed to be of volcanic origin." Rocks within the porphyroblastic gneiss member may have attained a higher metamorphic grade than any of the other rocks of the Marlboro Formation in this area, for according to Toulmin (1957, oral communication) this unit contains pyroxene-plagioclase assemblages indicative of the granulite facies.

## A member

The A member of the Marlboro Formation contains a variety of lithologic types including amphibolite, quartzite, calc-silicate rock, impure quartz schist or gneiss, and biotite-hornblende schist. A measure of the compositional heterogeneity of this unit is provided by the estimated modes presented in table 4. The rocks of the A member are interfingered and transitional with the B member of the Marlboro Formation, but their relationship to the porphyroblastic gneiss member is unknown.

### Amphibolite

Amphibolite units of the Marlboro Formation have been mapped in the Concord, Wilmington, and Reading quadrangles. Within the separately mapped amphibolite units amphibolite or plagioclase amphibolite is predominant, almost to the exclusion of other rock types common to the A member. The amphibolite commonly is intercalated with layers of biotite-hornblende schist and contacts between amphibolite and adjacent units of the Marlboro are generally gradational. Amphibolite has been delineated only where it can be clearly recognized and conveniently mapped, but similar rocks are common to the undifferentiated A member of the Marlboro

Formation.

The amphibolites are generally dark gray to black, schistose, and commonly similar in appearance to the plagioclase amphibolite shown in plate 4B. A poorly defined layering is present in most of the amphibolites, where it is a reflection of either textural variation or compositional alternation. The textures are characteristically fine to very fine grained and hypidioblastic to xenoblastic; they are illustrated in plates 6B and 12B. Preferred orientations of amphibole needles were observed in a few exposures but they are difficult to measure owing to the generally fine-grained nature of the rock.

Common hornblende is the most prominent constituent of these rocks, ranging up to 65 percent by volume. The very fine-grained amphibolites in the central and eastern part of the Reading quadrangle in general are richer in hornblende than those exposed in and around the town of Burlington. Plagioclase is the most important of the lesser constituents and locally composes up to 55 or 60 percent of the rock. The plagioclase composition ranges from approximately $An_5$ to $An_{45}$ and averages about $An_{30}$. Epidote or zoisite, sericite, magnetite, calcite, chlorite, and sphene occur in accessory amounts. Epidote is a common secondary mineral and locally forms irregular veins crosscutting the schistosity. Calcite, which occurs both as small disseminated blebs and as crosscutting veins, is a generally minor phase but locally composes up to 7 percent of the rock.

The amphibolites are the metamorphic products of either impure limy siliceous sediments or andesitic to basaltic volcanics. It is possible that both metasediments and metavolcanics are presently manifested as amphibolite, but useful criteria for establishing the origin of any particular amphibolite are extremely limited. Primary textures and structures, for example, are generally lacking not only in the amphibolite, but throughout the Marlboro Formation east of the Lincoln-Lexington town line. Secondary calcite occurs commonly in the amphibolite, and Emerson (1917, p. 28) has observed limestone beds in the Marlboro Formation, but the concurrence of limestone and amphibolite is not an indication of the derivation of the latter from the former. In fact, quite the opposite argument might be made. Moreover, with the exception of sparsely occurring actinolite, no typical calc-silicate minerals have been discovered in the amphibolites, and this hardly favors an origin from limestone. (Tremolite and actinolite are locally prominent, however, in quartzitic rocks of the A member, and Cuppels (1962, written communication) has discovered a large wedge of tremolite schist cropping out within the Marlboro near Sandy Pond, Lincoln.) The gradational relationships between the amphibolites and other rocks of the Marlboro may (but do not certainly) preclude their being metamorphosed flows. The relatively hornblende-rich amphibolites in the central and eastern parts of the Reading quadrangle are possible exceptions to this generalization, however, for they are compositionally uniform throughout their extent and are apparently non-transitional with surrounding rocks. In balance, the available evidence favors derivation of the bulk of the amphibolites from a series of relatively mafic volcanic rocks.

Assemblages consisting of coexisting hornblende, andesine, biotite, and quartz show that the amphibolites have achieved a maximum metamorphic grade compatible with the staurolite-quartz subfacies of the almandine amphibolite facies (Fyfe, Turner, and Verhoogen, 1958, p. 228-229). Locally, however, retrograde metamorphism has converted these rocks in part to lower grade assemblages of the greenschist facies. A common retrograde feature is the development of discontinuous, fine-grained selvages of chlorite and magnetite around hornblende. Still another suggestion of retrogression is the correlation between plagioclase composition and epidote concentration in and around individual plagioclase crystals. Specimens with an abundance of epidote generally contain plagioclase of low An content. Plagioclase from one specimen, for example, in which epidote composed approximately 10 percent of the rock, was tentatively identified as $An_7$. This correlation suggests that lime and alumina were abstracted from the plagioclase during metamorphic retrogression to form epidote. Necessary iron or magnesium probably were obtained from hornblende retrogressing to chlorite.

## Quartzite

Layers of relatively pure to impure quartzite commonly are intercalated with the amphibolitic or dull-black schist of the A member of the Marlboro Formation. Indeed, this intimate association of quartzite and amphibolite is one of the characteristic features of the A member in this area. Where quartzite is the dominant lithologic type, quartzite units have been delineated separately on the geologic map.

The quartzite is typically massive to very faintly foliated and layered; boudinage structure is developed locally. Where individual layers are visible they average about 1 mm. in thickness; they are commonly less distinct in thin section than they are in hand specimen (see plate 15). Most of the quartzite possesses a very fine- to ultra-fine-grained xenoblastic, almost cherty appearing texture. The quartz grains commonly show a pronounced preferred orientation of their *c*-axes and boundaries between grains tend to be slightly serrated. A typical texture is shown in plate 15. Very light greenish-gray varieties predominate, but the quartzite is locally almost white.

The separately mapped quartzites are composed largely of quartz with subordinate amounts of microcline(?), plagioclase, biotite, muscovite-sericite, chlorite, actinolite, sphene, clinozoisite, and calcite. Within most of the quartzite units the rocks are relatively pure, and quartz in places composes up to 95 percent of the rock. Locally, however, the quartzite is enriched with calcium silicate minerals. The unit mapped southwest of Burlington center for example, contains rocks composed of quartz (35 percent), tremolite-actinolite (45 percent), plagioclase (15 percent), and accessory amounts of sphene and zircon. Color has not proved a useful criterion in differentiating the calc-silicate "quartzites" from true quartzites. The light-gray-green color imparted to the relatively pure quartzites by small amounts of disseminated chlorite is almost identical to the color of the calc-silicate varieties. Still other rocks mapped as quartzite may prove to be feldspathic quartzites, or quartz-feldspar gneisses characterized by sugary, quartzite-like textures. Where conspicuous feldspar augen remain these rocks are not easily confused with relatively pure quartzite, but elsewhere petrographic examination is required to determine their true nature.

The compositions of the quartzite suggest that it was derived from a series of somewhat silty or clayey and locally calcareous arenaceous or cherty rocks. The mineral assemblages characteristic of this facies are not particularly sensitive to changes in metamorphic grade, but the rocks probably attained a maximum grade embraced by the lower almandine amphibolite facies of Fyfe, Turner and

Verhoogen (1958, p. 228-229). The locally conspicuous presence of chlorite, sericite, actinolite, and minerals of the epidote group may be attributable to metamorphic retrogression to the greenschist facies.

### Undifferentiated A member of the Marlboro Formation

Rocks shown on the geologic map as undifferentiated parts of the A member of the Marlboro Formation consist chiefly of dull-black, strongly foliated biotite-hornblende schist, fine-grained quartz-feldspar gneiss, chloritic-quartzose schist or gneiss and chlorite schist, together with numerous intercalated, but unmapped, layers of quartz-feldspar gneiss, quartzite, and amphibolite.

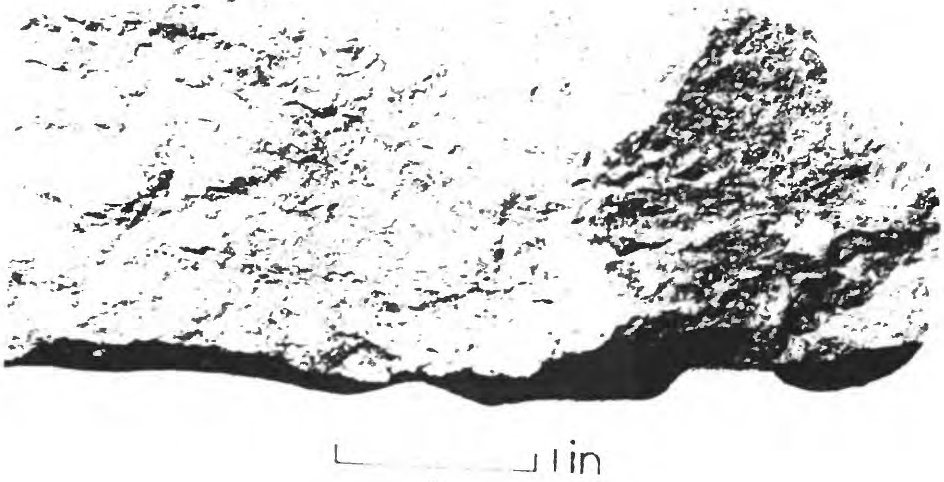
The dull-black schists occur chiefly in the Wilmington quadrangle, along the western border of the Reading quadrangle, and along the southern contact of the westward projection of the Andover Granite pluton. They are characteristically dull-black to gray in color, but they are locally transitional with distinctly lighter rocks. The black schists generally weather to greenish gray or other colors conspicuously lighter than the corresponding fresh rock. Layering and foliation are pronounced, but the schists are locally massive in appearance. The majority of the black schists possess a fine- to medium-grained xenoblastic texture and commonly include elliptical or lens-shaped feldspar crystals or aggregates more or less conformable with the foliation (see plate 5B). The majority of the lenses are very small but a few have been observed up to 8 mm. in length. The feldspar lenses or augen commonly are conspicuously strained and fractured, whereas the generally finer-grained quartz is relatively undeformed. In the extreme western part of the area considered here, the feldspar crystals are apparently less strained and fractured, but the quartz grains are prominently strained and generally coarser-grained than elsewhere in the area. Structural and textural features of the dull-black schists are illustrated in plates 5, 8, 11B and 14B.

The melanocratic schists of the A member are composed of varying amounts of hornblende, plagioclase, quartz, biotite, and epidote. Minor accessories include magnetite, sphene, and calcite. The composition of the plagioclase ranges between $An_{20}$ and $An_{45}$ and averages about $An_{30}$. Common hornblende is the dominant amphibole, but actinolite occurs locally. The calcite occurs both as veins and as finely disseminated, irregular blebs scattered throughout the schist. Epidote is a ubiquitous constituent, but it is not everywhere megascopically conspicuous. Large knots or boudins of amphibole up to 6 inches across, have been found in a few exposures of the dull-black schist north of the Woburn-Wilmington town line. The amphibole is grass green in color, low in iron, and probably compositionally similar to actinolitic hornblende. Similarly appearing

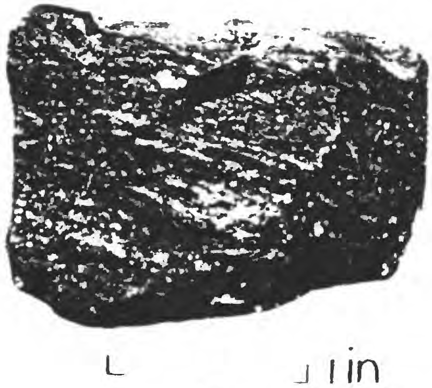
Plate 5

A. Hand specimen from the Marlboro Formation approximately 2000 feet north-northwest of Main St.-Forest St. intersection, Reading. Round to oval shaped crystals are plagioclase feldspar. Groundmass consists of dense mat of plagioclase, quartz, hornblende, biotite, chlorite, and epidote.

B. Dull-black, amphibolite schist from the A member of the Marlboro Formation exposed along Main St. near the Wilmington-Woburn town line, Wilmington. Note the thin, light-colored, discontinuous bands and porphyritic-like texture. Small, white flecks or "augen" are individual plagioclase feldspar grains.




A




B

boudins composed chiefly of epidote are manifested as one of the more conspicuous features of the black schists cropping out in the western part of the map area; they are apparently well exposed around Vose Pond, Maynard (see Hansen, 1956, p. 9-11, especially figures 3, 4, and 5).

In several exposures of the A member the rocks are composed of biotite-andesine-quartz gneiss. Although similar in composition to the gneissic rocks described with the B member, these rocks tend to be more massive and lack the prominent, laminated structure so characteristic of the rocks of the B member. The gneiss is generally fine-grained and xenoblastic, and locally contains small, rounded pods of quartzite.

Along the northern edge of the Marlboro Formation east of Burlington, and especially north of Reading center and in the extreme eastern part of the Reading quadrangle, a group of rocks is exposed that can best be described as chloritic-quartzose schist or gneiss. Although somewhat apt, this appellation oversimplifies the classification of a large group of rocks; they tend to be unified more by their prominently foliated, highly fractured, ultra-fine-grained, and greenish-gray nature than by their compositional characteristics.

The chloritic-quartzose schists commonly are very thinly and conspicuously layered and less commonly contorted into small tight folds. The layers range in thickness from a small fraction of a millimeter to 3 or 4 mm. A pervasive characteristic of the schist is its ultra-fine-grained, xenoblastic texture, in which the grain size averages between a fiftieth and a hundredth of a millimeter. Small rounded plagioclase grains occur locally. There is generally little mineralogical variation from layer to layer, and the variation present is manifested chiefly by secondary(?) minerals such as epidote. Textural and structural characteristics are illustrated in plates 6A and 14A.

The chloritic-quartzose schists west of Cedar Swamp are composed chiefly of quartz, potassium feldspar(?), plagioclase, chlorite and epidote. Calcite and sericite occur locally, and here and there fractures are filled with specular hematite that characteristically displays a pronounced ruby-red internal reflection. The fine-grained character of the schists generally precludes an accurate estimate of the relative amounts of quartz, potassium feldspar, and plagioclase present. However, parts of the schist appear to be composed mainly of quartz with very little admixed feldspar, whereas other parts are composed largely of plagioclase of approximately middle oligoclase composition (see table 1).

Along the eastern border of the Reading quadrangle the A member of the Marlboro Formation is composed chiefly of chloritic-quartzose schist locally enriched in calcite. This schist is similar in appearance but compositionally different from that exposed north of Reading center, in that it is generally richer in mafic constituents. Chlorite and epidote are much more abundant and amphibole is present locally. Exposures are extremely poor in the Reading quadrangle east of Reading center, so little may be said about the extent of the chloritic-quartzose schist through the central part of the quadrangle. Judging from the distribution of the few exposures present, it is likely that these schists comprise the greater part of the Marlboro Formation east of Reading center.

Relatively pure chlorite schist is exposed in a railroad cut along the northern edge of the Marlboro Formation in Wilmington, and roadcuts about 1.2-1.3 miles north of Reading center. The chlorite schists possess a strong, contorted schistosity, but are devoid of discernible layering. They characteristically show a fine-grained hypidioblastic texture. These schists are composed almost entirely of chlorite, but they are locally enriched with calcite.

The composition of the undifferentiated A member of the Marlboro Formation suggests that it was derived from a heterogeneous series of mafic to felsic volcanics, irregularly interbedded with impure, siliceous sediments. The common occurrence of calcite in these rocks points to the local admixture of calcareous sediments or subsequent hydrothermal alteration. It is inferred that the rocks of the undifferentiated facies of the A member attained a maximum metamorphic grade comparable with that shown by the intercalated amphibolites. As is true in other parts of the Marlboro Formation, however, effects of metamorphic retrogression locally have obscurred or destroyed the higher grade assemblages. In the chloritic-quartzose schists, for example, the mineral assemblages (see table 4) commonly are more compatible with the greenschist facies.

## Interpretation of structural and textural features of the Marlboro Formation

Differences of opinion have arisen over the proper interpretation and significance of many structures and textures of the Marlboro Formation as it occurs east of the Lincoln-Lexington town line. Accordingly, the several possible interpretations are discussed separately here.

According to Toulmin (1961, written communication), layering in the porphyroblastic gneiss member, arising from the regularly alternating sequence of plagioclase amphibolite with porphyroblastic gneiss, is strongly suggestive of original bedding. Palimpsest features other than bedding were not discovered in the porphyroblastic gneiss, but the textures apparently are relatively uncomplicated crystalloblastic phenomena. Similarly, textures characteristic of some of the separately mapped amphibolites (see plate 12B) seem to be simple crystalloblastic features. The significance of fabrics manifested elsewhere within the eastern reaches of the Marlboro Formation is less clear.

In considering rocks correlative with the Marlboro Formation described here, LaForge (1932, p. 16-18) only rarely attempted to explain their origin by reference to their structures and textures. Moreover, he neglected to include photographs illustrating the particular fabric alluded to, so that the reader is unable to compare directly the features described by LaForge with those observed by the writer.

LaForge (op. cit., p. 16) regarded the rocks correlative with the B member of the Marlboro Formation as a complex of mainly igneous gneisses. He noted that some of the coarser-grained gneisses "have been strongly sheared" and that some of the "porphyroid gneisses have the appearance of volcanic rocks, as if they were originally amygdaloidal lavas." Elsewhere, according to LaForge, relatively siliceous varieties occur "in which the layering is so regular and so much like stratification as to raise the question whether they are not recrystallized micaceous sandstones."

Black schists correlative with parts of the A member were interpreted by LaForge (op. cit., p. 17) as recrystallized basaltic tuffs on the basis of their association with "sheared and altered basaltic lavas." The "basaltic lavas" are undescribed. Still other units correlative with the A member are characterized, according to LaForge (op. cit.,

p. 18), "by the not uncommon occurrence" of "pebbly sandstone or even conglomerate." Rocks on strike with the specimen shown in plate 7 are described as a complex of silicic igneous (mainly volcanic) rocks interbedded with siliceous sediments, but LaForge (op. cit., p. 18) has not described the textures of these rocks.

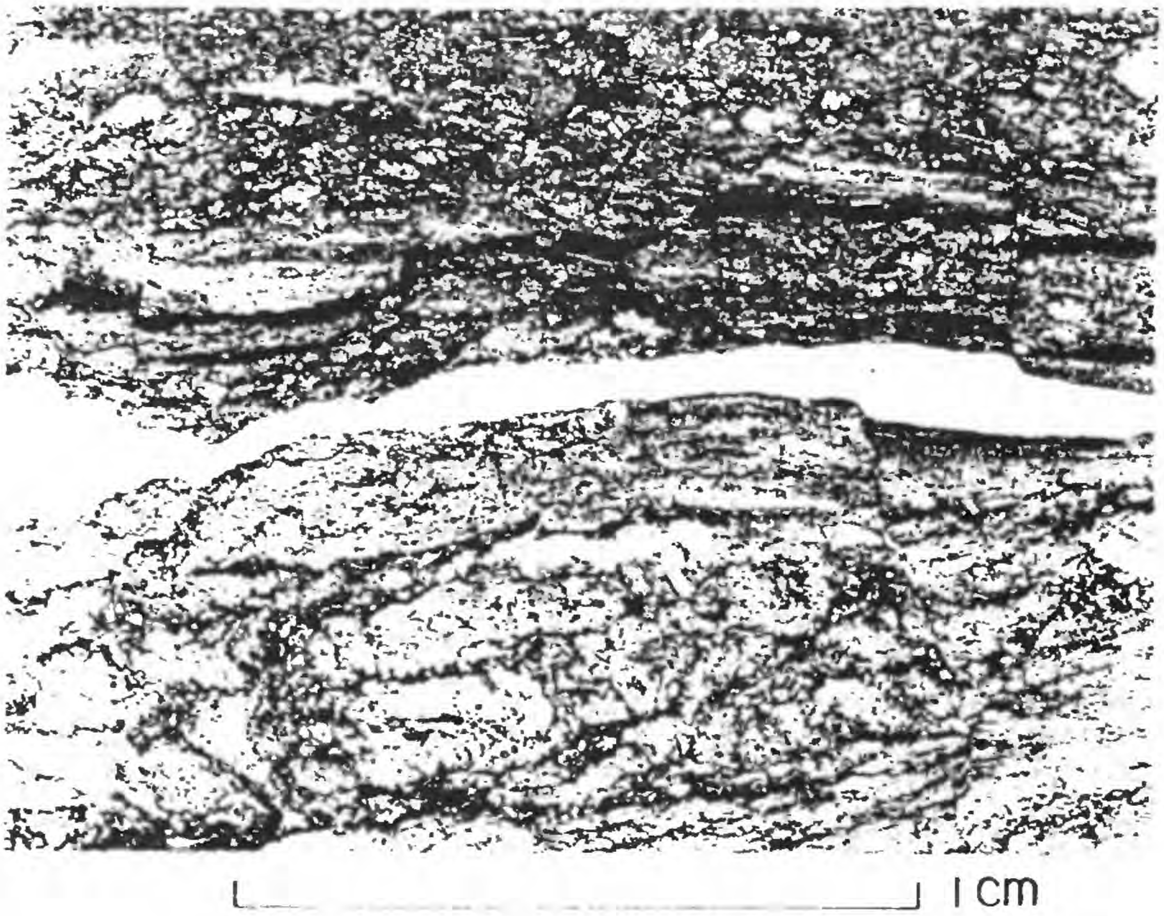
L. R. Page (1962, written communication) recently has examined parts of the Marlboro under discussion and has concluded that these rocks display a wide range of primary fabrics. For example, planar structural features such as those illustrated in plates 4 and 5B, are interpreted by Page as original bedding or layering, yet are not recognized as such by the writer. Moreover, the small feldspar lenses or ovoids embedded in the groundmass in plate 5B apparently are regarded by Page as (recrystallized?) amygdules, for he has questioned the writer's conclusions refuting this interpretation. Still another example is provided by the large, rounded grains shown in the photographs in plates 10 and 11A. These grains are considered primary clasts by Page, but are not so regarded by the writer.

In order to illuminate the nature of the structures and textures of the Marlboro Formation east of the Lincoln-Lexington town line, the series of photomicrographs in plates 6 through 16 have been arranged approximately in order across the strike from southeast to northwest. Most (but not all) of the randomly selected rocks used for this

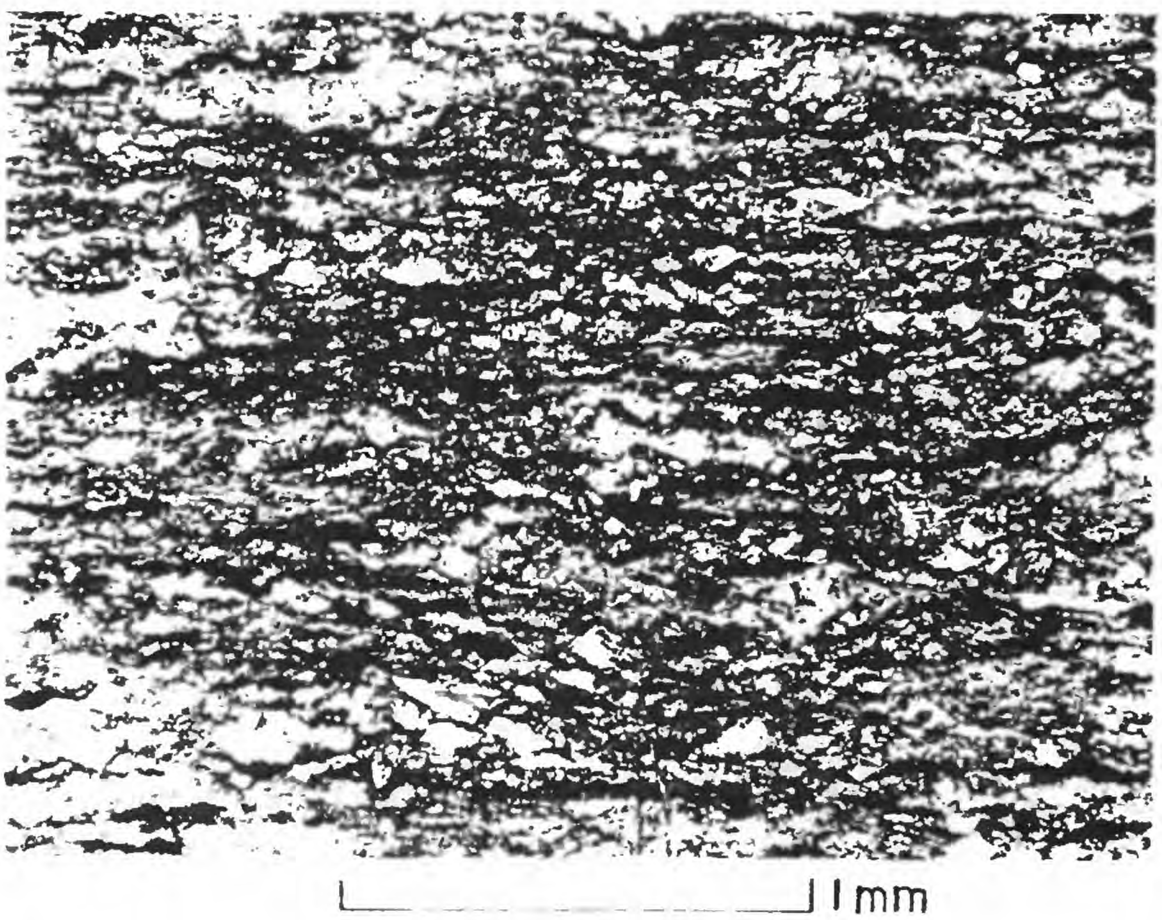
Plate 6

A. Photomicrograph of specimen from the undifferentiated A member of the Marlboro Formation exposed in quarry west of Norris Brook, 3000 feet northeast of crest of Upton's Hill, Peabody. The darker layers are composed chiefly of epidote, chlorite, and magnetite and the lighter layers are mainly quartz and plagioclase. Light, cloudy, relatively coarse grains are plagioclase. Plane light.

B. Photomicrograph of specimen from amphibolite facies of the A member of the Marlboro Formation exposed 2000 feet north of School St.-Mishawum Rd. intersection, Woburn. White, plagioclase; gray, hornblende; black, magnetite. Note how the foliation is defined by lenticles of magnetite. Crossed nicols.



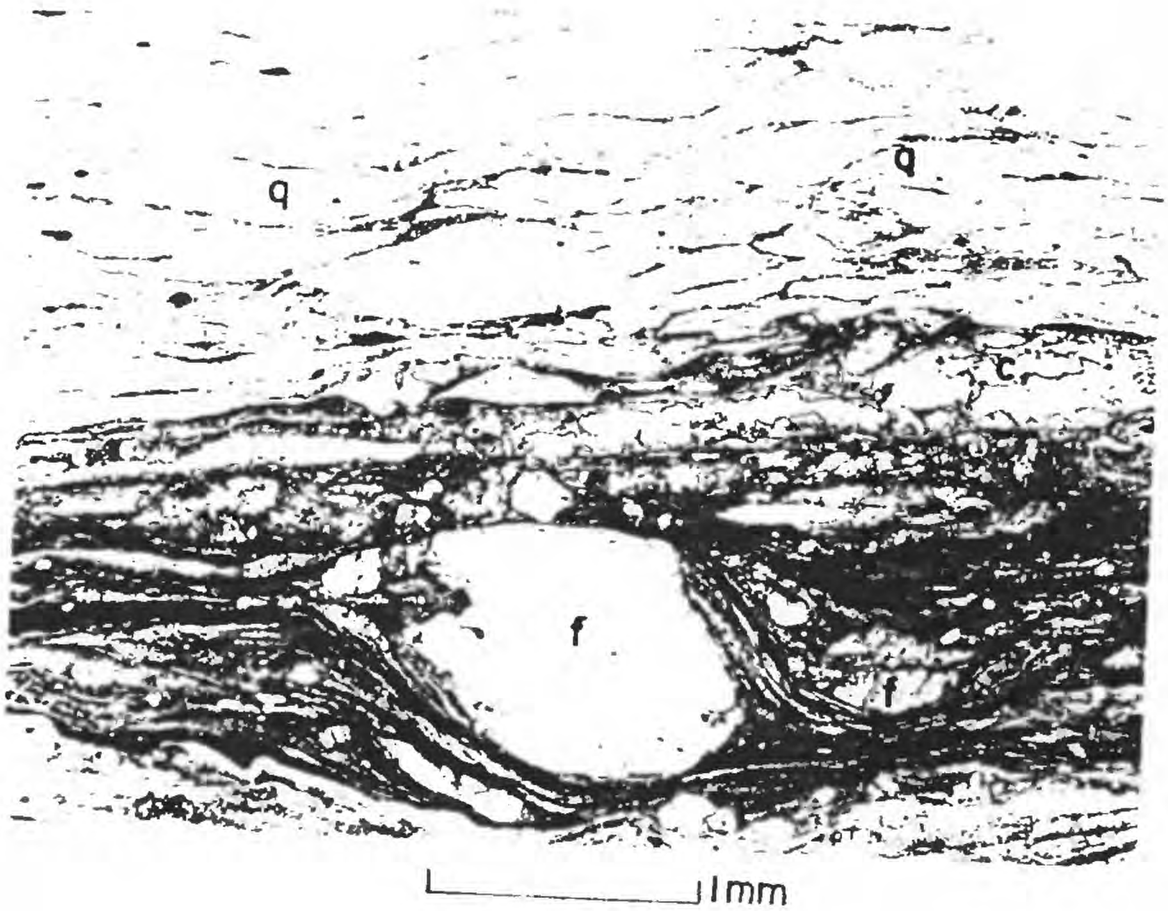

A



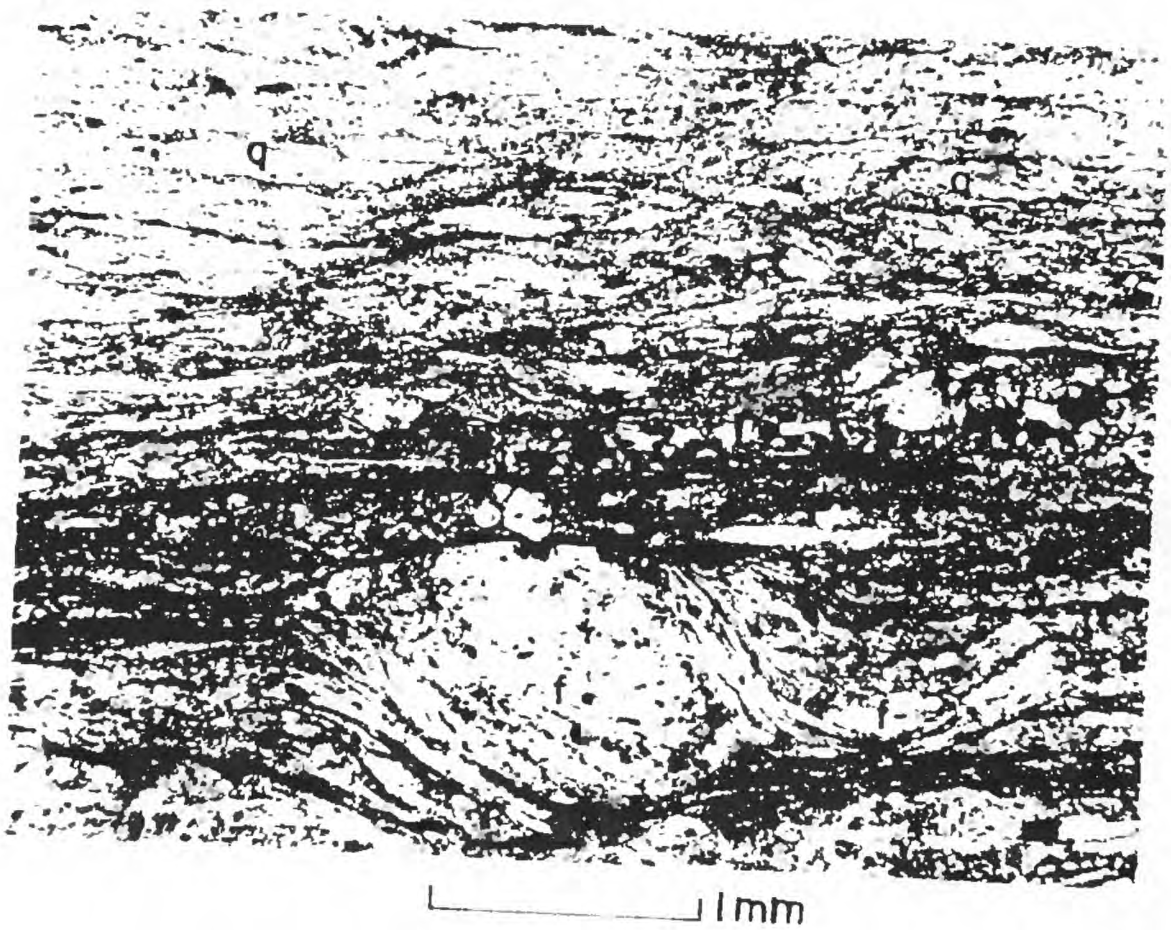

B

Plate 7

Photomicrographs of specimen from the undifferentiated A member of the Marlboro Formation exposed 1500 feet east of Alfred St.-Main St. intersection, Woburn. q, quartz; f, feldspar; c, chlorite. Material shown in the upper half of each photograph is almost entirely quartz. Darker layers shown in the lower half of each photograph are composed chiefly of chlorite and sericite. A. Plane light. B. Crossed nicols.



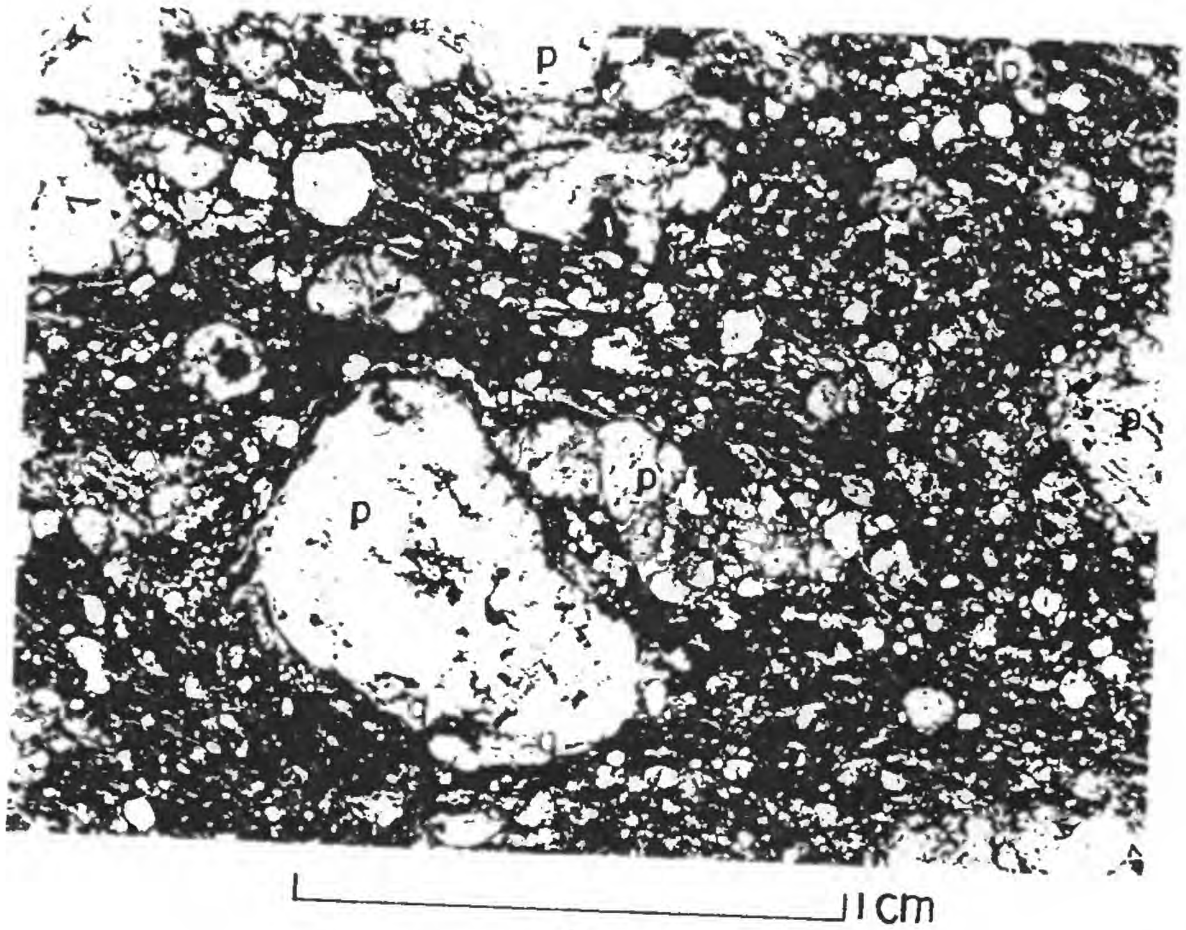

A



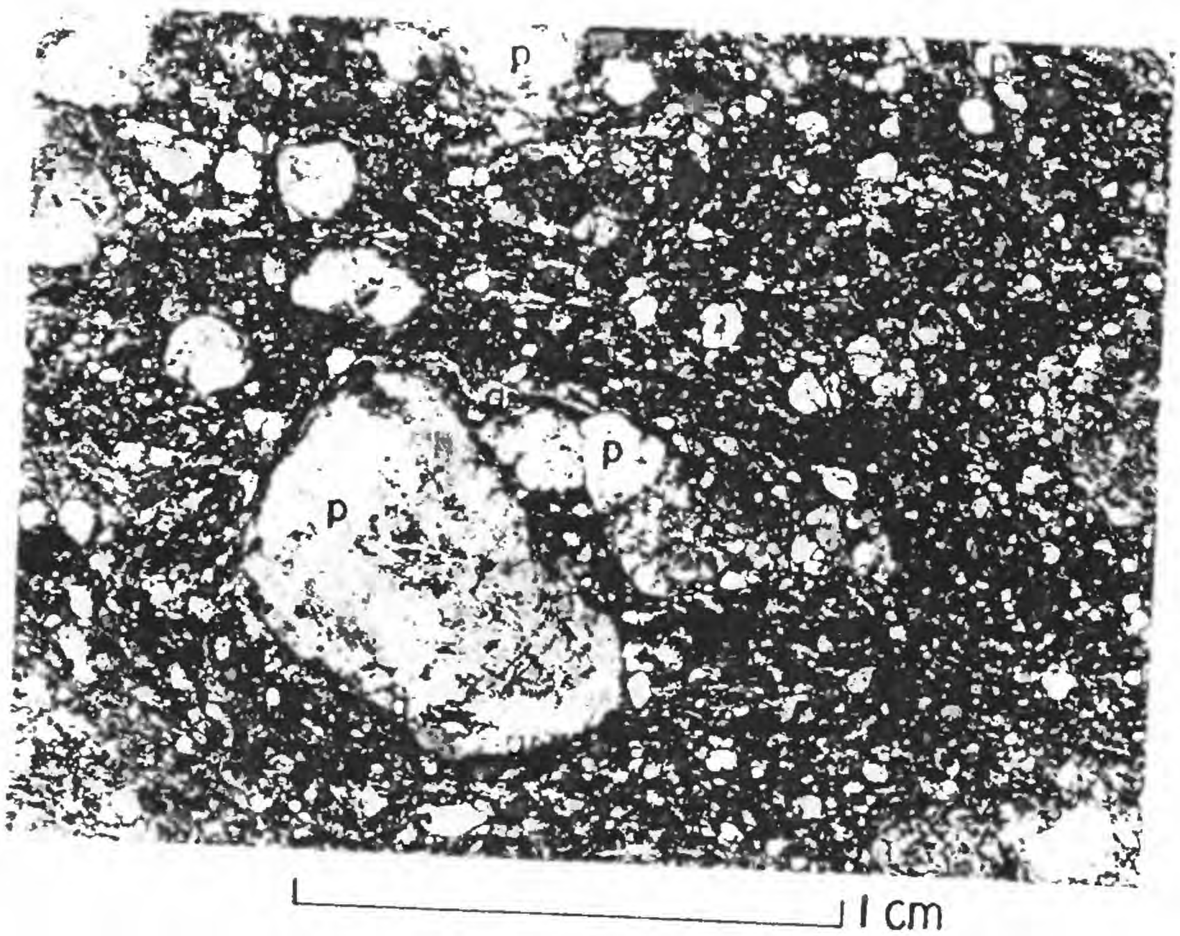

B

Plate 8

Photomicrographs of specimen from the A member of the Marlboro Formation exposed 2100 feet north-northwest of Main St.-Forest St. intersection, Reading. q, quartz; p, plagioclase; h, hornblende. Note the occurrence of quartz in reentrants in plagioclase and in fine-grained mosaic. Note also the shattered plagioclase crystal in center of photos. Specimen taken from outcrop adjacent to one from which hand specimen shown in plate 5A was procurred. A. Plane light. B. Crossed nicols.



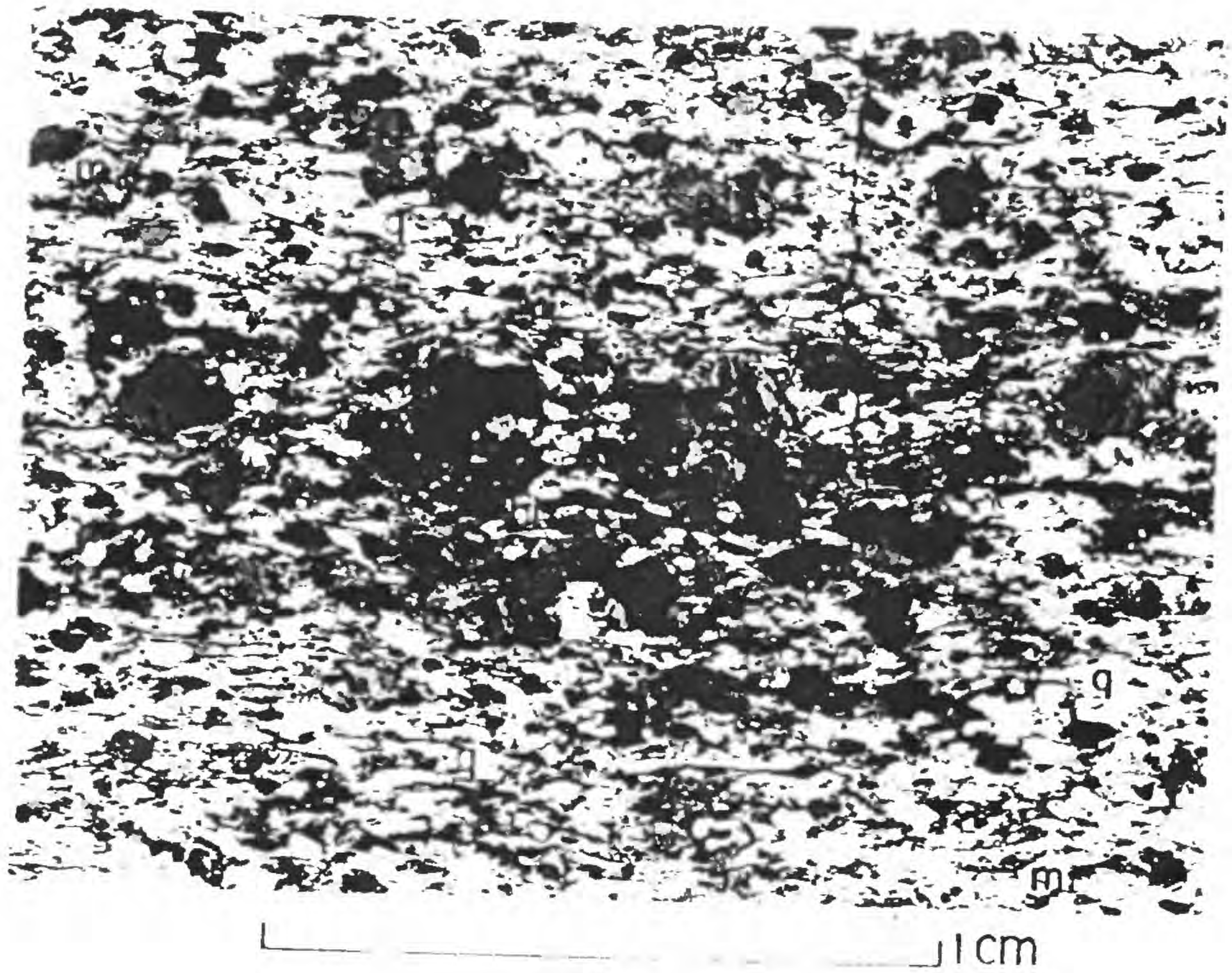

A



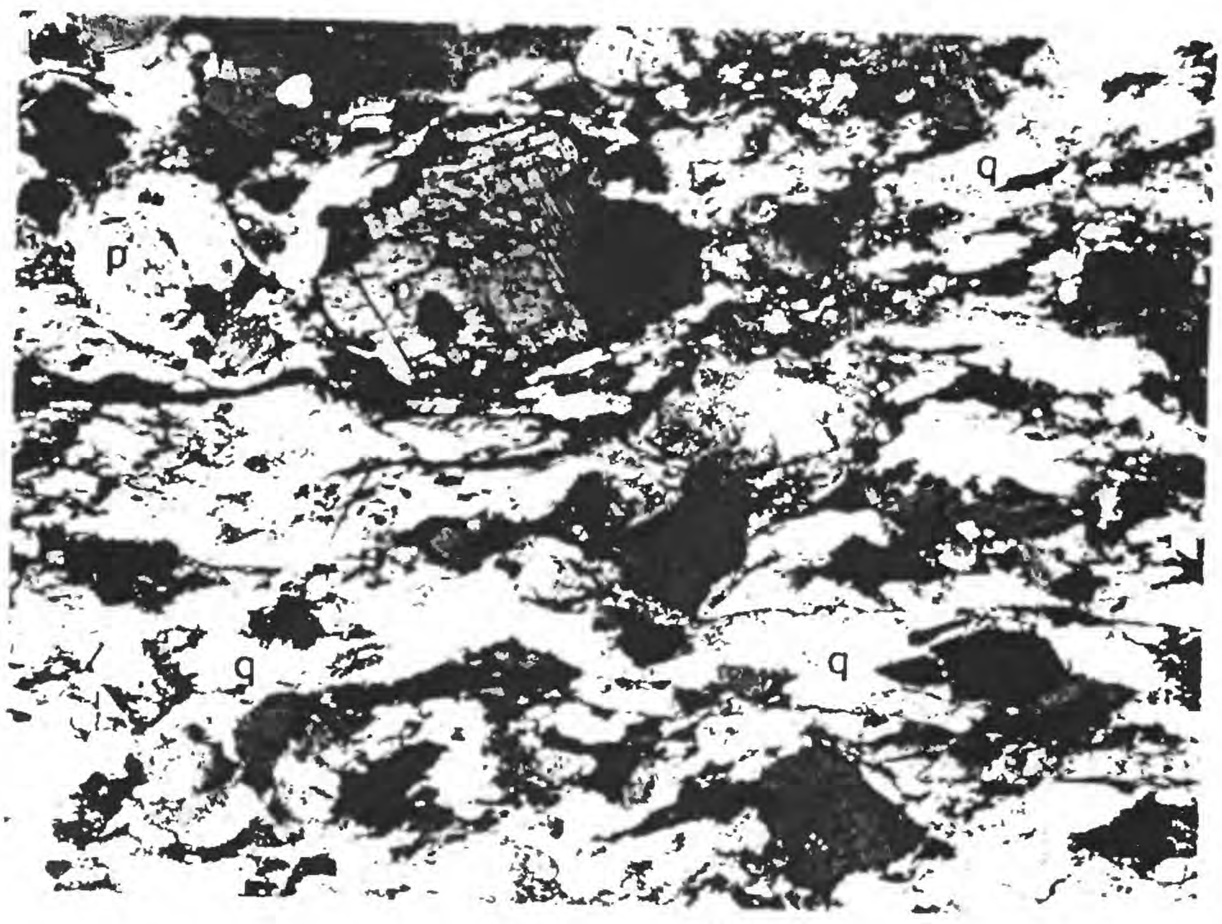

B

Plate 9

Photomicrographs of specimen from the B member of the arlboro Formation exposed 1300 feet east-northeast of St. arys Mission, Burlington. q, quartz; p, plagioclase; microcline; bi, biotite. Note the ribbon-like development of quartz. Quartz grains shown here are the coarsest served in the Marlboro Formation within the map area. ossed nicols. A. Low magnification. B. Closeup of ft central section of photo shown in A.




A




B

Plate 10

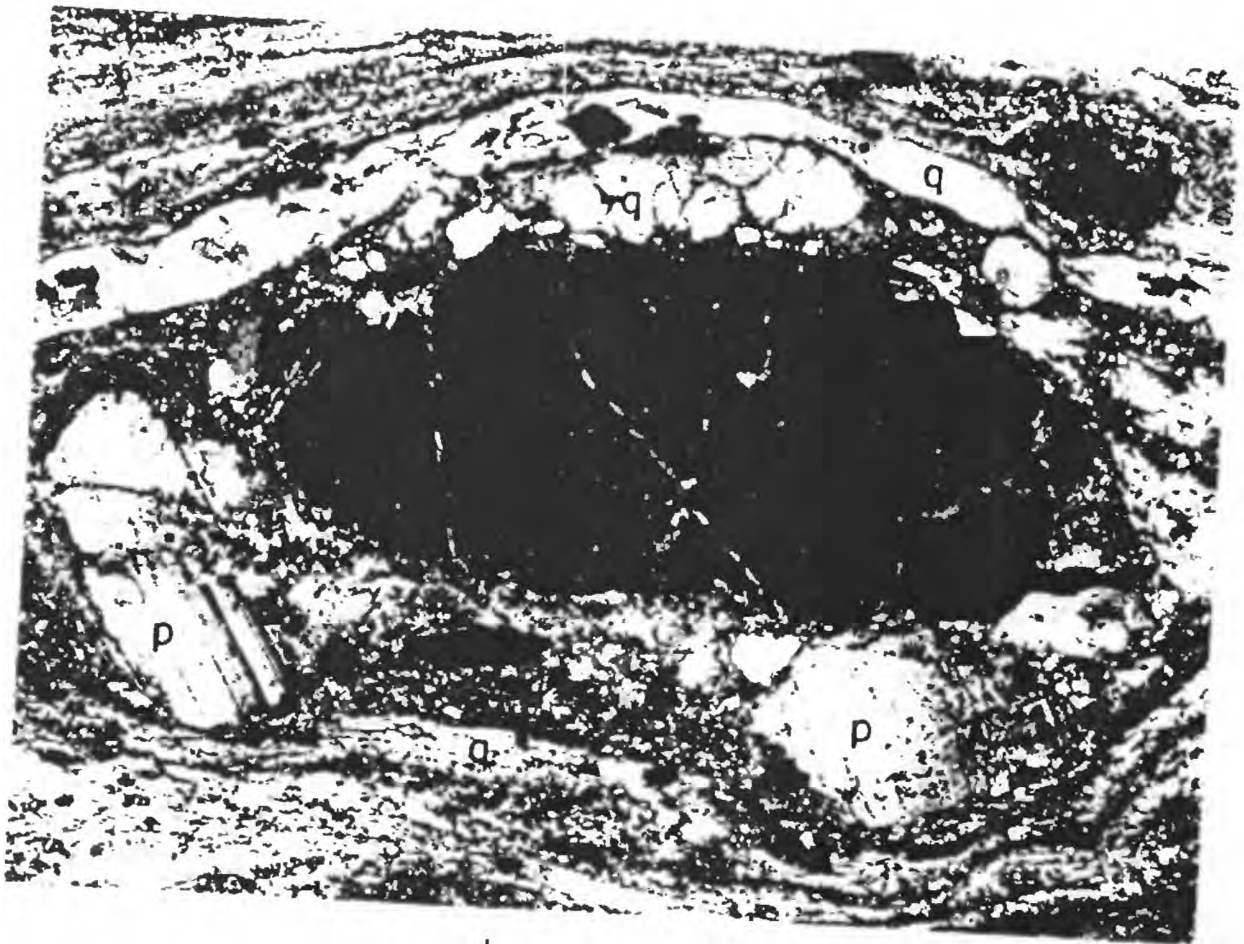
Photomicrograph of specimen from the undifferentiated A member of the Marlboro ormation exposed along Main St. near Wilmington-Woburn town line, Wilmington. Speci-en taken from transition zone between A and B members and is in most respects more ypical of the B member. From outcrop shown in plate 4A. q, quartz; p, plagioclase; , microcline; bi, biotite; a, amphibole. Crossed nicols.


1 cm
E
P

Plate 11

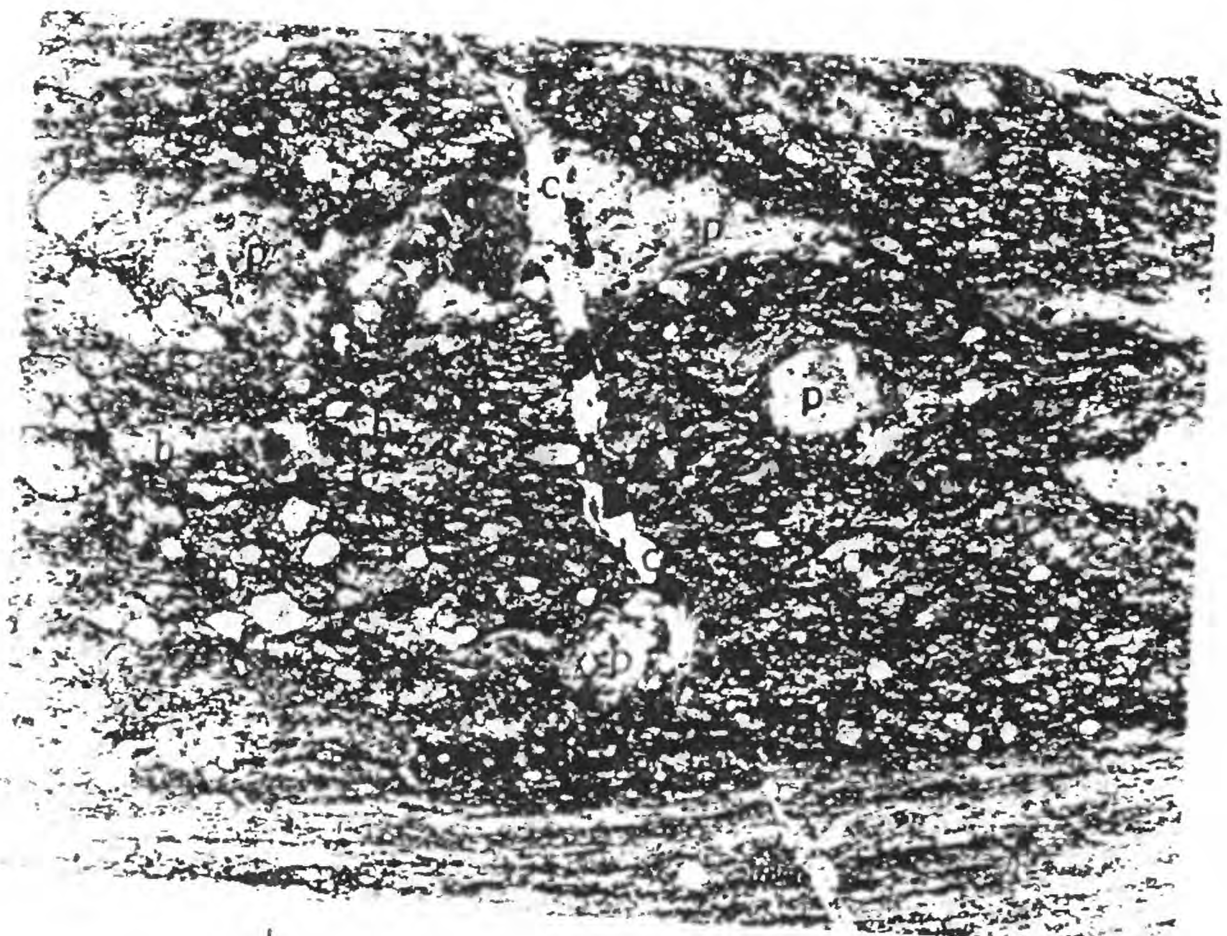
A. Photomicrograph of specimen from undifferentiated A member of the Marlboro Formation exposed along Main St. near Wilmington-Woburn town line, Wilmington. Specimen taken from transition zone between A and B members and is in most respects more typical of the B member. From outcrop shown in plate 4A. q, quartz; p, plagioclase; bi, biotite; a, amphibole. Groundmass consists of fine-grained mosaic of quartz, feldspar (chiefly plagioclase), muscovite, biotite, chlorite, and epidote. Crossed nicols. Closeup of left central section of photo shown in plate 10.

B. Photomicrograph of plagioclase amphibolite from the undifferentiated A member of the Marlboro Formation exposed 1400 feet south of Eames St.-Main St. intersection, Wilmington. Thin section cut from specimen similar to that shown in plate 5B. p, plagioclase; h, hornblende; c, calcite. Crossed nicols.




1mm

A



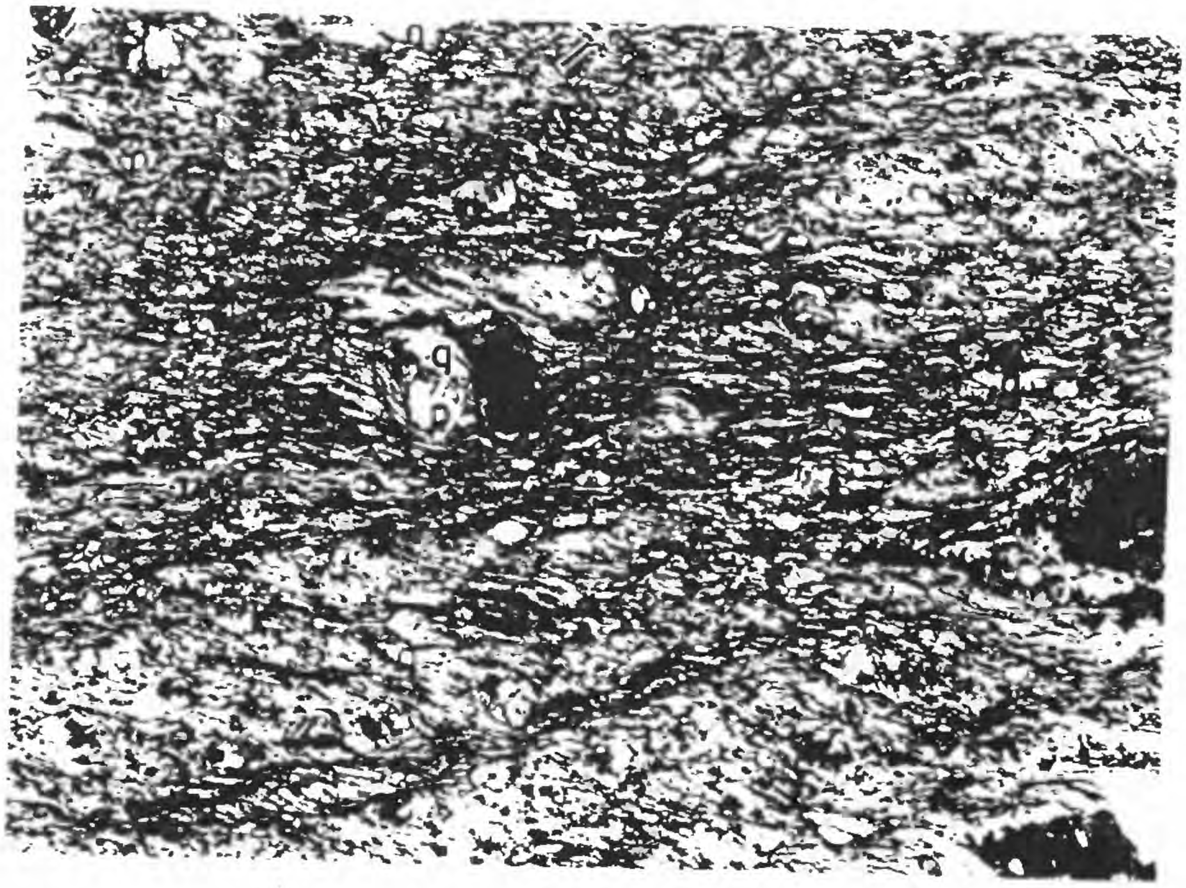

1cm

B

Plate 12

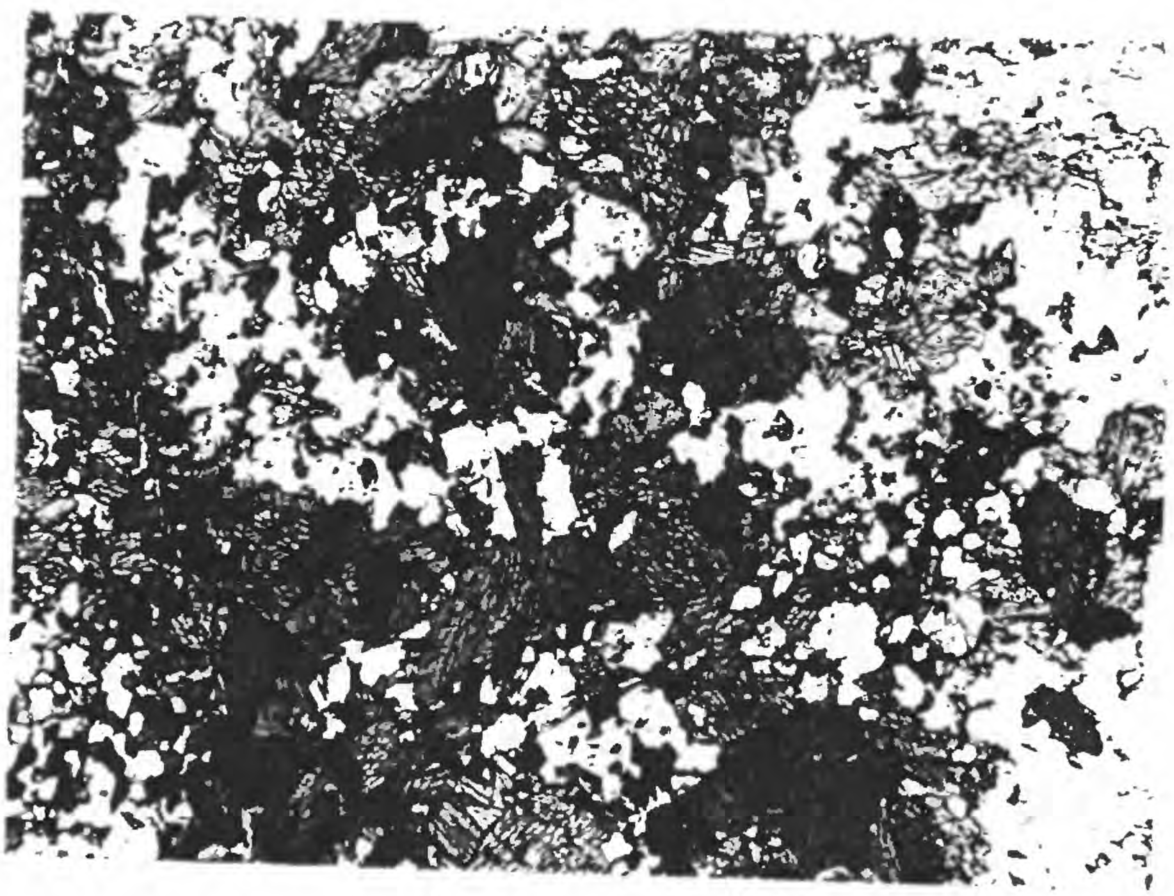
A. Photomicrograph of dull-black schist from the undifferentiated A member of the Marlboro Formation exposed 1800 feet south-southwest of Eames St.-Main St. intersection, Wilmington. q, quartz; p, plagioclase; bi, biotite; mu, muscovite. Most of the dark, fine-grained material is biotite. Note the development of foliation in two distinct directions. Crossed nicols.

B. Photomicrograph of specimen from amphibolite facies of the A member of the Marlboro Formation exposed 1100 feet south-southwest of Chestnut St.-Mill St. intersection, Wilmington. White, plagioclase; gray, hornblende; black, magnetite. Plane light.




1cm

A

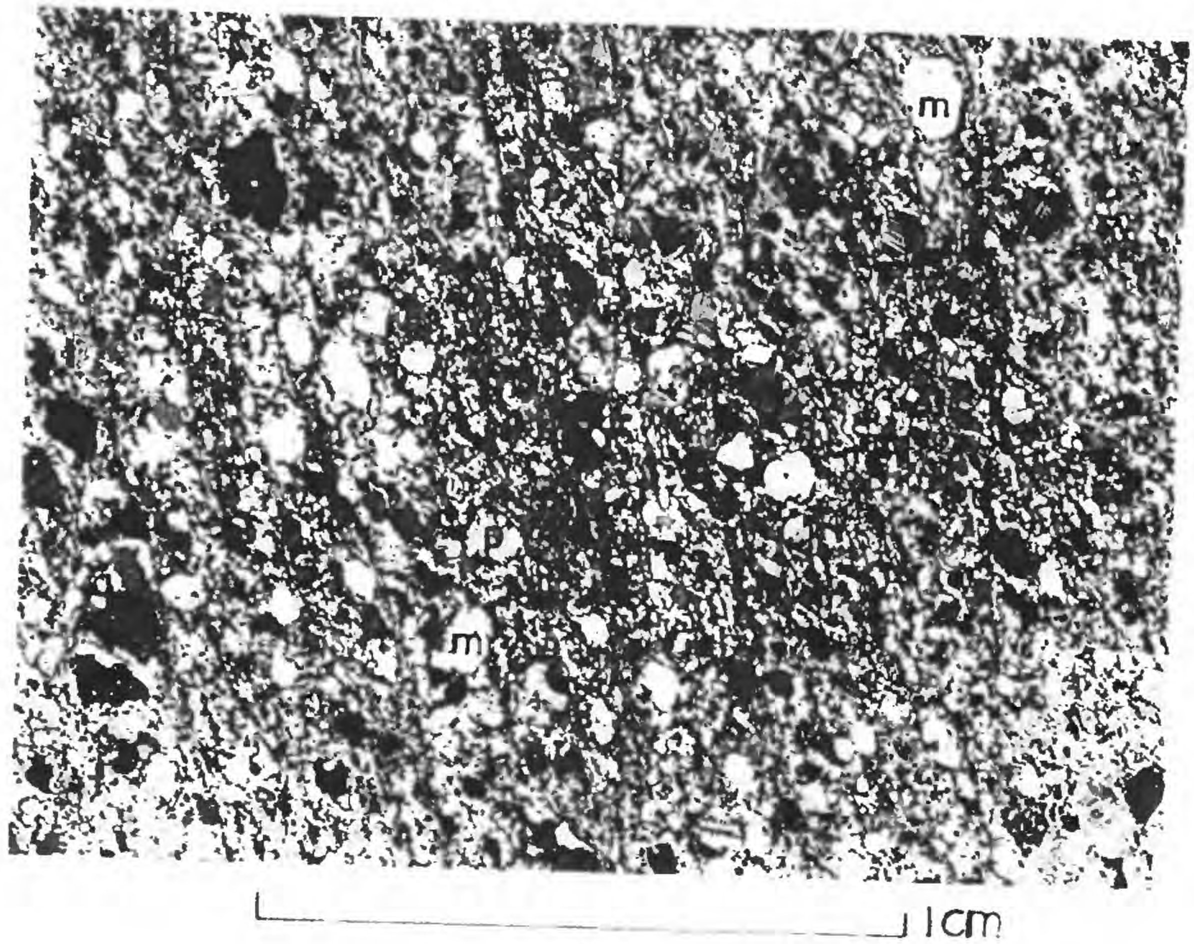


1mm

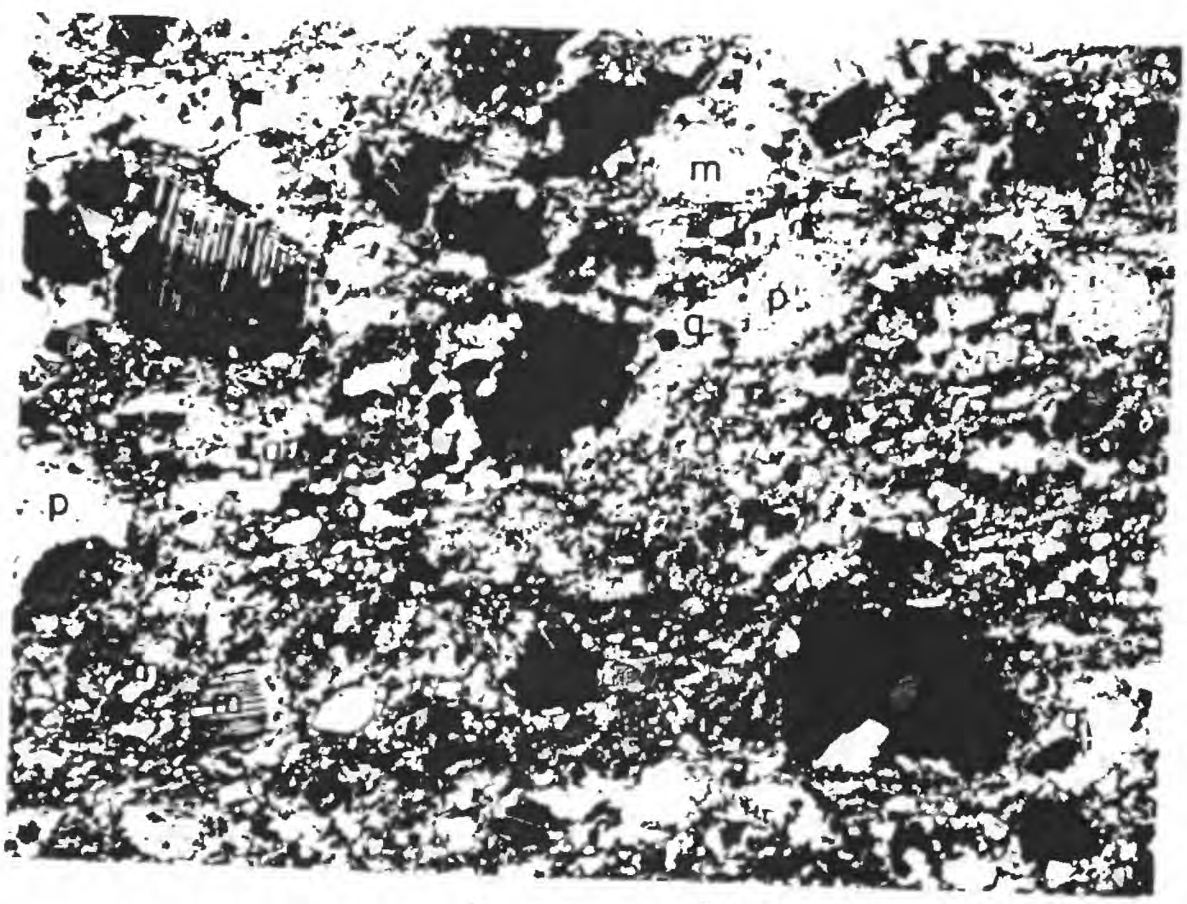
B

Plate 13

Photomicrographs of specimen from the undifferentiated A member of the Marlboro Formation exposed along the crest of the hill 1300 feet west-northwest of the crest of Peach Orchard Hill, Burlington. q, quartz; p, plagioclase, m, microcline; mu, muscovite, Note the rounded feldspar grains and well developed foliation. Crossed nicols.
A. Low magnification. B. Closeup of central section of photo shown in A.




A

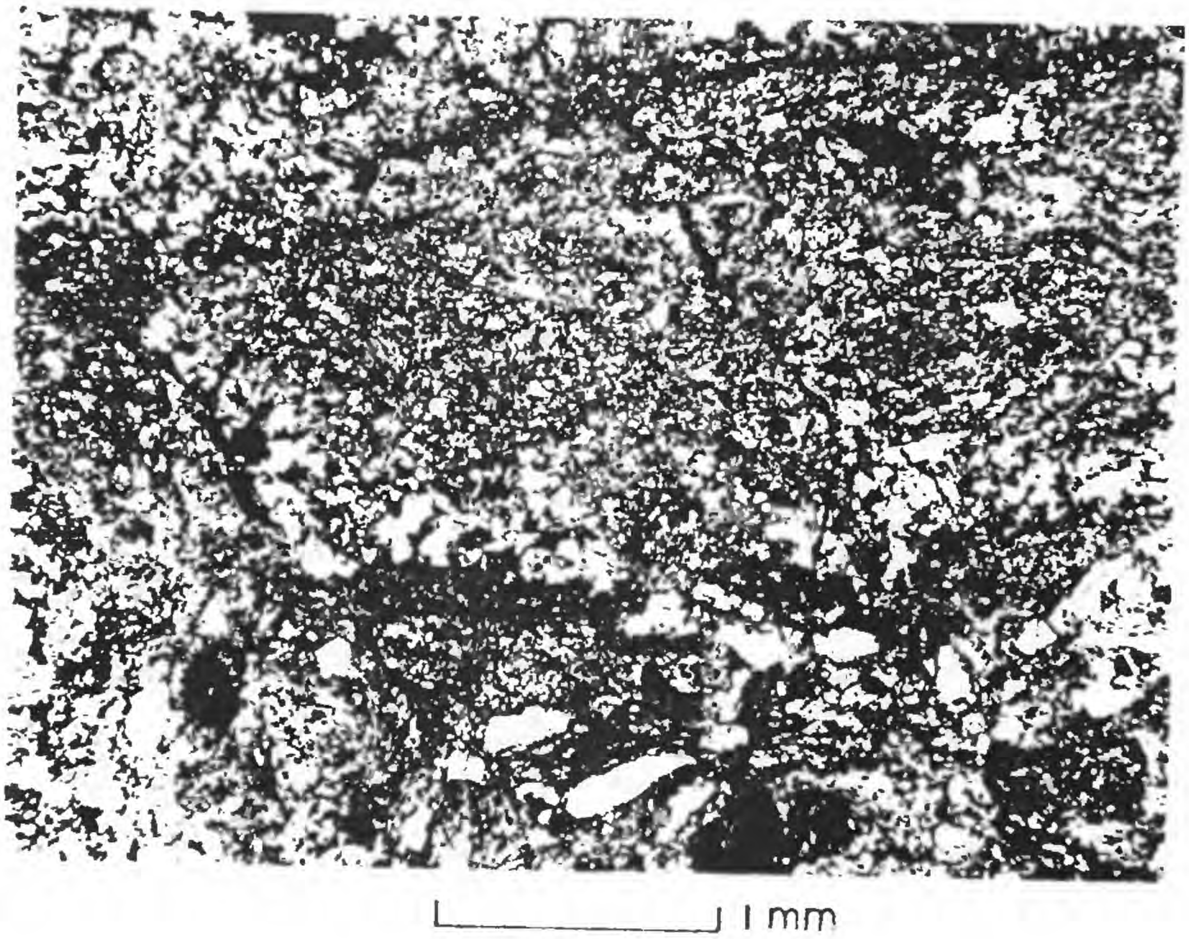



B

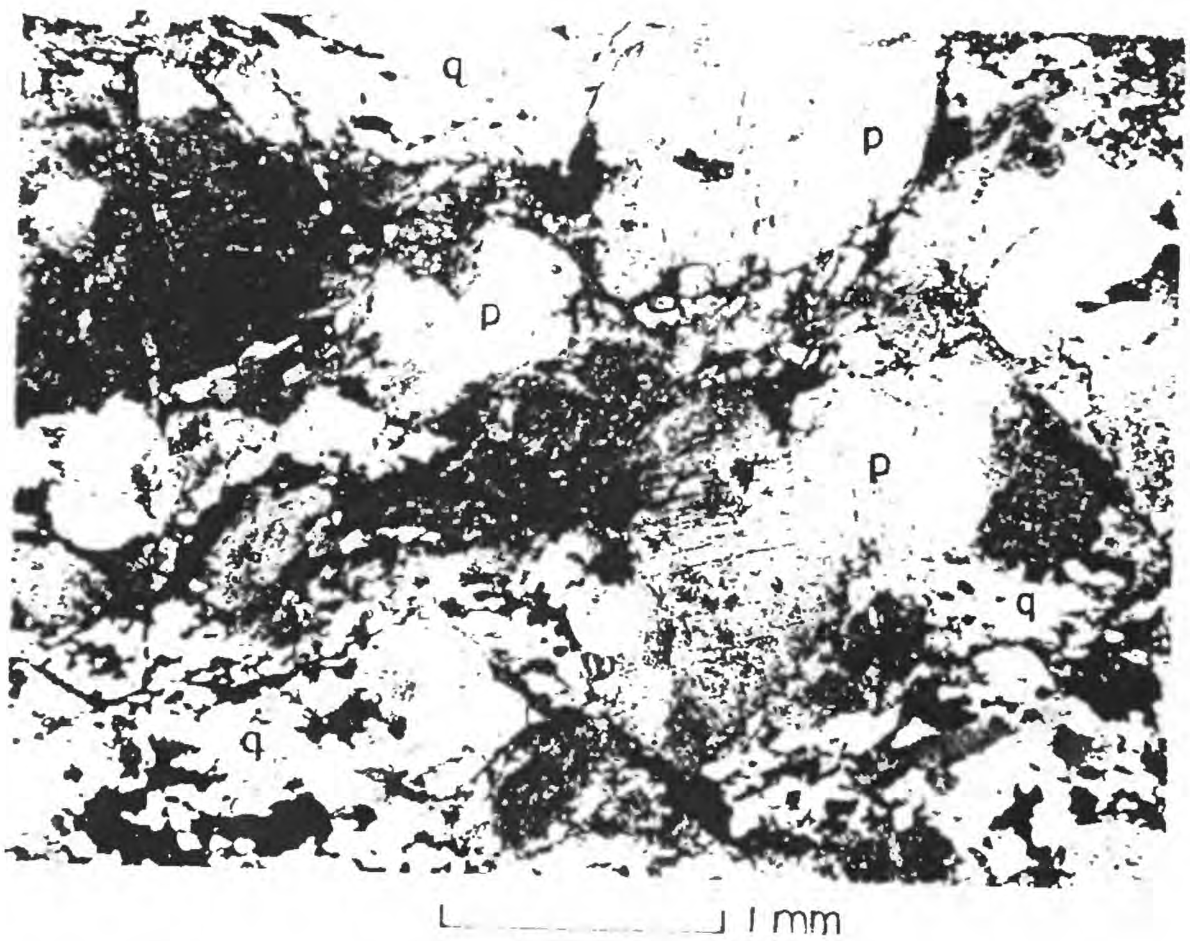
Plate 14

A. Photomicrograph of specimen from the A member of the Marlboro Formation exposed in railroad cut adjacent to Main St. overpass, 1.1 miles southeast of Wilmington center. Specimen composed chiefly of quartz (light colored material), sericite, chlorite (grayish material), and magnetite (black). Note the chaotic structure shown in this rock. Crossed nicols.

B. Photomicrograph of dull-black schist contained within rocks mapped with amphibolite of the A member of the Marlboro Formation exposed 300 feet northwest of Chandler Rd.-Mill St. intersection, Burlington. q, quartz; p, altered plagioclase. Crossed nicols.



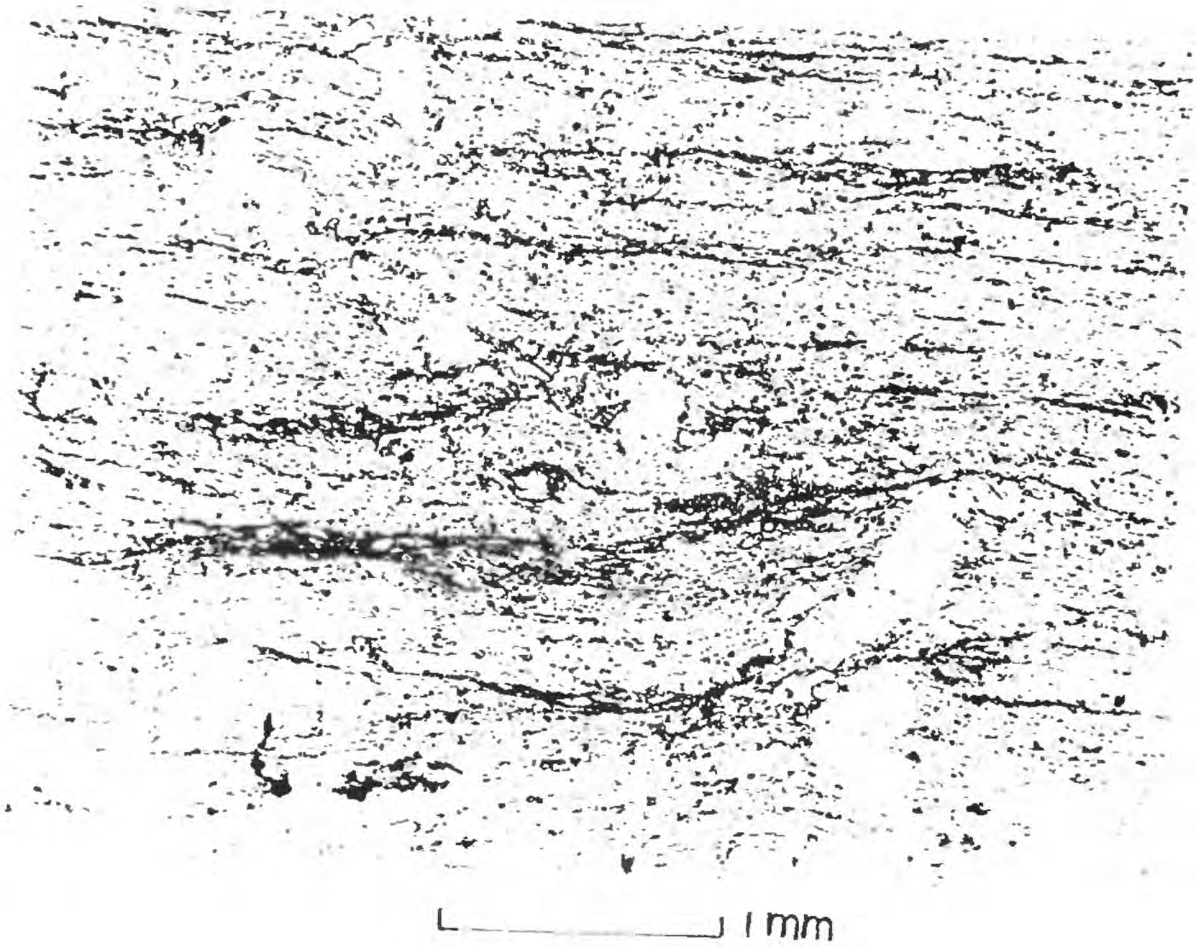

A



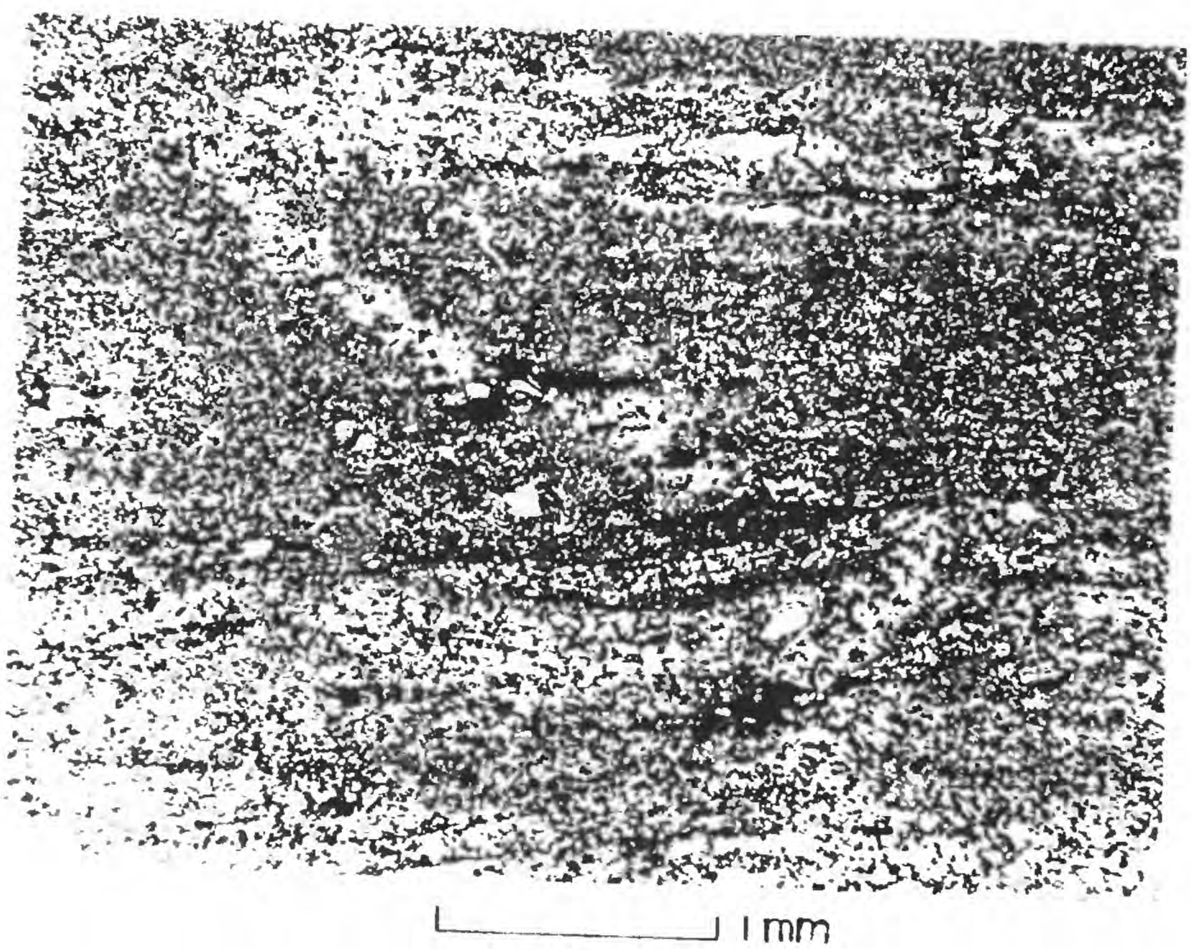

B

Plate 15

Photomicrographs of specimen from quartzite facies of the A member of the Marlboro Formation exposed 700 feet northwest of Chestnut St.-Mill St. intersection, Wilmington. This rock is composed almost entirely of quartz. Darker layers reflect the presence of sericite, chlorite, and calcite. Note the irregular fold defined by the relatively coarse-grained quartz layer. Identical in hand specimen to rocks collected from the Moine Thrust zone. A. Plane light. B. Crossed nicols.



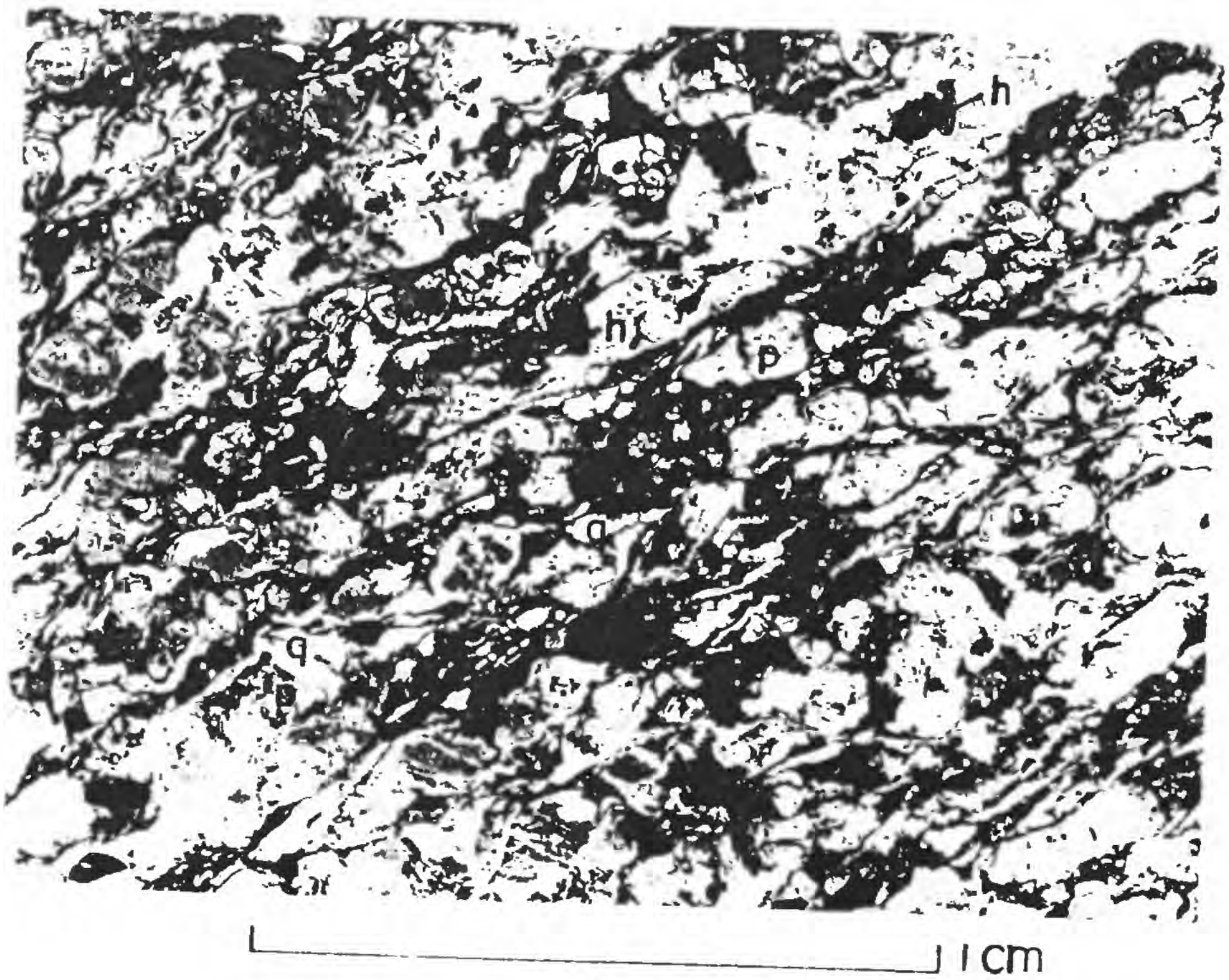

A



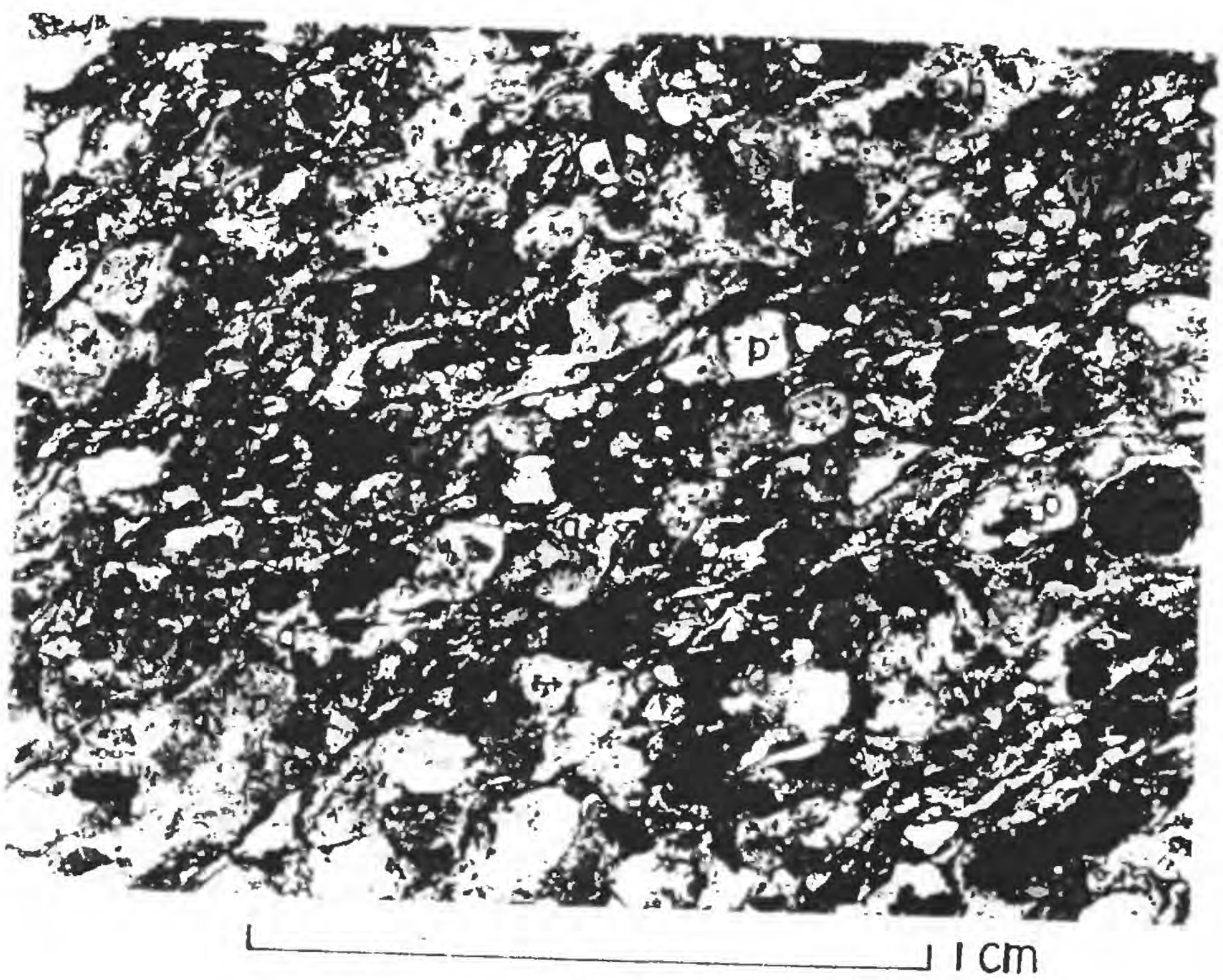

B

Plate 16

Photomicrographs of specimen from the B member of the Marlboro Formation exposed 600 feet west of Bedford St.-Lexington St. intersection, Burlington. q, quartz; p, plagioclase; h, hornblende. Quartz occurs entirely as a very—fine-grained mosaic within lenticular pods. Hornblende crystals commonly as large as plagioclase grains. A. Plane light. B. Crossed nicols.




A




B

series of photographs display features attributed by the writer to mylonitization or cataclasis. In large measure, then, this entire belt currently is thought to be composed of mylonites, phyllonites, augen schists or gneisses, blastomylonites, flaser gneisses, cataclasties, or otherwise sheared rocks.

The rocks within the Marlboro belt show several generally megascopic structural features (not all of which lend themselves to photography) suggestive of mylonitization or shearing. Many of the more leucocratic, siliceous rocks show the thin, very regular, varve-like layering of the typical hartschiefer. The layered nature of these rocks is shown faintly in the photomicrographs in plates 6A and 15, but it is much more conspicuous in hand specimen. The hartschiefer mylonites are particularly prominent along the northern edge of the Marlboro belt north of Reading center, and along a zone trending north-northeast, about one mile west of Mishawum Lake. Still another megascopic characteristic suggestive of shearing is the typical lensing in and out of lithologies on all scales. This feature may be seen in outcrop scale in plate 4. A common characteristic of mylonites, and one displayed by the Marlboro rocks, is foliation defined by lenticular feldspar grains together with "tails" of smaller grains strung out from the larger porphyroclasts. This feature is well illustrated in plate 5B. The fact than many of these rocks are compositionally layered does not mitigate against a mylonitic origin nor argue for a primary bedded origin for these structures (see, for example, Hsu, 1955, p. 340-343 and Christie, 1963, p. 428-429).

The nature of many of the porphyroclasts is suggestive of a mylonitic or sheared origin. The clasts almost without exception are composed of individual crystals rather than lithic fragments; several small zones containing polymineralic clasts have been found within these rocks, but they generally have been traceable over a few feet into apparently synkinematic dikes or sills. The clasts consist chiefly of twinned feldspar and in no case of quartz; the coarsest-grained quartz observed in this entire belt is shown in plate 9. These considerations tend to refute the notion that the clasts are arenaceous features and make it very unlikely that they are recrystallized amygdules or phenocrysts. Many of the clasts are fractured and bent, and some are so broken up that it is with difficulty that the separate pieces are recognized as having once belonged to the same grain. Various evidences of strain in the porphyroclasts are illustrated in plates 8, 10, 11, and 13.

The quartz fabric throughout much of the Marlboro Formation exposed east of Lincoln is strongly suggestive of mylonitization and/or recrystallization in a strongly anisotropic stress field. Quartz everywhere is substantially finer-grained than other non-micaceous phases, commonly flattened in the foliation plane, and less strained than quartz in adjacent, apparently less highly sheared rocks. These features are compatible with a hypothesis outlined to the writer by J. M. Christie (1962, oral communication) to the effect that quartz is more susceptible to granulation and recrystallization (neomineralization) than many other mineral phases. Thus, some of the effects of strain, such as undulatory extinction, are less apparent here than in less intensely deformed rocks. In other words, in an environment of pronounced shear, quartz may be in an anomalous prograde metamorphic state, while other phases, such as feldspar, are in the process of breaking down mechanically. The probability of intense shear is suggested in still another way by the almost classic quartz tectonite fabric locally manifested by the statistical orientation of c-axes. The preferred orientation of the optic axes is striking when viewed under the microscope with the quartz wedge or gypsum plate inserted, but it is apparent even in the photomicrographs in plates 7A, 9, and 11A.

Still another feature suggestive of mylonitization or shearing is the incipient development of a retrograde metamorphic facies in many of these rocks. While mineral assemblages throughout much of the Marlboro Formation show that these rocks have been metamorphosed to at least the almandine amphibolite facies, most of these same rocks contain phases of the greenschist facies, apparently the retrograde products of the higher grade assemblages.

Lastly, a comparison of the photographs in plates 4 through 16 with (1) those of rocks from undisputed mylonite zones and (2) those of experimentally sheared rocks (see Hsu, 1955, p. 334-347; Christie, 1960, pl. VII-VIII; Griggs, Turner, and Heard, 1960, pl 2 and 6; Christie, 1963, p. 436-439) is demonstrative of the sheared nature of the rocks described here.

## Correlation and age relationships of the Westboro-type quartzite and Marlboro Formation

It is probable that most of the rocks mapped with the Marlboro Formation are actually correlative with the Marlboro of the type locality. The Marlboro Formation has been traced without apparent interruption from its type area in the town of Marlboro eastward as far as Burlington, a distance of approximately 20 miles. There is in addition considerable lithologic similarity between the eastward extension of the Marlboro Formation and that of the type locality. However, correlation of the Westboro-type quartzite and the separately mapped members of the Marlboro Formation with equivalent rocks elsewhere, is a more difficult and perhaps insoluble problem. The problem arises in part from locally poor exposure and in part from the heterogeneous lithology of the Marlboro Formation, but in the writer's view it is attributable primarily to the deformed and commonly intensely sheared nature of these units. The problem is complicated further by the fact that rocks intrusive into the Marlboro probably have been included with it, owing to difficulties in distinguishing between sheared rocks of intrusive and non-intrusive origin. Because of the locally intense deformation, geometric relationships among the separately delineated units may have little or no stratigraphic significance, and age relations among units remain tentative. A possible explanation of the structural evolution of this belt (and the consequent stratigraphic complexities) is considered in the section on structural geology. Three generalized interpretations of the stratigraphic sequence within the Westboro-Marlboro section of northeastern Massachusetts are given in table 5.

The Westboro Quartzite cannot be traced continuously from its type locality to exposures in the Reading quadrangle or elsewhere in the metropolitan Boston area. As indicated earlier, Emerson adopted the procedure of mapping as Westboro any of those areas in which quartzite was "sufficiently preponderant to give character and a name to the mass as a whole." The typical association of the Marlboro Formation with large masses of Westboro-type quartzite elsewhere in central Massachusetts and Rhode Island, makes this a reasonable approach, but it is suspected that stratigraphic relationships between the Marlboro Formation and "Westboro" Quartzite are not everywhere the same. Emerson

Table 5. Stratigraphic interpretations of the Westboro-Marlboro section (as defined in this report) in this area and two adjacent areas

This area

| | | |
|---|---|---|
| Marlboro Formation | A member | Chloritic-quartzose schists (not separately mapped) |
| | | Largely amphibolites, schists, and interbedded quartzites; transitional with B member of Marlboro Formation |
| | Porphyroblastic gneiss member | Interlayered porphyroblastic gneiss and plagioclase amphibolite |
| | B member | Largely quartzo-feldspathic gneisses |
| Westboro-type quartzite | Chiefly massive quartzite | |

Salem quadrangle (after Toulmin)

| | | |
|---|---|---|
| Marlboro Formation | Chloritic schists<br>Amphibolites (locally developed) | |
| | Unit B | Interlayered porphyroblastic gneiss and plagioclase amphibolite (equivalent of porphyroblastic gneiss member of this area) |
| | Unit A | Plagioclase amphibolite |

Table 5. (cont.)

Boston area (after LaForge)

| | |
|---|---|
| Woburn Formation | Chiefly interbedded siliceous sediments and siliceous volcanics (probably equivalent in part of chloritic-quartzose schists of A member of Marlboro Formation of this area) |
| Marlboro Formation | Chiefly gray, green, and brown schists |
| Westboro Quartzite | Chiefly light colored quartzite |
| Waltham Gneiss | Complex of gneisses of several sorts (probably equivalent of B member of Marlboro Formation of this area) |

(1917, p. 24) concluded, apparently on the basis of areal relations with the supposedly Archean Northbridge Granite-Gneiss, that the Westboro Quartzite was older than the Marlboro Formation; recent investigations in Rhode Island, however, suggest that the relationships between the two formations are somewhat complicated. Quinn, Ray, and Seymour have reintroduced the term Blackstone Series for the rocks in Rhode Island shown on Emerson's map (1917, pl. X) as Westboro Quartzite and Marlboro Formation; Emerson's usage has been "abandoned in the Pawtucket quadrangle because the interpretation of the stratigraphy and structure (indicates that) the Westboro is not at the base of the sequence." The writer, therefore, prefers to identify the quartzite in this area as Westboro-type, rather than as the specific correlative of the Westboro Quartzite of the type area.

What is defined here as the B member of the Marlboro Formation is essentially continuous with what LaForge (1932, p. 16-17, pl. 1) has called the Waltham Gneiss. The Waltham Gneiss is not shown as such on Emerson's geologic map of Massachusetts (see plate 2), but it is approximately coincident with the gneisses and schists of undetermined age (gn) cropping out in the towns of Woburn, Burlington, and Lexington. Bell (1948, p. 202-209) reexamined the Waltham Gneiss defined by LaForge and concluded that in the type locality and elsewhere it was simply part of the Marlboro Formation. Bell made one conspicuous exception to the above generalization, however, in introducing a "sheared granite" unit that occupies more or less the position of LaForge's Waltham Gneiss where it occurs in the town of Burlington. In the writer's view the B member is not clearly distinguishable from the rest of the Marlboro and should not now be defined as a separate formation. However, even though the B and A members are not clearly separable, the A member may have been thrust over the B member with the concomitant development of a broad, diffuse shear zone between the two units. Should this prove the proper interpretation, the B member, as LaForge suspected, may be correlative only in part (if at all) with the Marlboro Formation exposed elsewhere.

Most of what has been mapped here as the A member of the Marlboro is continuous along the strike with rocks mapped simply as Marlboro Formation by Emerson and LaForge. However, these earlier writers have delineated separate formations in two localities within what the writer has mapped with the A member.

Both Emerson (1917, pl. X) and LaForge (1932, pl. 1) show a band of Westboro Quartzite extending into Burlington center from the south. This band lies near the center of the Marlboro belt and is more or less continuous with several quartzite zones within the A member as mapped here. The main mass of Westboro-type quartzite, on the other hand, lies along the southern margin of the Marlboro belt and is not demonstrably correlative (on the basis of lithology or lithologic sequence) with the quartzite cropping out near Burlington center. Thus it is likely that the northwestern band of "Westboro Quartzite" mapped by Emerson and LaForge is simply one of several major quartzite zones within the Marlboro Formation.

LaForge (1932, p. 18) defined as the Woburn Formation a unit shown on his map (1932, pl. 1) as striking roughly northeast into the Wilmington quadrangle, immediately east of the eastern contact between the A and B members of the Marlboro Formation as shown in plate 1. According to LaForge (1932, p. 18) the Woburn Formation is composed of interbedded siliceous sediments and siliceous igneous rocks that are "well laminated and have frequently been taken for quartzite." LaForge shows the Woburn Formation where it enters the Wilmington quadrangle as approximately 1,000 feet in width with a minimum stratigraphic thickness of about 500 feet. This it may be, but if the Woburn Formation actually exists here, it is not composed chiefly of siliceous rocks. Along the northern extension of the Woburn zone as mapped by LaForge, the dominant rock type is amphibolite with which are associated subordinate amounts of black schists, and still lesser amounts of thinly laminated quartzose rocks; an example of the last is shown in plate 7. Bell (1948, geologic map) has limited the extent of the Woburn Formation to essentially the area of its type locality; he apparently recognized that the Woburn (as defined by LaForge) did not extend uninterruptedly into the Wilmington quadrangle. It is possible that LaForge's Woburn Formation is in part correlative with the chloritic-quartzose schists of the A member of the Marlboro Formation, for the siliceous rocks of the "Woburn" zone are similar to the relatively siliceous schists cropping out along the northern flank of the Marlboro belt. However, if the writer has correctly interpreted as mylonitic those textures shown in plate 7, it is probable that LaForge delineated a mylonite zone in attempting to map the Woburn Formation. Regardless of their origin, rocks of this lithology commonly are intercalated with other facies of the A member and cannot be conveniently delineated or separated; accordingly, they are assigned here to the undifferentiated A member of the Marlboro Formation.

Establishing the relative age of the Westboro-type quartzite and Marlboro Formation on the basis of local areal relationships has proved extremely difficult. Where it is exposed in Reading and Lynnfield, the Westboro-type quartzite appears to dip beneath the Marlboro Formation. South of this area, Bell (1948, p. 23) has noted "some evidence that the Westboro quartzite grades upward into dark colored chloritic quartz schist" that may be equivalent in part with the chloritic-quartzose schist in the Wilmington and Reading quadrangles. However, structural studies, described in detail in the section on major structures, suggest that the Westboro-type quartzite may overlie the Marlboro Formation along the overturned limb of a recumbent fold. It is equally possible (if not probable) that the Westboro-type quartzite is in fault contact with the A member of the Marlboro Formation. Owing to the lack of definitive criteria Emerson's views are retained and it is concluded tentatively that the Westboro-type quartzite is at the base of the Westboro-Marlboro section as it occurs in this area.

The age of the B member, relative to other units of the Marlboro and the Westboro-type quartzite, currently is indeterminate. LaForge (1932, p. 15-17) concluded on the basis of its appearance that the Waltham Gneiss was Archean, and thus underlay the Marlboro which he judged to be Algonkian. Limited structural evidence supports this view. Where they crop out in the towns of Burlington, Wilmington, Woburn, and Reading, the A and B members seem to define crudely a large overturned fold. Analysis of the available structural data suggests that this fold plunges to the east-northeast and that the A member, in a geometric sense at least, overlies the B member. However, as the B and A members may be in fault contact, geometric relationships between the two are not necessarily definitive.

Toulmin (1958, written communication) concluded from his studies in the Salem quadrangle that the porphyroblastic gneiss member lay beneath the chloritic schists and relatively pure amphibolites of the Marlboro Formation (see table 5). Accordingly, the porphyroblastic gneiss member may be in part correlative with the B member of the Marlboro. Owing to the generally sheared nature of the B member the possible equivalence of the two cannot be demonstrated simply by lithologic comparison.

Emerson (1917, p. 24) considered the Westboro Quartzite and Marlboro Formation to be Algonkian because (1) they rest "apparently unconformably, upon the Northbridge granite gneiss" that he believed to be Archean, and (2) in accordance with a suggestion of Woodworth and LaForge, the Marlboro at least "abounds in volcanic rocks, whereas the Cambrian along the Atlantic seaboard is generally free from volcanic rocks." LaForge (1932, p. 19) observed in addition that the fossiliferous Cambrian rocks of the Boston area are lithologically dissimilar and much less intensely metamorphosed than the Westboro-Marlboro group. Thus he also assigned this group to the Precambrian (op. cit., p. 15).

Hansen (1956, p. 12-14) has discussed in detail the validity of the above suggestions and has concluded that the assignment of a Precambrian age to the Westboro-Marlboro group is tenuous at best. However, Hansen's doubts stem chiefly from his conviction that the adjacent Nashoba Formation is Carboniferous in age, yet seemingly conformable with the Marlboro. Toulmin (1957, written communication), on the other hand, has shown that what is mapped as Marlboro

Formation in the Salem quadrangle probably is overlain unconformably by fossiliferous strata of Late Silurian age. Furthermore, the Milford Granite intrudes the Marlboro-Westboro group (Emerson, 1917, p. 165); Emerson (op. cit., p. 164) considered the Milford a Devonian rock on the basis of its field relationships, and recent radioactive age determinations indicate that it has an average (minimum) age of 355 million years (Webber, Hurley, and Fairbairn, 1956, p. 580). The above considerations almost surely rule out the possibility of a Carboniferous age and suggest that the bulk of the Marlboro Formation is Middle Silurian or older. As a further refinement it is likely, but not directly provable, that the Marlboro pre-dates the Merrimack Group of probable Middle Silurian age (see section on Boxford Formation).

The establishment of a maximum age limit for the Westboro-Marlboro group is an even more difficult problem. Abundance of volcanic rocks and intensity of metamorphism are considered insufficient evidence of the age assigned by earlier workers. Moreover, a maximum age of Late Cambrian is implied by a recent Rb-Sr whole-rock radiometric date of 535±15 million years for the supposedly underlying Northbridge Granite-Gneiss (Moorbath et al., 1962, p. 7). L. R. Page (1962, written communication) has concluded that the lithologic nature of the Marlboro suggests a correlation with dated Ordovician rocks in New Hampshire. Page's interpretation is probably correct, though currently unprovable, and the Westboro-Marlboro group is assigned tentatively to the Ordovician.

## Metamorphic rocks near Hawkes Pond

A unique group of metamorphic rocks crops out near Hawkes Pond in Saugus and Lynnfield. The unnamed rocks described below occupy two narrow bands; one along the northeast shore of Hawkes Pond in Lynnfield and the other near the southern end of the pond in Saugus. It is possible or probable that these rocks are correlative with the Marlboro Formation, but they are considered separately owing to their isolated situation and unique character.

Exposures along the northeast shore of Hawkes Pond consist largely of medium- to dark-gray, fine-grained, porphyroblastic hornfels and thinly layered gneiss. The more conspicuous and massive hornfels are composed chiefly of quartz, plagioclase, biotite, cordierite, and garnet. An estimated mode is presented in table 6. The composition of the hornfels leaves little doubt that it has been derived through metamorphism of a relatively aluminous sediment. No thin sections were made from the thinly layered gneiss, but it appears to be highly quartzose.

Outcrops along the south shore of Hawkes Pond consist chiefly of calc-silicate rock. The color of the calc-silicate rock ranges from medium to light gray, but the

Table 6. Estimated modes of metamorphic rocks at Hawkes Pond

| | A. | B. |
|---|---|---|
| Quartz | | 40 |
| Plagioclase | 45 | 30 |
| Tremolite-actinolite | 28 | |
| Diopside | 17 | |
| Biotite | 3 | 13 |
| Chlorite | 2 | |
| White mica | 3 | 2 |
| Carbonate | 2 | |
| Cordierite | | 10 |
| Garnet | | 5 |
| Opaque | tr. | |

A(R-154). Calc-silicate rock 300 ft. south-southeast of intersection of Newburyport Turnpike with Saugus-Lynnfield town line

B(R-158). Hornfels along northeast shore of Hawkes Pond 1000 ft. north of Saugus-Lynnfield town line lighter varieties predominate. Layering, though irregular, is much more conspicuous and the rocks are generally coarser grained than the hornfelses to the north. The calc-silicate rocks are composed of andesine, actinolite, diopside, biotite (in part altered to chlorite), and minor amounts of pyrite, calcite, and magnetite. An approximate mode is given in table 6. Tremolite-actinolite and diopside together compose from 40 to 50 percent of the rock and it is reasonably certain that the rock has been derived through metamorphism of a marl or impure limestone.

The mineral assemblages of the Hawkes Pond rocks may have arisen in response to regional metamorphism. However, these rocks have been subjected to at least two separate periods of intrusion, and the assemblages are roughly comparable with those of pelitic rocks of the hornblende hornfels facies described by Fyfe, Turner, and Verhoogen (1958, p. 201-207). It is probable, therefore, that the Hawkes Pond rocks are the products of contact metamorphism.

Clapp (1921, p. 18) has discussed briefly "hornfelses" cropping out in the towns of Lynn, Saugus, and Melrose. Within this group he has included "metamorphosed basic volcanic rocks (that) are common in the southern part of the county (Essex)," and which show by "their amygadaloidal texture and their occurrence as agglomerates" that "they are of volcanic origin." Volcanic or metavolcanic rocks have not been discovered within the belt of metamorphic rocks near Hawkes Pond.

## Boxford Formation

The Boxford Formation is here named for a group of prominently layered rocks cropping out in the South Groveland and Reading quadrangles; the name has been chosen because of the extensive development and good exposures of this unit in the town of Boxford (Castle, in review). The rocks assigned to the Boxford Formation are shown on Emerson's (1917, pl. X) preliminary map of Massachusetts as undifferentiated gneisses, Salem Gabbro-Diorite, or Marlboro Formation (see pl. 2). In this area the Boxford Formation forms a broad anticlinal belt trending generally northeast, but curving towards the southeast along the eastern edge of the South Groveland quadrangle. The belt is bounded on the south and west by plutonic rocks and abuts against rocks of the Merrimack Group to the north. A smaller patch of the Boxford Formation occurs in the southwest corner of the South Groveland quadrangle and extends a short distance into the Reading quadrangle, where it appears to be continuous with somewhat similar rocks of the Nashoba Formation. The main belt of the Boxford Formation locally has a maximum width of approximately three miles. Its thickness cannot be estimated with certainty owing to the facts that it is chiefly in contact with intrusive rocks and the amount of repetition is unknown; its maximum thickness probably exceeds 5,000 feet.

The best exposures occur in the upper member of the Boxford where the formation consists chiefly of thinly layered, very fine-grained rocks that range widely in composition from amphibolite to sericite schist. The extent of this compositional range is suggested by the approximate modes presented in table 7, and it is, in fact, textural and structural characteristics rather than composition that best define the rocks of the upper member. The dominant rock type of the lower member is not known with certainty, for exposures are scarce within this zone; mica schists and gneisses apparently achieve a greater prominence, and amphibolite seems markedly diminished.

Lower member

Quartz-mica schist is perhaps the major rock type within the lower member of the Boxford. It is generally bluish to purplish gray on fresh surfaces and weathers to a rusty-buff color. The schists are well to poorly laminated and generally possess a fine- to medium-grained hypidioblastic texture. They consist chiefly of muscovite, quartz, biotite, and aluminum-silicate phases (andalusite and fibrous sillimanite) and contain accessory amounts of plagioclase (oligoclase?), magnetite, and chlorite. An approximate mode is given in table 7.

Amphibolites occur locally in the lower member of the Boxford Formation, and are in part almost identical to the

Table 7. Estimated modes of rocks from the Boxford Formation

| | Lower member | | Upper member | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | A. | B. | C. | D. | E. | F. | G. | H. | I. | J. | K. |
| Quartz | 43 | 20 | | | 47 | 15 | | | 5 | 25 | 10 |
| Plagioclase | 47 | 5 | 20 | 30 | 30 | 19 | 60 | | 60 | | 4 |
| Microcline | | | | | 20 | | | | | | |
| Hornblende | | | 25 | 65 | 5 | | 16 | | | | |
| Tremolite | | | | | | | | | 14 | | |
| Actinolite | | | | | | | | 90 | | | |
| Diopside | | | 15 | | | | | | | | |
| Biotite | 8 | 20 | 25 | | 6 | | | | | 15 | |
| Chlorite | | | 3 | | | 15 | 2 | 5 | 3 | 2 | 6 |
| White mica | | 35 | | | | 45 | 7 | | | 37 | 63 |
| Epidote | | | | 1 | | | 3 | 2 | 4 | | |
| Sillimanite | | 8 | | | | | | | | 3 | 5 |
| Andalusite | | 10 | | | | | | | | 15 | 7 |
| Garnet | | | | | | 2 | | | | | |
| Apatite | | | | | | | 3 | | | | |
| Sphene | | | 4 | tr. | 1 | | 5 | | 6 | | |
| Carbonate | | | 8 | | | | 2 | | | | |
| Opaque | 2 | 2 | | 4 | 1 | 4 | 2 | 3 | 8 | 3 | 5 |

A(R-199). Quartz-feldspar gneiss along Andover Bypass 2000 ft. north-northeast of Rocky Hill Rd.-Andover Bypass intersection, Andover

Table 7. (cont.)

B(G-210). Quartz-mica schist near crest of knoll 1900 ft. northwest of Pine Plain Rd.-Willow Rd. intersection, Boxford

C(G-19). Thinly layered calc-silicate gneiss 2300 ft. north-northwest of Washington St.-Willow Rd. intersection, Boxford

D(G-20). Amphibolite 2800 ft. north-northeast of Washington St.-Main St. intersection, Boxford

E(G-170). Thinly layered quartz-feldspar gneiss 3200 ft. south-southeast of Washington St.-Uptack St. intersection, Groveland

F(G-171). Mica schist 2500 ft. southeast of Washington St.-Salem St. intersection, Groveland

G(G-682). Thinly layered gneiss at northern tip of Towne Pond, Boxford

H(G-63). Actinolite schist from inlier of Boxford Formation near Brooks School, North Andover

I(G-42). Fine-grained gneiss 2000 ft. east-southeast of summit of Byers Hill, Boxford

J(G-42). Mica schist 2000 ft. east-southeast of summit of Byers Hill, Boxford (interlayered with I)

K(G-823). Sericite schist 2200 ft. north-northeast of Salem St.-Summer St. intersection, North Andover thinly layered, fine-grained varieties that occur higher in the section. However, a relatively coase-grained amphibolite, dissimilar to any that occurs in the upper member, is exposed in a zone along Nelson Street north of Baldpate Pond. The amphibolite in this zone is fine to medium grained, and possesses a poorly defined porphyroblastic texture. It is essentially uniform in appearance and composition throughout the area of its occurrence, and it is not transitional with the rocks immediately above or below. It is composed almost entirely of approximately equal amounts of plagioclase and hornblende and contains small amounts of an unidentified talc-like mineral.

Gneissose rocks, tentatively assigned to the lower member, occur in the extreme northwest corner of the Reading quadrangle and southwest corner of the South Groveland quadrangle. Where best exposed, this group of rocks consists of an interbedded series of white- to medium-gray quartz-plagioclase gneiss and markedly subordinate amphibolite. The gneiss is composed of plagioclase (albite to sodic oligoclase), quartz, and varietal amounts of biotite, actinolite, and chlorite. An approximate mode is given in table 7 and chemical and modal analyses are presented in table 8. The interbedded amphibolites are impure varieties that might be described more properly as plagioclase-hornblende schists.

The lower member of the Boxford Formation apparently

Table 8. Chemical analyses, norms, and modal analyses of rocks from the Boxford Formation

Chemical analyses[1/] [2/]

| | Lower member | Quartz-plagioclase gneiss member | Upper member |
|---|---|---|---|
| | A. | B. | C. |
| $SiO_2$ | 75.8 | 74.5 | 45.4 |
| $Al_2O_3$ | 12.9 | 13.9 | 16.2 |
| $Fe_2O_3$ | .6 | .6 | 1.9 |
| FeO | 2.5 | 2.0 | 10.6 |
| MgO | 1.0 | 1.1 | 5.9 |
| CaO | .86 | .13 | 10.6 |
| $Na_2O$ | 4.6 | 6.0 | 3.3 |
| $K_2O$ | .65 | .80 | .27 |
| $TiO_2$ | .26 | .19 | 3.0 |
| $P_2O_5$ | .06 | .04 | .55 |
| MnO | .06 | .04 | .18 |
| $H_2O$ | 1.1 | .88 | 1.2 |
| $CO_2$ | <.05 | .06 | <.05 |
| Sum | 100 | 101 | 99 |

Table 8. (cont.)

Norms[2/]

| | A. | B. | C. |
|---|---|---|---|
| Quartz | 41.67 | 33.40 | |
| Corundum | 3.16 | 3.06 | |
| Orthoclase | 3.89 | 5.01 | 1.67 |
| Albite | 38.79 | 51.40 | 28.29 |
| Anorthite | 4.18 | .28 | 28.92 |
| Wollastonite | | | 8.59 |
| Enstatite | 2.51 | 2.81 | 1.91 |
| Ferrosilite | 3.82 | 3.03 | 1.73 |
| Forsterite | | | 9.08 |
| Fayalite | | | 9.08 |
| Magnetite | .93 | .93 | 2.78 |
| Ilmenite | .46 | .30 | 5.77 |
| Apatite | | | 1.34 |
| Calcite | | .10 | |
| Sum | 99.41 | 100.32 | 99.16 |

Table 8. (cont.)

Modal analyses[3/]

| | A. | B. | C. |
|---|---|---|---|
| Quartz | 34.4 | 28.6 | |
| Plagioclase | 52.8 | 62.2 | 31.6 |
| Hornblende | | | 59.0 |
| Biotite | 10.2 | .4 | .7 |
| Chlorite | .8 | 8.0 | .3 |
| White mica | 1.4 | | 1.0 |
| Epidote | | .5 | .2 |
| Apatite | | | .2 |
| Zircon | | tr. | |
| Opaque | .2 | .2 | 7.0 |

A(C-4). Quartz-plagioclase gneiss west side of highway 1800 ft. north-northeast of Gould Rd.-Andover Bypass intersection, Andover. Points counted: 500. Plagioclase composition $An_{12\pm4}$

B(C-7). Quartz-plagioclase gneiss 2300 ft. N35°W of Bailey Lane-Andover St. intersection, Georgetown. Points counted: 1000. Plagioclase composition $An_{5\pm4}$

C(C-8). Amphibolite south side of Ipswich Rd., 1600 ft. west-northwest of Herrick Rd.-Ipswich Rd. intersection, Boxford. Points counted: 1000. Plagioclase composition $An_{45\pm4}$

Table 8. (cont.)

1/ U. S. Geological Survey Rapid Rock Analysis Laboratory

2/ All figures weight percent

3/ All figures volume percent

has been derived from a series of interbedded volcanics (amphibolites) and argillaceous to impure arenaceous sediments (quartz-mica schists and quartz-plagioclase gneiss).

## Quartz-plagioclase gneiss member

A distinctive quartz-feldspar gneiss marker crops out near the middle of the Boxford section exposed in this area. Exposures of the gneiss are poor, but the unit is sufficiently unique to warrant its separation from the rest of the formation. It is possible or even likely that the quartz-plagioclase gneiss member represents the development of a facies equivalent of the comparably positioned gneissic rocks of the lower member. However, as the two groups of rocks apparently are discontinuous along the strike, no attempt is made here to correlate one with the other.

The only exposures of the gneiss member in the map area occur just south of Rock Pond in Georgetown and south of Baldpate Pond in Boxford. Insofar as may be determined from the few exposures present, the gneiss is structurally conformable with the adjacent Boxford Formation throughout its extent. Its outcrop belt has a maximum width of about 2,000 feet and a maximum thickness of about 1,000 feet; these figures may be excessive by a factor of two, however, as the base of the member cannot be located with precision.

The quartz-plagioclase gneiss is uniformly pearly white to very light gray on fresh surfaces, and weathers to a dull, chalk-white color. It is distinctly foliated, but unlike other units of the Boxford Formation, it is generally unlayered. It has a granoblastic, generally fine-grained, but somewhat coarser texture than most of the rocks of the Boxford Formation. It is composed chiefly of albite and quartz with minor amounts of chlorite, apparently derived from the alteration of biotite. No other minerals, except a few tiny grains of apatite, zircon, and magnetite or ilmenite, were evident in thin section. Quartz composes up to 35 percent, chlorite makes up about 8 percent, and the remainder of the rock is composed of very sodic plagioclase that has a maximum An content of about $An_{10}$. Chemical and modal analyses of a specimen from the quartz-plagioclase gneiss member are given in table 8.

The origin of the rock is difficult to explain owing to its anomalously high soda content, but its chemical composition is perhaps more suggestive of a sodic dacite than an argillaceous to arenaceous sediment. The calculated norm (see table 8) is close to that of a normal trondhjemite, and it is not unlikely that the rock was derived from a trondhjemitic extrusive.

### Upper member

Rocks exposed in the upper member of the Boxford Formation include schist, gneiss, calc-silicate rock, amphibolite, quartzite, and a host of other intermediate types (see table 7). The majority of the rocks are compositionally gradational between two or more petrologic "end members," and there is consequently a remarkable amount of mineralogic heterogeneity within a stratigraphic thickness of about 4000 feet. Amphibolites are perhaps the commonest rocks of the upper member; they are transitional with other facies both along and across the strike. As the amphibolites are in part separately delineated they are discussed separately, but they are by no means confined to the individually mapped amphibolite zones.

## Amphibolite

The amphibolites of the upper member of the Boxford Formation apparently are everywhere intergradational with other rocks. Locally, however, it has proved practicable to map amphibolite units separately. These units have been delineated only where amphibolite is dominant and conspicuous within a mappable group of exposures.

The amphibolites range from black to gray and generally possess a faint greenish tint. They are uniformly thinly layered with laminae ranging from a fraction of a millimeter to several centimeters in thickness. Their textures are without exception very fine grained and generally hypidioblastic. The amphibolites range in composition from almost monomineralic hornblende rocks to quartz-hornblende-plagioclase schists or gneisses. Layers containing virtually nothing but hornblende commonly are intimately intercalated with others that contain very little hornblende. However, where the rock as a whole is composed chiefly of amphibolite or plagioclase amphibolite layers, the entire rock is considered an amphibolite. The composition of the plagioclase is difficult to determine owing to its very fine-grained nature, but where measurements were made it ranged from very sodic to calcic andesine. Epidote is a common but minor accessory mineral in the amphibolites. Calcite composes up to two percent of some of the specimens, but it is apparently a secondary product. Magnetite, chlorite, sphene, and apatite occur as minor constituents. Chemical and modal analyses of an amphibolite from the Boxford Formation are presented in table 8.

The origin of the amphibolites is obscure. There is no positive evidence favoring their derivation from either limy sediments or basic volcanic rocks. Limestones are unknown in the Boxford Formation, but calc-silicate rocks are not uncommon. Thus it might be supposed that metamorphism of a marl or siliceous limestone would produce a rock more in keeping with the mineralogical composition of the observed calc-silicate rocks, rather than the amphibolites. If the amphibolite has been derived from a relatively mafic volcanic, its chemical composition (see table 8) should approximate that of an average andesite or basalt (see table 9). The compositions of the amphibolite and average andesite differ chiefly in their silica and potash content, and

Table 9. Chemical and normative compositions of andesite and basalt. Computed from analyses given in Data of Geochemistry (Washington, 1924)

Chemical compositions[1/]

| | A. | B. |
|---|---|---|
| $SiO_2$ | 55.82 | 50.90 |
| $Al_2O_3$ | 16.49 | 16.23 |
| $Fe_2O_3$ | 3.25 | 3.31 |
| FeO | 3.78 | 6.44 |
| MgO | 4.53 | 7.01 |
| CaO | 6.51 | 8.58 |
| $Na_2O$ | 3.51 | 2.99 |
| $K_2O$ | 3.04 | 1.80 |
| $H_2O$ | 1.74 | 1.36 |
| $TiO_2$ | .63 | 1.00 |
| $ZrO_2$ | .01 | |
| $P_2O_5$ | .35 | .40 |
| $V_2O_3$ | .02 | |
| MnO | .17 | .14 |
| NiO | .01 | .01 |
| BaO | .13 | .06 |
| SrO | .04 | .03 |
| $Li_2O$ | tr. | tr. |
| $FeS_2$ | .02 | .02 |
| $SO_3$ | | .01 |
| Cl | | .02 |

Table 9. (cont.)

Normative compositions1/ 2/

| | A. | B. |
|---|---|---|
| Quartz | 5.1 | 1.9 |
| Orthoclase | 18.0 | 8.6 |
| Albite | 29.7 | 24.0 |
| Anorthite | 20.1 | 26.0 |
| Nephelite | | .6 |
| Diopside | 8.8 | 12.1 |
| Hypersthene | 7.5 | 8.2 |
| Olivine | 2.5 | 7.7 |
| Magnetite | 3.7 | 4.8 |
| Hematite | .7 | |
| Ilmenite | 1.1 | 1.9 |
| Apatite | .5 | .6 |

A. Average of 6 analyses of andesite given by Washington (1924, p. 458)

B. Average of 7 analyses of basalt given by Washington (1924, p. 460-461)

Table 9. (cont.)

1/ All figures weight percent

2/ Normative phases employed here differ from those used elsewhere in report primarily in the femic group. Diopside and hypersthene are used here in place of wollastonite, enstatite, and ferrosilite, and olivine is used in place of forsterite and fayalite less markedly in the amounts of line and iron present. There is a much closer correspondence in chemical composition between the amphibolite and the average basalt. If the oxidation state of the iron is disregarded, and it is assumed that the parent rock was somewhat less siliceous and potassic than the average, it is tempting to conclude that the amphibolite has been derived from a basalt. However, the thinly laminated and compositionally transitional nature of many of the amphibolites does not accord fully with this explanation. Basalts are characteristically laid down as flows rather than pyroclastic deposits, and it is improbable that metamorphism of a series of flows would produce a group of rocks of the type described. If, however, these rocks have been subjected to appreciable metamorphic differentiation, silica, potash, and perhaps soda, may have been subtracted from a generally more andesitic and partly tuffaceous parent during metamorphism. In spite of the anomalies alluded to above, the compositional similarities are sufficiently pronounced to lead one to conclude that the amphibolites probably have been derived from a series of basalts locally admixed with more felsic volcanics.

### Undifferentiated upper member

The undifferentiated upper member of the Boxford Formation consists in large part of amphibolite, but a number of other rock types are represented as well. Owing to the uniformly very-fine-grained nature of these rocks, accurate field estimates of bulk composition could not be made, but amphibolites or amphibolitic rocks are probably dominant even in the undifferentiated parts of this unit.

Layers of true calc-silicate rock occur in parts of the upper member, but they were not separately mapped nor even recognized as such in the field. Inasmuch as calc-silicate rocks generally were not identified in the field, it is difficult to estimate the extent of their occurrence within the upper member. It would appear from a moderately systematic sampling that they comprise no more than 10 percent of the unit. Rocks here classed as calc-silicates have a wide mineralogical range, but their bulk chemical composition (except for variations in the inferred amounts of iron and magnesium present) is restricted within fairly narrow limits.

The calc-silicate rocks generally are light to medium gray and commonly thinly layered by color or mineralogical composition. They are extremely fine grained and locally almost aphanitic. The less siliceous rocks within this group commonly manifest a well developed hypidioblastic texture, whereas the more siliceous specimens present a typical granoblastic appearance.

The only phase apparently common to all of the rocks here classed with the calc-silicates is andesine. Amphiboles ranging from tremolite to actinolitic-hornblende are only slightly less prominent. Diopside commonly is associated with this facies and locally composes up to 20 percent of the rock; in those specimens in which diopside does not appear tremolite is generally a conspicuous constituent. Biotite-plagioclase schists are locally interlayered with laminae composed of more typical calc-silicate assemblages. Calcite occurs in many of the calc-silicate rocks, particularly those that contain quartz. Common accessory minerals include epidote, sphene, sericite, and pyrite.

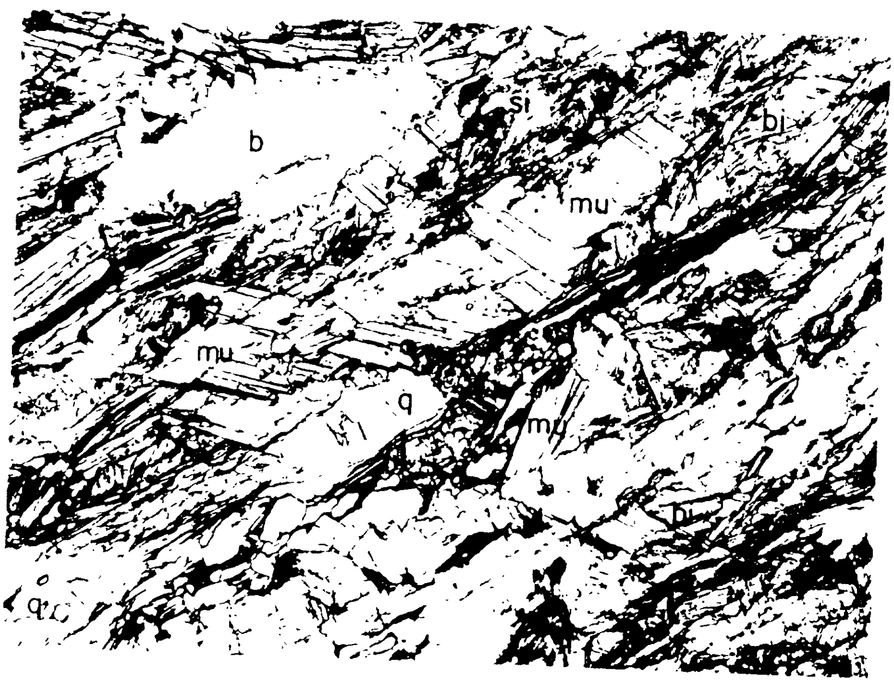
Sericite schists and gneisses occur to a limited extent in the upper member of the Boxford. These rocks generally are found in zones several tens of feet to a small fraction of an inch in thickness. The more gneissic varieties are thinly laminated, and all but those adjacent to granitic contacts (see plate 17) are fine to ultra fine grained. They range from very light greenish gray to almost white on fresh surfaces, and characteristically weather to a rusty-yellow color. The dominant mineral species in these rocks is sericite, but it is commonly inconspicuous in hand specimen, even where it is extensively developed. Microcline composes from 10 to 30 percent of many of the samples, and small amounts of quartz were observed locally. Sillimanite is a common constituent of the mica schist, but it generally makes up no more than a few percent of the rock. Clinozoisite or epidote, sphene, and andalusite occur locally. Other rocks within the upper member of the Boxford, megascopically

Plate 17

A. Photomicrograph of specimen from the upper member of the Boxford Formation exposed 700 feet east-southeast of Pond St.-Lake Shore Rd. intersection, West Boxford. q, quartz; mu, muscovite; bi, biotite (altering to chlorite); a, andalusite; si, fibrolitic sillimanite. This specimen taken from outcrop near the Boxford Formation-Andover Granite contact. Coarser grained and far more contorted than most rocks contained within the upper member of the Boxford. Plane light.

B. Photomicrograph of mica-quartz schist outlier of the upper member of the Boxford Formation; contained within the Andover Granite exposed along Great Pond Rd. south of Lake Cochichewick. mu, muscovite; bi, biotite; si, fibrolitic sillimanite; q, quartz; b, balsam. Note the development of micaceous cleavage in two distinct directions. Plane light.


A




B

identical with the sericite schist, are composed chiefly of quartz and albite.

The pronounced mineralogical heterogeneity of the upper member of the Boxford Formation is indicative of a complex depositional history. The chemical and mineralogical complexities may be partly attributable to the effects of an alternately transgressing and regressing sea. If this normal depositional effect has been coupled with intermittent volcanic activity, as is suggested by the abundant amphibolite, the petrologic complexity may be reasonably explained.

## Metamorphism

The common occurrence of sillimanite within many of the more pelitic units (see table 7) of the Boxford Formation suggests that these rocks locally have reached a metamorphic grade compatible with the sillimanite-almandine subfacies of the almandine amphibolite facies of Fyfe, Turner, and Verhoogen (1958, p. 228, 230-231). It is not certain, however, to what extent the presence of the higher grade assemblages may be attributed to contact phenomena, as opposed to the effects of a more general "regional" metamorphism. Miyashiro (1961, p. 306), for example, has found that synkinematic contact facies of the andalusite-sillimanite type are essentially identical to those developed through regional metamorphism of the same general area. Thus the widespread coexistence of andalusite and sillimanite (in which andalusite almost certainly pre-dates sillimanite) in this area, may suggest only that these rocks have been metamorphosed under relatively low pressure in response to a regionally developed rise in the isothermal surfaces (op. cit., p. 279-281, 285). All that can be said with reasonable certainty is that the preservation of andalusite makes it very unlikely that these rocks ever were subjected to pressures greatly in excess of 8 kilobars, whereas the ubiquitous occurrence of sillimanite would seem to demand that temperatures ultimately rose well above 300°C. (see figure 3).

## Correlation and age

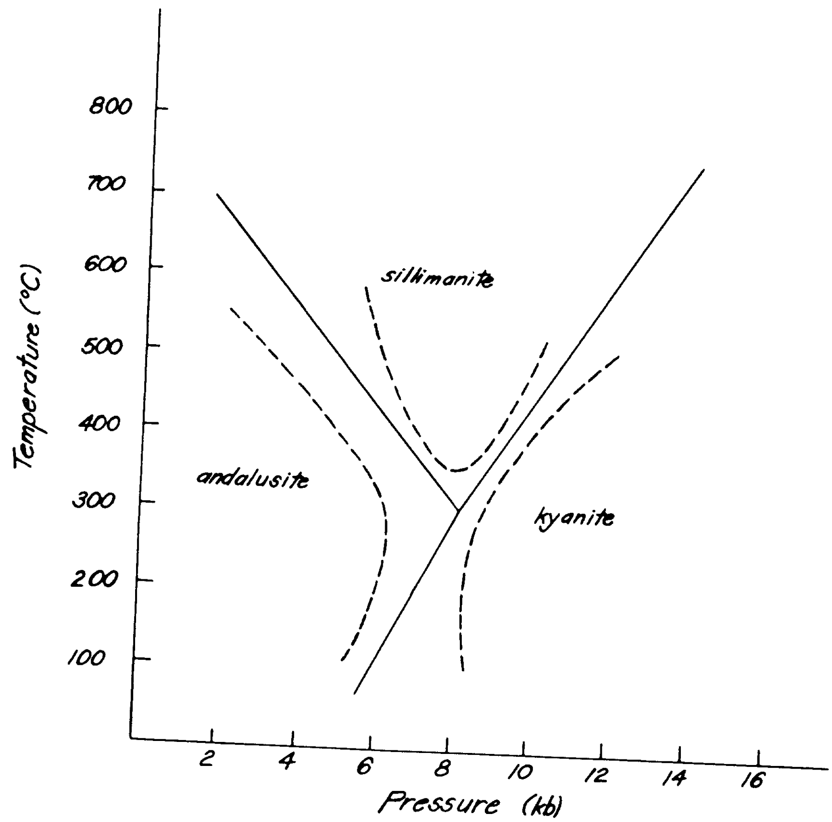
The Boxford is isolated from most of the other metasediments in the area; suggested correlations are consequently highly speculative.

The Boxford Formation cropping out in the northwestern corner of the Reading quadrangle is on strike with the adjacent Nashoba Formation, and it would be reasonable to conclude that the two are at least in part correlative. However, a comparison of their lithologies, and particularly their sequence of lithologies (see discussion of the Nashoba Formation), suggests that the Nashoba is either faulted against or unconformably overlies the Boxford.

Although it ultimately becomes lost in a complex of Paleozoic igneous rocks, the Boxford Formation strikes

Figure 3

Experimentally determined phase equilibrium relations in the aluminum silicate system. Dashed lines show probable limits of error (after Bell, 1963).


800
700
600
500
400
300
200
100
Temperature (°C)
sillimanite
andalusite
kyanite
2
4
6
8
10
12
14
16
Pressure (kb)

southwest toward the lithologically similar Marlboro Formation; the two formations accordingly may well be at least in part correlative. A direct demonstration of this suggested correlation should prove very difficult, however, as a pronounced structural discontinuity may separate the two units, and the extensive deformation of the locally occurring Marlboro precludes any detailed comparison of the two formations. There is, then, no positive evidence sustaining a correlation of the Boxford and Marlboro Formations, but their possible equivalence is at least consistent with the picture of the regional geology developed in the course of this investigation.

A nearby unit that bears a striking resemblance to the Boxford is the Rye Formation of southeastern New Hampshire. According to Billings (1956, p. 38-39) the Rye Formation consists of two members; the lower member is a metasedimentary unit and the upper member a metavolcanic unit containing amphibolite and fine-grained biotite gneiss. This description corresponds roughly with that of the Boxford Formation as described here. The writer has examined parts of the Rye Formation in detail and has noted a pronounced similarity between the rocks of the Rye area and those of the Boxford Formation. The most recent investigator of the stratigraphy of southeastern New Hampshire, R. F. Novotny, has inspected in company with the writer a number of typical exposures within the Boxford Formation; he concurs in the view that the two formations are possibly, if not probably, correlative (1957, oral communication). There are a number of minor lithologic differences between the two formations, but these differences may be attributed to facies changes between the separate areas. Indeed, there appear to be conspicuous facies changes within the Rye Formation itself (Novotny, 1957, oral communication), and there is some detectable lateral variation within the Boxford. Unfortunately the possible equivalence of the Rye and Boxford Formations probably will not be demonstrated through detailed areal studies, for they are separated by a large plutonic complex.

If the Boxford and Rye Formations are actually correlative, the Boxford is almost certainly pre-Devonian and probably pre-Silurian. According to Novotny (1957, oral communication), the Rye Formation conformably underlies the Merrimack Group where they occur together in southeastern New Hampshire. As the Merrimack Group is probably Middle Silurian (see discussion on the age of the Merrimack Group), the Rye (or Boxford) is probably Silurian or older. Although the Rye and Merrimack are apparently structurally conformable, the striking lithologic contrast between the two units suggests that they are not transitional. The writer, therefore, is inclined to the view that a disconformity exists between the two formations, and that the Rye is at least as old as Ordovician. (The Boxford Formation probably is in fault contact with the Merrimack Group where they occur together in the South Groveland quadrangle; there is accordingly little hope of confirming locally and directly the presumably pre-Middle Silurian age of the Boxford.)

The establishment of a maximum age for the Boxford (or Rye) is no less difficult than it is for the Marlboro. Katz (1917, p. 167-168) regarded the Rye Formation as an Algonkian(?) complex. He based this view, however, on the "areal relations and the similarities in lithology and association of the rocks in Rye and Portsmouth, N. H. to those of the Algonkian(?) in eastern Massachusetts." The Marlboro Formation is typical of the rocks then (1917) considered Algonkian. If the Marlboro is not Precambrian but Ordovician, and if the Boxford and Marlboro are in part correlative, as seems likely, the Boxford is Ordovician as well and is so considered here.

## Brimfield-type schist

Schistose rocks similar in part to those described as Brimfield Schist by Emerson (1917, p. 68-72), are distributed somewhat erratically over the map area. Where they occur locally these rocks consist chiefly of quartz-mica (or sericite) schist together with markedly lesser amounts of biotite schist and amphibolite. The position in the regional framework of what is mapped here as Brimfield-type schist currently is in doubt, and stratigraphic relationships among the locally discontinuous segments are obscure. For these reasons and because exposures of this unit are exceedingly poor, these rocks are referred to in a tentative manner as "Brimfield-type." The probable relationships of the Brimfield-type schist to adjacent units and the type Brimfield, are considered under the heading of correlation and age of the Brimfield-type schist and Nashoba Formation.

The Brimfield-type schist within the map area occurs in five general locals: (1) in a lenticularly shaped area in Marlboro center where it is apparently conformable with the adjacent Marlboro Formation; (2) in an east-northeast trending belt in Sudbury, Concord, and Lincoln where it again is apparently conformable with the Marlboro Formation; (3) in a belt extending northeast from Carlisle through Billerica center into Tewksbury; (4) in a series of more or less continuous exposures along the south shore of the Merrimack River between Lawrence and Lowell; (5) in a group of discontinuous inliers surrounded by the Andover Granite. The first two listed occurrences have not been studied by the writer and their descriptions are necessarily cursory.

The Brimfield-type schist cropping out in Marlboro center apparently is typical of the Brimfield facies, in that Emerson (1917, p. 69) has not suggested that it departs noticeably from the "coarse, red-brown muscovite schist" characteristic of this unit. These particular rocks, however, may contain in addition appreciable amounts of cordierite and sillimanite as these phases commonly are developed within the Brimfield where (as in Marlboro center) it has been intruded by granite (Emerson, 1917, p. 69). Where they occur in Lincoln, Concord, and Sudbury the Brimfield-type rocks consist of "rusty weathering, hematitic, quartz-sericite-biotite schists" locally interbedded with "fine-grained, thinly bedded amphibolite" (N. P. Cuppels, 1962, written communication). According to Cuppels the schist in Concord and Lincoln is also characterized by the local development of feldspar and eyes of barren quartz. The western reach of this mica schist belt has been included with the Marlboro Formation by Hansen (1956, p. 8-9), but its description and position are such that it is almost certainly continuous with the Brimfield-type schist mapped in Concord and Lincoln by Cuppels.

The Brimfield-type schist mapped or studied by the writer (i.e., that occurring in localities 3, 4, and 5) consists chiefly of several varieties of muscovite schist. Fresh exposures of sericite schist cropping out along the Merrimack River are generally silvery white or gray. The coarser-grained muscovite schists along the Concord River and within the small inliers in the granite, tend to be duller with locally developed green and yellow hues. Even where only moderately weathered the muscovite schists are conspicuously stained with iron oxide, and scarcely an exposure was seen in which the schists were not literally crumbling apart, with the concomitant development of a "punky" aspect.

The muscovite schists are generally foliated and commonly layered. Foliation in exposures along the south shore of the Merrimack River is flat to gently undulate, whereas that occurring elsewhere within the Brimfield-type schist is slightly to intensely contorted. Where foliation is developed within the isolated schist inliers in the Andover Granite, the generally warped surfaces are attributable or complementary to bulbous quartz lenses. Unequivocal bedding has not been recognized within the schist, but it is presumably parallel to layering defined by the contacts between amphibolite and mica schist, and possibly parallel to compositional layering within the schist itself. Within the sericite schist along the Merrimack River, the mica crystals commonly are oriented in two distinct directions at an angle of about 30 degrees with each other. Accordingly, there must exist at least an incipient foliation at a substantial angle with bedding. Other than bedding, the only possibly relict features observed within the schist consist of granule- to pebble-size knots of quartzite within a schist inlier in Andover center. The textures within the muscovite schist range from fine to medium grained and hypidioblastic to xenoblastic. Not surprisingly, the coarsest grained schists occur near the granite contacts.

The muscovite schists consist almost entirely of muscovite, quartz, plagioclase, and chlorite. Sillimanite, garnet, and biotite occur locally, and most specimens contain iron sulfides or oxides. Approximate modes are presented in table 11, and chemical and modal analyses are given in table 10. Quartz is almost completely absent in the sericite schist exposed along the Merrimack River, but it is abundant within other outcrops of the Brimfield-type schist. Sillimanite and garnet occur in the isolated schist inliers within the Andover Granite and probably occur within the belt cropping out along the Concord River, but the latter occurrence cannot be confirmed inasmuch as rocks from this zone have not been subjected to microscopic examination.

Highly biotitic rocks assigned to the Brimfield-type schist occur in two exposures within foliated granite cropping out in South Lawrence and in several exposures along the south shore of the Merrimack River near the western edge of the Lawrence quadrangle. The biotitic schists exposed in South Lawrence are prominently foliated, very fine grained, and almost phyllitic in appearance. They are composed chiefly of biotite together with lesser amounts of quartz and accessory ilmenite or magnetite. The biotite schist exposed along the Merrimack River consists of roughly equal proportions of plagioclase and biotite together with lesser amounts of sericite pseudomorphous after staurolite.

The mica schists clearly have been derived from a

Table 10. Chemical analyses, norms, and modal analyses of rocks from the Brimfield-type schist

Chemical analyses[1/] [2/]

| | A. | B. |
|---|---|---|
| $SiO_2$ | 50.2 | 46.4 |
| $Al_2O_3$ | 23.0 | 15.6 |
| $Fe_2O_3$ | 4.3 | 2.0 |
| FeO | 4.9 | 8.1 |
| MgO | 2.8 | 6.8 |
| CaO | .17 | 13.2 |
| $Na_2O$ | 2.5 | .55 |
| $K_2O$ | 4.3 | 1.4 |
| $TiO_2$ | 1.2 | 2.6 |
| $P_2O_5$ | .09 | .55 |
| MnO | .04 | .15 |
| $H_2O$ | 5.4 | 1.8 |
| $CO_2$ | <.05 | .35 |
| Sum | 100 | 100 |

Table 10. (cont.)

Norms[2/]

| | A. | B. |
|---|---|---|
| Quartz | 14.30 | 2.94 |
| Corundum | 15.19 | |
| Orthoclase | 27.25 | 8.35 |
| Albite | 22.54 | 4.71 |
| Anorthite | | 36.73 |
| Wollastonite | | 10.12 |
| Enstatite | 7.43 | 17.27 |
| Ferrosilite | 3.82 | 9.36 |
| Magnetite | 6.71 | 3.01 |
| Ilmenite | 2.43 | 5.01 |
| Apatite | .34 | 1.34 |
| Calcite | | .80 |
| Sum | 100.01 | 99.64 |

Table 10. (cont.)

Modal analyses 3/

| | A. | B. |
|---|---|---|
| Quartz | | 6.0 |
| Plagioclase | 41.3 | |
| Hornblende | | 52.2 |
| Biotite | 6.8 | |
| Chlorite | 11.7 | 5.0 |
| White mica | 36.8 | 12.4 |
| Sphene | .2 | 5.1 |
| Clinozoisite | | 18.7 |
| Calcite | | .8 |
| Opaque | 3.7 | |

A(C-1B). Mica schist along south bank of Merrimack River 1000 ft. east of Lawrence-Lowell quadrangle boundary. Points counted: 1000. Plagioclase composition $An_{10\pm4}$

B(C-1A). Amphibolite along south bank of Merrimack River 1000 ft. east of Lawrence-Lowell quadrangle boundary (interlayered with A). Points counted: 900.

1/ U. S. Geological Survey Rapid Rock Analysis Laboratory

2/ All figures weight percent

3/ All figures volume percent

Table 11. Estimated modes of rocks from the Brimfield-type schist and Nashoba Formation

| | Brimfield-type schist | | Nashoba Formation | |
|---|---|---|---|---|
| | A. | B. | C. | D. |
| Quartz | 2 | 60 | 12 | 51 |
| Plagioclase | | 10 | 8 | 35 |
| Biotite | 10 | 10 | 40 | 10 |
| Chlorite | 3 | | 4 | |
| White mica | 80 | 17 | 15 | 2 |
| Graphite(?) | 2 | | | |
| Sillimanite | | | 8 | |
| Apatite | | tr. | | |
| Garnet | | | 10 | 1 |
| Opaque | 3 | 3 | 3 | 1 |

A(L-19). Sericite schist along south shore of Merrimack River 1600 ft. north of St. Francis Seminary, Andover

B(L-21). Mica-quartz schist east of railroad station, Andover

C(W-9). Mica schist along shore of Fosters Pond, 1500 ft. south-southeast of Rattlesnake Hill Rd.-Woburn St. intersection, Andover

D(W-226). Biotite gneiss 3000 ft. west of Salem St.-Middlesex Ave. intersection, Wilmington series of argillaceous sediments. The more quartzose varieties probably were initially somewhat arenaceous, and the highly biotitic schists apparently were relatively rich in iron and magnesia.

Amphibolite occurs locally within the Brimfield-type schist of this area. As noted earlier, Cuppels has found it interlayered with mica schist in Concord and Lincoln, but its petrography here is not known in detail. Elsewhere within the Brimfield-type schist, amphibolite is found in exposures in South Lawrence and along the Merrimack River.

The amphibolite cropping out in South Lawrence is conformable with a biotite schist layer of the Brimfield-type schist. It is dark greenish gray, moderately well foliated, and its texture is essentially fine to medium grained and hypidioblastic. The amphibolite here is composed of hornblende, highly saussuritized plagioclase, magnetite, and secondary clinozoisite and calcite. Hornblende composes more than half and highly altered plagioclase makes up approximately 30 percent of the rock. The clinozoisite occurs as veins and as disseminated blebs, and the calcite is confined to well-defined veins.

Amphibolite also is found interbedded with the sericite schist cropping out along the Merrimack River in the western part of the Lawrence quadrangle. The amphibolite exposed here is heavily coated with iron oxides and more distinctly foliated and considerably finer grained than that exposed in

South Lawrence. A relatively light colored hornblende composes up to 55 percent, and clinozoisite and muscovite (which does not occur in discrete bands) make up as much as 30 percent of the amphibolite in this zone. Quartz, calcite, chlorite, and sphene are present in accessory amounts. Plagioclase was not identified in those specimens examined by the writer. A chemical and modal analysis of this amphibolite is given in table 10. Plagioclase amphibolite occurs in this same area, but it crops out 50-100 yards south of the main outcrop belt of the Brimfield-type schist; its position is such that it may fall within the supposedly transitional contact zone between the Brimfield-type schist and adjacent Nashoba Formation.

The amphibolite exposed in South Lawrence is probably a metamorphosed basalt, for its composition as derived from its mode does not differ markedly from the composition of an average basalt (table 9). The amphibolite interbedded with the sericite schist along the Merrimack River, however, may have descended from a non-volcanic parent. Its mode is high in clinozoisite and sphene and devoid of plagioclase. Its calculated norm is even more revealing, in that it is extremely rich in anorthite and poor in albite. The compositional characteristics in general are those of a calc-silicate derived from an impure limestone or dolomite.

## Metamorphism

Mineral assemblages developed within the Brimfield-type schist exposed along the Merrimack River (see table 10) indicate that these rocks have attained a metamorphic grade at least as high as the quartz-albite-epidote-biotite subfacies of the greenschist facies (Fyfe, Turner, and Verhoogen, 1958, p. 223). The occurrence of sillimanite and garnet in the muscovite schist inliers within the Andover Granite, however, suggests that the Brimfield-type schist locally may have reached grades as high as the sillimanite-almandine subfacies of the almandine amphibolite facies (*op. cit.*, p. 231).

## Nashoba Formation

The Nashoba Formation has been named and defined by Hansen (1956, p. 31-32) to include "a great mass of metamorphic rocks...that extends northeastward across east-central Massachusetts" and encompasses much of what was mapped by Emerson (1917, pl. X) as "gneisses and schists of undetermined age." Hansen has divided the Nashoba Formation into three mappable units; biotite gneiss, amphibolite, and marble. Biotite gneiss and amphibolite are recognized, but neither marble nor well developed calc-silicate rocks were discovered within the Nashoba Formation in this area. According to Hansen (1956, p. 28-29), the Nashoba is transitional through an amphibolite zone with a mica schist unit which in turn is on strike with the Brimfield-type schist cropping out along the Merrimack River east of Lowell. Jahns (1960, written communication) since has confirmed the presence of a gradational contact between the Nashoba Formation and an adjacent mica schist unit in the Ayer quadrangle, where "the two formations are lithologically intergradational across the strike for many tens of feet." Owing, perhaps, to limited exposure and considerable intrusion, the transitional nature of this contact is not generally evident locally.

The Nashoba Formation in this area occurs chiefly in two broad wedge-shaped belts coalescing near the western edge of the map area. The northern belt crops out over an area of six or seven square miles around the intersection of the Lawrence, Lowell, Billerica, and Wilmington quadrangle boundaries. The southern belt extends from the northern part of the town of Wilmington southwestward through Billerica and Bedford, and along the northern edge of the southwestward extension of the Andover Granite. Elsewhere in this area the Nashoba is confined to relatively small inliers in younger igneous rocks. The southern belt has a maximum width of about 2 miles, but no reliable estimates have been made of its thickness owing to probable repetition of the section and sparse exposure. In the type locality Hansen (1956, p. 32) was able to say only that the "thickness (of the Nashoba Formation) may well exceed

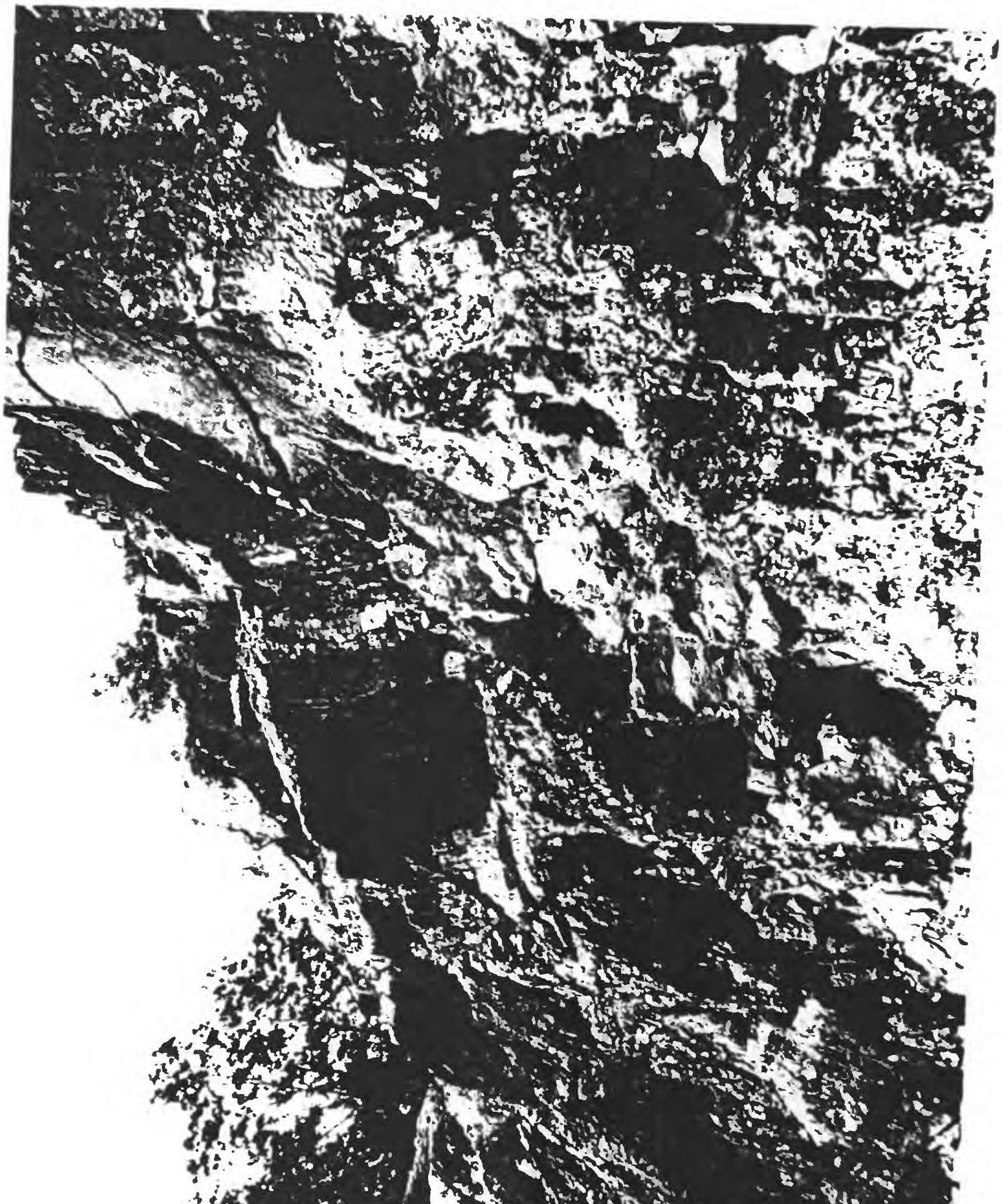
5,000 feet."

## Biotite gneiss

The biotite gneiss is light gray to pearly white; in its more micaceous facies it commonly develops a rusty weathered surface. Foliation is prominent and generally gently warped or folded; in some exposures, such as those along the south side of North Street in Tewksbury, it is highly crenulate. A degree of foliation common to the biotite gneiss in the extreme southwestern corner of the Wilmington quadrangle is illustrated in plate 18. Locally developed layering generally is a reflection of compositional variation between alternately highly micaceous and relatively nonmicaceous zones. Whether or not this layering is a reflection of original bedding is not known, for it may have been brought about locally through processes of metamorphic differentiation. Undoubted bedding has not been seen in any of the exposures of the biotite gneiss in this area, but Hansen (1956, p. 32) has reported well-defined bedding from the gneiss in the area of the type locality. The gneiss is medium to coarse grained; granoblastic textures predominate, but there is a tendency toward idiomorphism on the part of feldspar and several accessory minerals. What may be rounded, feldspathic quartzite pebbles, three-eighths of an inch or less in diameter, have been seen in some exposures (fig. 4A). These "pebbles" generally are not recognized as such without

Plate 18

Dikes of unfoliated, garnetiferous, binary granite of the Andover Granite cross-cutting the biotite gneiss facies of the Nashoba Formation in the extreme southwestern corner of the Wilmington quadrangle.



the aid of a microscope, for the biotite gneiss has been thoroughly intruded with quartz veinlets now manifested as small, discontinuous lenses that locally resemble deformed pebbles.

In the area of the type locality, where the Nashoba Formation is far better exposed than here, rocks mapped with the biotite gneiss facies include quartzite, amphibolite, and marble as well as gneiss (Hansen, 1956, p. 32-35). Within this area, however, the biotite gneiss facies is composed almost entirely of biotite-plagioclase-quartz gneiss, the predominant facies of the type locality (op. cit., p. 32). Here and there within the biotite gneiss, however, generally concordant concentrations of mica are developed as true mica schists. These schist layers characteristically are no more than a fraction of an inch thick, but within several of the isolated inliers they attain thicknesses of 5 or more feet.

Everywhere it has been studied in this area the biotite gneiss contains quartz, sodic-plagioclase, and at least some biotite. Compositional differences within the gneiss consist chiefly of variations in the quartz-plagioclase ratio and in the presence or absence of muscovite. Quartz is the major mineral throughout the biotite gneiss facies and composes from 40 to 70 percent of the rock. Sodic plagioclase makes up roughly 20 to 50 percent of the gneiss. The composition of the plagioclase normally ranges from $An_5$ to about $An_{30}$. The only exception to the generally sodic nature of the plagioclase was noted in a thin section from the biotite gneiss exposed near Lubber Brook where it crosses the Billerica-Wilmington town line. The gneiss within this zone contains plagioclase of calcic andesine or sodic labradorite composition, but is otherwise similar to the biotite gneiss exposed elsewhere within the Nashoba. Biotite is the major varietal mineral of the biotite gneiss and normally composes from 5 to 25 percent of the rocks of this facies. It ranges from a very high iron (almost black in thin section) to a light phlogopitic variety. The biotite is generally intensely pleochroic and locally includes small blebs of quartz and plagioclase. Muscovite is present throughout much of the biotite gneiss, but it is most conspicuously developed in the northern belt of the Nashoba Formation. Garnet is a ubiquitous constituent of the gneiss but generally composes less than 2 percent of the rock; it occurs either uniformly disseminated through the gneiss or in concentrations along contacts with quartz veins and pegmatites. Other accessory minerals locally present within the gneiss include sillimanite, magnetite, ilmenite, apatite and zircon. Potassium feldspar is thought to be totally absent from the biotite gneiss exposed within the map area. Approximate modes of specimens from the biotite gneiss are presented in table 11 and modal analyses and a chemical analysis are given in tables 12 and 13 respectively.

Table 12. Modal analyses of rocks from the Nashoba Formation[1/]

| | A. | B. |
|---|---|---|
| Quartz | 61.4 | 50.2 |
| Plagioclase | 20.9 | 33.6 |
| Biotite | 12.6 | 13.8 |
| White mica | 2.8 | 2.2 |
| Sillimanite | 1.9 | |
| Apatite | .1 | tr. |
| Zircon | tr. | |
| Opaque | .2 | .2 |

A(C-2). Biotite gneiss in roadcut along North St., 150 ft. north of benchmark 213, Tewksbury. Points counted: 1000. Plagioclase composition $An_{17\pm4}$

B(L-979). Biotite gneiss from inlier in Andover Granite along High Plain Rd., 1450 ft. west-northwest of High Plain Rd.-Beacon St. intersection, Andover. Points counted: 500. Plagioclase composition $An_{10}$.

1/ All figures volume percent

Table 13. Chemical analysis, norm, and modal analysis of biotite gneiss from the Nashoba Formation[1/]

Chemical analysis[2/] [3/]

| | |
|---|---|
| $SiO_2$ | 77.9 |
| $Al_2O_3$ | 10.4 |
| $Fe_2O_3$ | .7 |
| FeO | 3.2 |
| MgO | 1.4 |
| CaO | .64 |
| $Na_2O$ | 1.8 |
| $K_2O$ | 1.9 |
| $TiO_2$ | .67 |
| $P_2O_5$ | .13 |
| MnO | .08 |
| $H_2O$ | 1.1 |
| $CO_2$ | <.05 |
| Sum | 100 |

Table 13. (cont.)

| Norm[3/] | |
|---|---|
| Quartz | 55.96 |
| Corundum | 4.59 |
| Orthoclase | 11.12 |
| Albite | 15.19 |
| Anorthite | 2.50 |
| Enstatite | 3.51 |
| Ferrosilite | 4.35 |
| Magnetite | .93 |
| Ilmenite | 1.37 |
| Apatite | .34 |
| Sum | 99.86 |

Table 13. (cont.)

Modal analysis 4/

| | |
|---|---|
| Quartz | 61.4 |
| Plagioclase | 20.9 |
| Biotite | 12.6 |
| White mica | 2.8 |
| Sillimanite | 1.9 |
| Apatite | .1 |
| Zircon | tr. |
| Opaque | .2 |

1/ (C-2). Biotite gneiss in roadcut along North St., 150 ft. north of benchmark 213, Tewksbury. Points counted: 1000. Plagioclase composition $An_{17\pm4}$

2/ U. S. Geological Survey Rapid Rock Analysis Laboratory

3/ All figures weight percent

4/ All figures volume percent

The high silica content and high $Al_2O_3/K_2O+Na_2O+CaO$ shown by the chemical analysis, together with the generally large amounts of modal quartz present, leave little doubt that the gneiss was derived from locally clay-rich arenaceous sediments.

## Amphibolite

Amphibolite has been mapped in several localities within the Nashoba Formation. The main body of amphibolite crops out in the town of Billerica, and smaller masses occur in the town of Wilmington.

The northeast trending amphibolite band cropping out in Billerica is particularly well exposed immediately north of Nutting Lake, where it may be almost 5000 feet wide and very nearly this thick. Where it is exposed in Billerica the amphibolite is a dense black, prominently and smoothly foliated, steeply-dipping rock. It generally possesses a thinly banded appearance owing to the presence of thin, discontinuous feldspathic seams. Everywhere the amphibolite is exposed it is uniformly fine grained and hypidioblastic. Hornblende is the major constituent, and plagioclase and quartz(?) occur in varying amounts. No microscopic study was made of the amphibolite in Billerica, but it is presumably similar in composition to the amphibolites of the Nashoba Formation described in detail by Hansen (1956, p. 35-38). The most striking feature of this unit is its precise areal definition. It is apparently in no way transitional with the biotite gneiss at either contact, and in this sense it is unlike the majority of the amphibolites common to both the Marlboro and Boxford Formations.

The amphibolite bands cropping out near Martins Pond are no more than several tens of feet wide; they have been delineated separately because of their unique nature. They are gray to black, distinctly foliated, generally fine grained, and locally porphyroblastic. The Martins Pond amphibolites are composed chiefly of hornblende and plagioclase with accessory amounts of sphene, magnetite and pyrite. Small amounts of epidote occur in tiny veinlets. Hornblende composes up to 50 percent of the amphibolite, and plagioclase of median andesine composition makes up about 40 percent of the rock.

The only other amphibolite observed locally within the Nashoba Formation occurs several hundred yards east of Silver Lake in the center of the Wilmington quadrangle. The amphibolite exposed here is greenish gray to black, somewhat gneissic, fine to medium grained, and hypidioblastic. It is composed chiefly of highly altered plagioclase, common hornblende, and zoisite. Sphene, sericite, and garnet occur in accessory amounts. The sphene occurs in well-defined zones or veins and zoisite is disseminated throughout the rock.

The origin of the amphibolites contained in the Nashoba

Formation is unknown. Hansen (1956, p. 36-38) has concluded that the majority of the amphibolites exposed in the type locality have been derived from limestone, but he feels that some may be of volcanic origin. He has suggested that the amphibolites "were basic in character before migmatization of the area started," for the distribution of the amphibolite bands is such that their presence cannot be explained by the advance of a basic front. Jahns (1960, written communication), however, doubts that these amphibolites originated from limestone, owing to "the occurrence, in places almost side by side, of amphibolites and 'clean' marbles in the Ayer and Westford quadrangles." The field relations of the amphibolite member north of Nutting Lake are suggestive of a volcanic or even an intrusive origin. It is remotely possible that this amphibolite represents a reef deposit in the midst of an otherwise consistently uniform sequence of arenaceous to locally argillaceous sediments. This possibility is viewed with considerable doubt by the writer, for one would have to resort to the use of very special mechanisms to explain the obviously large amounts of iron, magnesia, and alumina present. The composition of the "amphibolite" in the central part of the Wilmington quadrangle is such that it may very well be the metamorphic product of a siliceous limestone or dolomite.

## Hornblende Gneiss

What is referred to here as hornblende gneiss occurs as two narrow bands within and adjacent to the amphibolite northeast of Nutting Lake. Neither band is more than about 300 feet wide, and both are apparently conformable with the regional structure. The genesis of the hornblende gneiss may be unrelated to that of the remainder of the Nashoba Formation, and the rock is described at this point only for convenience.

The hornblende gneiss exposed in the southeast band is black to dark salt-and-pepper gray and is commonly stained along joint surfaces by iron oxides. As far as may be determined from the few exposures present it is generally massive to faintly foliated and shows little development of compositional layering. The texture is generally hypidioblastic and ranges from fine to coarse grained, and from equigranular through porphyroblastic and glomeroporphyroblastic. Coarse laths of plagioclase that commonly include smaller grains of hornblende locally impart a poikiloblastic appearance to the rock.

The hornblende gneiss is composed chiefly of roughly equal amounts of hornblende and plagioclase. The hornblende is either an actinolitic or low-iron variety of common hornblende, for its color is distinctly lighter and more yellowish than the common hornblende contained in adjacent amphibolitic rocks. Hornblende occurs as tiny, uniformly disseminated crystals, as aggregates of tiny crystals, and as coarse-grained subhedral crystals. Compositional differences among hornblende grains in the three separate habits could not be detected through optical measurement. The plagioclase composition ranges between $An_{50}$ and $An_{60}$. It is only slightly sericitized, shows no zoning, and occurs for the most part as relatively coarse-grained laths. Sphene is a prominent accessory mineral and commonly occurs as fine-grained aggregates surrounding magnetite or ilmenite crystals. Apatite composes up to 2 percent of the hornblende gneiss and occurs as tiny euhedral crystals. Epidote has developed in scattered patches as a secondary mineral.

Although the only known occurrences of the hornblende gneiss are closely associated with the amphibolites of the Nashoba Formation, it is doubtful that the two rocks have a common origin; their fabrics are completely dissimilar, and it is difficult to conceive of a metamorphic process that would selectively impose such unique characteristics on rocks that initially belonged to a continuous, genetically related sequence. Considerations of composition and occurrence suggest that the hornblende gneiss has been derived from intrusive sills of gabbroic composition.

## Metamorphism

The degree and nature of the metamorphism that brought the Nashoba Formation to its present state are conjectural.

The mineral assemblages tabulated in column C in table 11 and column A in table 12 suggest locally intense (high temperature) regional metamorphism within the sillimanite-almandine subfacies of the almandine amphibolite facies of Fyfe, Turner, and Verhoogen (1958, p. 230-231). Mineral assemblages developed away from the main body of the granite (see column D, table 11), however, indicate that metamorphic grade within the Nashoba Formation may drop to the staurolite-quartz subfacies (*op. cit.*, p. 229) or even lower.

The commonly occuring intergrowth between fibrolitic sillimanite and muscovite in the more pelitic rocks of the Nashoba, suggests that the sillimanite may have developed from muscovite in response to rising temperature. However, these same muscovite-sillimanite-bearing rocks are apparently devoid of potassium feldspar that, in theory, should have evolved with the concomitantly developing sillimanite; this suggests in turn that the system may have been open with respect to K and $H_2O$. Moreover, in several localities adjacent to the Andover Granite the muscovite is almost certainly post-kinematic and probably post-dates the formation of sillimanite. At least some of the muscovite, then, may have formed from preexisting sillimanite in response to potassium metasomatism associated with granitic intrusion.

Retrogressive effects in the Nashoba include the alteration of biotite to chlorite and micaceous pseudomorphs after garnet. Secondary epidote occurs locally in veins and as tiny disseminated blebs in plagioclase.

## Correlation and age of the Brimfield-type schist and Nashoba Formation

The Brimfield-type schist cropping out along the Merrimack River, is essentially continuous with rocks striking southwest from Lowell that were mapped as Brimfield Schist by Emerson (1917, pl. X). The mica schist that occurs in Lincoln, Concord, and Sudbury is more or less continuous with and occupies a stratigraphic position comparable to that of rocks mapped with the Brimfield in Marlboro center (Emerson, 1917, pl. X; pl. 2, this report). Correlation of the remaining lenses of Brimfield-type schist with rocks mapped elsewhere as Brimfield, is based entirely on lithologic similarity.

Emerson (1917, p. 77-78) concluded that the Brimfield was at least in part the correlative of the Worcester Phyllite (a unit that occurs sparingly, if at all, in this area), and differed from the Worcester only in terms of metamorphic grade. According to Emerson (op. cit., p. 77-78), "even though these rocks (Brimfield Schist) are much more metamorphosed, every effort to find boundaries separating them from the less altered rocks (Worcester Phyllite)... in the Worcester area has failed." He goes on to say that "I began the study of the rocks around Worcester with a prejudice in favor of such boundaries and for a long time urged my assistants to find them, but at last I gave up the quest." A third of a century later R. H. Jahns, L. W. Currier, M. E. Willard, and W. R. Hansen (Hansen, 1956, p. 20) reached the same conclusion from detailed studies of the rocks in the Ayer and Hudson quadrangles. Hansen accordingly defined a new unit, the Worcester Formation, to include both the Worcester Phyllite and Brimfield Schist of previous reports.

Emerson's almost reluctant conclusion equating the Brimfield Schist and Worcester Phyllite, recently has been challenged by geologists working in supposedly equivalent strata in Connecticut. According to J. L. Rosenfeld (1962, oral communication) the Brimfield Schist of central Massachusetts is the correlative of the Collins Hill Formation of central Connecticut. Detailed mapping in the Middle Haddam quadrangle of Connecticut by Rosenfeld and Eaton, indicates that the Collins Hill Formation is in turn unconformably overlain by the Bolton Group (Rodgers and Rosenfeld, 1956, p. 19, fig. 3). Rosenfeld (1962, oral communication) since has tentatively correlated a gray, non-rusty graphitic schist within the Bolton Group with the Worcester Phyllite. To the extent that the preceding correlations are valid, the Worcester Phyllite and Brimfield Schist are not correlative. There is, however, a complicating factor pertinent to the present discussion. Hansen (1956, p. 20) has pointed out that whether or not the Brimfield-type schist east of

Worcester should be correlated with the type Brimfield is problematical, for "the two areas are separate and the schist is not exposed continuously between them." In fact, studies by Callaghan (Wilmarth, 1938, p. 267) indicate that the Brimfield Schist as presently mapped may include several formational units that are stratigraphically distinct. The conjectures of Rosenfeld and others, then, may be of limited utility in solving this problem of possible equivalence between the Worcester Phyllite and Brimfield-type schist as they occur east of Worcester.

As the Brimfield-type schist cropping out in the Hudson and Ayer quadrangles is intergradational and conformable across the strike with the Nashoba Formation, both units apparently belong to the same general stratigraphic group. This observation permits an alternate approach to the age of the Brimfield-type schist relative to the Worcester Phyllite. According to L. R. Page (1962, written communication), examination of continuous exposure along the recently constructed Wachusetts aqueduct has confirmed an earlier suggestion by Hansen (1956, p. 13-14), that the Nashoba and Marlboro are conformable and transitional. Hansen's structural interpretation (1956, p. 51) is such that the Brimfield-type schist lying to either side of the Nashoba belt predates the latter formation. Page (1962, written communication), on the other hand, views the Marlboro-Brimfield-Nashoba section as a massive homoclinal structure, such that the southern belt of Brimfield-type schist should be older and the northern belt younger than the adjacent Nashoba. Either way, however, as the Marlboro Formation probably predates the Merrimack Group (certainly predates it if the Rye and Marlboro are demonstrably correlative), and the Merrimack Group in turn almost certainly underlies the Worcester Phyllite (see discussion on age of the Worcester Phyllite, this report), it follows that the rocks of the Nashoba Formation and Brimfield-type schist underlie rather than overlie the Worcester Phyllite as has been suggested previously (Hansen, 1956, p. 21). It is tentatively concluded, therefore, that the Brimfield-type schist and Worcester Phyllite are not correlative.

There is little question that the Nashoba Formation mapped here is actually correlative with that of the type area, for one is easily traceable into the other. Within this area the Nashoba pinches out to the northeast where it is truncated against the lower member of the Boxford Formation, that in turn grades upward into amphibolitic rocks (upper member of the Boxford) tentatively correlated with the Marlboro. Page (1962, written communication) has studied a line of continuous exposure within the Nashoba and Marlboro along the Wachusetts aqueduct and has concluded that the Nashoba grades downward into the amphibolitic Marlboro. It seems unlikely, therefore, that the Nashoba and Boxford are equivalent to any great extent. Southwest of the Hudson quadrangle the Nashoba narrows conspicuously and its possible correlatives in Connecticut are conjectural. H. R. Dixon (1962, written communication) has concluded from studies in eastern Connecticut that the Nashoba is probably correlative with the upper part of the Putnam Formation. Rosenfeld and Eaton (1963, oral communication), however, have suggested recently that the Nashoba may be correlative with the Hebron Gneiss, which in turn may be correlative with the upper Collins Hill.

The preceding paragraphs are reflective of the shaky nature of any geologic age assignment to the Brimfield-Nashoba group. Emerson (1917, p. 78; 86-87) and Hansen (1956, p. 18-19) concluded that rocks mapped here with the Brimfield-type schist and Nashoba Formation are Carboniferous. This conclusion, however, was based on their conviction that these rocks are continuous with or conformably overlie the supposedly Carboniferous Worcester Phyllite. However, the probable pre-Carboniferous age of the Marlboro, together with the transitional nature of the Marlboro-Nashoba contact, almost certainly rules out any possibility that the Nashoba or Brimfield-type schist are younger than Devonian. As the Marlboro Formation may be Ordovician, it is reasonable to suppose that the conformable and transitional Nashoba is of similar age. This supposition is substantiated in part by the studies of Rodgers and Rosenfeld (1956, p. 23) which suggest that the Collins Hill (Brimfield-type equivalent) is correlative with the Partridge Formation of New Hampshire. The Partridge in turn is thought to be correlative with the Cram Hill of eastern Vermont that has been correlated along the strike with graptolite bearing Middle Ordovician slates northwest of Lake Memphremagog, Quebec.

### Serpentinite at Lynnfield center

A small mass of serpentinite, the occurrence of which has been known for many years (Hitchcock, 1841, p. 159), is located in Lynnfield center. Owing to poor exposure it is difficult to depict the configuration of the serpentinite body, but it appears to be roughly conformable with the regional strike, at least 1½ miles long, and approximately ½ mile wide.

The serpentinite is generally very dark gray, massive, and ultra-fine grained. Fresh exposures have a mottled appearance in which greenish material appears to be scattered against a background of darker, mafic constituents. It is prominently slickensided locally, and the slickenside surfaces commonly manifest a dusky-blue to gray-blue color. The bluish substance is apparently a serpentine mineral.

The serpentinite ranges from an almost pure (95 percent) antigorite rock to one in which serpentine minerals compose no more than 50 percent of the rock. The less pure varieties contain magnesium-rich olivine, colorless amphibole, chlorite, magnetite, and small blebs of carbonate as well as antigorite. The antigorite in all the specimens examined occurs as a fine-grained, hypidiomorphic mat, that is generally confined to more or less equidimensional blocks devoid of other minerals. The "veins" separating individual blocks of antigorite are composed chiefly of amphibole and tiny blebs of magnetite. The olivine occurs in irregular patches and is commonly veined by antigorite or chlorite. It is clear, then, that olivine predates the antigorite in part, but the paragenetic relationships between amphibole and antigorite have not been established.

The origin of the serpentinite is conjectural. The serpentinite cropping out in Lynnfield center is the only substantiated occurrence of serpentinite in this area, and there are thus no other occurrences with which it may be compared. Sears (1905, p. 133) has reported serpentinite from the extreme southwest corner of the South Groveland quadrangle, but the writer was unable to confirm the presence of this occurrence. In addition, several natives of Andover have told the writer of a "soapstone" deposit in the southeastern section of their town, but the writer again was unable to locate the deposit. As the serpentinite at Lynnfield center is in no sense transitional with the Marlboro Formation that together with various igneous rocks presumably encloses it, it is tentatively concluded that it has been derived through the alteration of an ultramafic intrusive, or by "cold" intrusion of serpentinite along one of the locally developed shear zones.

If the serpentinite is an intrusive rock, it is probably Ordovician or younger, for it is almost completely surrounded by the Marlboro Formation. As Billings (1956, p. 106) has observed that "there are no authentic examples in New England of ultramafic rocks cutting demonstrable Silurian or Devonian rocks," the serpentinite at Lynnfield center is assigned tentatively to the Ordovician. However, its close association with a major east-northeast trending movement zone, currently thought to have been active through Devonian time (see section on structural geology, this report) suggests that it may be much younger than Ordovician.

## Silurian(?) rocks

Metasediments of probable Middle Silurian age crop out over the northern parts of the Lawrence and South Groveland quadrangles. The age of these rocks is based chiefly on their correlation with fossil bearing rocks in Maine, and to some extent on their relationships to dated(?) rocks in New Hampshire and Massachusetts. Although locally tightly folded, the Silurian(?) rocks of this area are much less metamorphosed than the Ordovician(?) rocks described in the preceding sections.

### Merrimack Group

The term Merrimack Group is employed here to include the Kittery Quartzite and Eliot Formation. The name was first proposed by Edward Hitchcock and subsequently formalized by his son, C. H. Hitchcock, in 1870 (Wilmarth, 1938, p. 1353). C. H. Hitchcock applied the name Merrimack Group to the mica schists, slates and quartzites contained in the valley of the Merrimack River in Massachusetts, and to similar rocks in southeastern New Hampshire. This terminology subsequently was modified by Crosby, Clapp, and Emerson who referred to this belt of rocks variously as Merrimac Schist, Merrimac quartzite and schist, and Merrimack Quartzite. In southeastern New Hampshire Billings (1952, p. 23; 1956, p. 43) assigned the collective term Merrimack

Group to the Kittery Quartzite and Eliot and Berwick Formations south of latitude 43°00', beyond which they had not been separately mapped. Usage is essentially the same here, except that the name is employed in a formal stratigraphic sense to include a group of formations that are transitional with each other, rather than in lieu of the differentiation of individual formations.

Only a small part of the Merrimack Group is exposed locally, and no estimates of its thickness may be made. According to Sriramadas (in Billings, 1956, p. 43) the Merrimack Group is 16,000 feet thick where it is exposed in the Manchester quadrangle along Route 28 between Canobie Lake and Massabesic Lake, New Hampshire.

## Kittery Quartzite

The Kittery Quartzite was named by Katz (1917, p. 168) for exposures of quartzite in the town of Kittery, Maine. It occurs locally within a broad, poorly exposed east-northeast trending belt that occupies the northern half of the Lawrence quadrangle and the northwest corner of the South Groveland quadrangle.

### Actinolitic quartzite

An actinolitic quartzite facies has been delineated within the presumably lower part of the Kittery Quartzite exposed here, *i.e.*, toward the northwest across the strike.

The separately mapped actinolitic quartzite is confined to the northern half of the Lawrence quadrangle and is best exposed around Methuen center. The rocks of this facies differ from the quartzites that occur elsewhere in the Kittery only in their actinolite content.

In hand specimen the actinolitic quartzite is a light- to very-light-greenish-gray, massive to faintly-foliated rock. Conspicuous compositional layering is generally absent, but one thin interbed of micaceous quartzite was discovered near Methuen center. Actinolite needles locally show a preferred orientation, but unlike those in the quartzites of the Lowell area (Jahns, 1948, p. 93), the actinolite crystals here are generally too fine grained to allow measurement of their orientation. The texture of the rock is typically granoblastic to hypidioblastic and fine to medium grained. Where the actinolitic quartzite has been exposed for long periods, the actinolite crystals commonly weather out leaving a characteristically pocked surface.

The actinolitic quartzite is composed chiefly of quartz with notably lesser amounts of actinolite and biotite. Chlorite, epidote, calcite, and sphene occur in accessory amounts. The more actinolitic rocks are commonly but not everywhere relatively free of biotite (see estimated mode (A) in table 14).

The actinolitic quartzite apparently was derived from a slightly to moderately impure, arenaceous sediment. The

Table 14. Estimated modes of rocks from the Merrimack Group

| | Kittery Formation | | | | Eliot Formation |
|---|---|---|---|---|---|
| | A. | B. | C. | D. | E. |
| Quartz | 65 | 70 | 75 | 55 | 48 |
| Plagioclase | | | | | 10 |
| Actinolite | 10 | | | | |
| Biotite | 18 | 25 | 14 | 24 | 8 |
| Chlorite | 4 | | 3 | 5 | |
| White mica | | 1 | | 13 | 30 |
| Epidote | 3 | 3 | 1 | | |
| Apatite | | tr. | | | |
| Carbonate | | | 5 | | |
| Sphene | tr. | tr. | | | |
| Flourite | | | tr. | | |
| Opaque | | | 2 | 3 | 3 |

A(L-17). Actinolitic quartzite 2000 ft. south-southwest of Pelham St.-Forest St. intersection, Methuen

B(L-16). Biotitic quartzite 3400 ft. northwest of Pelham St.-Cross St. intersection, Methuen

C(L-1). Biotitic quartzite adjacent to south abutment of dam, Lawrence

D(L-1). Mica-quartz schist adjacent to south abutment of dam, Lawrence (interbedded with C)

E(G-8). Sericite-quartz schist from Kittery Quartzite-Eliot Formation transition zone 1400 ft. south of Mt. Hayman, Boxford presence of actinolite, rather than some other mafic phase common to the Kittery, is presumably reflective of an original compositional variant. This is demonstrated on a microscopic scale by the alternation of biotitic and actinolitic layers that transect the regional foliation and obviously have been subjected to the same degree and type of metamorphism (see figure 4B).

## Undifferentiated Kittery Quartzite

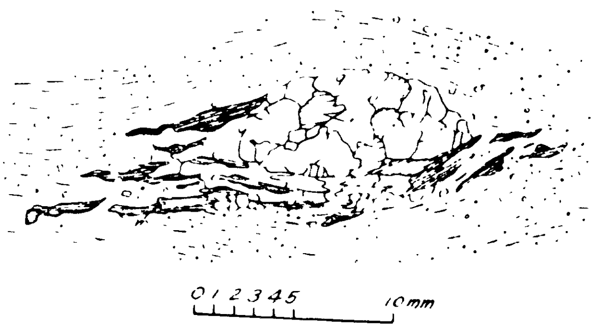
The undifferentiated Kittery Quartzite consists of massive to foliated quartzites and micaceous quartzites, locally interbedded with quartz-mica schist. Fresh exposures are typically gray to purplish-gray in color, but the rocks are somewhat lighter and greener in the more massive facies. The Kittery is one of the few formations in this area in which bedding can be recognized unequivocally. Toward the top of the Kittery, where its bedded nature is most conspicuous, the beds range from a few inches to approximately 2½ feet in thickness. Alternating beds of micaceous quartzite and quartz-biotite schist are particularly well developed in exposures adjacent to the dam across the Merrimack River in Lawrence. Schistosity and bedding ordinarily are not conformable, but their angle of divergence is generally less than 20 degrees.

The quartzites are typically equigranular, fine grained, and granoblastic, but a few large quartz grains occur

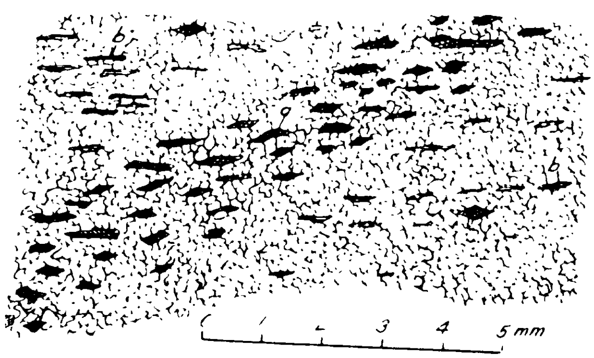
Figure 4

A. Diagrammatic thin section sketch of specimen from the Nashoba Formation exposed 300 feet southeast of Reservation Rd.-Cutler Rd. intersection, Andover. The coarse-grained knot is composed of quartz (q) and plagioclase feldspar (f), and is partly surrounded by coarse-grained mica (m).

B. Diagrammatic thin section sketch of actinolitic quartzite from the Kittery Quartzite exposed 1500 feet south-southeast of Pelham St.-Forest St. intersection, Methuen. Zone of actinolite (a) needles transgresses the general foliation of the rock determined by the orientation of biotite (b) plates.




A




B

locally that may be unreconstituted sand grains preserved from the original sediment. The rocks consist chiefly of quartz and biotite together with minor amounts of actinolite, calcite, epidote, fluorite, and ilmenite. Quartz composes up to 80 percent but probably averages less than 70 percent of the rock. The average biotite content is about 15 percent, but the quartzite locally consists of up to 25 percent biotite. Calcite composes up to 5 percent of some of the specimens and was probably a primary constituent of the rock, as it was present to some degree in fully two-thirds of the samples examined. Approximate modes of the quartzite are given in table 14.

The locally interbedded schist beds are generally thinner than the quartzite beds, averaging between 5 and 6 inches in thickness. They are also dull to purplish gray, but consistently darker than the adjacent quartzites. Compositional layering is locally evident in thin sections of the schist, but unlike the "macrolayers" formed by alternating layers of quartzite and schist, the very thin schist layers commonly have been intensely contorted into small isoclinal folds in which the axial planes parallel the schistosity. The texture of the schist is hypidioblastic to granoblastic and generally very fine grained.

The schist interbeds are composed chiefly of quartz, biotite, and sericite, with some chlorite and minor amounts of ilmenite. Quartz is the predominant mineral in the schist and composes up to 50 percent of the rock. The major compositional difference between quartzite and schist, other than in the amount of quartz, is in the abundant sericite in the schist. Biotite and sericite are for the most part intimately intergrown and do not occur in segregated layers.

The undifferentiated Kittery Quartzite apparently was derived from a series of somewhat argillaceous quartz sands. With advancing geologic time these essentially arenaceous sediments became progressively and rhythmically enriched in pelitic constituents, such that most of the rocks in the higher parts of the section cannot be accurately described as quartzites. It is inferred that the changing character of sedimentation reflected in the Kittery section, is attributable to the effects of a generally transgressing sea.

## Eliot Formation

The "Eliot slate" was named by Katz (1917, p. 169) for exposures of this rock in the towns of Eliot and Kittery, Maine, and Dover, Newington, Stratham, Exeter, Madbury, Durham, and Lee, New Hampshire. The "Eliot slate" since has been renamed and redefined as the Eliot Formation by Billings (1956, p. 40), for "although slate is an appropriate lithologic appellation in the type locality, it is not satisfactory for those areas where the formation is more metamorphosed."

The Eliot Formation crops out locally in the north-central section of the South Groveland quadrangle. It is conspicuously foliated and apparently structurally conformable and transitional with the adjacent Kittery Quartzite, so that the boundary between the two formations must be arbitrarily defined. Those zones in which relatively massive quartzite is subordinate or absent are included here with the Eliot Formation. All but one of the exposures of the Eliot Formation contain some quartzite, but the quartzite is typically argillaceous and more in the nature of a quartz schist than that characteristic of the Kittery.

The Eliot Formation in this area consists of very micaceous quartzite, sericite-quartz schist, and phyllite. The quartzitic layers are medium gray, distinctly foliated and fissile, and very fine grained. Where weathered the quartzitic rocks commonly develop a splotchy, buff-colored surface, apparently attributable to numerous small grains of oxidized pyrite. In addition to quartz the quartzitic layers contain albite, sericite, biotite or phlogopite, plagioclase, and limonite. The phyllite is medium- to silvery-gray in color, somewhat slaty in appearance, extremely fissile, locally crenulated, and ultra-fine grained. Sericite, biotite, and quartz are thought to be the major phyllitic minerals, but chlorite may be prominent locally.

The Eliot Formation is clearly the metamorphic product of a generally argillaceous, but partly arenaceous sedimentary sequence.

## Metamorphism in the Merrimack Group

Metamorphic grade within the Merrimack Group is uniformly low and thus contrasts sharply with that of the Ordovician(?) rocks to the south. It is inferred from the mineral assemblages tabulated in table 14 that metamorphic grade in these rocks is nowhere above the quartz-albite-epidote-biotite subfacies of the greenschist facies (Fyfe, Turner, and Verhoogen, 1958, p. 217-218, 223); along the eastward extension of the Eliot Formation it may be even lower, locally dropping to the quartz-albite-muscovite-chlorite subfacies (*op. cit.*, p. 219).

## Correlation and age of the Merrimack Group

Exposures of the Kittery Quartzite and Eliot Formation in this area are separated by approximately 10 miles from corresponding rocks that have been traced southwestward from their respective type localities in Maine and New Hampshire. The Kittery and Eliot as such have been mapped along the coast as far south as the Massachusetts border (Novotny, 1956, oral communication), but they have not been delineated to the southwest. However, in a report describing the geology of the Newburyport West quadrangle, Massachusetts, Schneer (1957, written communication) defined separate quartzite and phyllite units within the Merrimack Group. It is not clear from Schneer's report whether he gives these units formational status within the Merrimack, but he does suggest that the phyllite band may be correlative with the Eliot Slate of Katz. It is evident from Schneer's map that the phyllite band is roughly continuous with the Eliot Formation mapped in the South Groveland quadrangle, and that the quartzite belt is more or less continuous with the Kittery Quartzite in the Lawrence and South Groveland quadrangles. In the latter instance, however, the separation between mapped areas is at least 5 miles.

There is little doubt that at least two of the formations of the Merrimack Group in southeastern New Hampshire have their counterparts in northeastern Massachusetts. Nevertheless, the precise division between these two formations is conjectural. In this area the boundary between the Kittery Quartzite and the Eliot Formation has been established according to the presence or absence of massive quartzite layers. Billings (1956, p. 44), however, has indicated that the Merrimack Quartzite of Emerson (what is mapped here chiefly as Kittery Quartzite) is the probable correlative of the Eliot Formation and is not the "equivalent" of the Kittery, for it "is at best an impure quartzite." If Billings has employed the term "equivalent" in a time-stratigraphic sense, the writer would certainly agree. In a formational sense, however, the Kittery Quartzite of southeastern New Hampshire approximates the Kittery of this area much more closely than does the Eliot Formation.

The age of the Kittery Quartzite relative to that of the Eliot Formation is thought to have been satisfactorily established in southeastern New Hampshire, where the Eliot Formation conformably overlies the Kittery Quartzite around the Rye anticline (Katz, 1917, p. 169; Novotny, 1956, oral communication).

The geologic age of the Merrimack Group as yet has not been established definitely and different writers have assigned these rocks to periods ranging from Cambrian to Carboniferous. The only direct evidence relating to the age of the Merrimack is alleged to have reposed in the geological museum at Amherst College, where there is supposed to have been "a block of gray quartzite...which seems to be a flattened cast of a calamite. One side is fluted and rusty as if from the crumpling and removal of the epidermis, but on the flat surface traces of the ribbing still remain and bear a resemblance to that of Calamites cannoeformis. The block was labeled simply 'Lowell, Mass.' by Edward Hitchcock, and is supposed to have come from the Merrimack quartzite" (Emerson, 1917, p. 59). Billings (1956, p. 102) has discovered what he has termed "pseudocalamites" in the Kittery Quartzite north of Lawrence. The structure of the "pseudocalamites" is apparently inorganic and has resulted from the intersection of foliation with a slightly folded quartzite vein. It is not unlikely that Hitchcock's specimen is similar in nature. Sears (1905, p. 84) has written of fossil-bearing Cambrian argillites from Methuen and Archelaus Hill in West Newbury. However, it is unclear from the text whether Sears meant that these exposures actually contained fossils or whether they were similar in appearance to fossil-bearing rocks found elsewhere. The aforementioned localities have been examined by a number of students, and careful searching has failed to confirm the presence of fossils in any of the rocks of the Merrimack Group.

Remaining evidence pertaining to the age of the Merrimack Group rests on (1) a series of somewhat tenuous stratigraphic correlations and (2) radioactive age determinations on rocks intrusive into the Merrimack. Billings (1952, p. 23-29; 1956, p. 99-105) has summarized the pertinent field evidence and has demonstrated the plausibility, at least, of assigning the Merrimack Group to the Silurian. Two limiting approaches are available; one by way of correlation with rocks underlying supposedly fossiliferous strata in Massachusetts and New Hampshire, and the other through direct correlation with fossiliferous units in Maine.

The available evidence in central Massachusetts indicates that the Merrimack Group is overlain by the Worcester Phyllite (Emerson, 1917, p. 77; Hansen, 1956, p. 21; Jahns, 1952, p. 108). The Worcester in turn has been thought to be Carboniferous by many workers (Emerson, 1917, p. 77; Hansen, 1956, p. 18-19), for it reportedly contains Carboniferous fossils. These fossil identifications are doubted by some (Billings, 1956, p. 101) and it is not certain, furthermore, that the allegedly fossiliferous strata are actually contained within the Worcester Phyllite. Nevertheless, even if a Carboniferous age is accepted for the Worcester, the problem is not resolved, for the nature of the contact between the Worcester and the underlying Merrimack is debatable. Emerson (1917, p. 77) has reported that the Oakdale Quartzite (Merrimack Group equivalent) "grades into the overlying Worcester phyllite by an easy transition, without visible unconformity or interruption." On the other hand, studies in this same area by Novotny (1957, oral communication) suggest a pronounced angular unconformity between the Oakdale and Worcester. Arguments presented by Hansen (1956, p. 23) and Billings (1956, p. 102) also tend to support the view that an indeterminate hiatus may be reflected by the Worcester Phyllite-Merrimack Group contact. Thus, although a minimum age of Carboniferous probably is indicated, field relations are such that the age of the Merrimack Group is not apt to be established through its relationship to the Worcester Phyllite.

According to Billings (1952, p. 24) the Littleton Formation of New Hampshire contains Lower Devonian fossils; in the Mt. Pawtuckaway area the Littleton apparently conformably overlies the Berwick Formation of the Merrimack Group (Freedman, 1950, p. 475-476). This evidence indicates, as noted by Freedman (1950, p. 488), that the Merrimack Group probably is Lower Devonian or older.

Correlations with rocks in the Waterville, Maine area (Billings, 1956, p. 103-104) suggest that the Merrimack Group is probably Middle Silurian. Moreover, if it is accepted that the Merrimack is as old as Silurian (as seems likely), there is local evidence tending to corroborate Billings' correlation with rocks older than Late Silurian. The Merrimack apparently is completely free of volcanics, yet Upper Silurian rocks developed locally (Newbury Formation) are primarily volcanic. It seems doubtful that these two units could have accumulated side by side during the same geologic epoch with little if any volcanic contamination of the Merrimack.

Lead-alpha age determinations recently have been made on rocks intrusive into the Merrimack Group in southeastern New Hampshire (Lyons, et al., 1957, p. 536). The mean age of these intrusive rocks as determined by this method is 294±12 million years. These age determinations, at best, then, do little more than support the probable minimum Carboniferous age of the Merrimack Group, already indicated by its relationship to the Worcester Phyllite.

Several lines of evidence have been adduced that limit the minimum age of the Merrimack Group, but there is no satisfactory approach to the establishment of its maximum age. If the Rye Formation can be dated independently as

Ordovician, the Merrimack may be bracketed fairly certainly between Lower Devonian and Ordovician. In summary, all the substantive evidence available is most consistent with a Middle Silurian age for the Merrimack Group.

## Rocks of middle Paleozoic age

### Upper Silurian rocks

Volcanic rocks of almost certain Late Silurian age crop out along the eastern edge of the Reading quadrangle. The age of these rocks is based on their correlation with a fossil bearing sequence exposed several miles east of this area. Although arealy insignificant, considerable importance may attach to these rocks as they provide a possible means for establishing the maximum age of a large group of igneous rocks thought to be intrusive into them.

### Newbury Formation

Priestley Toulmin, III (1957, written communication) and J. B. Thompson recently have discovered a narrow, southwest trending belt of interbedded volcanics and fossiliferous sediments in the northwest quarter of the Salem quadrangle. The name Newbury Formation has been given to this unit and "is an extension of the name Newbury Volcanic Complex, applied by LaForge...to the rocks of the Parker River area, south of Newburyport, Mass." (Toulmin, 1961, written communication).

It is likely that the melanocratic rock exposed three-quarters of a mile southeast of Middleton center belongs to a volcanic facies of the Newbury Formation. This rock is medium to dark greenish gray and generally massive, but there is a vague suggestion of foliation in parts of the exposure. It is very fine grained and locally possesses a porphyritic texture in which the phenocrysts reach a maximum diameter of approximately 1 mm. The rock is composed chiefly of plagioclase, quartz, and epidote together with small amounts of chlorite and dolomite(?). An approximate mode is presented in table 15. Plagioclase composes up to 60 percent of the rock and its composition is estimated to be about $An_5$. It may contain up to 25 percent quartz, but as the quartz occurs largely within the very fine-grained groundmass, an accurate estimate of its percentage is difficult. Epidote is unusually abundant and composes from 15 to 20 percent of the rock. The epidote occurs chiefly as tiny grains scattered throughout the feldspar phenocrysts and is not confined to well-defined zones or veins.

A second group of rocks correlated with the Newbury Formation crops out north of the Ipswich River in the extreme east-central section of the Reading quadrangle. These exposures consist of thinly-layered, aphanitic flesh-colored rocks sharply transitional with a lighter colored, porphyritic, massive facies.

The thinly-layered rock is composed chiefly of feldspar and quartz with accessory amounts of sericite and epidote. The feldspar includes both plagioclase and potassium feldspar, but it is difficult to estimate the relative amounts of the individual feldspar phases present, owing to the

Table 15. Estimated modes of rocks from the Newbury Formation

| | A. | B. |
|---|---|---|
| Quartz | 15 | 30 |
| Plagioclase | 60 | 40 |
| Orthoclase(?) | | 21 |
| Chlorite | 3 | |
| White mica | | 8 |
| Epidote | 20 | 1 |
| Carbonate | 2 | |

A(R-36). Dark gray porphyry south of Oakdale Cemetery along east side of Ipswich River, Middleton

B(R-118). Flesh colored aphanitic rock 1700 ft. southwest of South Main St.-River St. intersection, Middleton fine-grained nature of the rock and the moderate degree of feldspar alteration. Quartz probably makes up less than one-third of the rock, and sericite and epidote (which have been derived chiefly from alteration of feldspar) together compose no more than 10 percent. An estimated mode of the thinly-layered rock is given in table 15. The lighter colored porphyry is characterized by the presence of spherical phenocrysts of quartz up to 2 mm. in diameter, set in an aphanitic groundmass. The porphyritic rock was not examined in thin section, but its mineral assemblage probably approximates that of the thinly-layered rock.

The composition of the leucocratic rocks described above is strongly suggestive of a sodic rhyolite, and the texture of the porphyry makes it virtually certain that these rocks are at least in part volcanic. The origin of the melanocratic rock exposed southeast of Middleton center is less clear. The writer initially considered this rock a metavolcanic, but its mineralogical composition and the nature and degree of its alteration closely parallel that of the adjacent Newburyport(?) Quartz Diorite, which suggested that it might be a border facies of this unit. Toulmin (1960, written communication), however, has discovered rounded quartz phenocrysts in nearby exposures of this same rock in the Salem quadrangle, which suggests that it is volcanic in origin and improbably correlative with the Newburyport(?) Quartz Diorite.

## Correlation and age

The metavolcanic rock exposed southeast of Middleton center is correlated with the Newbury Formation because (1) it is presumably an extrusive rock, and (2) it is on strike with the fossiliferous Newbury Formation exposed 1½ to 2 miles to the northeast. The leucocratic volcanic rocks are correlated with the Newbury chiefly because of their great lithologic similarity to volcanic rocks within the main belt of the Newbury Formation exposed in the Georgetown quadrangle.

The Newbury Formation is the only paleontologically dated unit in northeastern Massachusetts. According to W. B. N. Berry and A. J. Boucot (1962, written communication) the Newbury "has yielded rhynchonellids and ostracods which may be of Ludlow age, but the fossil collections are not conclusive," and it is possible but doubtful that they could be of Devonian age. However, fossiliferous rocks almost certainly derived from the Newbury Formation have been discovered recently in glacial outwash deposits exposed in the Georgetown quadrangle. According to Boucot (1963, oral communication) these rocks contain a definitive Ludlovian fauna, and thus support the assignment of the Newbury Formation to the Upper Sillurian (or uppermost Middle Silurian).

## Rocks of late Paleozoic age

### Devonian(?) metasedimentary rocks

Metasediments tentatively assigned to the Lower Devonian crop out in the Lawrence quadrangle. These rocks are probably the youngest of the metasediments exposed in the area, but their minimum geologic age is particularly tenuous. Their age is inferred chiefly from their probable relationship to the Merrimack Group and from correlations with similar rocks in New Hampshire and Connecticut. Although locally contorted or otherwise deformed, none of the Devonian(?) metasediments are higher grade than greenschist facies.

#### Worcester(?) Phyllite

Rocks included here with the Worcester Phyllite crop out in South Lawrence, just north of Mt. Vernon Park. Exposures of the Worcester(?) are the poorest of any formation in the area, and the writer is very uncertain of the areal distribution of this unit. Rocks locally mapped with the Worcester include conglomerate as well as phyllite.

#### Harvard Conglomerate Lentil

The Harvard Conglomerate was first described and named by W. O. Crosby (Wilmarth, 1938, p. 921). Emerson (1917, p. 66-67) subsequently redefined and renamed the unit the Harvard Conglomerate Lentil, a usage retained by Hansen (1956,

p. 20-23) in his report on the Hudson and Maynard quadrangles. The Harvard Conglomerate occurs in the Hudson quadrangle as a band up to 2,000 feet wide (Hansen, 1956, pl. 1), but it gradually thins to less than 200 feet as it is traced northeastward.

The presence of the Harvard Conglomerate in this area has been established by Jahns (1957, written communication). He has reported conglomerate from three exposures; one along the south shore of the Merrimack River near the western border of the Lawrence quadrangle, another on a small knob 2,200 feet southwest of the intersection of Andover Street and South Broadway in South Lawrence, and a third "800 feet south-southeast of Andover Street and 2,100 feet west-southwest of South Broadway." Unfortunately none of these conglomeratic exposures has been seen by the writer. When visited by the writer the exposure along the river was thickly coated with slime and no identifiable conglomerate was discovered in the course of systematic sampling. Granting its existence, however, its close geographic association with the Brimfield-type schist, as opposed to phyllitic rocks more typical of the Worcester, suggests that it is improbably correlative with the Harvard; thus it has not been included with the Harvard on the geologic map. The exposures in South Lawrence apparently were obliterated during construction shortly after being visited by Jahns, and careful examination of the rubble failed to confirm the presence of the conglomerate.

According to Jahns (1957, written communication), the Harvard Conglomerate in the Lawrence quadrangle is almost identical to that exposed to the southwest, and consists of a series of interbedded pebble and phyllite or schist layers. The pebble beds within the conglomerate formerly exposed in Lawrence are as much as 15 inches thick. The pebbles have a maximum dimension of approximately one-half inch but are generally "pea-sized"; they consist chiefly of quartzite and what is apparently a sandy schist. The matrix and the material interbedded with the pebbly layers consist chiefly of "punky" quartzitic schist and dull-greenish-gray phyllite. Jahns has concluded that the Harvard Conglomerate exposed in the city of Lawrence is no more than and possibly less than 10 feet thick.

The Harvard Conglomerate of the type area was considered a basal conglomerate by Crosby (Wilmarth, 1938, p. 921) and its stratigraphic situation in both the type locality and this area is not inconsistent with this view. Nevertheless, the description of the locally developed Harvard supplied by Jahns accords with that of a turbidite, and data are insufficient to draw any definitive conclusions on the depositional environment of the Harvard Conglomerate in this area.

## Undifferentiated Worcester(?) Phyllite

Exposures of the Worcester(?) Phyllite exclusive of the Harvard Conglomerate, are limited to several outcrops in

South Lawrence.

A dark, blue-gray phyllite similar to that exposed in the type locality of the Worcester Phyllite, occurs in South Lawrence. The phyllite exposed here is prominently foliated, highly contorted, (see plate 19A), and devoid of recognizable bedding or compositional layering of any sort. It is composed of muscovite, chlorite, quartz, and a small amount of what is tentatively identified as graphite. Muscovite and chlorite are the predominant phases, but quartz composes up to 30 percent of the rock. The average grain size of the phyllite is between 0.01 and 0.02 mm., but relatively large quartz grains, up to 0.5 mm. in length, are also present.

The undifferentiated Worcester(?) Phyllite is thought to have been derived from a series of locally carbonaceous, argillaceous rocks. The metamorphic grade of the phyllitic rocks in South Lawrence probably falls within the quartz-albite-muscovite-chlorite subfacies of the greenschist facies (Fyfe, Turner, and Verhoogen, 1958, p. 219).

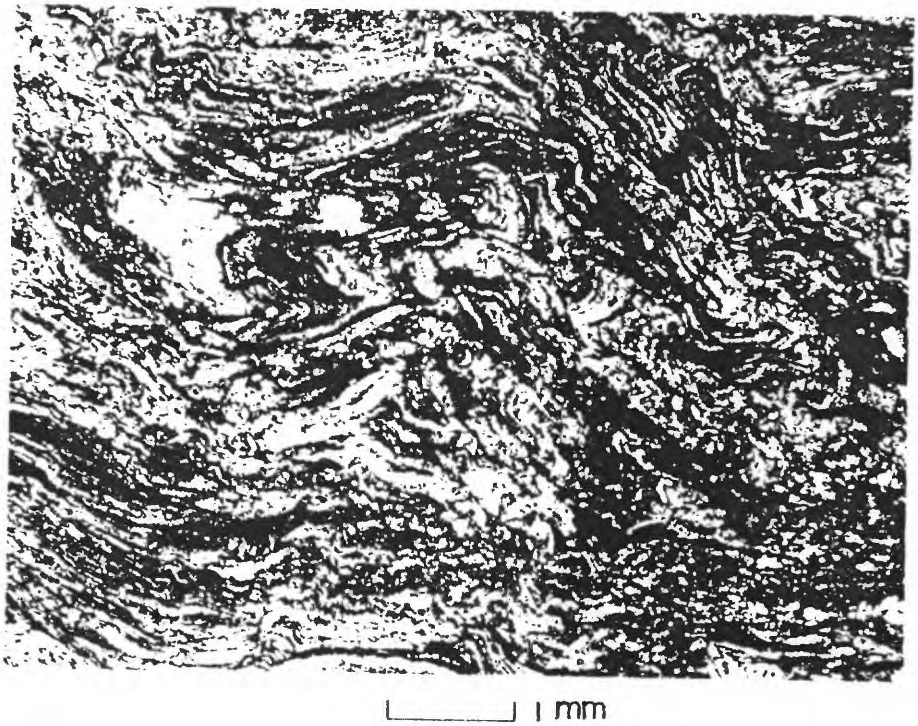
## Correlation and age of the Worcester(?) Phyllite

Rocks locally mapped with the Worcester Phyllite are correlated with those of the type locality primarily for two reasons: (1) the Harvard Conglomerate has been traced through to this area from the type locality by R. H. Jahns and M. E. Willard (1952, oral communication); (2) the phyllite exposed

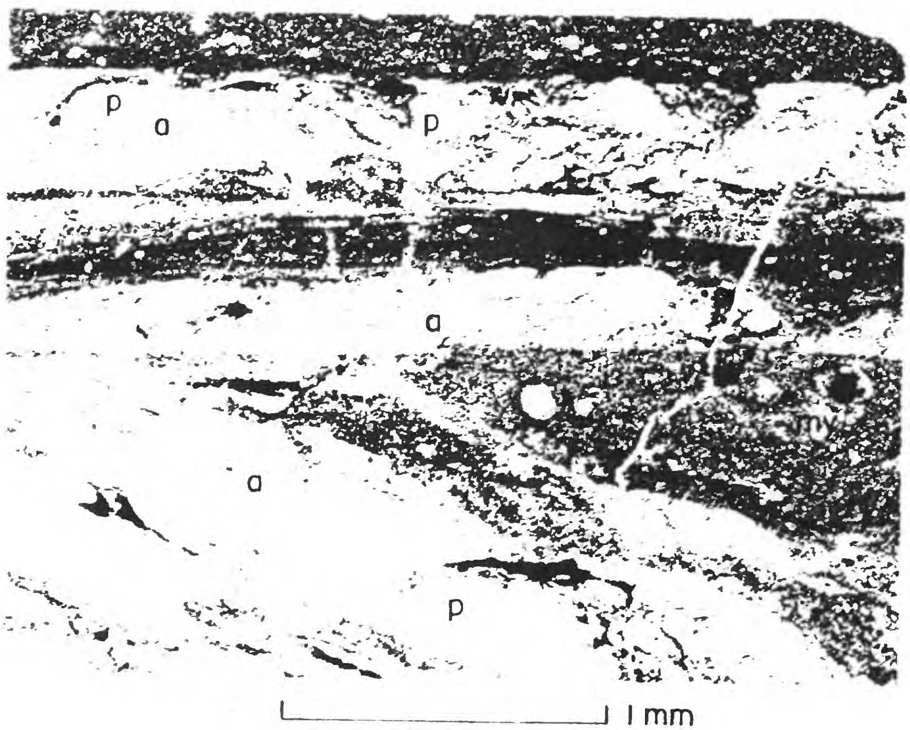
Plate 19

A. Photomicrograph of highly contorted Worcester(?) Phyllite exposed 1900 feet west-northwest of Broadway-Mt. Vernon St. intersection, South Lawrence. No systematically arranged structural elements could be discerned in the outcrop area and this structural heterogeneity is apparently characteristic of the phyllite down to the field of a single thin section. Plane light.

B. Photomicrograph of highly sheared gabbro or diorite from the Dracut Diorite exposed near the top of Nickel Mine Hill, Dracut. p, plagioclase; a, amphibole; my, mylonite. Plane light.




A




B

in South Lawrence bears a striking resemblance to that of the type area. Should either of the preceding reasons prove inadequate, the presence of the Worcester Phyllite in this area should not be easily demonstrable. For example, it is at least possible that the phyllite is actually correlative with the Eliot Formation rather than the Worcester. This is presently considered unlikely only because there is evidence of a hiatus between the Kittery and Worcester(?) that is not known to occur between the Kittery and Eliot (see below).

Two specific lines of evidence indicate that the Worcester Phyllite overlies the Merrimack Group. According to Emerson (1917, p. 77) "in pitching folds the Oakdale (Merrimack Group equivalent north of Worcester) regularly passes under the Worcester." Moreover, Jahns (1941, p. 1911) has noted that the Harvard Conglomerate "contains pebbles that appear to be of Merrimack quartzite," suggesting a hiatus between the deposition of the Merrimack and the Worcester. The age of the Worcester Phyllite relative to other metasedimentary units in this area cannot be established directly.

The Worcester Phyllite has been assigned to the Carboniferous by almost every geologist who has investigated this unit (Perry, 1885, p. 157; White, 1912, p. 114; Emerson, 1917, p. 63-64; Hansen, 1956, p. 18-19). This age assignment has been based almost entirely on the discoveries by Perry (1885, p. 157) and White (1912, p. 114) of Carboniferous plant fossils in the graphitic anthracite of the old Worcester coal mine that is thought to lie within the Worcester Phyllite. Billings (1956, p. 101), however, has questioned the identification of these fossils and has suggested that the "fossils" may be "two sets of crinkles intersecting at such an angle as to simulate lepidodendron." Furthermore, there is a distinct possibility that a hiatus exists between the fossil-bearing strata and most of the rocks generally mapped with the Worcester Phyllite. The areal relations are obscure in the vicinity of the Worcester coal mine, and no evidence has been adduced to date that tends to confirm or refute the possibility of a hiatus.

It is reasonable to suppose from its relationship to the Merrimack Group that the Worcester Phyllite is probably post-Middle Silurian. Furthermore, Rosenfeld (1962, oral communication) and others have indicated that the Worcester is probably correlative with the phyllitic, upper part of the Bolton Group in Connecticut. Rosenfeld in turn has correlated the upper Bolton with the Lower Devonian Littleton Formation of New Hampshire. Assuming that the suggested correlations are valid, the Worcester Phyllite is assigned here to the Lower Devonian.

## Devonian(?) igneous rocks

Rocks described under this heading are confined to a single small pluton cropping out along the western edge of the Lawrence quadrangle. The geologic age of these rocks is inferred from the probable age of the rocks they intrude, and from their relationship to adjacent and presumably younger Devonian or Carboniferous igneous rocks.

## Dracut Diorite

The name "Dracut diorite" was applied by Emerson (1917, p. 221-223) to a group of intrusive rocks exposed near Lowell and Dracut, Massachusetts. The easternmost stock of the Dracut, and the only one that occurs in this area, was believed to be essentially norite and was so named by both Fairbanks (Wilmarth, 1938, p. 630) and Dennen (1943, p. 26-41). Emerson's usage is retained in this report, however, as the term norite is considered too restrictive for the diverse rock types contained within the pluton. Inasmuch as this particular stock has been studied in relative detail by Dennen and Jahns (1953, oral communication), only a cursory petrographic examination has been attempted.

The Dracut Diorite of this area occurs almost entirely within the Lawrence quadrangle where it forms the eastern end of a small stock intruding the Kittery Quartzite. Rocks exposed within the stock vary markedly in mineralogical composition, but no attempt has been made to map the several easily distinguishable types, owing to the heterogeneity of the formation and the generally poor exposure. The most prominent rock type exposed is diorite or gabbro, but tonalite crops out locally. Thin stringers of granitic pegmatite, probably related to the nearby Andover Granite, crosscut the diorite, and Jahns (1960, written communication) has discovered pods and dikelets of gabbroic pegmatite within the Dracut. Xenoliths of impure quartzite are common, particularly along the southeastern margin of the stock.

Fresh exposures of the Dracut range in color from almost black in the more mafic varieties, to light gray in the tonalite. A faint to pronounced greenish hue, probably attributable to the presence of alteration products, is present in almost every exposure. Weathered outcrops locally are stained with iron oxides, but they are generally lighter than corresponding fresh exposures. The rocks of the Dracut are essentially massive, but a crude foliation occurs in exposures near its contact with the Kittery Quartzite and in parts of Nickel Mine Hill. The several facies in places form a breccia, and fully half the thin sections examined manifested some evidence of extensive shearing along thin zones, generally only a fraction of a millimeter in thickness (see plate 19B). The massive rocks are generally hypidiomorphic, medium grained, and equigranular, becoming somewhat porphyritic along the south flank of Nickel Mine Hill.

The dioritic and gabbroic rocks of the Dracut are composed chiefly of plagioclase, pyroxene, and hornblende. Highly sericitized plagioclase composes from 15 to 60 percent of the rock. It ranges in composition from about $An_{40}$

to $An_{50}$. Dennen (1943, p. 36-37) has reported bytownite from the Dracut, and it is conceivable that some of the highly altered plagioclase observed by the writer may go above $An_{60}$. Plagioclase zoning is not uncommon, but it generally is better reflected by differential alteration than it is by differences in extinction angle. According to Dennen (1943, p. 37) "plagioclase was seen to be younger than the pyroxene" in every thin section studied; the writer, however, was unable to adduce paragenetic criteria suggesting that crystallization of either mineral species preceded the other. Pyroxene and amphibole together compose from 30 to 80 percent of the diorite exposed away from the margin of the stock. Pyroxene was seen in every thin section examined from the central part of the stock, but the particular species was identifiable (as augite) in only one or two cases. Hypersthene has been reported as a major constituent of the Dracut by Dennen (1943, p. 37) and Jahns (1960, written communication), but no orthopyroxene was positively identified by the writer. The pyroxenes commonly are mantled by chlorite selvages, and, according to Dennen (1943, p. 51), show greater alteration than do the feldspars. This was not the case in those sections examined by the writer. The amphiboles consist largely of green to brown hornblende that occurs chiefly as reaction rims surrounding pyroxene. Tremolite and actinolitic tremolite were seen in several of the more highly altered specimens, but it is doubtful that they are primary phases. Olivine, apparently in major quantities, was reported by Dennen (1943, p. 38) from noritic rocks, but it was not observed in the limited study made by the writer. Apatite, rutile, magnetite, and ilmenite occur in varying amounts as accessory minerals. Sulfides are scattered throughout the more mafic parts of the stock, but they are concentrated in a small zone on the north side of Nickel Mine Hill. As the name suggests, this area was once exploited for the nickel that occurs within this sulfide pocket. The nature and extent of the deposit are considered in a subsequent section.

Exposures of the tonalitic facies of the Dracut are confined to a small area adjacent to its contact with the Kittery. The tonalitic rocks manifest a more pronounced foliation and are generally more sodic than the rocks toward the center of the stock. Plagioclase has an average composition of about $An_{30}$ and composes from 55 to 65 percent of the rock. In general, zoning is more apparent and alteration less intense than in the plagioclase contained within the less siliceous facies. Quartz, essentially absent in the central part of the stock, composes up to 25 percent of the tonalite. The major mafic constituent of the tonalite is locally altered biotite. Small amounts of hornblende also were seen, but no pyroxene was observed. Accessory minerals of the tonalite are approximately the same as those of the more melanocratic facies, except for the apparent absence of sulfides.

## Origin

The Dracut stock is an intrusive igneous body. The origin of its several facies and the nature of its observed alteration are more speculative matters. Emerson (1917, p. 223) suggested that the Dracut Diorite is "of the same general age as the Ayer granite, but slightly older, and... represent(s) the first solidified and more mafic portion of the magma, which crystallized into a rock richer in biotite and other mafic minerals and poorer in quartz and orthoclase than the normal (Ayer) granite." This, in essence, is the view taken by Jahns (1957, oral communication) in explaining the composite Dracut stock north and west of Lowell. The reason for the relatively altered character of many of the Dracut rocks is particularly obscure. Dennen (1943, p. 51) felt that hydrothermal alteration of the norite was negligible, but it is hardly negligible relative to that obtaining in surrounding rocks. The hydrothermal alteration is attributed by the writer to late magmatic or deuteric activity, rather than to post-intrusion phenomena, because: (1) evidence of hydrothermal alteration is much more pronounced in the Dracut Diorite than in the surrounding rocks; (2) with the exception of the area around the abandoned nickel mine, alteration effects are not concentrated in specific zones but are scattered irregularly throughout the more mafic parts of the stock.

## Correlation and age

The Dracut Diorite is unique within this area and doubtfully correlative with any other locally exposed rock. There is some similarity between the tonalitic rocks of the Dracut stock and those of the nearby Sharpners Pond Tonalite, but the more mafic facies are dissimilar in terms of essential mineral composition and degree and type of alteration. It may also be significant in this regard that the Dracut is intrusive into the Merrimack Group, whereas the Sharpners Pond is not known to be intrusive into the Merrimack in this area. The gross composition of the Dracut is similar to that of the Salem Gabbro-Diorite exposed in Salem (Clapp, 1921, p. 21), but a suggested correlation should be completely speculative.

As the Dracut is clearly intrusive into the Kittery Quartzite, it probably postdates all the metasediments in the area (excepting, perhaps, the Newbury Formation and Worcester(?) Phyllite). If the Kittery is assumed to be Middle Silurian, and the younger(?) Andover Granite is considered Acadian in age, the Dracut Diorite is probably Devonian.

## Devonian or Carboniferous igneous rocks (Subalkaline intrusive series)

In keeping with the terminology of Clapp (1921, p. 21-25) and Toulmin (1961, written communication), a major group of locally developed igneous rocks has been designated as the subalkaline intrusive series. The rocks of the subalkaline series range in composition from gabbro-diorite to siliceous alaskite and pegmatite and fall within the peraluminous and, to a lesser extent, metaluminous groups of Shand (1951, p. 228-229). The assignment of separately mapped members to this series, however, stems only in part from peculiarities of chemical composition; inclusion in the intrusive series is based much more on considerations of phase composition, petrographic characteristics, and general field relationships. The Sharpners Pond Tonalite and Andover Granite together comprise fully 90 percent of the subalkaline intrusive series cropping out within the map area. The assignment of other units to this series is based chiefly on their tentative correlation with either the Sharpners Pond or the Andover.

Determination of the geologic age of these rocks is dependent in large part on subtleties of occurrence and to some extent on their relationship to presumably younger, radiometrically dated igneous rocks. Relative ages between units have not been established in all cases, and the following order of presentation does not necessarily reflect their order of emplacement.

## Sharpners Pond Tonalite

The Sharpners Pond Tonalite has been named for the generally melanocratic igneous rocks, well exposed in the vicinity of Sharpners Pond, North Andover (Castle, in review). Most of the rocks included here with the Sharpners Pond formerly were mapped under the name Salem Gabbro-Diorite (see plate 2). However, an average mode for all the rocks contained within the Sharpners Pond would fall well within the tonalite and well outside the gabbro-diorite range. Moreover, there now appears to be reason for doubting the age equivalence of the Sharpners Pond with the type Salem (Toulmin, 1958, written communication). It is for these reasons that these rocks have been described under this new name, recognizing nevertheless that some sort of equivalence between the Sharpners Pond and the Salem is not at all unlikely. The Sharpners Pond Tonalite has been divided into three separate but transitional facies for purposes of mapping and description; (1) hornblende diorite, (2) biotite-hornblende tonalite, and (3) biotite tonalite. The basis of mapping is the preponderance of the named lithology in the area so mapped, and the threefold classification thus is somewhat arbitrary.

The Sharpners Pond Tonalite occupies 40 to 50 square miles of the area considered in this report. The greater part of the formation crops out in the South Groveland and Reading quadrangles where it intrudes the Westboro-type quartzite and Marlboro and Boxford Formations. Lesser amounts occur in the southeastern section of the Wilmington quadrangle, and a few "sills" adjacent to outliers of Brimfield-type schist have been mapped in the southeastern quarter of the Lawrence quadrangle. Outside of the Lawrence quadrangle exposures of the Sharpners Pond are generally good, and contacts with the rocks it intrudes are more accurately defined than most.

## Hornblende diorite facies

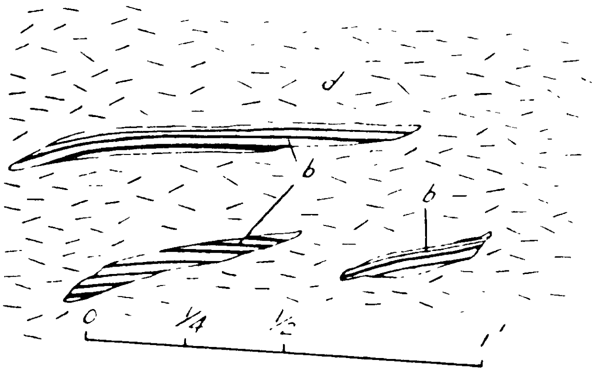
The hornblende diorite facies crops out over more than half the area mapped with the Sharpners Pond Tonalite, and it is best developed in the eastern and southeastern parts of the map area. There are very few localities, however, where it (or any other facies for that matter) is present to the complete exclusion of the other facies of the formation. The hornblende diorite facies is found in its purest form in intrusions of the Sharpners Pond in the northeast corner of the South Groveland quadrangle, and in the northeast section of the Reading quadrangle.

The rocks of the hornblende diorite facies are characteristically melanocratic, ranging from black to dark greenish gray. They are generally massive, but planar structures are manifested locally (see figure 5A). The presence of foliated hornblende diorite within the Sharpners Pond creates an important mapping problem, for some of these rocks probably would have been mapped with the Marlboro amphibolites had they been observed in isolated exposures.

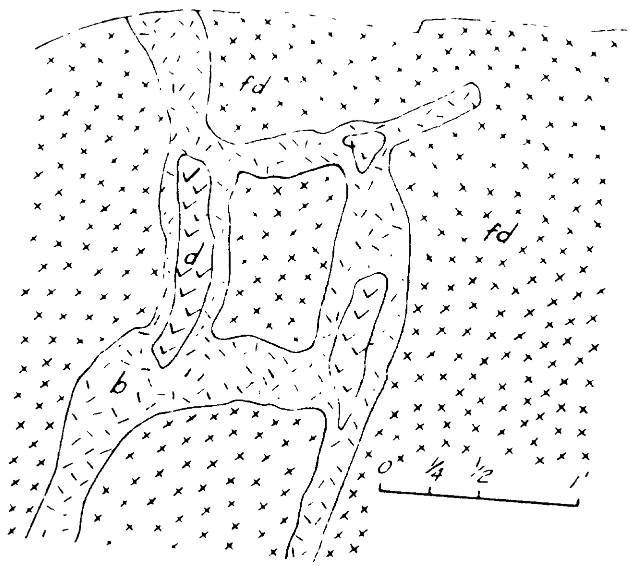
Figure 5

A. Diagrammatic sketch of gneissic diorite (d) of the Sharpners Pond Tonalite exposed at south end of Bruin Hill, North Andover. Note that long axes of inclusions of the Boxford Formation (b) roughly parallel the foliation within the host.

B. Diagrammatic sketch of outcrop in the Sharpners Pond Tonalite 3900 feet east of northern tip of Creighton Pond, Middleton. Fine-grained diorite (fd) apparently has been intruded along a rude fracture system by a coarse-grained, lighter-colored diorite (d). Medium-grained biotitic tonalite or granodiorite (b) subsequently intruded the rock along the pre-established path of earlier dioritic intrusion.




A




B

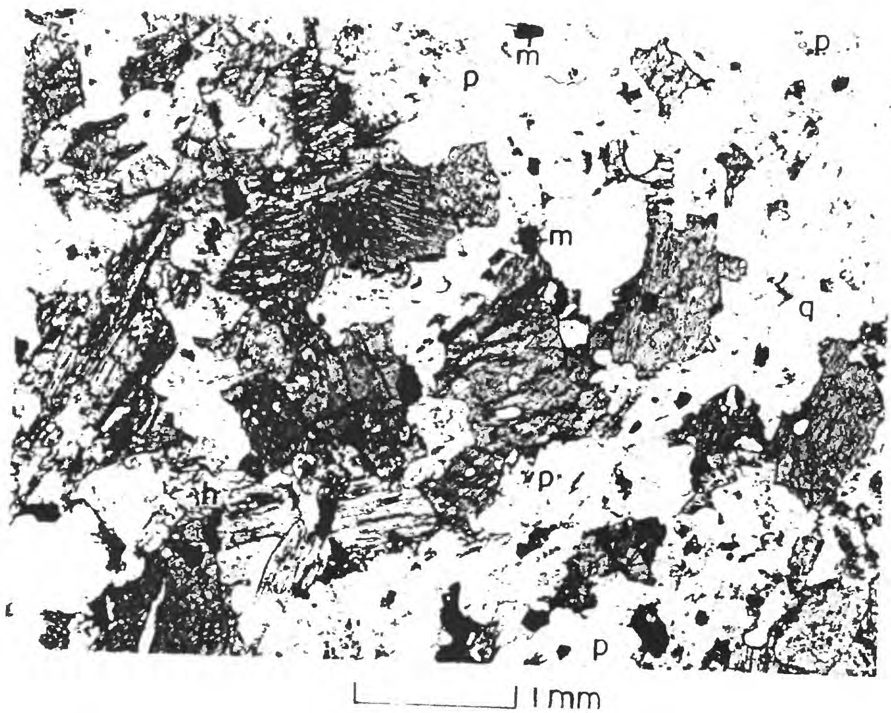
The hornblende diorite is generally equigranular, medium to coarse grained, and hypidiomorphic to allotriomorphic in texture (see plate 20). Poikilitic textures (figure 6A) are uncommon but present. Porphyritic textures were observed in fine-grained hornblende gabbro(?) dikes crosscutting the Fish Brook Gneiss, but it is not certain that the dikes are related to the Sharpners Pond. Poorly developed porphyries also were seen in the northeast corner of the South Groveland quadrangle and in roadcuts in the extreme southwestern part of the Reading quadrangle. Where crosscutting relationships occur among the rocks of the hornblende diorite facies, the coarser grained facies are generally younger (see figure 5B), but age relationships between porphyritic and equigranular types are obscure.

Rocks mapped with the hornblende diorite facies include some tonalite and minor amounts of gabbro. A slightly quartzose hornblende diorite is the most representative rock of the hornblende diorite facies (see table 16). Rocks included with this facies are composed chiefly of plagioclase and hornblende, together with varietal amounts of quartz and biotite. The most common accessories include sphene, apatite, and magnetite. Secondary chlorite and epidote together compose up to 15 percent of some of these rocks. Plagioclase composition ranges from $An_{28}$ to $An_{55}$ and averages around $An_{40-45}$. Generally normal, but vaguely defined zoning is not uncommon in the plagioclase, but it was totally absent

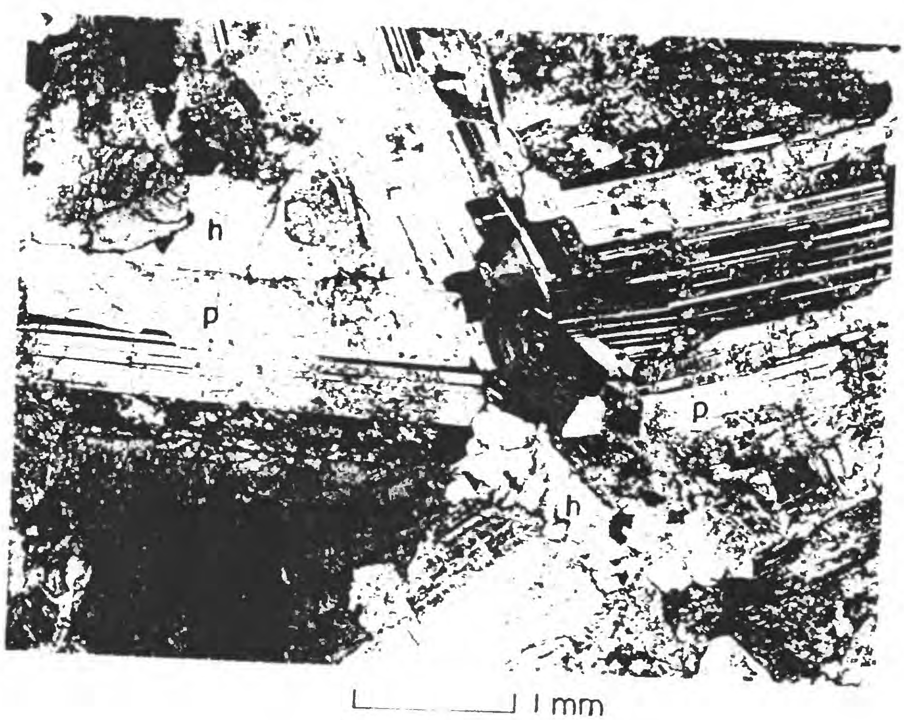
Plate 20

A. Photomicrograph of specimen from the hornblende diorite facies of the Sharpners Pond Tonalite exposed 3000 feet north of Creighton Pond in the South Groveland quadrangle. p, plagioclase; c, chlorite; e, epidote; h, hornblende; m, magnetite. Plane light.

B. Photomicrograph of specimen from the hornblende diorite facies of the Sharpners Pond Tonalite exposed 3400 feet east of souther tip of Creighton Pond, Middleton. p, plagioclase; h, hornblende. Idiomorphism is more pronounced here than in any other section examined from the Sharpners Pond. Crossed nicols.




A

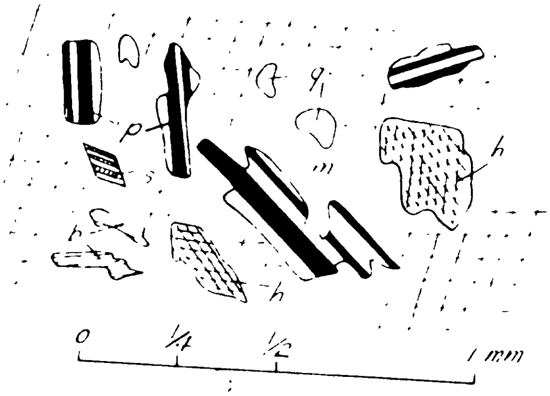



B

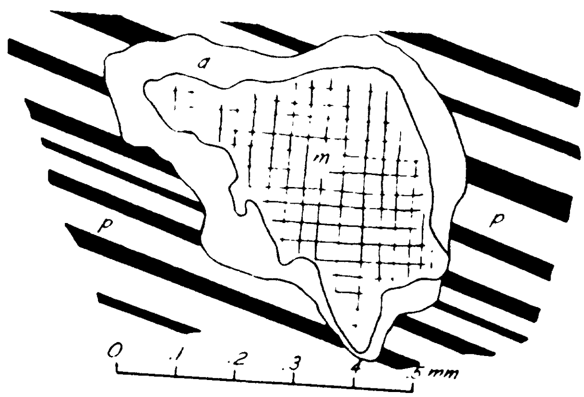
Figure 6

A. Diagrammatic thin section sketch of specimen taken from brecciated zone of hornblende diorite facies of the Sharpners Pond Tonalite exposed 3800 feet east-southeast of eastern tip of Creighton Pond, Middleton. The dioritic breccia clasts are set within a granitic host and microcline crystals up to 4 mm. long are scattered irregularly through the diorite in the vicinity of the granite host. The microcline (m), as shown in this sketch, poikilitically (or poikiloblastically) includes plagioclase (p), quartz (q), hornblende (h), biotite (b), and sphene (s).

B. Diagrammatic thin section sketch of leucocratic rock exposed within the biotite-hornblende tonalite facies of the Sharpners Pond Tonalite, approximately one mile south of North Reading State Sanitarium. Occurrence of albite (a) apparently is controlled by localization of microcline (m) within the plagioclase (p).




A




B

Table 16. Modal analyses of rocks from hornblende diorite and biotite-hornblende tonalite facies of the Sharpners Pond Tonalite[1/]

| | Hornblende diorite facies | | | | |
|---|---|---|---|---|---|
| | A. | B. | C. | D. | E. |
| Quartz | | | | 4.3 | 7.2 |
| Plagioclase | 45.1 | 52.3 | 51.8 | 48.6 | 35.0 |
| Microcline | | | | | |
| Hornblende | 38.2 | 36.8 | 33.6 | 18.9 | 29.7 |
| Pyroxene(?) | | | | .3 | |
| Biotite | .6 | | 7.3 | 12.9 | |
| Chlorite | 10.4 | 1.7 | 1.5 | 2.4 | 4.4 |
| White mica | | | 1.4 | | 19.5 |
| Epidote | .9 | 3.0 | .5 | 2.0 | 1.7 |
| Sphene | | | | | .8 |
| Apatite | .9 | .8 | 1.0 | 3.2 | .5 |
| Zircon | | | .1 | | |
| Carbonate | tr. | | | .6 | |
| Opaque | 3.8 | 5.4 | 2.8 | 6.8 | 2.2 |

Table 16. (cont.)

| | Biotite-hornblende tonalite facies | | | |
|---|---|---|---|---|
| | F. | G. | H. | I. |
| Quartz | 16.6 | 14.7 | 18.6 | 13.1 |
| Plagioclase | 43.7 | 48.9 | 47.2 | 46.2 |
| Microcline | .6 | | | |
| Hornblende | 10.6 | 17.6 | 22.3 | 13.9 |
| Pyroxene(?) | | | | |
| Biotite | 20.2 | 16.6 | 9.9 | 22.7 |
| Chlorite | 1.5 | | .9 | |
| White mica | 2.3 | | | |
| Epidote | 2.0 | .4 | .3 | .9 |
| Sphene | 2.0 | 1.2 | .4 | 2.3 |
| Apatite | .4 | .5 | .1 | .7 |
| Zircon | | | .1 | |
| Carbonate | | tr. | .1 | |
| Opaque | .1 | .1 | .1 | .2 |

A(W-3). Diorite from Main St.-Andover Bypass intersection, Andover (occurs within biotite-hornblende tonalite facies). Points counted: 1000. Plagioclase composition $An_{38±4}$

B(G-612). Diorite 2600 ft. S80°E of eastern tip of Creighton Pond, Middleton. Points counted: 1000. Plagioclase composition $An_{47±4}$

Table 16. (cont.)

C(L-967A). Diorite along western edge of Rabbit Pond, Andover (occurs within biotite-hornblende tonalite facies). Points counted: 1000. Plagioclase composition $An_{37±4}$

D(R-358). Biotitic diorite 1000 ft. N60°E of intersection of Reading-Wakefield-Woburn town lines, Reading. Points counted: 1000. Plagioclase composition $An_{32±4}$

E(W-259). Gneissic diorite 1100 ft. S13°W of Woburn St.-Park St. intersection, Wilmington (occurs within biotite-hornblende tonalite facies). White mica exists entirely as alteration product in plagioclase. Points counted: 1000. Plagioclase composition $An_{35±4}$

F(L-967). Biotite diorite along western edge of Rabbit Pond, Andover. Points counted: 1000. Plagioclase composition $An_{30±4}$

G(G-784). Biotite-hornblende tonalite 2900 ft. S33°E of Gray St.-Boston St. intersection, North Andover. Points counted: 1000. Plagioclase composition $An_{32±4}$

H(G-351). Biotite-hornblende tonalite 2100 ft. S73°E of Winter St.-Foster St. intersection, North Andover. Points counted: 1000. Plagioclase composition $An_{35±4}$

I(R-211). Biotite-hornblende tonalite 2700 ft. N70°W of Mill St.-Jenkins Rd. intersection, Andover. Points counted: 1000. Plagioclase composition $An_{36±4}$

1/ All figures volume percent

in fully half the specimen examined (see plate 20B). A few grains of rutilated plagioclase were observed, but rutilation is uncommon. Much of the plagioclase is moderately to extremely saussuritic or sericitic, particularly in the cores, and many of the crystals are somewhat deformed. Hornblende is generally greenish-black in hand specimen, and in thin section it ranges pleochroically from light yellow green to dark blue green. Small blebs of pyroxene(?) embedded in hornblende crystals were seen in two specimens, but most of whatever pyroxene may have been present initially probably has been altered to hornblende. As shown in table 16, quartz-free diorites occur locally in the hornblende diorite facies, but most specimens contain a small amount of free silica. Biotite or its chloritic alteration product are present throughout much of this facies, but they are subordinate mafic constituents. Magnetite and ilmenite together range from a mere trace to as much as 10 percent of the rock; examination in reflected light suggests that ilmenite is subordinate to magnetite. Sphene is a common constituent, locally composing up to 2 percent of the hornblende diorite. Apatite was identified in most thin sections from the hornblende diorite facies, and it is particularly conspicuous in the more mafic varieties.

A chemical analysis and norm of a relatively mafic specimen from the hornblende diorite facies are presented in table 17.

Table 17. Chemical analysis and norm of rock from hornblende diorite facies of the Sharpners Pond Tonalite[1/]

| Chemical analysis[2/] | |
|---|---|
| $SiO_2$ | 49.84 |
| $Al_2O_3$ | 17.45 |
| $Fe_2O_3$ | 1.64 |
| FeO | 9.43 |
| MgO | 4.77 |
| CaO | 8.34 |
| $Na_2O$ | 3.90 |
| $K_2O$ | 1.35 |
| $TiO_2$ | 1.56 |
| $P_2O_5$ | .10 |
| MnO | .15 |
| BaO | tr. |
| SrO | tr. |
| S | .12 |
| $H_2O^+$ | .54 |
| $H_2O^-$ | .26 |
| Sum | 99.45 |

Table 17. (cont.)

Norm[2/]

| | |
|---|---|
| Orthoclase | 7.79 |
| Albite | 33.02 |
| Anorthite | 26.90 |
| Wollastonite | 5.92 |
| Enstatite | 2.11 |
| Ferrosilite | 2.51 |
| Forsterite | 6.89 |
| Fayalite | 8.63 |
| Magnetite | 2.08 |
| Ilmenite | 3.03 |
| Apatite | .34 |
| Pyrite | .29 |
| Sum | 99.51 |

1/ Diorite near Colonial Golf and Country Club, Lynnfield. M. F. Connor, analyst (Washington, 1917, p. 480-481)

2/ All figures weight percent

## Biotite-hornblende tonalite facies

The biotite-hornblende tonalite facies occurs chiefly over a triangularly shaped area in the South Groveland, Reading, and Wilmington quadrangles. Good exposures of a relatively homogeneous part of this facies crop out along a belt extending from the northwest corner of the Reading quadrangle toward the center of the South Groveland quadrangle. It is transitional on map and outcrop scale with both more mafic and more felsic rocks of the Sharpners Pond Tonalite. Where age relationships have been established between biotite-hornblende tonalite and other rocks of the complex, the biotite-hornblende tonalite consistently has been found to be younger than more dioritic rocks and older than more felsic rocks.

This facies is defined by the prominence of biotite-bearing hornblende tonalite. Ideally the classification of igneous rocks of this general composition should be based at least in part on quartz content. This proved impracticable, however, in attempting to map the Sharpners Pond, for the writer's field estimates of quartz content commonly erred by 50 to 100 percent. Biotite content, on the other hand, proved a variable that could be estimated with greater accuracy. Moreover, it was observed that as the percentage of biotite rises the quartz content tends to increase (albeit irregularly), and hornblende tends to fall off in amount. The proportion of biotite, therefore, seemed a useful measure of gross composition. Accordingly, where biotite becomes a conspicuous constituent (generally at least 10 percent) of the hornblendic Sharpners Pond, the rocks have been mapped as the biotite-hornblende tonalite facies.

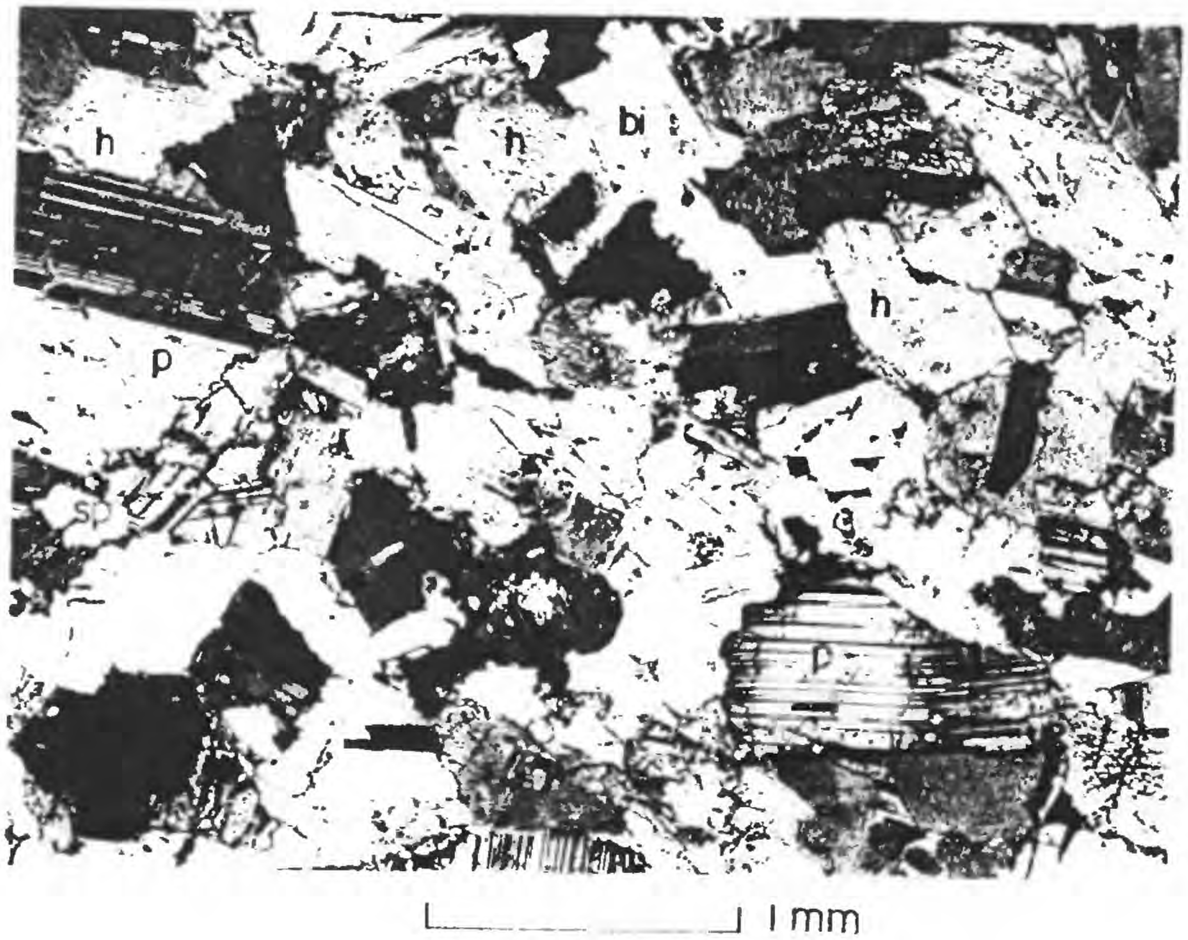
Differences between the biotite-hornblende tonalite facies and the other mapped facies of the Sharpners Pond are entirely a matter of degree. The rocks of this facies are generally dark to salt-and-pepper gray, but somewhat lighter than those of the hornblende diorite facies. Foliation is apparently better developed within the biotite-hornblende tonalite facies, but this impression may be in part a reflection of the tabular habit of the mica. Grain size tends to be somewhat finer, and idiomorphic habit of the mineral phases seems less well developed (see plate 21A) than in the rocks of the hornblende diorite facies.

Plagioclase remains the most prominent constituent in the biotite-hornblende tonalite, but it tends to be less altered and more sodic than that of the hornblende diorite. The range in plagioclase composition is between $An_{30}$ and $An_{40}$, and the An content averages about $An_{35}$. The quartz content is of course somewhat greater than in the more mafic facies and ordinarily ranges from 15 to 20 percent. Biotite becomes a major constituent in this facies, generally composing from 16 to 18 percent of the rock, but it is commonly altered in part or completely to chlorite. The distribution of accessory minerals is about the same as in the hornblende

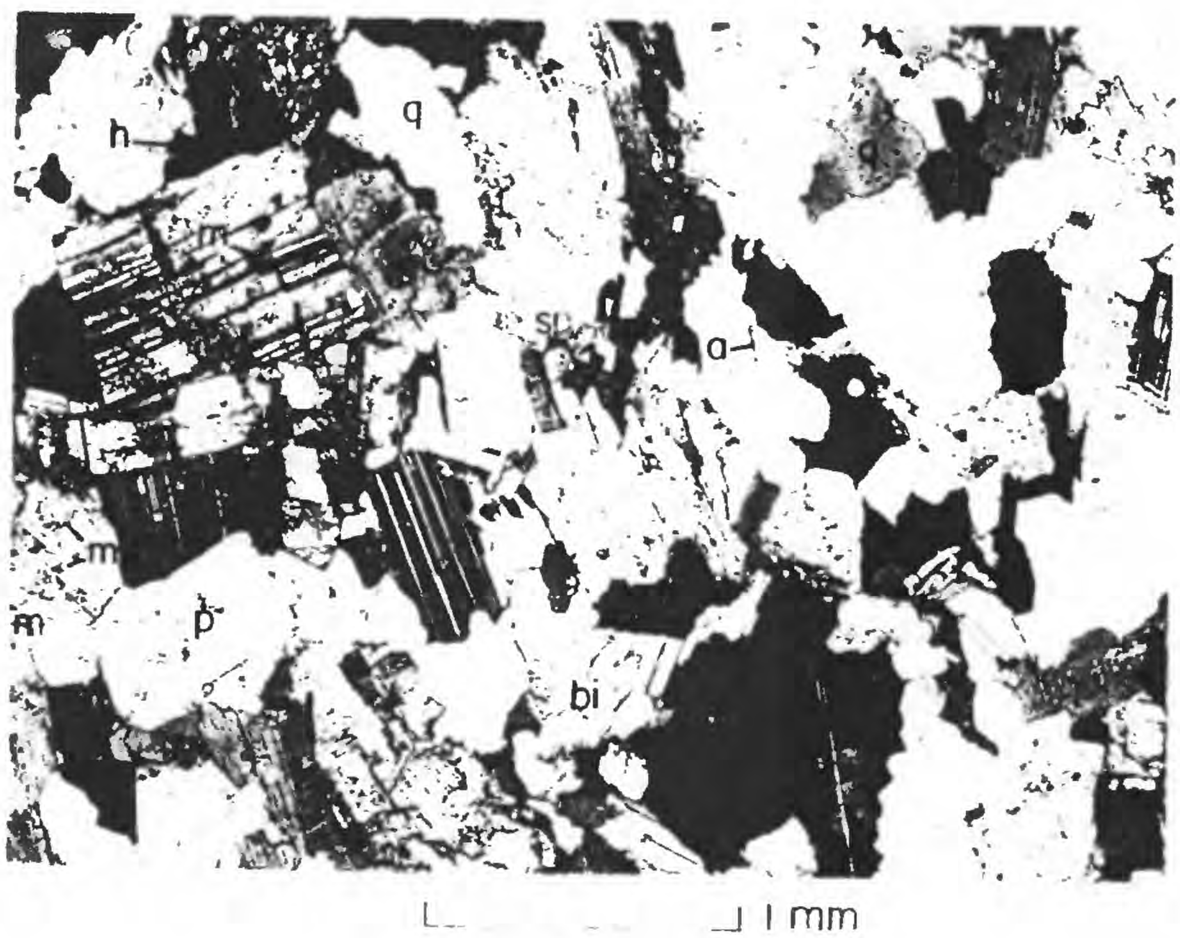
Plate 21

A. Photomicrograph of specimen from the biotite-hornblende tonalite facies of the Sharpners Pond Tonalite exposed 2100 feet east of Mt. Vernon St.-Park St. intersection, North Reading. p, plagioclase; h, hornblende; bi, biotite; sp, sphene; c, calcite. Crossed nicols.

B. Photomicrograph of specimen from the biotite tonalite facies of the Sharpners Pond Tonalite exposed along the north shore of Middleton Pond south of Wills Hill. q, quartz; p, plagioclase; m, microcline; h, hornblende; bi, biotite; sp, sphene; a, apatite. Note microcline occurring in both intragranulár and intergranular habits. Crossed nicols.




A




B

diorite, except that magnetite is diminished and sphene is more prominent. Modal analyses are presented in table 16.

### Biotite tonalite facies

Rocks mapped with the biotite tonalite facies crop out conspicuously over about 4 square miles of the north-central Reading quadrangle. The rocks of this unit formerly were mapped in part as Salem Gabbro-Diorite, but most were heretofore included with the Andover Granite (see plate 2). This facies is the most heterogeneous of those mapped with the Sharpners Pond in that (1) there is a considerable range in major mineral content, and (2) the rocks are generally mixed with those of other facies (see plate 22). The biotite tonalite facies is diffusely transitional with both the biotite-hornblende tonalite facies and the Andover Granite, and its boundaries with both rock units are very poorly defined. The facies is characterized by the predominance of biotite tonalite in which hornblende is either absent or distinctly subordinate to biotite.

The biotite tonalite ranges from very light to medium gray and is notably lighter in color than the previously described facies. The rocks are somewhat foliated, but there is little system in the planar structures developed (see plate 22), and they are generally too indistinct to measure. The textures are fine to medium grained and range from hypidiomorphic to allotriomorphic. The degree of

Plate 22

Exposure within the biotite tonalite facies of the Sharpners Pond Tonalite cropping ut along the north shore of Middleton Pond south of Wills Hill. Dark gray blocks are iotite-hornblende tonalite and lighter gray, salt-and-pepper rock is biotite tonalite. hin, leucocratic dikes are tonalite or granodiorite with relatively little admixed iotite.

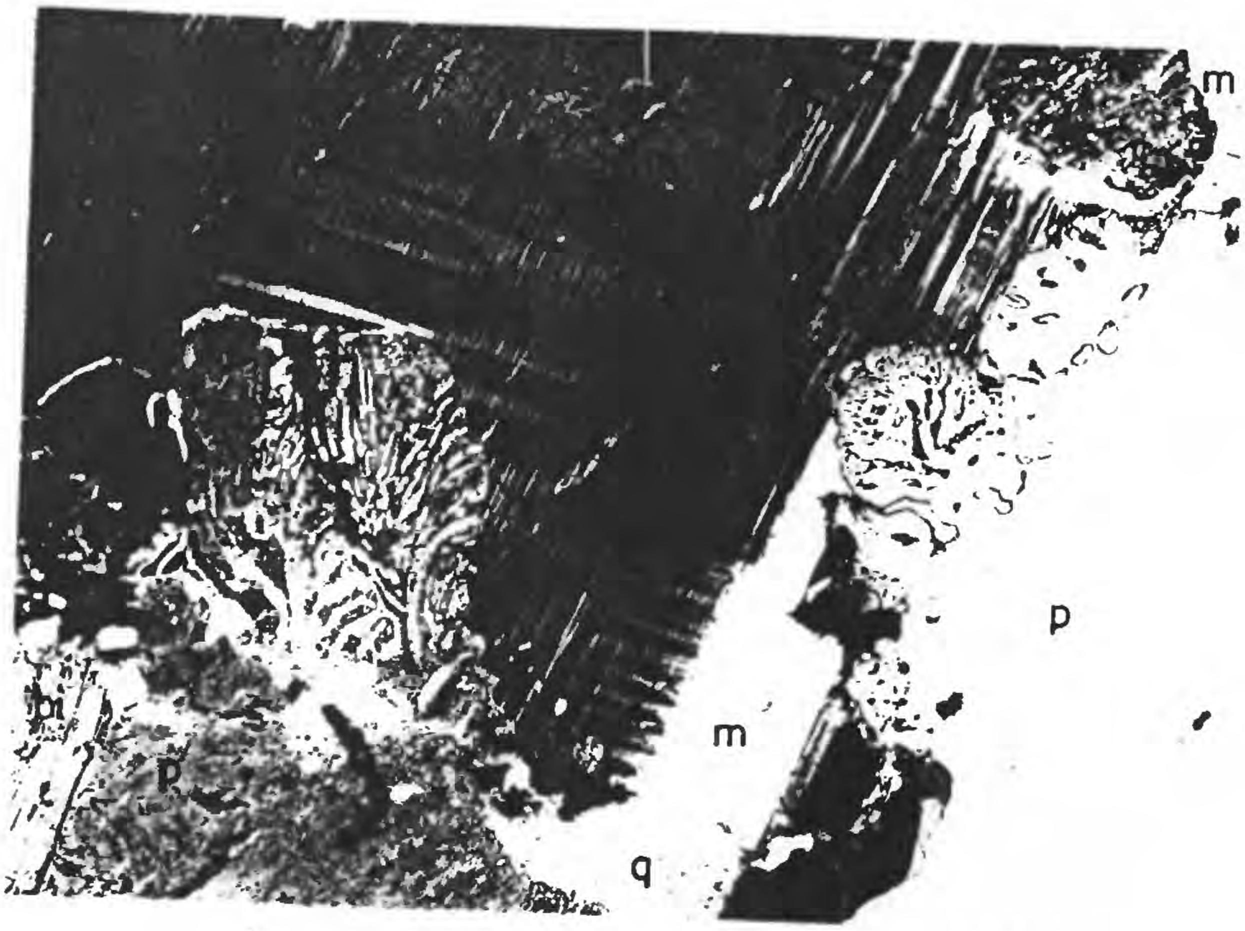
textural uniformity and idiomorphism seems to be in part a fundtion of composition. Those rocks of relatively uniform grain size and somewhat idiomorphic crystal habit (plate 21B) tend to be those of simple tonalitic composition. Rocks of more allotriomorphic configuration and irregular or intricate grain boundaries (plate 23) characteristically are those of substantial potassium feldspar content.

The rocks of the biotite tonalite facies are composed chiefly of plagioclase, quartz, and biotite, together with minor amounts of hornblende, sphene, apatite, and magnetite, and locally major amounts of microcline. Modal analyses are presented in table 18. Plagioclase composes from 28 to 56 percent of the biotite tonalite, and it is commonly bent and fractured. Its composition ranges from $An_{24}$ to $An_{33}$ and averages about $An_{30}$. Plagioclase zoning is generally inconspicuous; as often as not it is shown better by selective sericitic alteration than it is by differences in extinction angle (see figure 8A). Albite(?) occurs locally along plagioclase-microcline contacts (figure 6B), where it probably formed by reaction or unmixing from microcline. Quartz is commonly strained and composes from 25 to 36 percent of the biotite tonalite. The average quartz content is about 30 percent and thus is well above that of the biotite-hornblende tonalite facies. Biotite composes up to 24 percent of the biotite tonalite, but the average biotite content is estimated to fall between 10 and 12 percent, and thus is

Plate 23

A. Photomicrograph of granodiorite from the biotite tonalite facies of the Sharpners Pond Tonalite exposed at intersection of North Street and Haverhill Street, North Reading. q, quartz; p, plagioclase; m, microcline; bi, biotite. Note the typically developed myrmekite in which the quartz vermes neck down toward the plagioclase-microcline contact. The plagioclase composition apparently holds constant from myrmekitic to non-myrmekitic sections. The outer fringes of the plagioclase crystals in left half of photo are optically continuous with the perthitic plagioclase in microcline. Crossed nicols.

B. Photomicrograph of adamellite from the biotite tonalite facies of the Sharpners Pond Tonalite exposed 2850 feet south of Forrest St.-Marblehead St. intersection, North Reading. q, quartz; p, plagioclase; m, microcline; bi, biotite; myrmekite at arrows. Note that myrmekitic and non-myrmekitic plagioclase shown here occur as clearly separable species. Crossed nicols.




1 mm

A


1 mm

B

Table 18. Modal analyses of rocks from biotite tonalite facies of the Sharpners Pond Tonalite[1/]

| | A. | B. | C. | D. | E. | F. | G. | H. | I. |
|---|---|---|---|---|---|---|---|---|---|
| Quartz | 25.3 | 25.7 | 28.7 | 36.0 | 28.4 | 30.4 | 27.2 | 29.0 | 40.2 |
| Plagioclase | 46.1 | 56.1 | 49.7 | 47.6 | 49.6 | 39.4 | 39.9 | 28.2 | 56.7 |
| Microcline | | | 1.2 | 1.7 | 3.4 | 18.0 | 23.0 | 33.0 | tr. |
| Hornblende | .4 | 3.9 | 1.1 | | | | | | |
| Biotite | 23.7 | 12.0 | 16.6 | 11.7 | 7.4 | 8.4 | 6.8 | 5.6 | 2.2 |
| Chlorite | 1.2 | | | .6 | 5.0 | 1.0 | .8 | .2 | .4 |
| White mica | | | .3 | 1.0 | 3.6 | 1.8 | 1.4 | 2.2 | |
| Epidote | .3 | .1 | 1.3 | .9 | 1.8 | 1.0 | .7 | 2.4 | .2 |
| Sphene | 1.6 | .4 | .5 | .1 | .6 | | .2 | .4 | |
| Apatite | 1.3 | 1.4 | .3 | .3 | .2 | tr. | .1 | tr. | .2 |
| Zircon | .1 | | tr. | | | | tr. | | |
| Carbonate | | | | .2 | | | | | |
| Garnet | | | | | | | | tr. | |
| Opaque | | .4 | .3 | | .2 | | | | .1 |

A(L-974). Biotite tonalite, old quarry 2500 ft. N79°E of Summer St.-Elm St. intersection, Andover. Points counted: 1000. Plagioclase composition $An_{31\pm4}$

B(W-6) Biotite tonalite 1200 ft. N55°E of Salem St.-Woburn St. intersection, Wilmington. Points counted: 1000. Plagioclase composition $An_{25\pm4}$

C(R-40). Biotite tonalite 2400 ft. west of Maple St.-Main St. intersection, North Reading. Points counted: 1000. Plagioclase composition $An_{33\pm4}$

Table 18. (cont.)

D(R-249). Biotite tonalite along east side of Haverhill St., 200 ft. south of Haverhill St.-North St. intersection, North Reading. Points counted: 1000. Plagioclase composition $An_{27\pm4}$

E(R-42) Biotite tonalite along north shore of Middleton Pond, 2250 ft. S56°W from summit of Wills Hill, Middleton. Points counted: 500. Plagioclase composition $An_{31\pm4}$

F(R-76). Biotite granodiorite 2800 ft. south of Marblehead St.-Forest St. intersection, North Reading. Points counted: 500. Plagioclase composition $An_{28\pm4}$

G(C-11). Biotite granodiorite along east side of Haverhill St. 350 ft. south of Haverhill St.-North St. intersection, North Reading. Points counted: 1000. Plagioclase composition undetermined

H(R-86). Biotite adamellite 1900 ft. N60°W from southeastern tip of Swan Pond, North Reading. Points counted: 500. Plagioclase composition undetermined

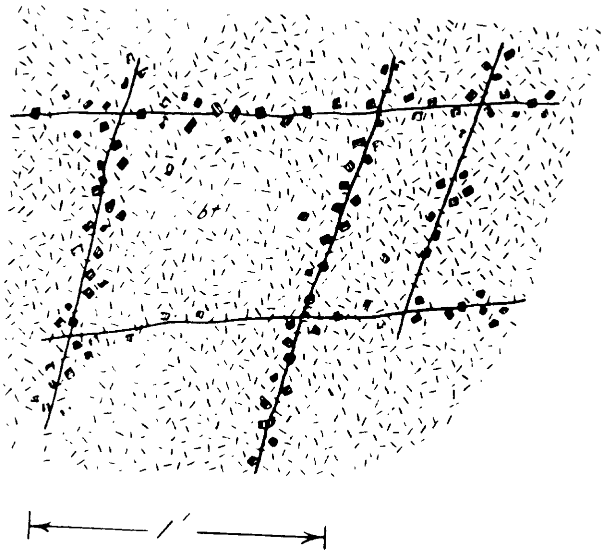
I(W-1080). Faintly foliated tonalite 2950 ft. N5°W of Mill St.-Winn St. intersection, Burlington. Points counted: 1000. Plagioclase composition $An_{15\pm4}$. May belong to Nashoba Formation

1/ All figures volume percent

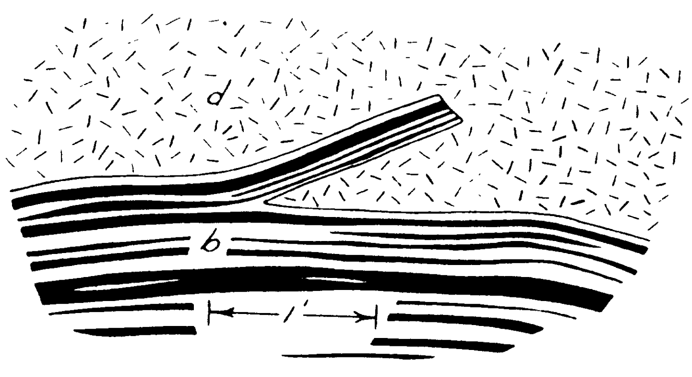
Figure 7

A. Diagrammatic sketch of outcrop within the biotite tonalite (bt) facies of the Sharpners Pond Tonalite 2500 feet west of the summit of Wills Hill, Middleton. Note the comspicuous development of alkali feldspar phenocrysts (one-eighth to one-half inch in length) along the joints.

B. Diagrammatic sketch of exposure north of Lawrence Road, Boxford, showing the contact between hornblende diorite (d) of the Sharpners Pond Tonalite and banded gneiss (b) of the Boxford Formation. Note how part of the gneiss has been pulled away from the main body of the rock.




A

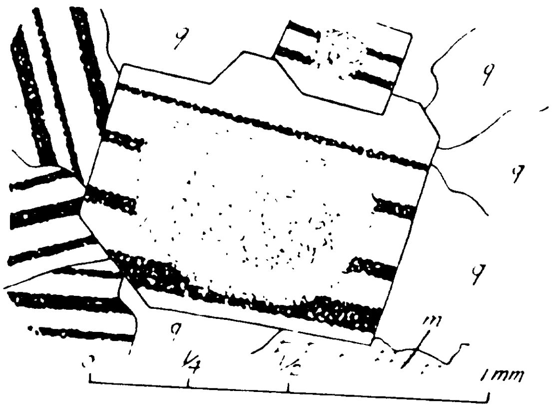



B

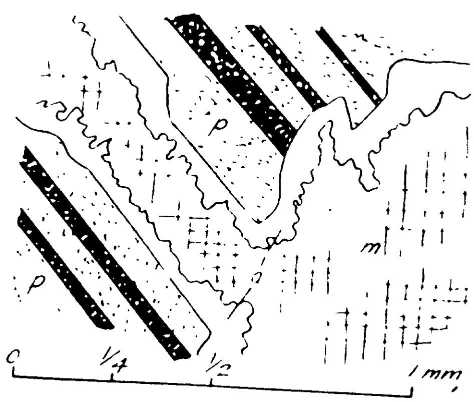
Figure 8

A. Diagrammatic thin section sketch of specimen from unmapped leucocratic dike contained within Sharpners Pond Tonalite 1700 feet northwest of intersection between Boxford St. and Boxford-North Andover town line, North Andover. Note the development of euhedral and poorly zoned plagioclase crystals against anhedral quartz (q) and microcline (m) grains. Plagioclase along the left side of sketch and in the outer zones of the euhedral crystals is highly sodic ($An_{5-10}$). The composition of the highly altered central cores is unknown.

B. Diagrammatic thin section sketch of specimen from the Newburyport(?) Quartz Diorite exposed 1.2 miles southeast of Middleton center. Most of the plagioclase (p) in this part of the Newburyport(?) is highly saussuritized, whereas the albite (a) is clear and the somewhat perthitic microcline (m), which generally composes less than 10 percent of the rock, shows slight alteration. Note the smooth contact between albite and plagioclase and the very irregular contact between albite and microcline.




A




B

slightly below that of the biotite-hornblende tonalite. The essential differences between the two facies, then, lie in the general diminution in total mafic content and increase in quartz content in the biotite tonalite facies. The accessory minerals are similar in type to those found elsewhere in the Sharpners Pond, but they fall off sharply in amount. Rutilation of both quartz and feldspar is fairly common in rocks of this facies, but rutile is not shown in the modes owing to the small amount present and the fact that it is too fine grained to detect at standard point-counting magnifications.

It is in the biotite tonalite facies that potassium feldspar (microcline) makes its only significant appearance in the Sharpners Pond Tonalite. Microcline occurs as tiny grains filling interstices, as small uniformly oriented blebs in plagioclase, and as relatively large discrete grains. The range in microcline content in the biotite tonalite facies is shown in table 18. Specimens devoid of microcline are generally indistinguishable in hand specimen from those of granodioritic or adamellitic composition, so that the distribution of the more potassic rocks cannot be discerned with precision. However, microcline seems to be particularly prominent in rocks cropping out near those mapped with the Andover Granite, and in a series of alkalic, lit-par-lit-like layers exposed toward the eastern end of the main tonalite body. It is commonly very slightly perth-[illegible] and the plagioclase with which it is associated is locally myrmekitic (see plate 23).

An unusual occurrence of alkali feldspar (probably microcline) was noted in an exposure of biotite tonalite immediately west of Wills Hill in Middleton (see figure 7A). This outcrop is characterized by the presence of two approximately perpendicular joint sets, along which alkali feldspar "phenocrysts" up to one-half inch long have developed. The feldspar "phenocrysts" were not observed toward the centers of the blocks formed by the intersecting joints, and it is inferred that alkalic solutions have been channeled along the joint paths.

## Origin

It has been implied in the preceding pages that the Sharpners Pond Tonalite and Andover Granite belong to a continuous plutonic series. It might be considered inappropriate, therefore, to discuss the origin of these rock units separately. However, the writer has examined only part of the Sharpners Pond, whereas he has attempted a relatively comprehensive investigation of the Andover Granite. Moreover, although the formations are clearly transitional, there seems to be a natural compositional break between the two. The Sharpners Pond is overwhelmingly tonalitic, the Andover is essentially adamellitic, and rocks of granodioritic composition are volumetrically insignificant in both. For these reasons the writer has chosen to discuss the origin

Table 19. Chemical analysis, norm, and modal analysis of biotite granodiorite from mixed zone between the biotite tonalite facies of the Sharpners Pond Tonalite and the binary granite facies of the Andover Granite[1/]

Chemical analysis[2/] [3/]

| | |
|---|---|
| $SiO_2$ | 71.8 |
| $Al_2O_3$ | 15.1 |
| $Fe_2O_3$ | .4 |
| FeO | 2.2 |
| MgO | .87 |
| CaO | 2.1 |
| $Na_2O$ | 3.5 |
| $K_2O$ | 3.0 |
| $TiO_2$ | .36 |
| $P_2O_5$ | .11 |
| MnO | .06 |
| $H_2O$ | .87 |
| $CO_2$ | .06 |
| Sum | 101 |

Table 19. (cont.)

| Norm[3/] | |
|---|---|
| Quartz | 33.28 |
| Corundum | 2.75 |
| Orthoclase | 17.79 |
| Albite | 29.38 |
| Anorthite | 9.18 |
| Enstatite | 2.21 |
| Ferrosilite | 3.16 |
| Magnetite | .69 |
| Ilmenite | .76 |
| Apatite | .34 |
| Calcite | .10 |
| Sum | 99.62 |

Table 19. (cont.)

Modal analysis 4/

| | |
|---|---|
| Quartz | 27.2 |
| Plagioclase | 39.9 |
| Microcline | 23.0 |
| Biotite | 6.8 |
| Chlorite | .8 |
| White mica | 1.4 |
| Epidote | .7 |
| Sphene | .2 |
| Apatite | .1 |
| Zircon | tr. |

1/ (C-11). Granodiorite along east side of Haverhill St. 350 ft. south of Haverhill St.-North St. intersection, North Reading. Points counted: 1000. Plagioclase composition undetermined

2/ U. S. Geological Survey Rapid Rock Analysis Laboratory

3/ All figures weight percent

4/ All figures volume percent

of the Sharpners Pond at this point.

All or most of the rocks assigned to the Sharpners Pond Tonalite are the products of magmatic emplacement. Several lines of evidence substantiate this conclusion. (1) Cross-cutting relationships are extremely common among the several facies of the Sharpners Pond on the one hand, and between the Sharpners Pond and surrounding metamorphic rocks on the other hand (see figure 5B and plates 1 and 22). (2) Locally developed small scale features, such as are illustrated in figure 7B, virtually demand forcible fluid intrusion into solid rock. (3) In spite of local variations, the chemical and mineralogical similarity over the complex as a whole (particularly as contrasted with the compositional diversity of the surrounding metamorphic rocks) requires an homogenization of the materials from which the rocks formed. It is difficult to imagine how this homogenization could have been effected had these rocks not passed through a fluid stage at some time in their history.

The areal and outcrop relationships among the rocks of the Sharpners Pond indicate that the several facies were intruded in the order in which they have been described. Thus, successively later melts were progressively less mafic and more siliceous and alkalic. As a corollary of the above it may be inferred that emplacement of the Sharpners Pond began in the southeast and progressed toward the west and northwest.

The major problems connected with the origin of the Sharpners Pond Tonalite relate to the changing composition of the successively evolved magmas, and the nature of the physical environment in which these gross compositional changes took place.

There appear to be three possible explanations for the differing magma compositions presently reflected by the lithologic range within the Sharpners Pond. (1) It is conceivable that successive magma pulses were uniquely derived from separate sources. Although such a suggestion cannot be disproved, it provides no explanation for the progressively and consistently more felsic character of the successively intruded magmas. (2) Assimilation of country rock may have been responsible in part for changes in melt composition, at least to the extent that reaction may have occurred with the invading magma. However, partially resorbed and reconstituted blocks of country rock have not been found within the Sharpners Pond, nor is there any systematic compositional relationship between the Sharpners Pond and the surrounding metamorphic rocks. Bowen (1956, p. 182-185, 220-223), moreover, has outlined some excellent theoretical reasons for questioning the efficacy of simple assimilation (fusion) as a mechanism for promoting major changes in melt composition (where the magma heat is the chief energy source). (3) Clapp (1921, p. 55) has suggested that (to use his terminology) the Salem Gabbro-Diorite, Newburyport Quartz Diorite, and

Dedham Granodiorite all were derived from a single parent magma through a process of fractional crystallization. The writer is inclined to accept this explanation, in a general way at least, for the origin of the separate facies of the Sharpners Pond Tonalite, simply because it seems the most plausible of the several hypotheses.

Once crystallization of the "parent" magma had begun, fractional differentiation could proceed. Several possibilities are suggested. Differentiation of the "primary" magma may have taken place in an adjacent chamber (or chambers) concurrently with the emplacement of a relatively mafic facies of the Sharpners Pond. The mafic fraction of this postulated differentiation then would no longer be associated with the Sharpners Pond Tonalite. Regretably, this "explanation" does little more than create another problem, in that one is obliged to consider what might have become of the mafic accumulate. Clapp apparently envisioned fractionation and gravitational settling as taking place in a large, but poorly defined lopolith-like chamber. This explanation seems improbable, however, owing to the generally unstratified nature of the subalkaline series of Essex County. The subalkaline series becomes progressively more felsic from the southeast to the northwest, and is to this extent crudely stratiform, but it is nevertheless generally devoid of observable or mappable layering. Fractionation and resultant differentiation in an orogenic environment represents still another possibility. Under these conditions the development of a smoothly stratiform fraction would tend to be inhibited.

Crystallization probably proceeded very slowly, and equilibrium apparently was closely approached throughout the entire magmatic history of the Sharpners Pond. This is implied primarily by the generally poorly zoned plagioclase and the absence of pyroxene and prominence of hornblende (Bowen, 1956, p. 111-112). It may be inferred that the vapor pressure of $H_2O(P_{H_2O})$ played some part in controlling equilibrium during crystallization. The presence of hornblende indicates, of course, that the magma contained a small but significant amount of water from its inception. It is doubtful, however, that $P_{H_2O}$ ever rose to very high levels during the magmatic evolution of the Sharpners Pond Tonalite. Restricted $P_{H_2O}$ is strongly implied by the presence of myrmekite in the biotite tonalite facies, for it is thought that myrmekite is not apt to form in igneous rocks initially crystallized under elevated $P_{H_2O}$ (see discussion on the origin of the Andover Granite).

Crystallization temperatures in the Sharpners Pond Tonalite probably were moderately high throughout its history of emplacement. According to Yoder and Tilley (1962, p. 448-450) melting of tholeitic basalt at $P_{H_2O}$=5000 bars yields a stable plagioclase-hornblende-melt assemblage at 780-825°C. At temperatures around 940°C. ($P_{H_2O}$=5000 bars), however, pyroxene becomes stable. Considering the general absence of pyroxene in the Sharpners Pond, and assuming that $P_{H_2O}$ never rose above 5000 bars, it is probable that crystallization of the hornblende diorite facies began at approximately 800°C and very slowly dropped by as much as 100° during successive magmatic stages. It is difficult to estimate the pressure ($P_{total}$) that obtained during crystallization. The apparently widespread occurrence of andalusite in the contiguous Boxford Formation seems to be the only specifically limiting factor; it is doubtful that confining pressure during intrusion ever rose much above 8 kilobars (see figure 3).

The writer initially felt that the composition and distribution of the several facies of the Sharpners Pond Tonalite might be attributed in part to the effects of subsequent grantitic intrusion. Such broad scale phenomena as tonalitic belts that appear to become more felsic toward the main granite body, might then be explained by metasomatism of the Sharpners Pond through aqueous, siliceous, and alkali rich emanations from the intruding granite magma. However, a metasomatic hypothesis of this sort does not accord with such small scale features as biotite-hornblende tonalite dikes intruding a diorite host. Moreover, a strong argument against any metasomatic modification of the Sharpners Pond is that gradational relationships of the sort that occur between the Andover and Sharpners Pond, do not occur between the Andover and surrounding mafic metavolcanics as well.

## Correlation

It was noted in the introductory statement that most of the rocks mapped with the Sharpners Pond appear on Emerson's map of Massachusetts (1917, pl. X; this report, pl. 2) as Salem Gabbro-Diorite. The Salem Gabbro-Diorite was named by Clapp (Wilmarth, 1938, p. 1889; Clapp, 1921, p. 21) for exposures of this rock in the town of Salem, and about 200 square miles of northeastern Massachusetts subsequently were mapped as Salem Gabbro-Diorite. The type Salem has been described by Clapp (1921, p. 21) as a mafic rock transitional between gabbro and diorite and characterized by calcic plagioclase, hornblende, augite or diallage, and biotite. The Sharpners Pond Tonalite, on the other hand, is characterized by the general absence of gabbro, prominence of tonalite, and a mineral assemblage essentially free of pyroxene and plagioclase more calcic than andesine. Toulmin (1961, written communication), moreover, has concluded that many of the rocks included with the Sharpners Pond by the writer are actually of non-plutonic origin, and that the Salem probably belongs to an earlier period of igneous activity than does the Sharpners Pond. Thus it appears that the possible equivalence of the Sharpners Pond and Salem is very much in doubt.

Several observations, however, suggest that continuity between the Sharpners Pond and Salem should not yet be rejected out of hand. In the first place, it is clear from an inspection of plate 1 that the Sharpners Pond becomes generally more mafic toward the southeast (*i.e.*, toward the town of Salem), and correspondingly more like that of the type Salem Gabbro-Diorite. Secondly, Toulmin's assignment of the Salem to an older plutonic series rests in part with his observation that the rocks of the Sharpners Pond are notably fresher and less deformed than those of the Salem. It is conceivable, however, that these differences in alteration and deformation are attributable to differences in either mode of emplacement (*i.e.*, the degree of crystallinity obtaining in the successively intruded magmas) or geographic position relative to major tectonic lineaments. Lastly, mapping by the writer suggests that rocks assigned by Toulmin to the same period of igneous activity as the Salem Gabbro-Diorite, are actually comagmatic with the Sharpners Pond Tonalite (see description of the Newburyport(?) Quartz Diorite, this report).

Should the temporal equivalence of the Salem Gabbro-Diorite and Sharpners Pond Tonalite ultimately be disproved, it is still probable that many or most of the rocks formerly mapped as Salem Gabbro-Diorite north and northeast of this area (see Emerson, 1917, pl. X) are correlative with the Sharpners Pond.

## Salem(?) Gabbro-Diorite

Hansen (1956, p. 14-16, pl. 1) has mapped as Salem(?)

Gabbro-Diorite a complex of gabbros and diorites cropping out in the Maynard quadrangle. He has grouped these rocks with the Salem because of their general character and relationships to the surrounding rocks, but correlation with the type Salem is considered problematical by the writer. As these rocks apparently are nowhere in direct contact with the Andover Granite, they are described only cursorily here. For a detailed description the reader is referred to Hansen's report on the geology of the Hudson and Maynard quadrangles (1956, p. 14-16).

Rocks included with the Salem(?) Gabbro-Diorite in this area are confined to a narrow zone of outcrop along the southern border of the Marlboro belt in Sudbury and Concord. According to Hansen (1956, p. 15) these rocks consist chiefly of medium- to coarse-grained hornblende gabbro together with lesser amounts of fine-grained hornblende diorite. There is considerable textural and compositional heterogeneity within this unit, and the Salem(?) may actually include several separate intrusive units. The Salem(?) rocks apparently "invade the Marlboro formation in a complex and irregular manner" (Hansen, 1956, p. 15), but they are not known to be intrusive into any other formation within the map area.

The lithology and geologic occurrence of the Salem(?) Gabbro-Diorite suggest that it may be correlative in part with the hornblende diorite facies of the Sharpners Pond

Tonalite. Accordingly, it is included here with the sub-alkaline intrusive series.

## Assabet Quartz-Diorite

Hansen (1956, p. 46) and Cuppels (1962, written communication) have mapped a small pluton cropping out along the northern margin of the Andover Granite in Maynard and Concord as the Assabet Quartz-Diorite. The age of the Assabet is in doubt, and the limited available evidence suggests only that it postdates the Nashoba Formation and probably predates the Andover Granite. The writer has not studied the Assabet in the field, and the following description is drawn chiefly from Hansen's report on the Hudson and Maynard quadrangles.

The Assabet apparently is poorly exposed in both the Maynard (Hansen, 1956, p. 46) and Concord (Cuppels, 1962, written communication) quadrangles. It is, nevertheless, a major unit, cropping out alongside the westward extension of the Andover Granite for a distance of at least 9 miles. Hansen (1956, p. 46) has observed that "most exposures of the Assabet quartz-diorite (in the Maynard quadrangle) contain pegmatite and many also contain acid and intermediate aplitic dikes." Cuppels (1962, written communication) has discovered, moreover, that a biotitic facies of the Assabet exposed in the Concord quadrangle is thoroughly crosscut by micaceous and garnetiferous granite and pegmatite.

The rocks of the Assabet are characteristically medium grained, medium to dark gray, and slightly to moderately foliated. They are made up chiefly of andesine, hornblende, quartz, and biotite, and contain considerable accessory apatite and some sphene (Hansen, 1956, p. 46). A border variant exposed at the eastern end of the pluton and examined in thin section by the writer, is composed largely of plagioclase, quartz, and biotite and is apparently devoid of amphibole.

The Assabet is clearly intrusive into the Nashoba Formation, and Hansen (1956, p. 45-46) thought that it also postdated the Andover Granite. However, the latter conclusion stemmed in part from Hansen's conviction that the Andover (Gospel Hill Gneiss of Hansen's report) was simply a granitized facies of the Nashoba Formation. Inasmuch as the Assabet is intruded by rocks similar to those of the Andover Granite, it is felt by the writer that it probably predates the Andover.

## Correlation

The general lithology of the Assabet Quartz-Diorite suggests that it is correlative in part with the Sharpners Pond Tonalite. The single biotitic specimen examined by the writer, for example, was indistinguishable from rocks of the biotite tonalite facies of the Sharpners Pond exposed in North Reading and Middleton. The possible equivalence of these two groups seems to be supported, moreover, by the fact that the Assabet apparently bears the same relationship to the Nashoba and Andover as does the Sharpners Pond. For these reasons the Assabet Quartz-Diorite is grouped here with the many other igneous rocks of the area that are thought to belong to the subalkaline intrusive series.

## Newburyport(?) Quartz Diorite

Rocks mapped with the Newburyport(?) Quartz Diorite crop out along a zone trending roughly east-west across the central part of the Reading quadrangle and a short distance into the Wilmington quadrangle. The Newburyport Quartz Diorite was named for exposures of this rock in and around Newburyport, Massachusetts (Emerson, 1917, p. 177-178), and Clapp (1921, pls. I and II) subsequently mapped a number of small bosses or stocks of Newburyport throughout Essex County. Rocks mapped with the Newburyport(?) in this area are continuous in part with one of these isolated bosses in the town of Middleton. Exposures of the Newburyport(?) locally are limited so that its relationships with the surrounding metasediments and metavolcanics are not everywhere clear. It is likely that the Newburyport(?) Quartz Diorite and Marlboro Formation are in fault contact in the Wilmington and western Reading quadrangles, but the outcrop pattern is such that they are almost certainly in intrusive contact in the eastern half of the Reading quadrangle. Moreover, the fact that the outcrop belt of the Newbury Formation is interrupted by exposures of the Newburyport(?), and the existence of a stepped contact between rhyolitic rocks of the Newbury and rocks of the Newburyport(?) exposed over a distance of 3 to 4 feet, suggest that the Newburyport(?) may be intrusive into the Newbury as well as the Marlboro.

The typical Newburyport(?) Quartz Diorite in this area is a dense, dark-gray rock with a strong pistache-green overtone. A few exposures are characterized by the presence of pink feldspar. It is generally massive, but commonly highly fractured and slickensided. A rude foliation is prominent in the highly sheared zones, and in exposures such as those east of South Main Street in Middleton, large blocks of massive quartz diorite are bounded by relatively narrow zones of highly sheared material, imparting to the rock as a whole the appearance of a giant breccia. The textures are generally medium grained, hypidiomorphic, and equigranular in the massive parts, to fine grained and locally porphyritic (or porphyroclastic) in the sheared facies. Textural features related to specific mineral phases are discussed below.

The locally exposed Newburyport(?) Quartz Diorite is somewhat variable in composition, but the predominant minerals throughout the formation are highly altered plagioclase and quartz (see table 20). Plagioclase composes from 40 to 50 percent of those specimens sufficiently well preserved to

Table 20. Estimated modes of rocks from the Newburyport(?) Quartz Diorite

| | Granitic texture | | | Porphry texture | |
|---|---|---|---|---|---|
| | A. | B. | C. | D. | E. |
| Quartz | 22 | 25 | 25 | 15 | 20 |
| Plagioclase | 40 | 42 | 40 | 40 | 46 |
| Microcline | 3 | 10 | 4 | | |
| Chlorite | 15 | 9 | 15 | 15 | 7 |
| White mica | 6 | 5 | 5 | 7 | 8 |
| Epidote | 12 | 5 | 7 | 15 | 17 |
| Apatite | tr. | | | | |
| Sphene | | tr. | 1 | | |
| Carbonate | | | 1 | | |
| Opaque | 2 | 4 | 2 | 8 | 2 |

A(R-37). Greenish gray, medium-grained tonalite 900 ft. northwest of intersection between South Main St. and Reading quadrangle boundary, Middleton

B(R-312). Granodiorite 3300 ft. northeast of Franklin St.-Van Norden Rd. intersection, Reading

C(W-342). Tonalite 200 ft. east-southeast of West St.-Grove St. intersection, Wilmington

D(R-312). Gray porphry 3300 ft. northeast of Franklin St.-Van Norden Rd. intersection, Reading

E(W-343). Gray-green porphry 900 ft. east-northeast of West St.-Grove St. intersection, Wilmington measure mineral content, and plagioclase or its derivatives are probably present in roughly the same proportions in the highly altered rocks. It ranges in composition from $An_5$ to $An_{40}$. The relatively unaltered plagioclase generally ranges from oligoclase to median andesine, whereas the highly saussuritic material commonly falls in the albite range. Plagioclase is the only phase present showing any tendency toward idiomorphism (figure 8B). Quartz composes from 15 to 25 percent of the rock and occurs chiefly as interstitial material between plagioclase grains. Hornblende occurs locally in the relatively unaltered facies, but it is a minor constituent of the Newburyport(?) in this area. Microcline was seen in every thin section from the relatively massive and equigranular parts of the Newburyport(?), but it generally composes no more than 5 percent of the rock. Wherever it occurs the microcline is relatively unaltered and generally demonstrably younger than the plagioclase. Most of it is scattered through the interstices between plagioclase and quartz grains, but part of the microcline occurs as small, irregular blebs within plagioclase or intimately intergrown with albite (figure 8B). Apatite, magnetite, and small amounts of sphene occur as accessory minerals.

Several secondary minerals occur in quantity throughout the Newburyport(?) Quartz Diorite in this area. Chlorite is a conspicuous secondary mineral and composes up to 15 percent of the rock. It occurs as individual disseminated grains locally surrounding tiny bits of relic biotite or hornblende, in segregated clots or veins, and pseudomorphous after pyroxene(?). In exposures east of South Main Street, Middleton, chlorite veins or smears one-quarter to one-half inch thick, have the appearance of black, resinous tar. Some of these chlorite smears occur along slickensided surfaces, but elsewhere they are contained within small, well-defined veins crosscutting individual mineral grains in relatively undeformed rocks. Epidote is another important secondary mineral and comprises from 5 to 20 percent of the rock. It occurs to a limited extent as small irregular veins, but its chief occurrence is in the saussurite. Carbonate and limonite occur locally as secondary products.

## Origin

The Newburyport(?) Quartz Diorite is composed chiefly of intrusive igneous rocks, but details of its magmatic and post-magmatic history are obscure. Textural relations suggest that crystallization began in the plagioclase field and probably ended along or near an alkali feldspar-silica cotectic. Beyond this generalization, little may be said regarding its melt history. The nature and degree of alteration of the Newburyport(?) are its most distinctive characteristics and are in a sense a measure of its genetic unity, particularly if the alteration can be attributed to deuteric processes. However, it seems that the more highly altered parts of the formation are coincident with the highly sheared facies, suggesting that the alteration is a post-magmatic phenomenon. The only other evidence suggestive of late- or post-magmatic recrystallization consists of apparently unmixed blebs of potassium feldspar in plagioclase, and "perthitic" albite rims locally developed around microcline (see figure 8B).

## Correlation

The writer is unfamiliar with the Newburyport Quartz Diorite in its type locality. According to Clapp (1921, p. 23) the type Newburyport contains (among other things) relatively calcic plagioclase, hornblende, and augite, none of which occur in quantity within the quartz diorite in this area. However, as the Newburyport is arbitrarily defined and apparently transitional with other igneous rocks (Clapp, 1921, p. 23), Clapp's designation as Newburyport is retained for these rocks in this area.

It is likely that the Newburyport(?) Quartz Diorite is transitional with the Sharpners Pond Tonalite. It is particularly like the Sharpners Pond where it is exposed in and around a small quarry north of the Ipswich River in Middleton. These exposures would have been included with the Sharpners Pond had it not been for (1) their proximity to the main mass of the Newburyport(?), and (2) the character and degree of their alteration.

Rocks doubtfully correlative with the Newburyport(?) Quartz Diorite occur within the western extension of the Newburyport(?) outcrop belt. These rocks are generally fine grained and locally porphyritic, but they were mapped with the Newburyport(?) chiefly because of their alteration and their close (geographic) association with granitic textured rocks of the Newburyport(?). However, they are texturally and compositionally similar to (and perhaps correlative with) the melanocratic volcanics of the Newbury Formation (compare column A, table 15 and columns D and E, table 20).

## Andover Granite

The Andover Granite was named by C. H. Clapp in 1910 for exposures of muscovite granite, aplite, and pegmatite in and around the town of Andover, Massachusetts (Wilmarth, 1938, p. 52). The unit subsequently was described by Emerson (1917, p. 220-221) and later again by Clapp (1921, p. 27-29), but both descriptions are cursory and very general in nature. Hansen (1956, p. 39-41) recently has studied that part of the granite cropping out in the Hudson and Maynard quadrangles and his is the only moderately detailed description published to date.

The distribution of the Andover Granite (except for several small bosses cropping out southwest of Newburyport and west-southwest of Marlboro center) according to Emerson (1917, pl. X) is presented in plate 2. Clapp's (1921, pl. I) map of the Andover Granite cropping out in Essex County differs from Emerson's chiefly in the inclusion with the Andover by Clapp of about 15 square miles northwest of Haverhill (north of 42°45'). This investigation of the Andover Granite has been confined almost entirely to the area covered by plate 2; the Andover "pluton" northwest of Haverhill consists chiefly of impure quartzite and gneiss together with a relatively small amount of granite assigned by Emerson (op. cit., pl. X) to another formation (Ayer Granite), whereas the Andover alleged to crop out southwest of Newburyport and west of Marlboro is of very limited extent and considerably removed from the main granite body. There is generally good agreement between the distribution of the Andover as it currently is thought to occur (see plate 1) and its distribution as given by Emerson (see plate 2). The chief differences consist of the inclusion with the Andover on Emerson's map of the Fish Brook Gneiss, the unnamed gneiss in the Reading quadrangle, the adamellite near Middleton Pond, and the biotite tonalite facies of the Sharpners Pond Tonalite. A second, less significant difference stems from the fact that Hansen (1956, p. 48-50, pl. 1) and Jahns (1958, written communication) have differentiated as the Acton Granite that part of the "Andover" cropping out in the northern Maynard quadrangle and Westford quadrangle (see plate 2).

The currently recognized Andover Granite comprises a group of leucocratic, peraluminous, alkali to calcalkali feldspar, generally highly siliceous plutonic rocks ranging from alaskite to sodic tonalite or trondjhemite. The average mode of the "granite" approximates that of an adamellite. However, there is little point in modifying the name of the formation; inasmuch as many of the world's "granites" approach the composition of the Andover, it might be wiser, in accordance with the suggestion of Tuttle and Bowen (1958, p. 126-128), to modify the definition of "granite." The term "granite" ordinarily is used here in its more general sense to include adamellite and granodiorite as well as those rocks that fall within the definition of granite *senso stricto* (Johannsen, 1939, p. 144).

The Andover Granite is of mainly magmatic derivation, but it may be (doubtfully) partly metasomatic. Regardless of its primordial development, it almost certainly has been recrystallized extensively since it first evolved.

Rocks assigned here to the Andover Granite occupy approximately one-third (90-95 square miles) of the map area. Exposure is locally good to excellent, but the formation commonly is poorly exposed, particularly in the western parts of the Lawrence and Wilmington quadrangles. For purposes of mapping and description the complex of rocks included with the Andover has been divided into the following separate but transitional facies: (1) muscovite granite-gneiss, (2) biotite granite-gneiss, (3) fine-grained granite-gneiss, (4) undifferentiated granite-gneiss, (5) binary granite, and (6) pegmatitic granite. Characteristics used in differentiating the several facies in the field have been imposed in part upon the rocks subsequent to their formation; inclusion of a rock with a given facies, accordingly, does not necessarily reflect a primary genetic unity with the remainder of that facies. The individually mapped facies are described below without reference to their genesis which is considered separately. Moreover, inasmuch as the separate facies are believed to be roughly contemporaneous, the following order of presentation does not necessarily accord with their precise chronology of emplacement or formation.

### Muscovite granite-gneiss facies

The muscovite granite-gneiss facies occurs along an east-northeast trending belt up to one-half mile wide, extending across the width of the Lawrence quadrangle. It crops out conspicuously in South Lawrence north of Shawsheen Heights, but it is poorly exposed elsewhere. To the north this facies probably is in sharp contact with both the Worcester(?) Phyllite and the Merrimack Group, whereas it is in transitional contact with several other facies of the Andover Granite cropping out to the south. Where it is exposed in the large, abandoned quarries in South Lawrence the granite-gneiss has been crosscut by both pegmatite and diabase; a few inclusions of amphibolite or amphibolitic quartzite also occur within this group of exposures.

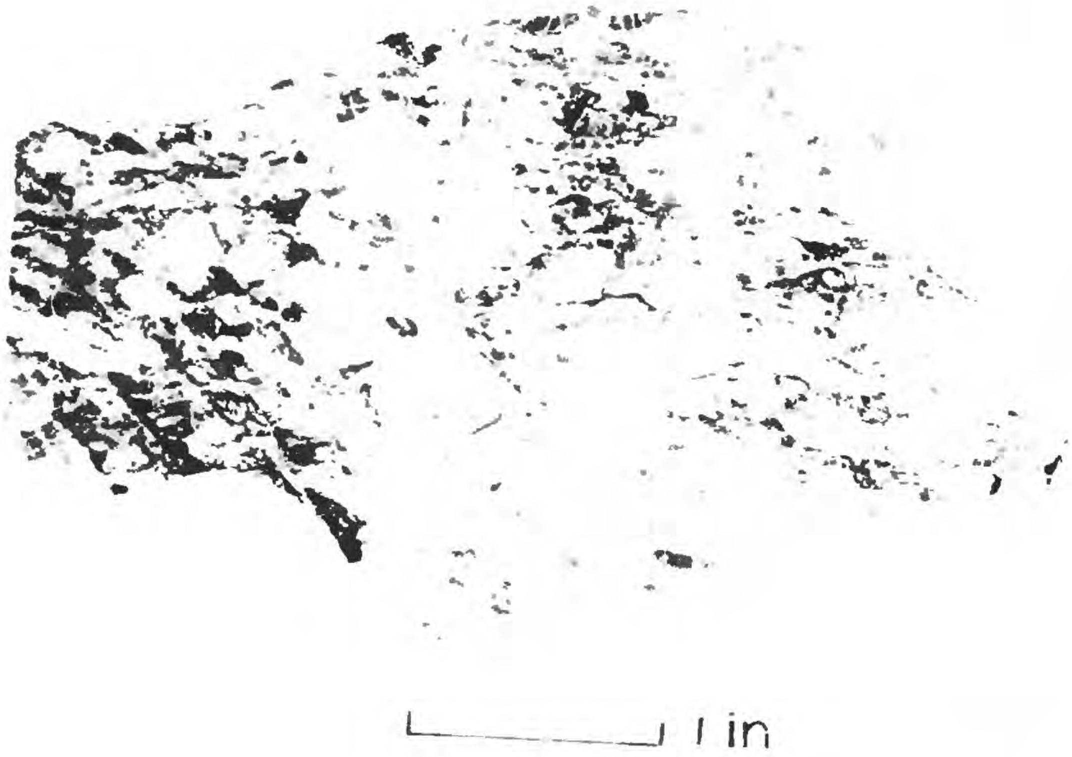
The muscovite granite-gneiss is characteristically pearly white with silvery flecks of muscovite distributed along the rift; it weathers to a light, dull-gray color. It is generally prominently foliated (see plate 24A), but locally, such as along Winthrop Avenue in South Lawrence, the foliation is so poorly defined that it cannot be measured. The attitude of the foliation is roughly conformable with the regional trend, striking northeast to east-northeast and dipping steeply to the northwest. The texture of the muscovite granite-gneiss is essentially xenomorphic and generally coarse-grained. Grain size, however, ranges down to very fine in the "groundmass," and the fabric is in general that of an augen- or flaser-gneiss (see plates 24A and 25A).

The muscovite granite-gneiss is composed mainly of alkali feldspars and quartz; the chief varietal mineral is muscovite and remaining phases occur in generally trivial amounts. Modal analyses of the muscovite granite-gneiss are presented in table 21. It should be recognized, however, that any single analysis of this rock is of limited value; All point counts referred to in this report have been made on standard size thin sections, and where the rock is of either coarse or irregular grain size (certainly the case here) the probability of obtaining a representative mode is

Plate 24

A. Section of muscovite granite-gneiss of the Andover Granite exposed in Mt. Vernon Park, Lawrence.

B. Foliated binary granite of the Andover Granite exposed 1800 feet northeast of Woburn St.-West St. intersection, Wilmington. Foliation in the granite roughly parallels that within the biotite-hornblende tonalite xenoliths.




A

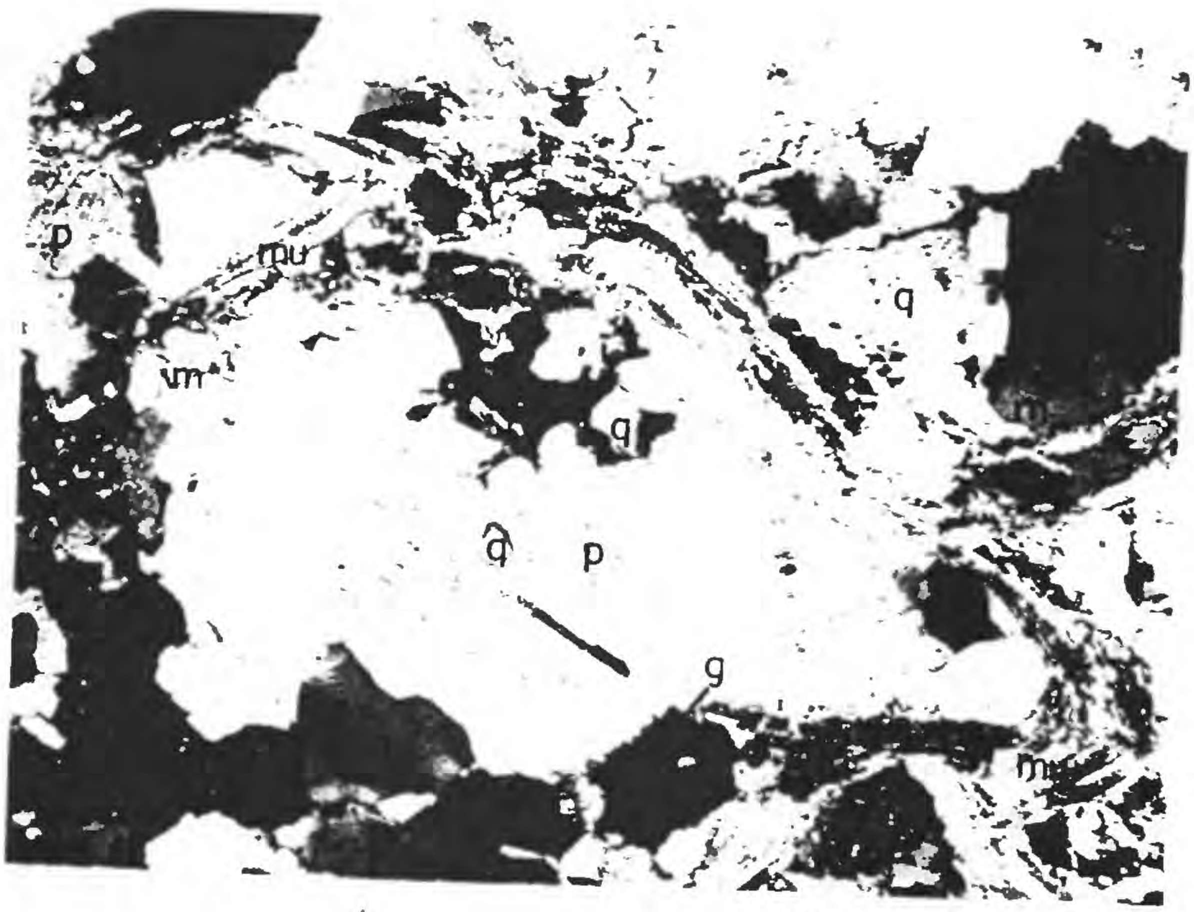
B

Plate 25

A. Photomicrograph of specimen from the muscovite granite-gneiss facies of the Andover Granite exposed in abandoned quarry, Mt. Vernon Park, South Lawrence. q, quartz; p, plagioclase; m, microcline; mu, muscovite; g, garnet. Note the extreme development of mortar structure. Crossed nicols.

B. Photomicrograph of specimen from the muscovite granite-gneiss facies of the Andover Granite exposed 900 feet southeast of North Parish Rd.-Winthrop Ave. intersection, South Lawrence. q, quartz; p, plagioclase; m, microcline; mu, muscovite; g, garnet. Note the vaguely zoned plagioclase and intergrowths between microcline and plagioclase. Crossed nicols.


A




B

Table 21. **Modal analyses of rocks from granite-gneiss facies of the Andover Granite**[1/]

| | Muscovite granite-gneiss facies | | Biotite granite-gneiss facies | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A. | B. | C. | D. | E. | F. | G. | H. |
| Quartz | 31.6 | 38.6 | 25.6 | 49.1 | 31.7 | 26.8 | 38.9 | 32.7 |
| Plagioclase | 27.8 | 28.2 | 25.8 | 19.7 | 27.8 | 32.2 | 25.1 | 32.6 |
| Microcline | 28.8 | 22.4 | 41.0 | 23.6 | 34.8 | 30.0 | 31.1 | 27.7 |
| Perthitic albite | .6 | | | | .4 | .6 | | .5 |
| Biotite | | 2.8 | 3.2 | .4 | 2.3 | 5.8 | .9 | 1.3 |
| Chlorite | .1 | | .1 | 2.6 | .5 | .4 | 1.4 | 1.4 |
| White mica | 11.2 | 7.8 | 4.9 | 4.1 | 1.7 | 4.2 | 2.4 | 3.4 |
| Epidote | | | .2 | .1 | .4 | .2 | | .1 |
| Garnet | .1 | .2 | .2 | .5 | .4 | tr. | .1 | .4 |
| Apatite | | | | | | | .1 | |
| Zircon | | | tr. | | tr. | | tr. | tr. |
| Opaque | | | | | | | | |

Table 21. (cont.)

| | Undifferentiated granite gneiss facies | | | | | Fine-grained granite-gneiss facies |
|---|---|---|---|---|---|---|
| | I. | J. | K. | L. | M. | N. |
| Quartz | 34.9 | 31.5 | 40.1 | 31.5 | 32.3 | 23.8 |
| Plagioclase | 38.6 | 29.7 | 25.5 | 25.5 | 34.3 | 32.0 |
| Microcline | 18.4 | 27.9 | 25.2 | 32.3 | 21.9 | 29.0 |
| Perthitic albite | | | | | | |
| Biotite | | | 3.3 | 2.9 | 1.1 | 1.2 |
| Chlorite | | 1.5 | | | | |
| White mica | 7.2 | 8.5 | 4.9 | 7.1 | 10.2 | 14.0 |
| Epidote | .1 | .2 | .6 | | .2 | |
| Garnet | .8 | .5 | | .3 | | |
| Apatite | | .1 | .3 | .4 | | |
| Zircon | | | .1 | | | |
| Opaque | | .1 | | | | |

A(C-13). Muscovite adamellite-gneiss 1500 ft. N66°E of Mt. Vernon St.-Beacon St. intersection, Lawrence. Points counted: 1000. Plagioclase composition $An_{7\pm4}$

B(L-13). Muscovite granodiorite-gneiss 1250 ft. N69°E of Mt. Vernon St.-Beacon St. intersection, Lawrence. Points counted: 500. Plagioclase composition undetermined

Table 21. (cont.)

C(L-1000). Granite-gneiss 700 ft. north of Pleasant St.-Bailey Rd. intersection, Andover. Points counted: 1000. Plagioclase composition $An_{8\pm4}$

D(L-1012). Granite-gneiss 850 ft. south of Kendall St.-Brown St. intersection, Tewksbury. Points counted: 800. Plagioclase composition $An_{8\pm4}$

E(C-3). Granite-gneiss at Kendall St.-North St. intersection, Tewksbury. Points counted: 1000. Plagioclase composition $An_{8\pm4}$

F(W-699). Adamellite-gneiss 1800 ft. N26°W of Foster Rd.-Gray St. intersection, Billerica. Points counted: 500. Plagioclase composition $An_{15\pm4}$

G(W-755). Granite-gneiss in railroad cut 2400 ft. S80°E of Andover Rd.-Wilmington Rd. intersection, Billerica. Points counted: 1000. Plagioclase composition $An_{13\pm4}$

H(C-10). Adamellite-gneiss in roadcut along U. S. Rte. 3, 800 ft. north of Concord River, Billerica. Points counted: 1100. Plagioclase composition $An_{15\pm4}$

I(NC-137). Granodiorite-gneiss 3400 ft. S20°E of Concord Turnpike-Concord Turnpike cut-off intersection, Lincoln. Points counted: 1000. Plagioclase composition $An_{12\pm4}$

J(NC-3). Adamellite-gneiss southwest flank of Fairhaven Hill, Concord. Points counted: 1000. Plagioclase composition $An_{12\pm4}$

Table 21. (cont.)

K(H-1). Adamellite-gneiss 1500 ft. S69°E of Broad St.-Hudson Rd. intersection, Hudson. Points counted: 1000. Plagioclase composition $An_{10\pm4}$

L(H-2). Granite-gneiss 2500 feet S10°W of Causeway St.-Marlboro Rd. intersection, Hudson. Points counted: 1000. Plagioclase composition $An_{10\pm4}$

M(H-3). Granodiorite-gneiss 6600 ft. N60°E of Spoon Hill Summit, Marlboro. Points counted: 1000. Plagioclase composition $An_{7\pm4}$

N(L-385). Adamellite-gneiss 1450 ft. S18°E of Chandler Rd.-North St. intersection, Andover. Points counted: 500. Plagioclase composition $An_{9\pm4}$

1/ All figures volume percent

reduced sharply.

Microcline generally composes from 20 to 30 percent of the rock and occurs largely in the augen, either as single or multiple crystals or intimately intergrown with plagioclase (see plate 25A). It is essentially nonperthitic, but perthitic intergrowths occur locally along plagioclase contacts. The microcline is relatively clear and unaltered (except for the reticulate development of muscovite within individual crystals), but it is commonly cracked, broken, or otherwise strained. Plagioclase makes up about one-third of the muscovite granite-gneiss; it ranges in composition from about $An_6$ to perhaps as high as $An_{15}$, but its median or average composition probably is about $An_{10}$. The plagioclase is rarely zoned, and it is generally much more sericitic or otherwise altered than the accompanying microcline (see plate 25B). It is locally myrmekitic, but myrmekite is a relatively inconspicuous assemblage in this facies. Bent and broken twins characterize the plagioclase of this facies; strain evidence of this sort, moreover, generally is much more striking in the relatively poorly foliated and weakly mortared rocks of the facies. The plagioclase generally forms smaller grains than does the microcline, but the occurrence of the two is otherwise about the same.

Microcline and plagioclase are characterized locally by several mutual textural relationships that seem to be common to other facies of the Andover as well. Of most significance perhaps, is the fact that grain boundaries between the two feldspar species commonly are exceedingly irregular and intricate; the degree of intricacy is shown to some extent in the photomicrographs in plate 25. A second textural relationship commonly developed within this facies is one in which microcline apparently is selectively intergrown along particular plagioclase twins; the relationship is similar to that illustrated in figure 9A for a specimen from the binary granite facies. Another characteristic intergrowth is one in which uniformly oriented blebs of microcline are contained wholly within individual plagioclase grains; the texture is suggestive of an antiperthite, but the microcline intergrowths are more irregular in form, size, and distribution than those characteristic of antiperthites.

Quartz composes from 25 to 40 percent of the muscovite granite-gneiss and occurs to a large extent within the finer-grained groundmass. Its grain size is apparently a function of the degree of mortaring; within the highly mortared specimens (see plate 25A) the quartz is everywhere very fine-grained, whereas it is commonly as coarse-grained as the feldspar in those specimens in which mortar structure is poorly developed (see plate 25B). Undulatory extinction is clearly observable in the coarser quartz crystals (plate 25B), but it is generally undetectable in the very fine-grained material. The quartz is rutilated locally, but rutilation is much less conspicuous here than it is in other facies of the Andover. The larger feldspar grains locally are cross-cut by microscopic veins of quartz, but both microcline and plagioclase are generally free of quartz inclusions other than myrmekitic vermes.

Muscovite is the most prominent, and in some cases the only mica present in the muscovite granite-gneiss. It composes from 4 to 12 percent of the rock and occurs chiefly in thin, commonly monomineralic, discontinuous layers of subhedral to anhedral crystals. Like quartz its grain size apparently is in part a function of the degree of granulation within the granite-gneiss (compare plates 25A and 25B). Muscovite also occurs in a reticulate pattern within microcline crystals where its orientation and distribution obviously have been controlled by the structure of the microcline. Biotite, generally altered in part to chlorite, composes up to 3 or 4 percent of the muscovite granite-gneiss; it occurs chiefly in association with the muscovite layers. Although it generally accounts for less than 1 percent of the rock, pink garnet is a ubiquitous constituent of this facies. It occurs as small to medium-size euhedral to subhedral grains uniformly disseminated throughout the rock. Other accessory minerals are ilmenite, magnetite, and zircon.

A chemical analysis and norm of a specimen of the muscovite granite-gneiss is presented in table 22. The analyzed specimen is illustrated in plate 25A.

Table 22. Chemical analyses, norms, and modal analyses of rocks from granite-gneiss facies of the Andover Granite

Chemical analyses[1/] [2/]

| | Muscovite granite-gneiss facies | Biotite granite-gneiss facies | |
|---|---|---|---|
| | A. | B. | C. |
| $SiO_2$ | 76.1 | 74.2 | 75.8 |
| $Al_2O_3$ | 13.9 | 14.5 | 13.6 |
| $Fe_2O_3$ | .6 | .3 | .3 |
| FeO | .5 | 1.6 | 1.3 |
| MgO | .16 | .38 | .25 |
| CaO | .16 | .61 | .16 |
| $Na_2O$ | 3.2 | 3.1 | 3.3 |
| $K_2O$ | 4.6 | 5.3 | 4.3 |
| $TiO_2$ | .08 | .11 | .12 |
| $P_2O_5$ | .07 | .10 | .08 |
| MnO | .04 | .10 | .06 |
| $H_2O$ | .68 | .47 | 1.2 |
| $CO_2$ | <.05 | .05 | .10 |
| Sum | 100 | 101 | 101 |

Table 22. (cont.)

Norms[2/]

| | A. | B. | C. |
|---|---|---|---|
| Quartz | 39.46 | 32.93 | 39.12 |
| Corundum | 3.36 | 2.75 | 3.57 |
| Orthoclase | 27.25 | 31.16 | 25.59 |
| Albite | 27.26 | 26.21 | 27.78 |
| Anorthite | .83 | 2.23 | |
| Enstatite | .40 | .90 | .50 |
| Ferrosilite | .40 | 2.64 | 1.85 |
| Magnetite | .93 | .46 | .46 |
| Ilmenite | .15 | .15 | .30 |
| Apatite | | .34 | .34 |
| Magnesite | | | .08 |
| Sum | 100.04 | 99.77 | 99.59 |

Table 22. (cont.)

Modal analyses[3/]

| | A. | B. | C. |
|---|---|---|---|
| Quartz | 31.6 | 31.7 | 36.0 |
| Plagioclase | 27.8 | 27.8 | 35.9 |
| Microcline | 28.8 | 34.8 | 30.5 |
| Perthitic albite | .6 | .4 | .6 |
| Biotite | | 2.3 | 1.4 |
| Chlorite | .1 | .5 | 1.5 |
| White mica | 11.2 | 1.7 | 3.7 |
| Epidote | | .4 | .1 |
| Garnet | .1 | .4 | .4 |
| Zircon | | tr. | tr. |

A(C-13). Muscovite adamellite-gneiss 1500 ft. N66°E of Mt. Vernon St.-Beacon St. intersection, Lawrence. Points counted: 1000. Plagioclase composition $An_{7±4}$

B(C-3). Biotite granite-gneiss at Kendall St.-North St. intersection Tewksbury. Points counted: 1000. Plagioclase composition $An_{8±4}$

C(C-10). Biotite-muscovite adamellite in roadcut along U. S. Route 3, 800 ft. north of Concord River, Billerica. Points counted: 1000. Plagioclase composition $An_{15±4}$

Table 22. (cont.)

1/ U. S. Geological Survey Rapid Rock Analysis Laboratory

2/ All figures weight percent

3/ All figures volume percent

Biotite granite-gneiss facies

The biotite granite-gneiss facies is the most homogeneous of the gneissic facies of the Andover; it is distinguished from the muscovite granite-gneiss by its more uniform appearance and the presence of biotite as a major varietal mineral. It occurs over about 25 square miles of the Lawrence, Wilmington, Lowell and Billerica quadrangles where it more or less envelops the northern tongue of the Nashoba Formation. Its presence is inferred over a wide area in part from the local development of boulder fields composed almost exclusively of biotite granite-gneiss, but it is generally poorly exposed; it is well exposed chiefly along the north shore of the Concord River in the Billerica quadrangle. Crosscutting pegmatite dikes and quartz veins crop out locally within this facies; they characteristically occur as thin, tabular bodies of relatively uniform width.

The biotite granite-gneiss is generally light gray to pearly white on fresh surfaces and weathers to the same light, dull-gray color characteristic of the weathered muscovite granite-gneiss. It is very slightly to moderately foliated throughout its extent, but the foliation is almost nowhere as well developed as it is within the muscovite granite-gneiss facies; the foliation is generally conformable with the regional structure. Mortaring was observed in fully two-thirds of the sections studied by the writer, but there are few places where its intensity approaches that developed within the muscovite granite-gneiss (incipient mortaring is evident along the upper part of the photomicrograph in plate 26A). The ubiquitous but poorly defined foliation commonly is defined by the mortaring; elsewhere it is attributable to the preferred orientation of mica (see plate 26A). The biotite granite-gneiss is characteristically coarse grained, essentially equigranular, and allotriomorphic or xenoblastic; larger than normal feldspar crystals locally impart an augen-like appearance to the rock. A characteristic texture is illustrated in plate 26A. Small, unmappable lenses of a fine- to medium-grained granite-gneiss crop out locally within the generally coarse-grained biotite granite-gneiss; they are apparently transitional and conformable with the more typical biotite granite-gneiss and apparently reflect a more intensely granulated part of this facies.

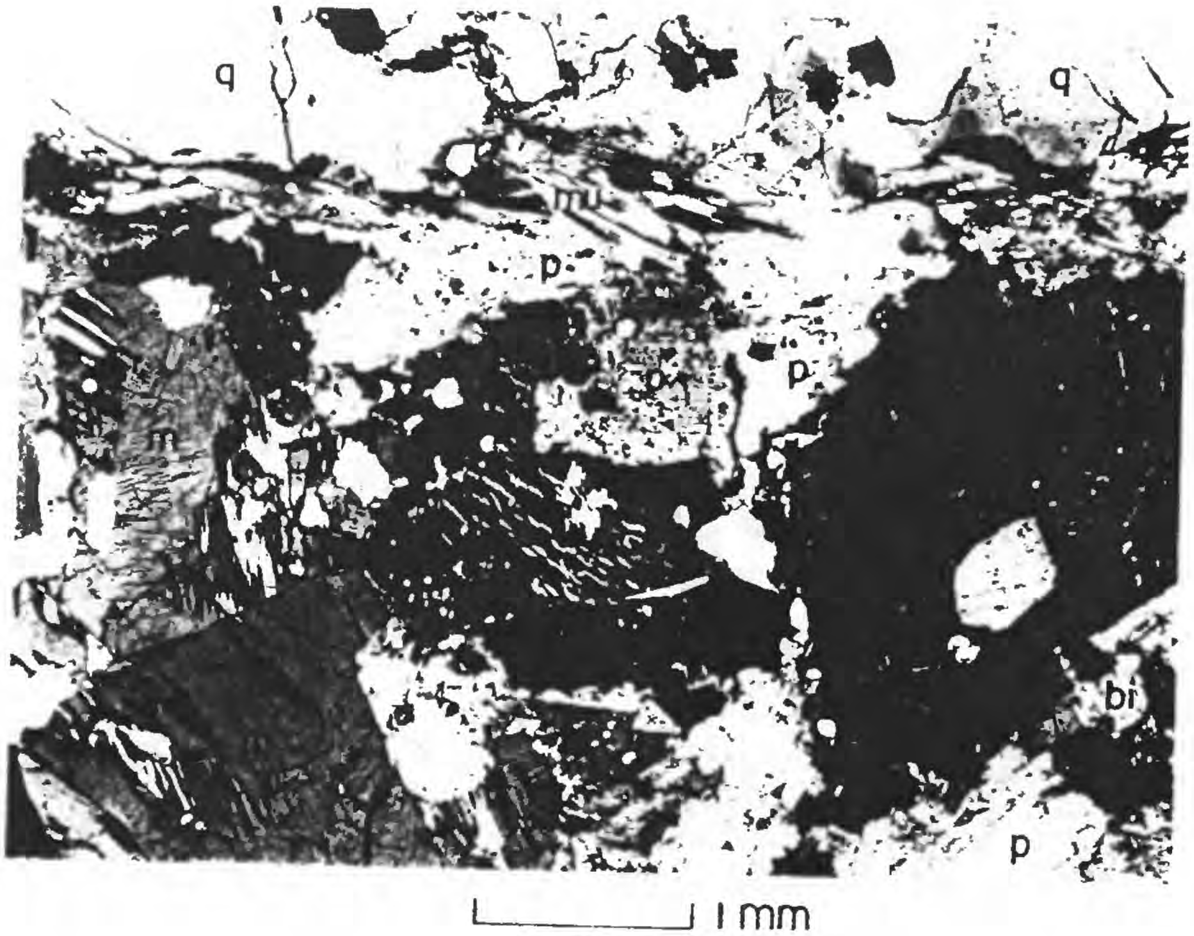
The biotite granite-gneiss, as is true of the muscovite granite-gneiss, is composed chiefly of alkali feldspars and quartz; it ranges from true granite to adamellite or even granodiorite. Where it occurs in the Lawrence and Wilmington quadrangles it is characteristically granitic in composition, whereas that cropping out in the Billerica quadrangle is more adamellitic or granodioritic (see table 21). Jahns (1957, oral communication) has even suggested that parts of the biotite granite-gneiss in the Billerica quadrangle may be essentially tonalitic.

Microcline composes from 20 to more than 40 percent of

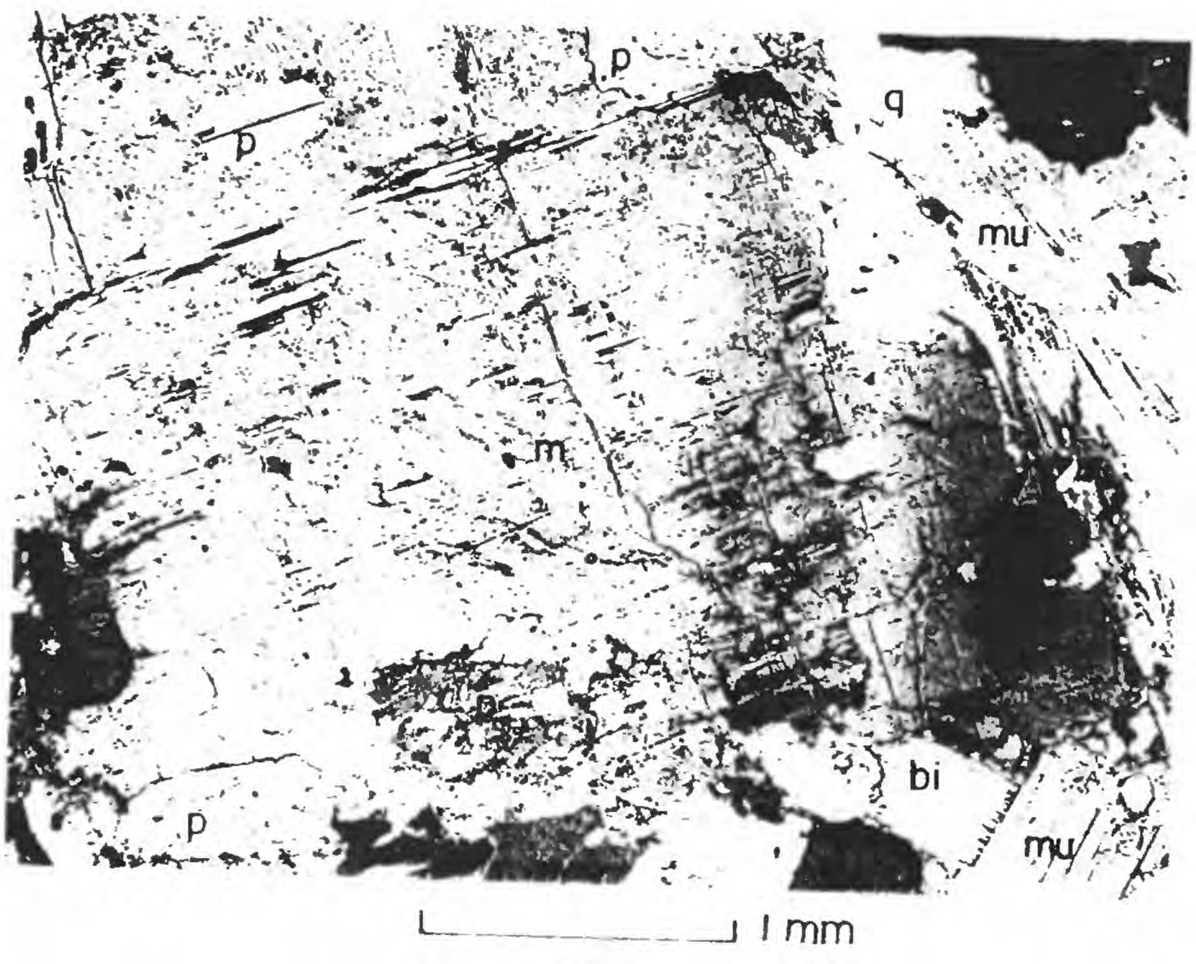
Plate 26

A. Photomicrograph of specimen from the biotite granite-gneiss facies of the Andover Granite exposed 700 feet north of Pleasant St.-Bailey Rd. intersection, Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite; bi, biotite. Textural relations shown here are typical of much of the biotite granite-gneiss and muscovite granite-gneiss. Mica commonly is concentrated in distinct folia within these facies. Crossed nicols.

B. Photomicrograph of specimen from the biotite granite-gneiss facies of the Andover Granite exposed 400 feet south of Kendall St.-North St. intersection, Tewksbury. q, quartz; p, plagioclase; m, microcline; mu, muscovite; bi, biotite; g, garnet. Development of perthite here is much more pronounced than is generally the case in the Andover Granite. Crossed nicols.




A



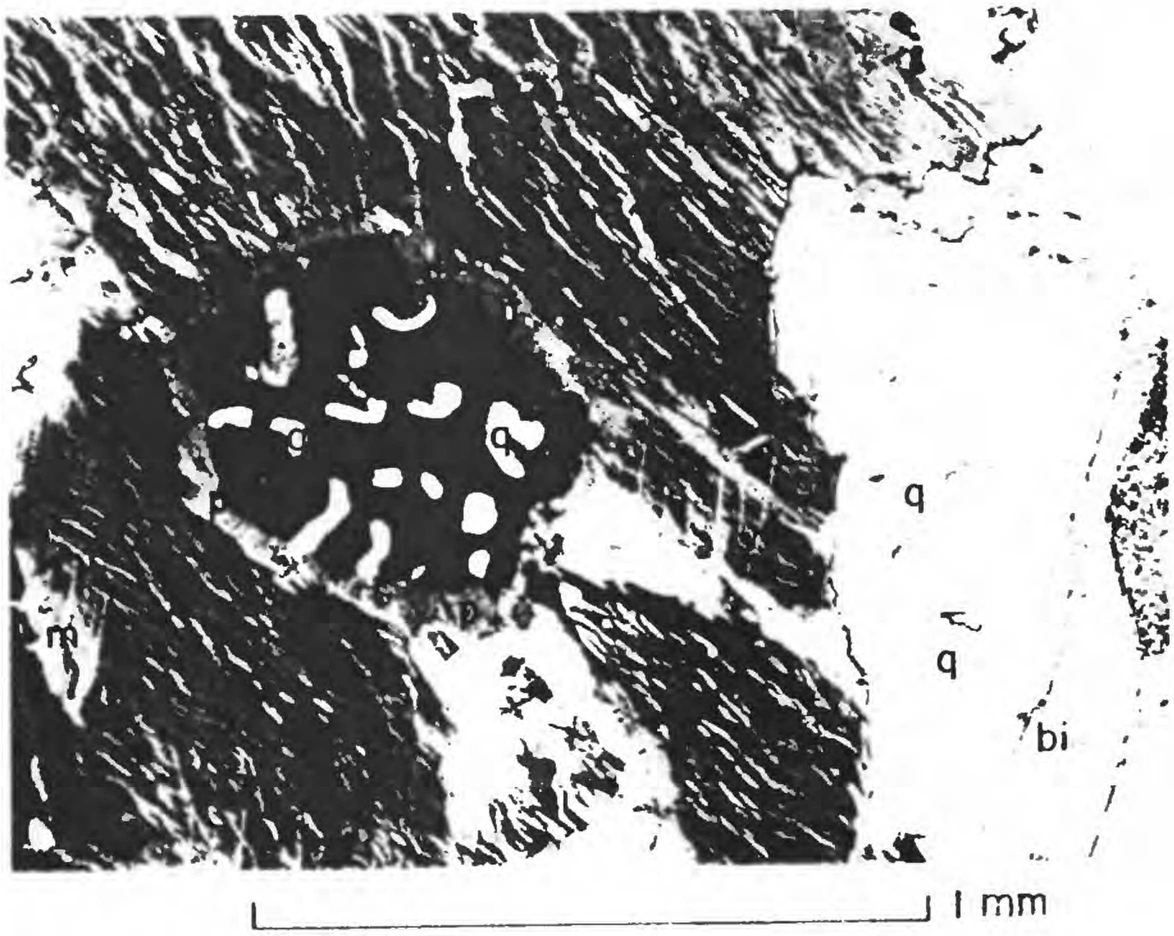

B

the biotite granite-gneiss, and it is commonly the chief constituent of the rock. It is relatively unaltered, locally perthitic (see plates 26B and 27A), and generally apparently unstrained. It occurs mainly as coarse, anhedral grains commonly enveloping other mineral phases. Plagioclase composes from 20 to 30 percent of the biotite granite-gneiss cropping out in the Lawrence and northern Wilmington quadrangles and up to 35 or more percent of the granite-gneiss occurring in the Billerica and west-central Wilmington quadrangles. Its composition ranges from about $An_8$ to $An_{20}$, but it falls chiefly in the calcic albite to sodic oligoclase range. Plagioclase zoning is almost completely absent. Myrmekite is ubiquitously developed within the biotite granite-gneiss where it occurs chiefly along the fringes of plagioclase grains in contact with microcline; a somewhat unusual occurrence is shown in plate 27A. The plagioclase throughout the biotite granite-gneiss is much more highly altered than the associated microcline; it is virtually unidentifiable in places owing to the dense mat of alteration products present. Bent and broken twins are not uncommon within the plagioclase, but evidence of strain is far less conspicuous here than in the muscovite granite-gneiss. Textural relationships between microcline and plagioclase are similar to those observed in the muscovite granite-gneiss, particularly as regards the complexity and irregularity of mutual grain boundaries. Microcline commonly

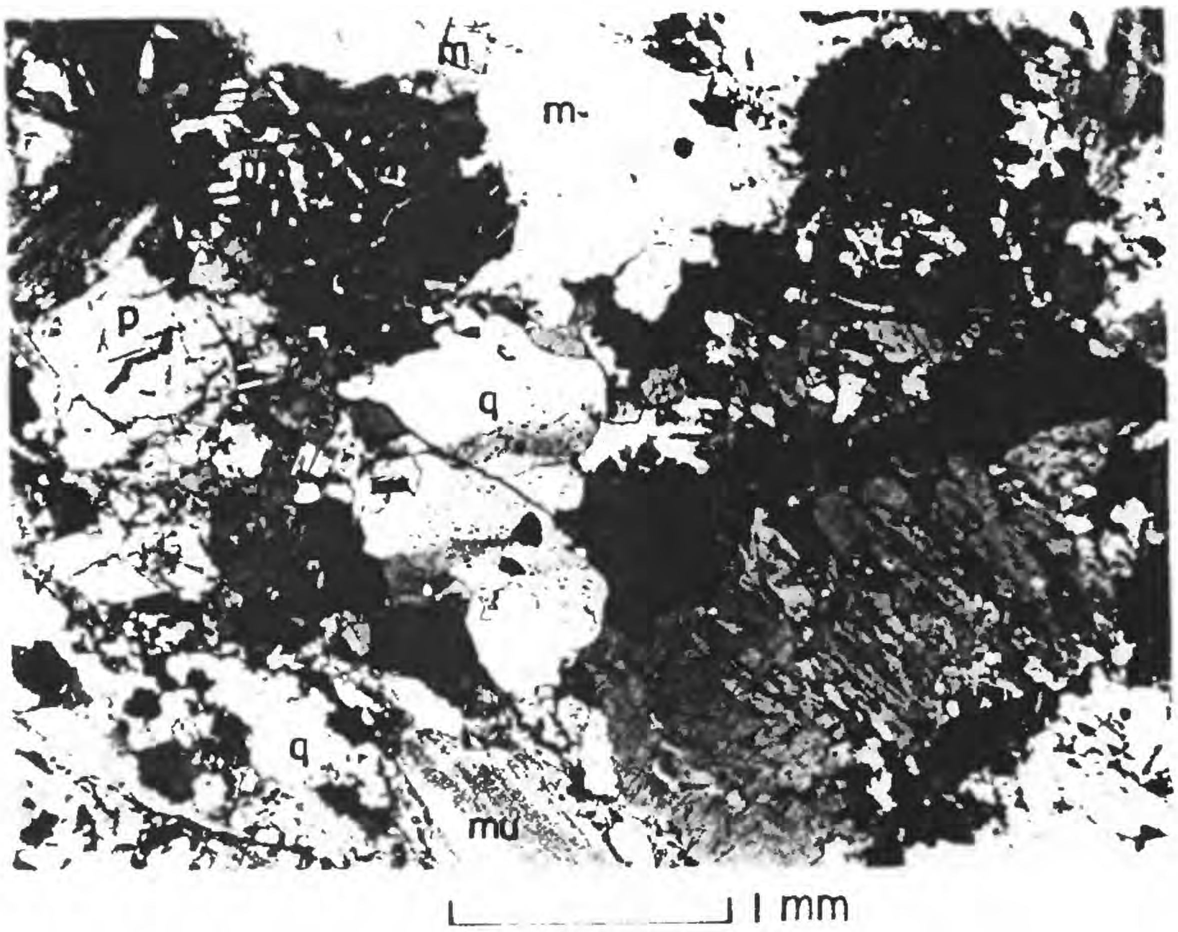
Plate 27

A. Photomicrograph of specimen from the biotite granite-gneiss facies of the Andover Granite exposed in railroad cut 600 feet south-southwest of Kendall St.-North St. intersection, Tewksbury. q, quartz; p, plagioclase; m, microcline; bi, biotite. Note that the myrmekitic quartz in the left central section of the photograph stops at boundary between inner and outer plagioclase zones. The outer plagioclase fringe is optically discontinuous with the perthitic plagioclase in surrounding microcline. Crossed nicols.

B. Photomicrograph of specimen from the undifferentiated granite-gneiss facies of the Andover Granite exposed 2000 feet west of crest of Round Top Hill, Hudson. q, quartz; p, plagioclase; m, microcline; mu, muscovite; bi, biotite altering to chlorite. Note the intricate embayment of plagioclase by microcline and local development of myrmekite in upper left and lower right corners of photo. Crossed nicols.




A




B

envelops or engulfs the plagioclase (see, for example, the intergrowth shown in the center of plage 26A) in such a way as to suggest the presence of a peninsula or island of plagioclase in a sea of potassium feldspar.

Quartz generally makes up about a third of the biotite granite-gneiss; a few unusual, and presumably non-representative, specimens were observed in which it appeared to comprise approximately half the rock. The quartz commonly shows undulatory extinction, and it is easily the most intensely granulated phase present. It is rutilated in part, but the rutilation is normally inconspicuous. Biotite, together with its chloritic derivative, generally makes up about 4 to 6 percent of the rock; it is intensely pleochroic and contains abundant, bright pleochroic haloes around what appear to be tiny zircon crystals. It occurs as uniformly disseminated grains and less commonly in ultra-thin, discontinuous mica layers or schlieren. Muscovite occurs in amounts roughly equal to or less than those of biotite plus chlorite. Its mode of occurrence is about the same as that of the biotite, but it is also found as tiny, uniformly oriented inclusions in plagioclase. Flesh-colored garnet is a common accessory in the biotite granite-gneiss where it locally composes up to more than 1 percent of the rock. The garnet is generally fresh and unaltered, but it is in part retrograded to a dense mat of very fine-grained micaceous products.

Chemical analyses and norms of the biotite granite-gneiss are presented in table 22.

A group of interesting pegmatite dikes and quartz veins occur within the biotite granite-gneiss cropping out south and east of Ames Hill in Tewksbury. The pegmatite dikes are generally vertical or nearly so; they range from less than an inch to several feet in thickness and remain remarkably uniform in width across a given exposure. The pegmatite is composed chiefly of feldspars, quartz, garnet and muscovite; it is apparently devoid of biotite. The muscovite occurs as hypidiomorphic, tabular books extending out from the dike walls at almost right angles; garnet occurs in conspicuous concentrations or clots, particularly along contacts. Age relationships between the pegmatite dikes and the associated quartz veins are indeterminate in the Ames Hill area, but elsewhere within the Andover, quartz veins crosscut the pegmatite. The quartz veins here are locally vuggy and lined with crystals of $\alpha$-quartz morphology.

### Undifferentiated granite-gneiss facies

The undifferentiated granite-gneiss facies consists chiefly of granite-gneiss in which either muscovite or biotite may occur as the main varietal mineral; it is defined in lieu of the differentiation of separate muscovite and biotite granite-gneiss facies within its outcrop area.

It occurs chiefly in the Marlboro, Hudson, and Maynard quadrangles, and in the western half of the Concord quadrangle. Where it occurs in the Hudson and Maynard quadrangles the undifferentiated granite-gneiss is coincident with the unit formerly mapped by Hansen (1956, p. 39-41, pl. 1) under the name "Gospel Hill Gneiss." It is probably best exposed in the Hudson quadrangle, but it is moderately well exposed throughout the area of its occurrence. The undifferentiated granite-gneiss has been invaded extensively by pegmatite, particularly in the northeastern section of the Marlboro quadrangle, and it apparently includes a number of lenses or blocks lithologically indistinguishable from adjacent units (Hansen, op. cit., p. 40).

In contrast with both the muscovite and biotite granite-gneiss facies, contacts between the undifferentiated granite-gneiss and adjacent rocks are at least in part well exposed (Hansen, op. cit., p. 40-41). According to Hansen (op. cit., p. 40), the granite-gneiss cropping out in the Hudson and Maynard quadrangles is clearly gradational with inliers of the Nashoba Formation exposed locally within its outcrop belt; the contact with the main body of the Nashoba Formation, however, is poorly exposed and may not be gradational. The granite-gneiss apparently is in relatively sharp contact with the Marlboro Formation; rocks within the contact zone pass from a normal granitic mineral assemblage into essentially uncontaminated mica schist and amphibolite over a distance of no more than two or three hundred yards. According to Hansen (*op. cit.*, p. 41), however, "mica schists of the Marlboro Formation are interbedded and conformable with the typical granite gneiss" across something more than 200 feet of section cropping out in the northeastern Marlboro quadrangle.

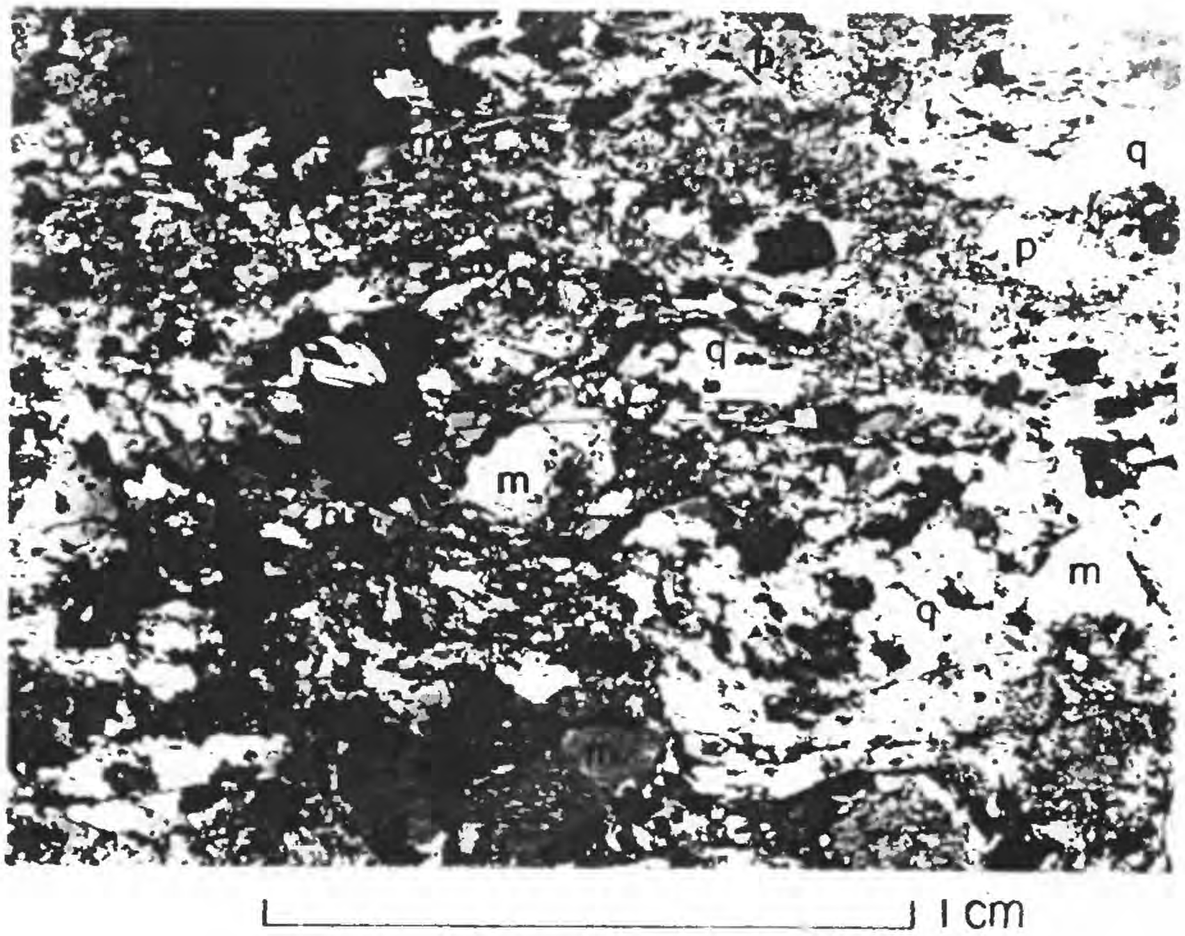
Hansen (*op. cit.*, p. 40) has reported that the granite-gneiss contains "a host of nonigneous relict structures, such as drag folds and what is probably original bedding that is closely parallel with the regional structure." In addition to the parallelism displayed by planar structures within and adjacent to the granite-gneiss, the orientation of linear elements within inclusions in the granite-gneiss "are in general accordance with those of the biotite gneiss and amphibolite outside" (Hansen, *op. cit.*, p. 40). Nevertheless, the foliation in the main body of the Nashoba Formation seems to be truncated by the Nashoba-Andover contact.

The undifferentiated granite-gneiss facies is composed of rocks common to both the muscovite and biotite granite-gneiss; it apparently differs from the biotite granite-gneiss to a greater extent than it does from the muscovite granite-gneiss. The parts of this facies examined by the writer are generally more prominently foliated and intensely granulated (see plate 28) than the biotite granite-gneiss. Microcline, moreover, locally manifests a degree of strain (see lower part of photomicrograph in plate 28A) virtually

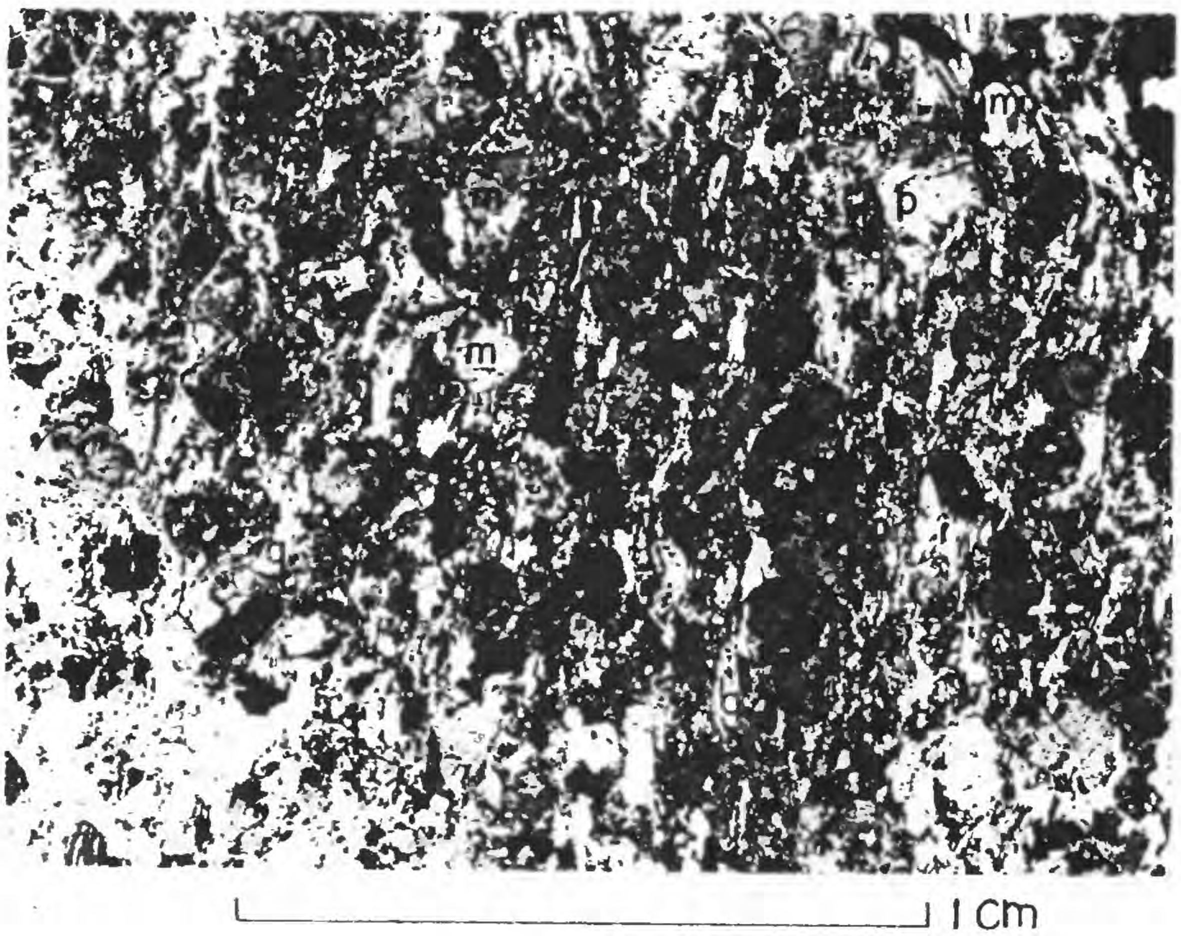
Plate 28

A. Photomicrograph of specimen from the undifferentiated granite-gneiss facies of the Andover Granite exposed .7 mile south-southeast of Broad Street School, Hudson. q, quartz; p, plagioclase; m, microcline; mu, muscovite; bi, biotite; b, balsam. Note the broken microcline crystals and mortared quartz. Crossed nicols.

B. Photomicrograph of specimen from the undifferentiated granite-gneiss facies of the Andover Granite cropping out within 300 feet of the Marlboro Formation in the extreme northeast corner of the Marlboro quadrangle. q, quartz; p, plagioclase; m, microcline; mu, muscovite. Crossed nicols




A




B

unknown in the biotite granite-gneiss. In terms of gross mineral composition the muscovite, biotite, and undifferentiated granite-gneiss are roughly comparable; muscovite, however, appears to be a more prominent varietal phase here than in the biotite granite-gneiss.

Fabrics of the undifferentiated granite-gneiss are illustrated in plates 27B and 28. Modal analyses are presented in table 21.

### Fine-grained granite-gneiss facies

The fine-grained granite-gneiss facies may be defined as a fine- to medium-grained variant of the previously described gneissic facies of the Andover Granite. Its occurrence as a mappable unit is limited to about 1 square mile northeast of Haggetts Pond in Adover. It is crosscut locally by irregularly shaped pegmatite bodies, but it is generally transitional with surrounding facies of the Andover.

The fine-grained granite-gneiss is very light gray to pearly white in fresh exposures, and it weathers to the very-light-gray, chalky color typical of much of the Andover Granite. It is the most prominently and consistently foliated unit among the several facies of the Andover; spacings between laminae commonly are on the order of a millimeter or less. Foliation in the exposures immediately east of Greenwood Road is particularly pronounced, but it becomes much less conspicuous traced toward the southeast. The foliation is defined by the preferred orientation of both mica and laminae of highly granulated quartz and feldspar. The texture of the fine-grained granite-gneiss is characteristically allotriomorphic or xenomorphic; it is generally seriate, ranging from very fine to medium grained.

The composition of the fine-grained granite-gneiss approximates that of the other gneissic facies of the Andover. It is composed chiefly of roughly equal amounts of quartz, plagioclase, and microcline, together with varietal amounts of mica. Textural relationships between potassium and plagioclase feldspar are generally obscure owing to the intense granulation, but they are characterized locally by the same grain boundary complexity manifested elsewhere within the Andover. The fine-grained granite-gneiss is seemingly most akin to the muscovite granite-gneiss, in that the volume of muscovite generally exceeds that of the biotite. Garnet commonly occurs in accessory amounts. A modal analysis of a single specimen from this facies is presented in table 21.

### Binary granite facies

The binary granite facies consists chiefly of generally massive, two-mica granitic rocks ranging from true granite to granodiorite. It crops out mainly over an irregularly shaped but generally elongate area of 12 or 13 square miles, extending from the central part of the Concord quadrangle through the southeast quarter of the South Groveland quadrangle. It is well exposed in the southwestern quarter of the Wilmington quadrangle and along the western part of the Reading-South Groveland quadrangle boundary; it tends to be poorly exposed elsewhere. Numerous unmapped dikes of binary granite invade most of the older formations (with the possible exceptions of the Marlboro Formation and the Merrimack Group) in the area, and the granite in turn is intruded locally by pegmatite. The binary granite facies is in transitional contact with the pegmatitic granite facies throughout most of the area of their mutual occurrence. It is also transitional with both the biotite tonalite facies of the Sharpners Pond Tonalite and parts of the Nashoba Formation exposed in the Wilmington quadrangle. Contacts between the binary granite and adjacent rocks cropping out elsewhere are generally sharp, well-defined boundaries of the sort illustrated in plate 18.

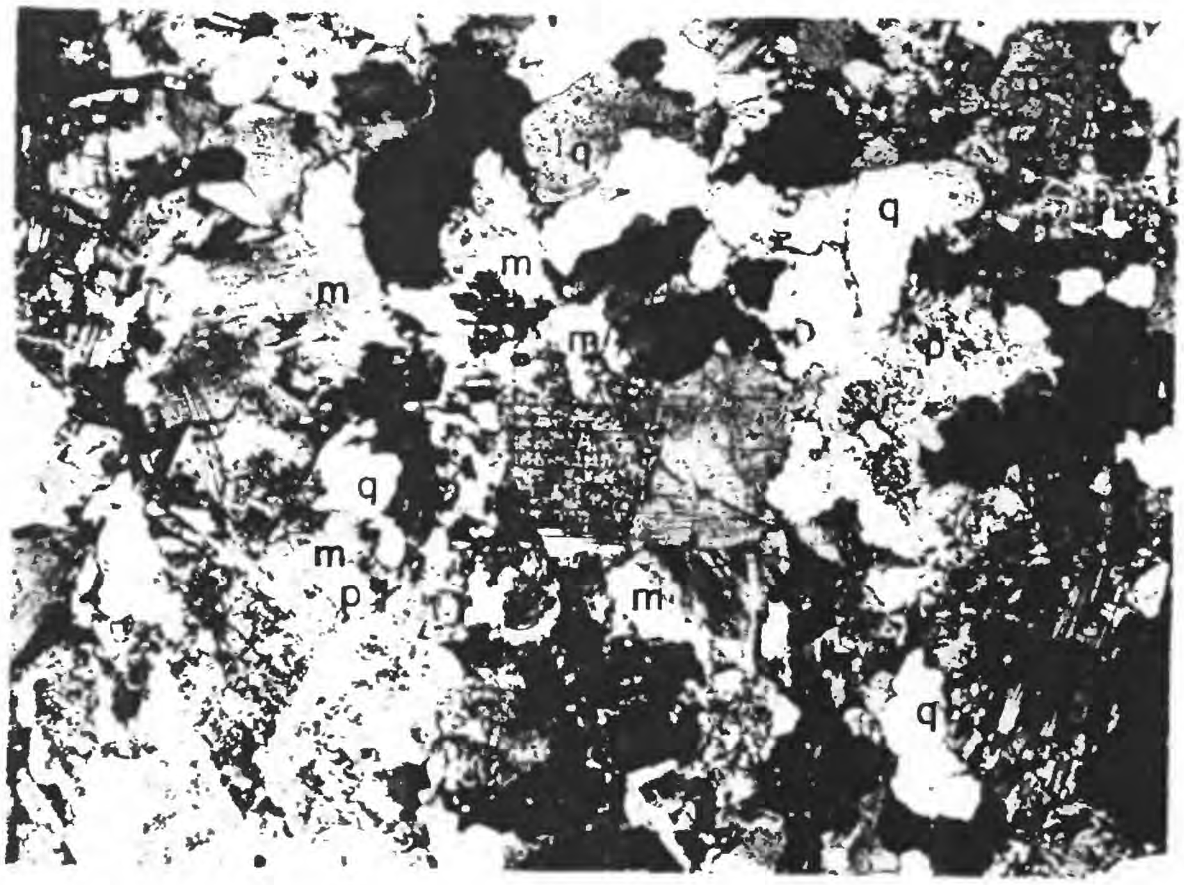
Fresh exposures of the binary granite are typically pearly-white to light-gray; tiny, pink flecks of garnet locally dot the surface. The less mafic portions weather to a chalk-white, whereas those containing moderate amounts of biotite commonly develop a greenish-gray hue. Patchy limonitic staining occurs locally, but it is generally inconspicuous. Foliation is absent or poorly defined throughout most of the binary granite facies. It is locally prominent, however, within a small group of exposures in the North Wilmington area, where it is roughly conformable with the regional structure. The foliation in these exposures also conforms with (1) that within the somewhat irregular, but generally tabularly shaped xenoliths of Sharpners Pond Tonalite and (2) that defined by the xenolithic blocks themselves (see plate 24B). Mortar structure occurs locally, particularly along the contact with the Sharpners Pond Tonalite in the southeastern quarter of the Wilmington quadrangle; detectable foliation, however, seems to be defined chiefly by the preferred orientation of mica. The texture of the binary granite is generally allotriomorphic and considerably more intricate than that normally thought of as granitic (see plates 29A, 30B, 31, and 32). Here and there, however, the texture tends toward hypidiomorphism, chiefly because of the locally idiomorphic habit of plagioclase (see plate 29B). Grain size ranges from very fine to coarse, but the rocks are generally medium grained. The binary granite is devoid of true porphyries, but a seriate appearance commonly is imparted to the rock through the presence of abnormally large potassium feldspar crystals (see plate 30A). The textural characteristics of particular minerals or mineral associations are considered in succeeding paragraphs.

The true granites associated with the binary granite facies are concentrated in the larger granite bodies extending from Wilmington center northeast through North Wilmington.

Plate 29

A. Photomicrograph of specimen from the binary granite facies of the Andover Granite exposed 2600 feet northeast of pumping station, North Wilmington. q, quartz; p, plagioclase; m, microcline. Note the intricacy of the intergrowths between plagioclase and microcline. Crossed nicols.

B. Photomicrograph of specimen from the binary granite facies of the Andover Granite exposed 800 feet south of Marblehead St.-Haverhill St. intersection, North Reading. q, quartz; p, plagioclase; m, microcline, mu, muscovite. Note the large, zoned, idiomorphic plagioclase crystal containing optically oriented inclusions of quartz. Specimen is apparently non-myrmekitic. Crossed nicols.

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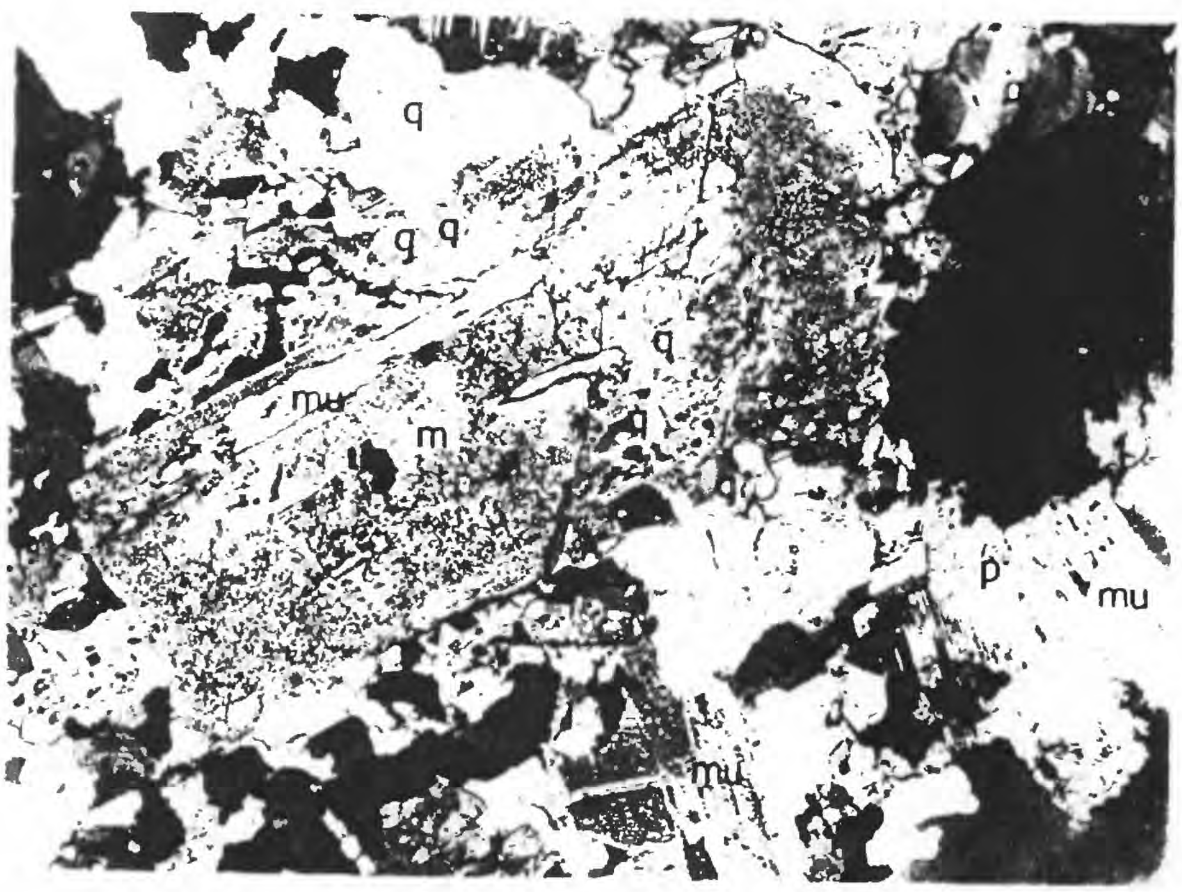
A



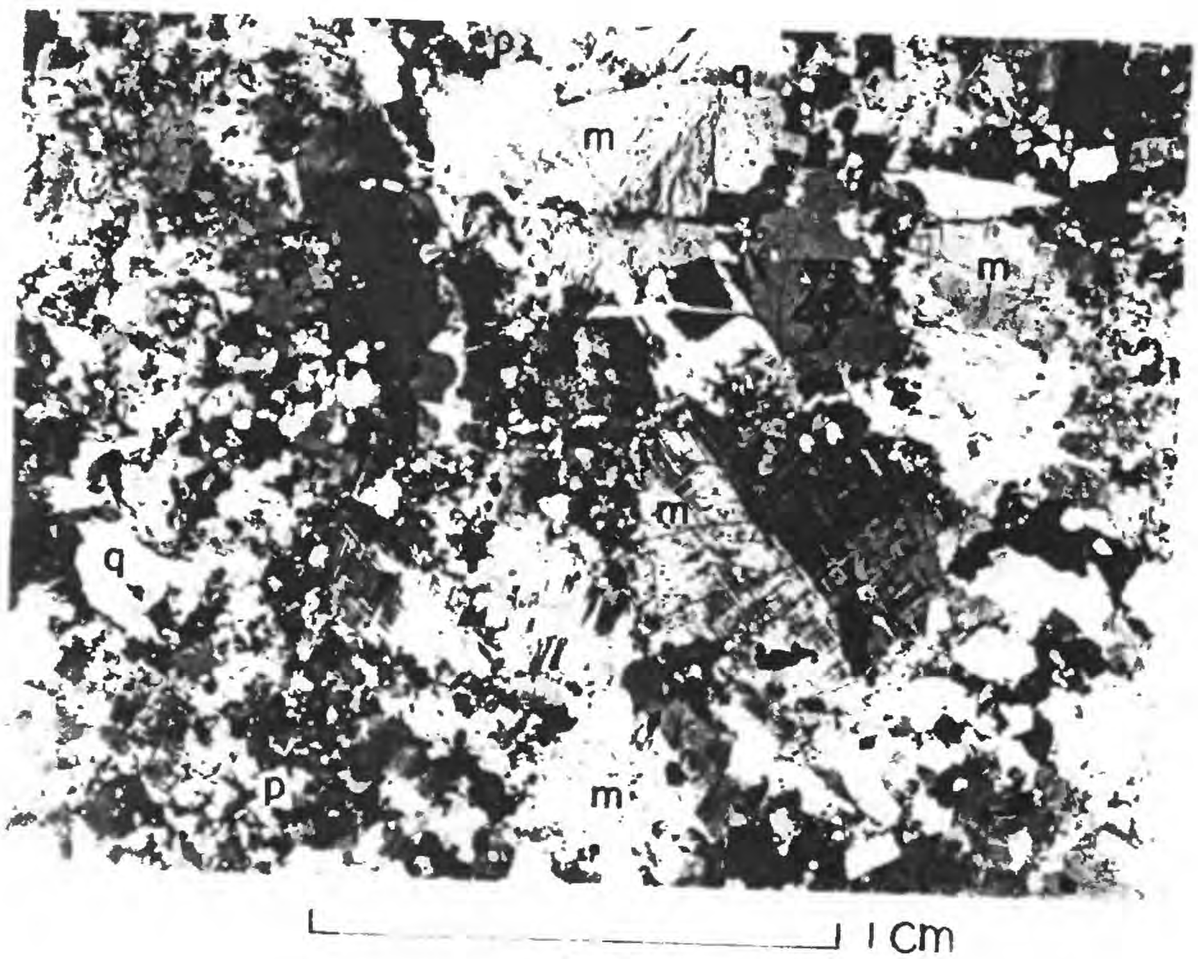

1 mm

B

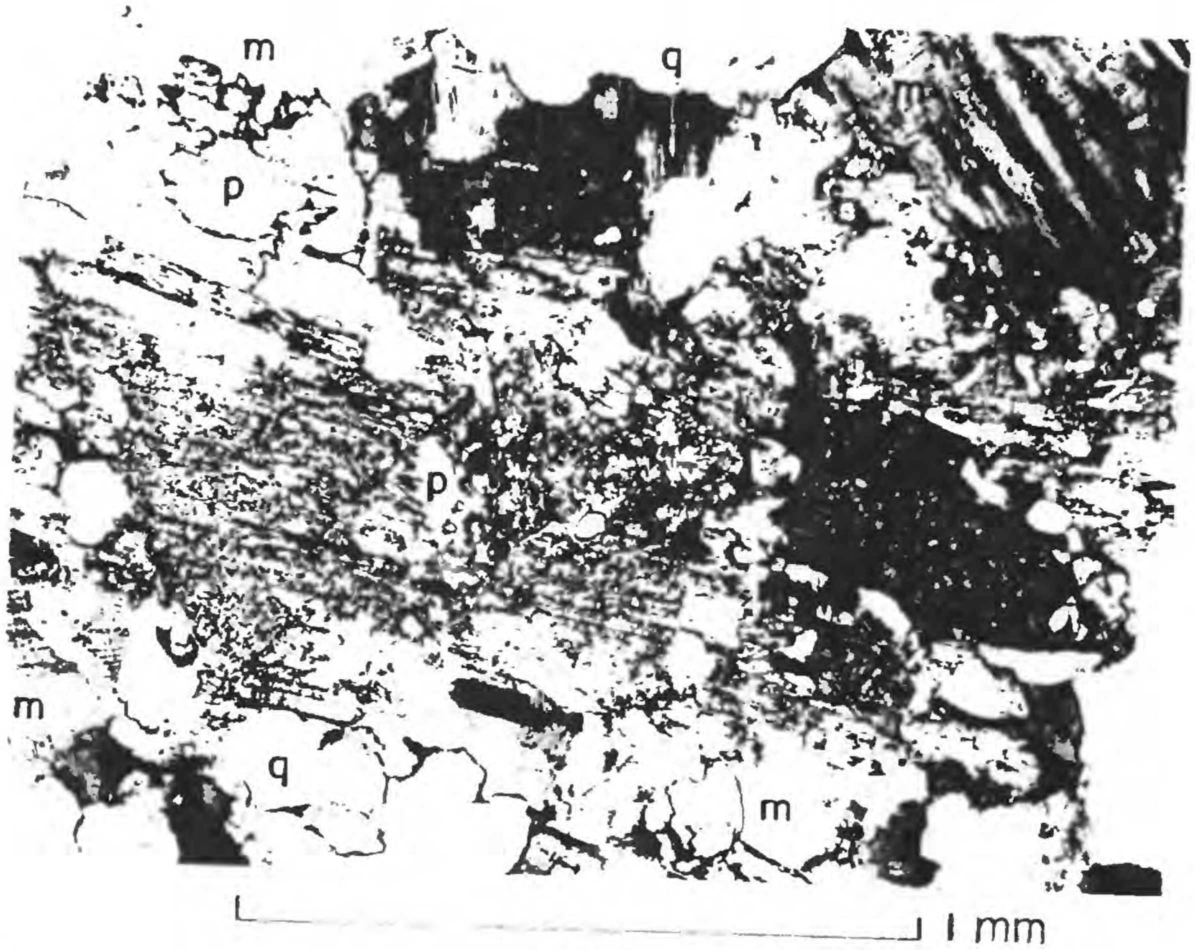
Plate 30

A. Photomicrograph of specimen from the binary granite facies of the Andover Granite exposed 3600 feet north of Mill St.-Chandler Rd. intersection, Burlington. q, quartz; p, plagioclase; m, microcline. Note the coarse microcline phenocrysts set in quartz-plagioclase "groundmass." Note also the veining of microcline by quartz. Crossed nicols.

B. Photomicrograph of specimen from the binary granite facies of the Andover Granite exposed 2600 feet northeast of pumping station, North Wilmington. q, quartz; p, plagioclase; m, microcline; bi, biotite altering to chlorite. Note the "peninsular" and "island" texture in upper left corner and myrmekite along right side of photo. Crossed nicols.




A

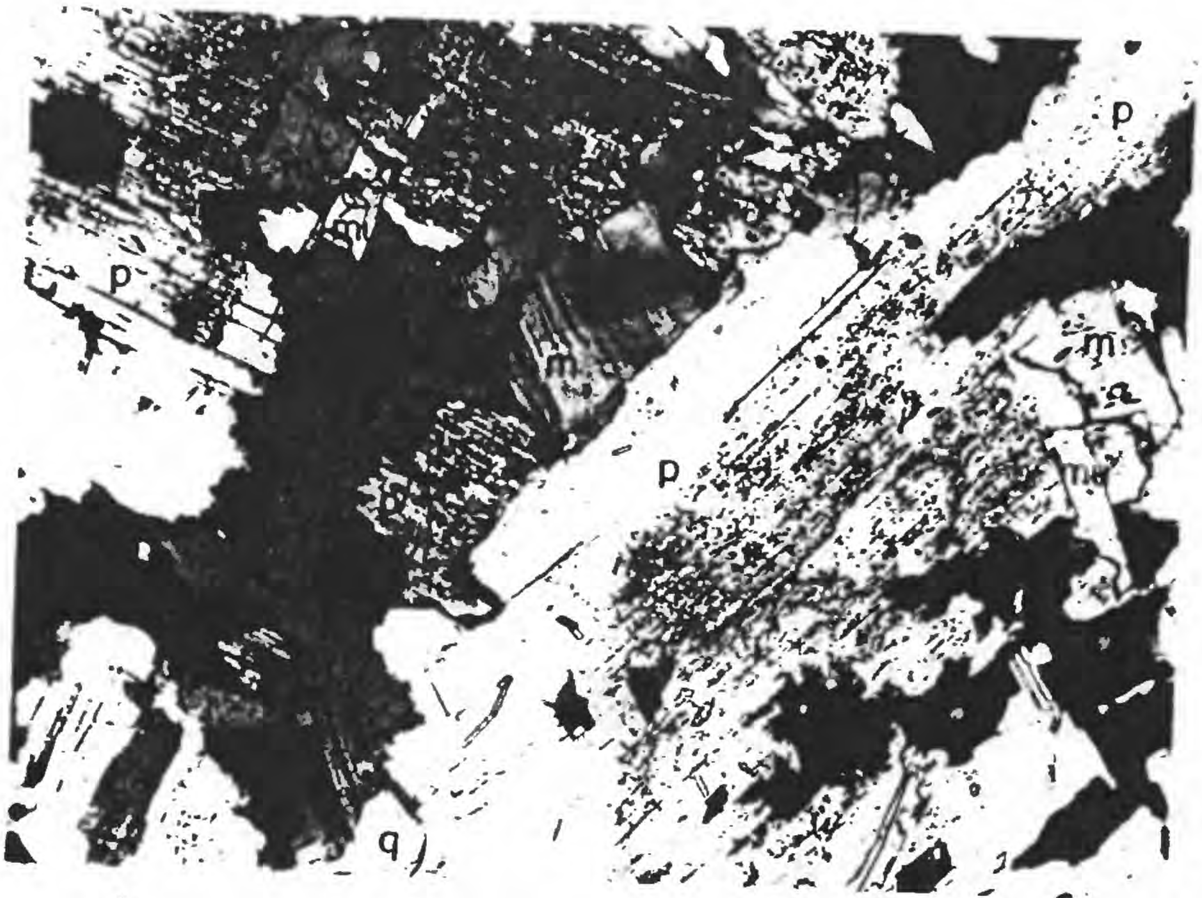



B

Plate 31

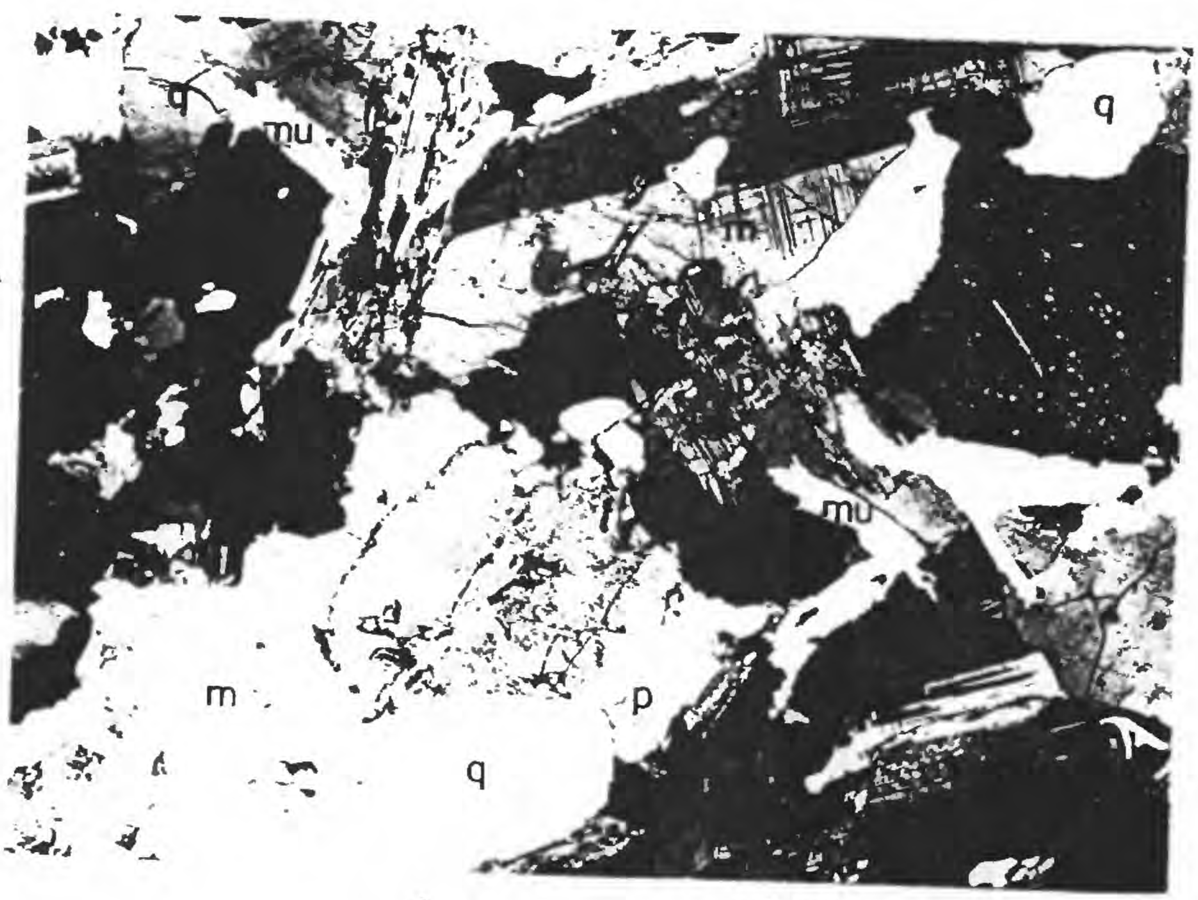
A. Photomicrograph of muscovite granite from the binary granite facies of the Andover Granite exposed 1500 feet east-southeast of Winter St.-Main St. intersection, North Reading. q, quartz; p, plagioclase; m, microcline; mu, muscovite. Note the extensive embayment of plagioclase by microcline and local development of "island" texture.

B. Photomicrograph of muscovite granite from the binary granite facies of the Andover Granite exposed in quarry 1700 feet north of Mill St.-Jenkins Rd. intersection, Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite; bi, altered biotite. Note the "island" texture and vaguely developed plagioclase zoning in central part of photo. Crossed nicols.




1 mm

A



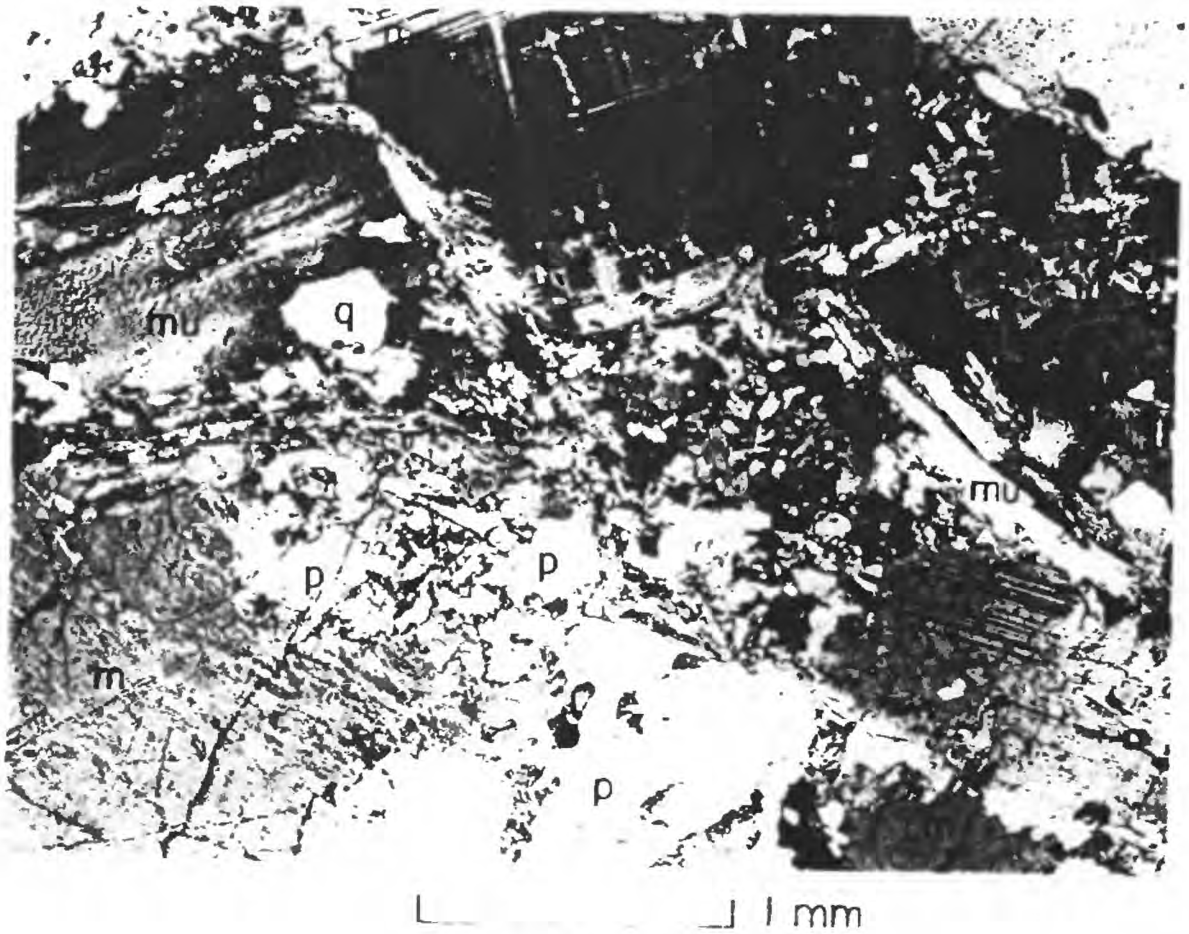

1 mm

B

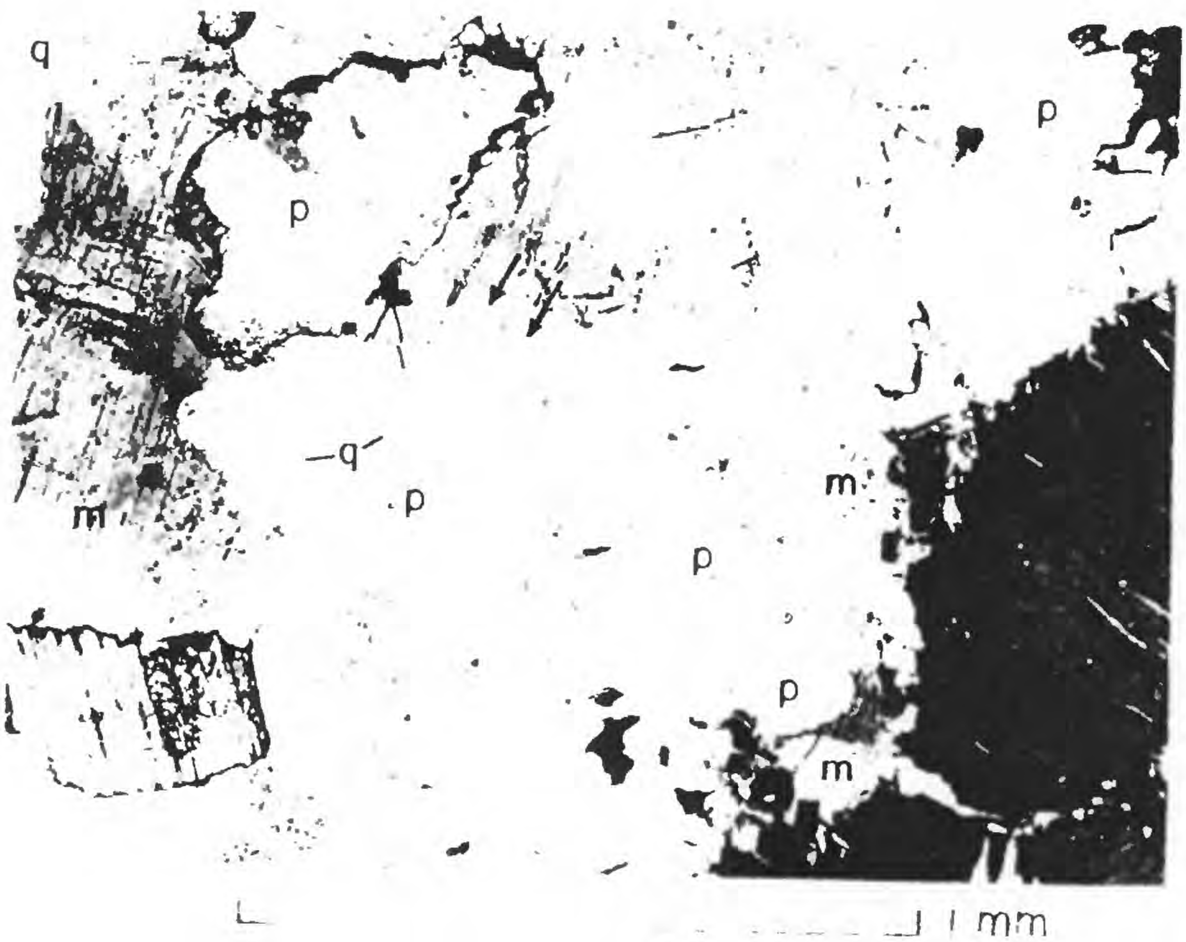
Plate 32

A. Photomicrograph of binary granite from the pegmatitic granite facies of the Andover Granite, exposed in railroad cut 2900 feet west of Salem St.-Middlesex Ave. intersection, Wilmington. q, quartz; p, plagioclase; m, microcline; mu, muscovite. Note the optical continuity of plagioclase across microcline and development of myrmekite in lower central part of photo. Crossed nicols.

B. Photomicrograph of specimen from the binary granite facies of the Andover Granite exposed at Crosby St.-Burlington Rd. intersection, Bedford. q, quartz; p, plagioclase; m, microcline. Note that the quartz stems in microcline (at arrows) are optically continuous with those in the adjacent plagioclase. Note also the intricate embayment of plagioclase by microcline in lower right quarter of photograph. Crossed nicols.




A




B

The granodioritic parts of this facies are most conspicuously developed among the small bosses exposed along the South Groveland-Reading quadrangle boundary. The remainder of the rocks mapped with the binary granite are essentially adamellitic in composition. Modal analyses for a group of widely distributed specimens from the binary granite are presented in table 23.

Microcline composes up to about 45 percent of the true granite and as little as 10 percent of the granodiorite. It occurs mainly as anhedral grains, generally comparable in size to those of the other major constituents; it occurs locally, however, as relatively large grains set within a finer-grained quartz-plagioclase "groundmass" (see plate 30A). The microcline is generally slightly perthitic, particularly along plagioclase contacts, but few examples have been found in which perthitic albite composes more than 1 or 2 percent of the host microcline. Very slight alteration is evident in almost all the microcline, but it is generally clear and rarely highly altered.

Plagioclase composes up to about one-half and as little as one-fifth of the binary granite; an average mode probably would contain between 30 and 35 percent plagioclase. Its composition ranges between measured extremes of $An_2$ and $An_{25}$ and probably averages about $An_{12}$. Zoning is relatively uncommon in the plagioclase of this facies, and it is more apt to be manifested by differential alteration than differences

Table 23. Modal analyses of rocks from binary granite facies of the Andover Granite[1/]

| | A. | B. | C. | D. | E. | F. | G. | H. |
|---|---|---|---|---|---|---|---|---|
| Quartz | 29.8 | 31.0 | 31.0 | 37.0 | 28.6 | 30.8 | 28.6 | 31.4 |
| Plagioclase | 35.8 | 36.9 | 27.4 | 36.8 | 42.3 | 43.4 | 46.0 | 30.6 |
| Microcline | 22.6 | 21.2 | 33.0 | 10.4 | 18.3 | 13.4 | 13.0 | 29.9 |
| Perthitic albite | | | | | | | | |
| Biotite | 11.0 | 9.6 | .2 | | 5.2 | 11.0 | 9.1 | .3 |
| Chlorite | .8 | .5 | 2.8 | .8 | .2 | .4 | .4 | 1.5 |
| White mica | | .3 | 4.8 | 10.8 | 3.5 | .3 | .9 | 5.3 |
| Apatite | .2 | .1 | | | .1 | .3 | .1 | tr. |
| Rutile | | | | .2 | | | | |
| Epidote | .8 | .4 | .6 | 1.2 | 1.8 | .2 | 1.0 | .2 |
| Garnet | | | | | | | | .2 |
| Zircon or thorite | .2 | | | | | .1 | | |
| Carbonate | | | .2 | 3.0 | | | | |
| Sphene | | | | | | | .5 | |
| Opaque | | .1 | | | | .1 | .4 | |

Table 23. (cont.)

| | I. | J. | K. | L. | M. | N. | O. | P. |
|---|---|---|---|---|---|---|---|---|
| Quartz | 34.3 | 33.4 | 37.8 | 35.2 | 31.0 | 27.2 | 33.4 | 35.5 |
| Plagioclase | 31.0 | 26.0 | 29.4 | 26.6 | 27.0 | 22.4 | 38.0 | 28.3 |
| Microcline | 27.3 | 31.4 | 19.8 | 27.7 | 34.2 | 43.6 | 18.6 | 28.0 |
| Perthitic albite | | .1 | | | | | | |
| Biotite | 2.8 | 1.3 | 1.4 | .1 | .4 | | | 4.3 |
| Chlorite | 1.0 | .8 | 1.0 | .4 | 1.4 | .8 | | |
| White mica | 1.7 | 7.0 | 10.6 | 9.5 | 4.2 | 1.4 | 10.0 | 3.5 |
| Apatite | | | | | | | tr. | .2 |
| Rutile | | | | | | | | |
| Epidote | 1.4 | | .2 | | | 1.8 | | tr. |
| Garnet | | tr. | | .3 | | .6 | tr. | .1 |
| Zircon or thorite | | | | | | | | .1 |
| Carbonate | | | | | | | | |
| Sphene | | | | | | | | |
| Opaque | .5 | | | | | .2 | | |

Table 23. (cont.)

| | Q. | R. | S. | T. | U. | V. | W. | X. |
|---|---|---|---|---|---|---|---|---|
| Quartz | 35.0 | 31.8 | 29.5 | 33.6 | 33.2 | 27.6 | 27.2 | 35.1 |
| Plagioclase | 24.0 | 28.2 | 27.0 | 44.7 | 32.2 | 31.2 | 27.5 | 29.8 |
| Microcline | 28.6 | 37.8 | 38.8 | 12.2 | 25.2 | 26.8 | 35.1 | 29.0 |
| Perthitic albite | | | | | | 2.2 | | |
| Biotite | | .5 | 3.3 | 5.5 | 4.8 | 5.8 | 2.3 | .3 |
| Chlorite | | | | .2 | .8 | .8 | 4.2 | |
| White mica | 11.8 | .7 | 1.0 | 1.6 | 3.4 | 5.0 | 3.7 | 5.7 |
| Apatite | tr. | | | .3 | .4 | | | |
| Rutile | | | | | | | | |
| Epidote | .4 | .8 | .1 | .9 | | 1.0 | | |
| Garnet | | .2 | .2 | | tr. | tr. | | .1 |
| Zircon or thorite | | | tr. | | | | | |
| Carbonate | | | | | | tr. | | |
| Sphene | | | | | | | | |
| Opaque | .2 | | .1 | | | .2 | | |

A(L-18). Granodiorite 1600 ft. east of Sacred Heart Cemetery, Shawsheen Heights, Andover. Points counted: 500. Plagioclase composition $An_{20\pm4}$

B(L-939). Granodiorite 2350 ft. N50°E of Andover Country Club clubhouse, Andover. Points counted: 800. Plagioclase composition $An_{20\pm4}$

C(G-60). Granite from quarry at Pleasant St.-Stevens St. intersection, North Andover. Points counted: 500.

Plagioclase composition An

Table 23. (cont.)

D(G-60). Granodiorite from quarry at Pleasant St.-Stevens St. intersection, Andover. Points counted: 500. Plagioclase composition $An_{5+4}$

E(G-746). Granodiorite 220 ft. N14°W of Harold Parker Rd.-Middleton Rd. intersection, North Andover. Points counted: 1000. Plagioclase composition $An_{24+4}$

F(G-749). Granodiorite 2300 ft. N53°W of Harold Parker Rd.-Middleton Rd. intersection, North Andover. Points counted: 1000. Plagioclase composition $An_{25+4}$

G(G-760). Granodiorite 200 ft. north of Berry Pond, North Andover. Points counted: 1000. Plagioclase composition $An_{22\pm4}$

H(C-12). Adamellite from roadcut along Haverhill St. 600 ft. south of Haverhill St.-Marblehead St. intersection, North Reading. Points counted: 1000. Plagioclase composition $An_{10\pm4}$

I(R-92). Adamellite 5800 ft. N89°E of North St.-Haverhill St. intersection, North Reading. Points counted: 1000. Plagioclase composition $An_{12\pm4}$

I(R-215). Granite 1700 ft. N5°E of Mill St.-Jenkins Rd. intersection, Andover. Points counted: 600. Plagioclase composition $An_{10\pm4}$

K(R-251). Granodiorite along southwestern edge of Frye Pond, Andover. Points counted: 500. Plagioclase composition $An_{9\pm4}$

Table 23. (cont.)

L(R-254). Adamellite 800 ft. south of Marblehead St.-Haverhill St. intersection, North Reading. Points counted: 1000. Plagioclase composition $An_{9 \pm 4}$

M(W-4). Granite 1100 ft. S9°E of Woburn St.-Salem St. intersection, Wilmington. Points counted: 500. Plagioclase composition $An_{10 \pm 4}$

N(W-8). Granite 2600 ft. N40°E of pumping station, North Wilmington. Points counted: 500. Plagioclase composition $An_{12 \pm 4}$

O(W-204). Granodiorite 1400 ft. east of Whitefield School, North Wilmington. Points counted: 500. Plagioclase composition $An_{12 \pm 4}$

P(W-240). Adamellite 750 feet S68°W of Church St.-Wildwood St. intersection, Wilmington. Points counted: 1000. Plagioclase composition $An_{15 \pm 4}$

Q(W-300). Granite 950 ft. S59°E of Woburn St.-Park St. intersection, Wilmington. Points counted: 500. Plagioclase composition $An_{5 \pm 4}$

R(W-524). Granite 1300 feet south of Butters Row-Chestnut St. intersection, Wilmington. Points counted: 1000. Plagioclase composition $An_{10 \pm 4}$

S(W-579). Granite 1400 ft. S15°W of Shawsheen Ave.—Aldrich Rd. intersection, Wilmington. Points counted: 1000. Plagioclase composition undetermined

Table 23. (cont.)

T(W-588). Granodiorite 2500 ft. N88°W of Main St.-Church St. intersection, Wilmington. Points counted: 1000. Plagioclase composition $An_{10\pm4}$

U(W-914). Granodiorite 1300 ft. N53°E of southwest corner of Wilmington quadrangle. Points counted: 500. Plagioclase composition $An_{14\pm4}$

V(W-1107). Granodiorite 1900 ft. N78°W of Burlington Ave.-Boutwell St. intersection, Wilmington. Points counted: 500. Plagioclase composition $An_{11\pm4}$

W(NC-23A). Granite 600 ft. N30°E of Bedford St.-Winter St. intersection, Lexington. Points counted: 1000. Plagioclase composition $An_{8\pm4}$

X(NC-23B). Pegmatitic adamellite 600 ft. N30°E of Bedford St.-Winter St. intersection, Lexington. Points counted: 1000. Plagioclase composition $An_{8\pm4}$

1/ All figures volume percent

in extinction angle (see plates 29B and 31B). Myrmekite is prominently developed in the plagioclase, particularly that more calcic than $An_{8-9}$; several occurrences are illustrated in plates 32 and 33. The degree of alteration in the plagioclase ranges widely, even within the same rock; it is commonly highly altered and almost everywhere more altered than adjacent microcline. The plagioclase of the binary granite is generally unstrained; where deformation does occur it is seemingly greater than that in the surrounding potassium feldspar.

The quartz content of the binary granite apparently is restricted within narrower limits than that of either feldspar. It composes between 27 and 38 percent of point-counted specimens and its average content is probably between 31 and 32 percent. It occurs chiefly as discrete, anhedral grains comparable in size to those of adjacent feldspar, and less commonly as small inclusions or tiny veins in other phases.

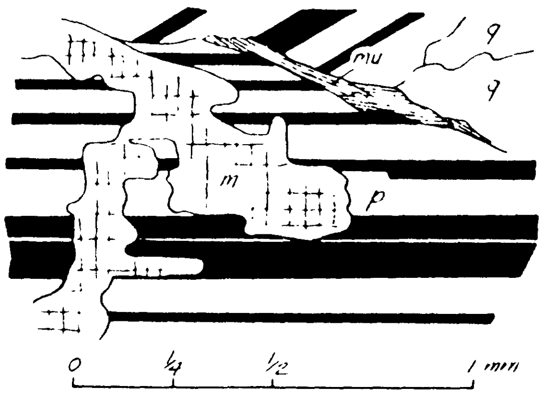
Both the quartz and feldspars of the binary granite commonly are rutilated. Easily distinguishable rutile crystals may be seen in the photomicrographs in plates 29B, 31A, 32B, and 36A.

Textural relationships are exceedingly complex between plagioclase and potassium feldspar on the one hand, and among the two feldspars and quartz on the other hand. They are best described by reference to figure 9 and the series

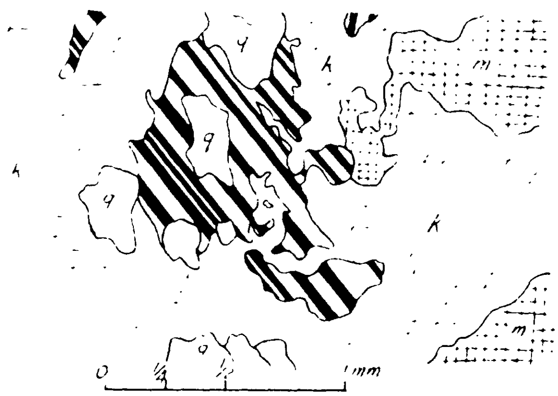
Figure 9

A. Diagrammatic thin section sketch of specimen from the binary granite facies of the Andover Granite exposed along west shore of Frye Pond, Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite, Note the preferred growth of microcline along or at right angles to the direction of albite twinning.

B. Diagrammatic thin section sketch of rock from the binary granite facies of the Andover Granite exposed 1500 feet S15°W of Shawsheen Ave.-Aldrich Rd. intersection, Wilmington. The potassium feldspar is manifested as slightly perthitic microcline (m) and what is probably untwinned microcline (k). Note the development of "island" texture in which the twinning and optical orientation of the small grains of plagioclase are continuous with that of the larger plagioclase crystal. Quartz (q) occurs both as relatively large crystals and as almost submicroscopic myrmekitic intergrowths in plagioclase.




A




B

of photomicrographs in plates 29-33 and 36-39.

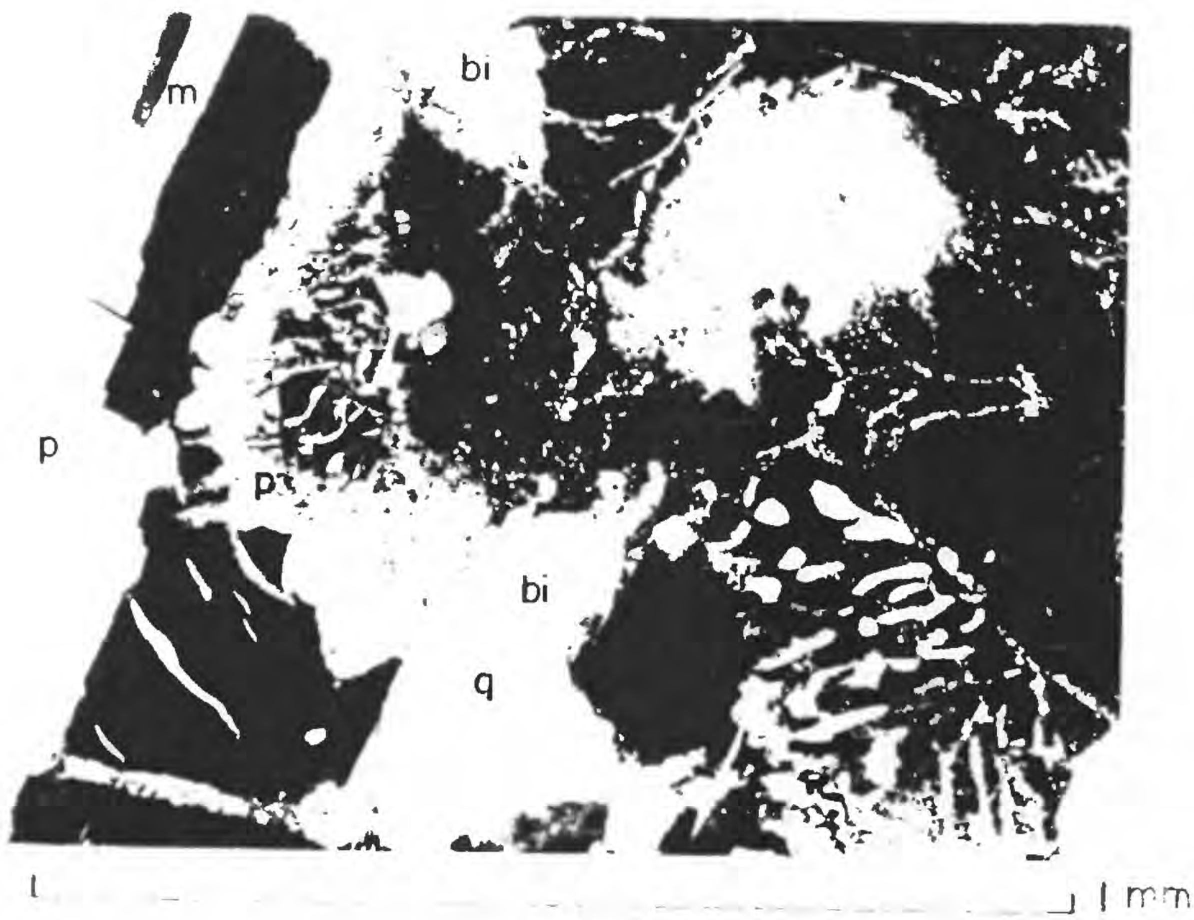
The same intricacy and irregularity in microcline-plagioclase contacts characteristic of the previously described facies of the Andover is the most pervasive textural relationship in the binary granite. This grain-boundary intricacy is illustrated in part in the photomicrographs in plates 29A, 30B, 32B, and 38B. Still another textural feature developed elsewhere in the Andover is one in which microcline occurs as irregularly shaped but uniformly oriented blebs surrounded by plagioclase. The example shown in figure 9A suggests that the growth of the microcline almost certainly has been controlled by the structure of the plagioclase. What may be referred to as "peninsular" and "island" texture is developed extensively between plagioclase and microcline in the binary granite. The relationship is illustrated diagrammatically in figure 9B. "Peninsular" and "island" texture is characterized by locally attenuated or apparently disconnected protuberances of one feldspar crystal within another. Although outliers of microcline locally are enveloped as "islands" in plagioclase, the reverse occurrence is considerably more conspicuous here. In order to qualify as "island" texture it is of course necessary that the "islands" be in optical continuity with the main feldspar grain; where "islands" of plagioclase occur within microcline it is helpful if there exists continuity in twinning as well, for it should be otherwise difficult to

Plate 33

A. Photomicrograph of specimen from the binary granite facies of the Andover Granite exposed east of Sacred Heart Cemetery, Shawsheen Heights, Andover. q, quartz; p, plagioclase; m, microcline; bi, biotite. Note the extension of the optically oriented myrmekitic quartz stems beyond the plagioclase grain boundary into microcline. Crossed nicols.

B. Photomicrograph of specimen from the binary granite facies of the Andover Granite exposed 2400 feet northwest of Harold Parker Rd.-Middleton Rd. intersection, North Andover. q, quartz; p, plagioclase; m, microcline; bi, biotite. Note the zoned plagioclase. Myrmekitic quartz necks down and almost disappears at outer zone. Outermost plagioclase fringe (at arrow) is optically continuous with albite lamellae in the adjacent microcline. Crossed nicols.


A

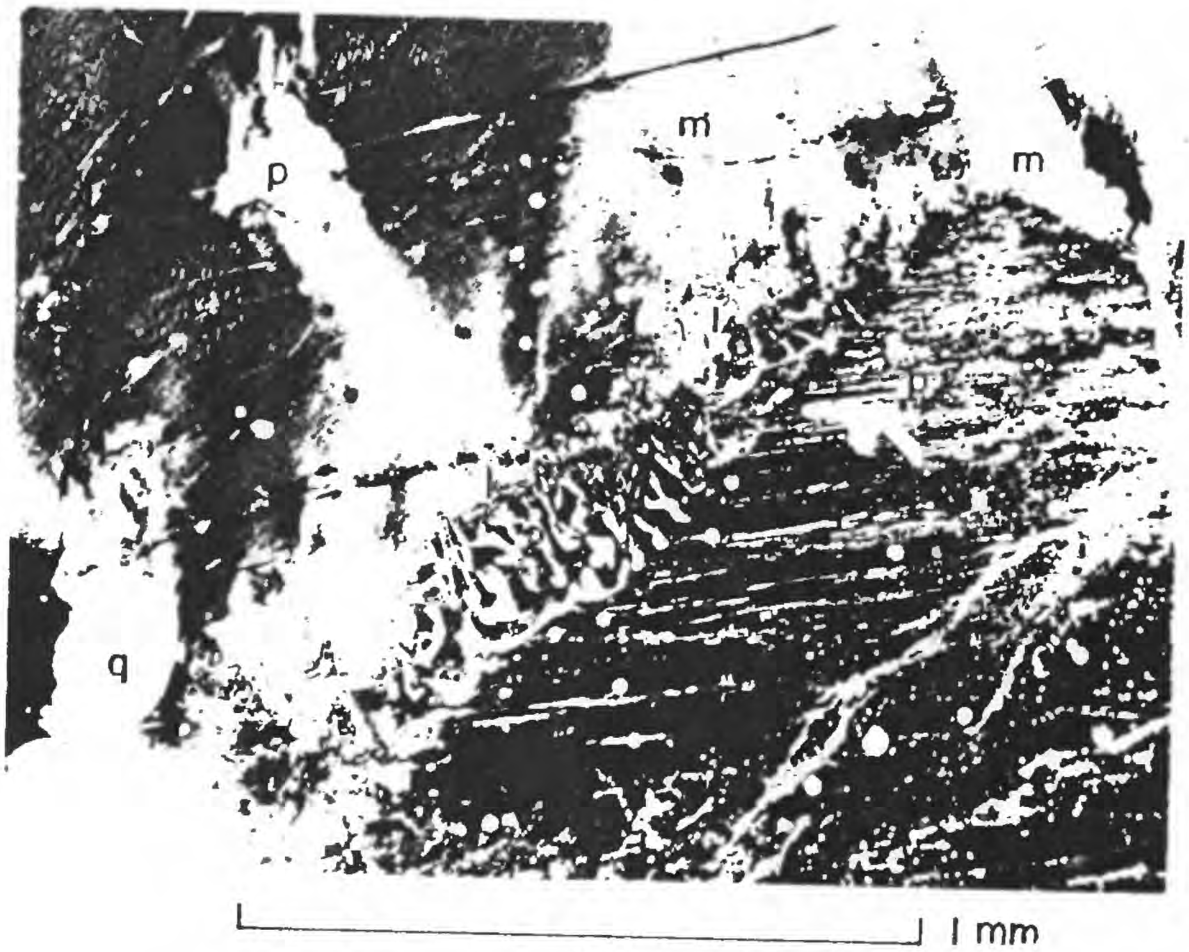



B

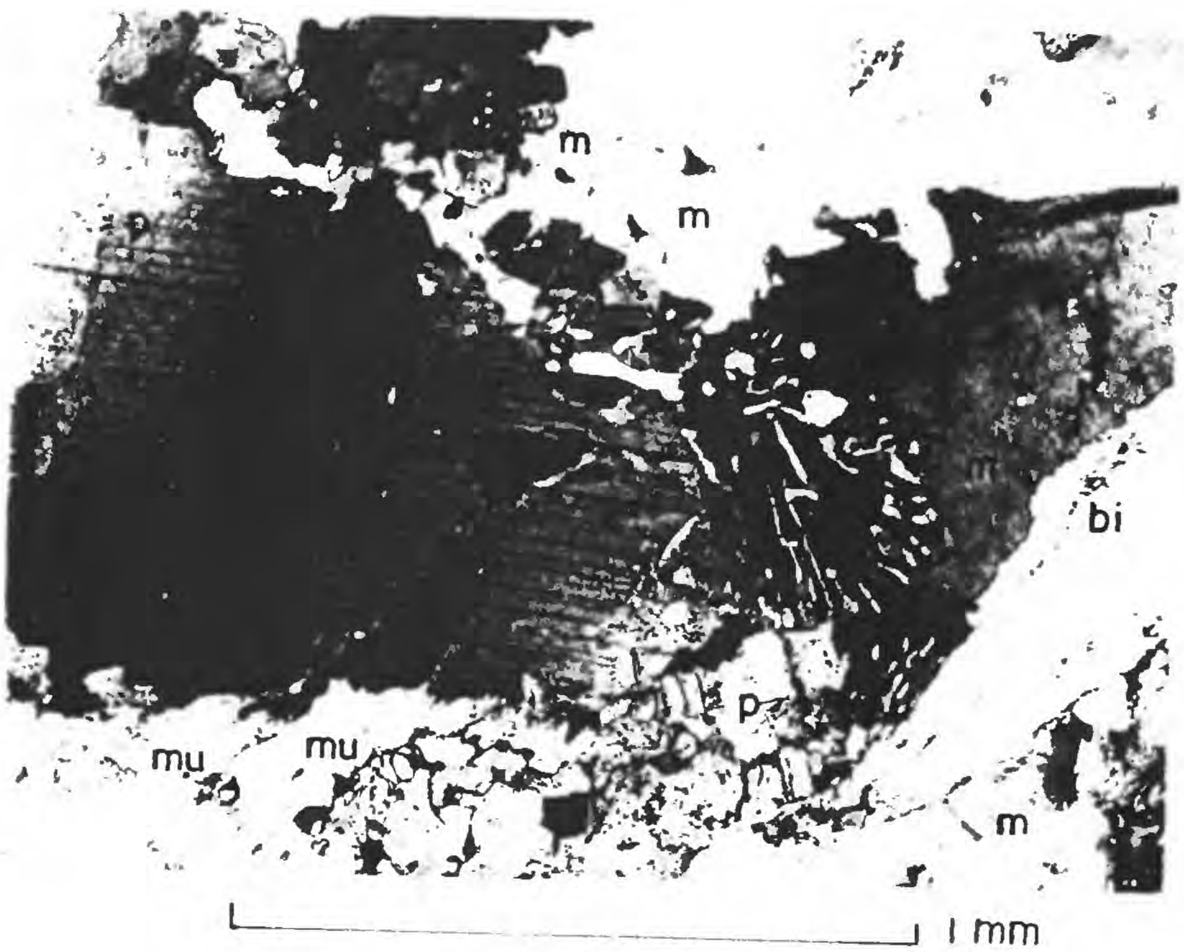
Plate 34

A. Photomicrograph of relatively fine-grained specimen from the pegmatitic granite facies of the Andover Granite exposed 1800 feet northeast of Great Pond Rd.-Marbleridge Rd. intersection, North Andover. q, quartz; p, plagioclase; m, microcline. The plagioclase here occurs in: (1) an outer myrmekitic zone in which the quartz stems neck down into generally sparse, filaments; (2) a main myrmekitic zone; (3) a non-myrmekitic zone. The plagioclase composition apparently differs slightly from zone to zone. Note that the boundary between zones 2 and 3 is a relatively smooth, straight line. Crossed nicols.

B. Photomicrograph of specimen from the pegmatitic granite facies of the Andover Granite exposed 3100 feet northeast of Summer St.-Elm St. intersection, Andover. q, quartz, p, plagioclase; m, microcline; mu, muscovite; bi, biotite. Note the development of myrmekite, intricate embayment of plagioclase by microcline, and broken plagioclase phenocryst. Crossed nicols.




A




B

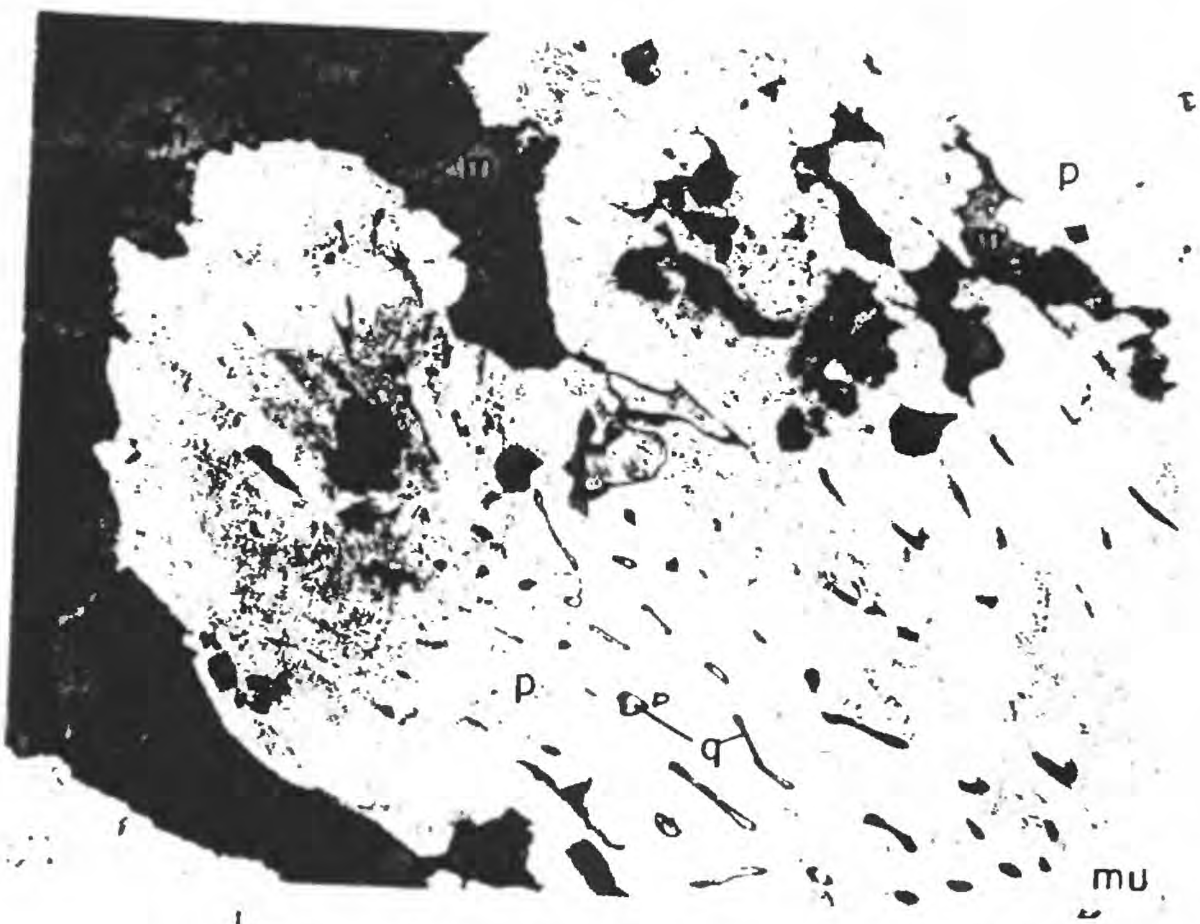
Plate 35

A. Photomicrograph of myrmekite developed within the pegmatitic granite facies of the Andover Granite exposed along the south side of Elm St., 1900 feet northeast of Elm St.-Summer St. intersection, Andover. q, quartz; p, plagioclase; m, microcline; bi, biotite; a, apatite. Crossed nicols.

B. Photomicrograph of specimen from the pegmatitic granite facies of the Andover Granite exposed in quarry north of Cutler Road, West Parish Cemetery, Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite. Note the embayment of plagioclase by microcline and the apparent compositional change along the plagioclase fringe. Crossed nicols. Close up of left central section of photo shown in Plate 41B.


.1 mm

A

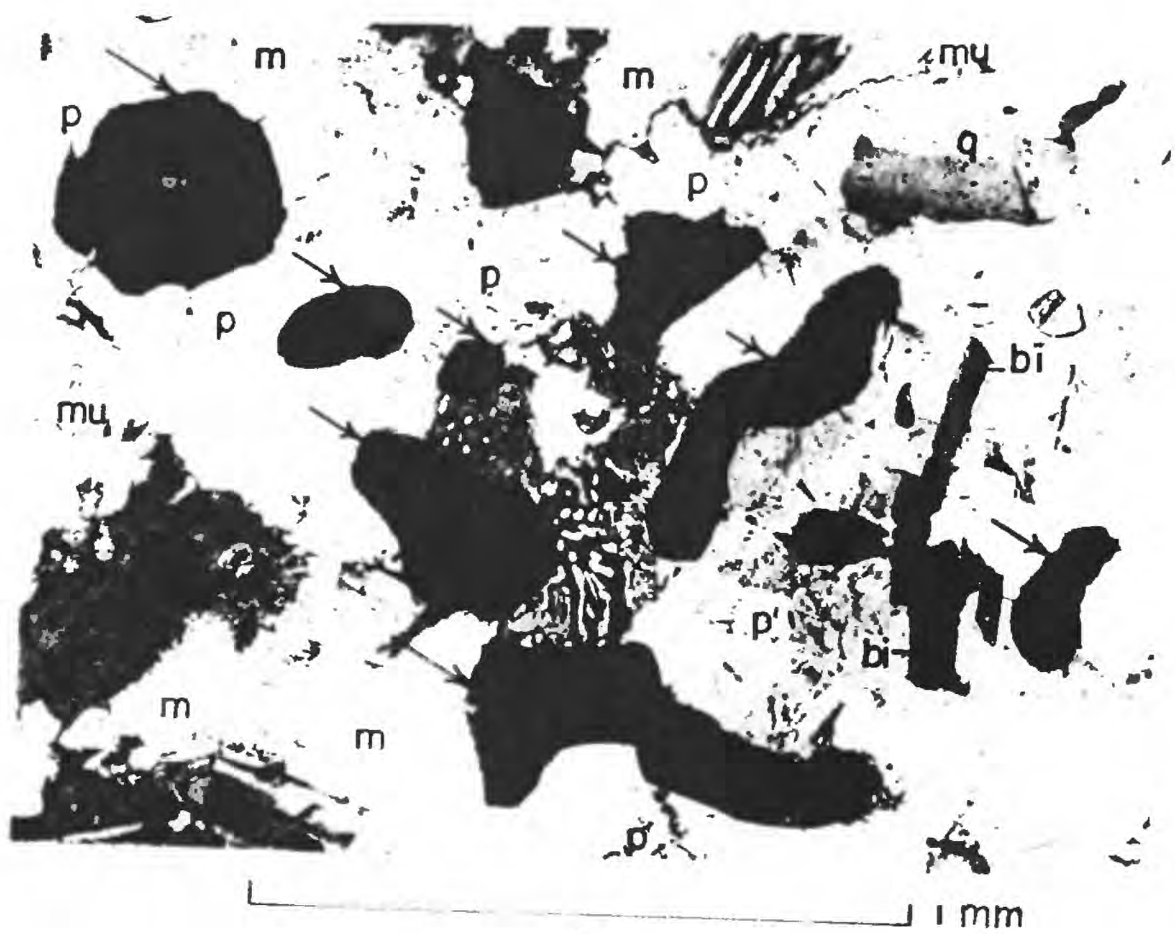



1 mm

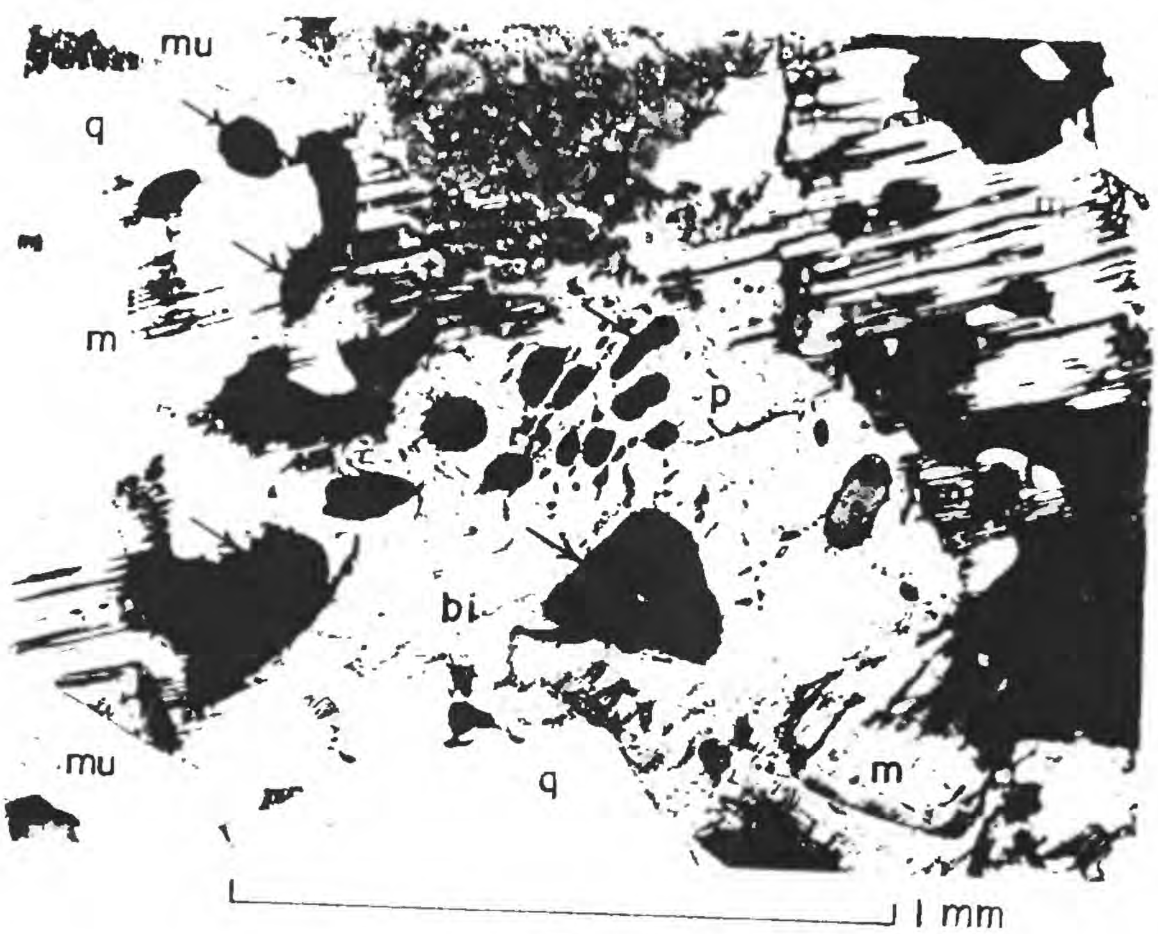
B

Plate 36

Photomicrographs of specimen from the binary granite facies of the Andover Granite exposed 900 feet west-southwest of Glen Rd.-Church St. intersection, Wilmington. q, quartz; p, plagioclase; m, microcline; mu, muscovite; bi, biotite. Gray to black quartz blebs (at arrows) in both photographs are oriented optically across their respective fields of view. Note that the orientation of the quartz blebs if maintained across grain boundaries. Crossed nicols. A. Note the well developed myrmekite in the center of the photograph. B. Note that the oriented quartz blebs are generally finer-grained toward the center of the photograph.




A




B

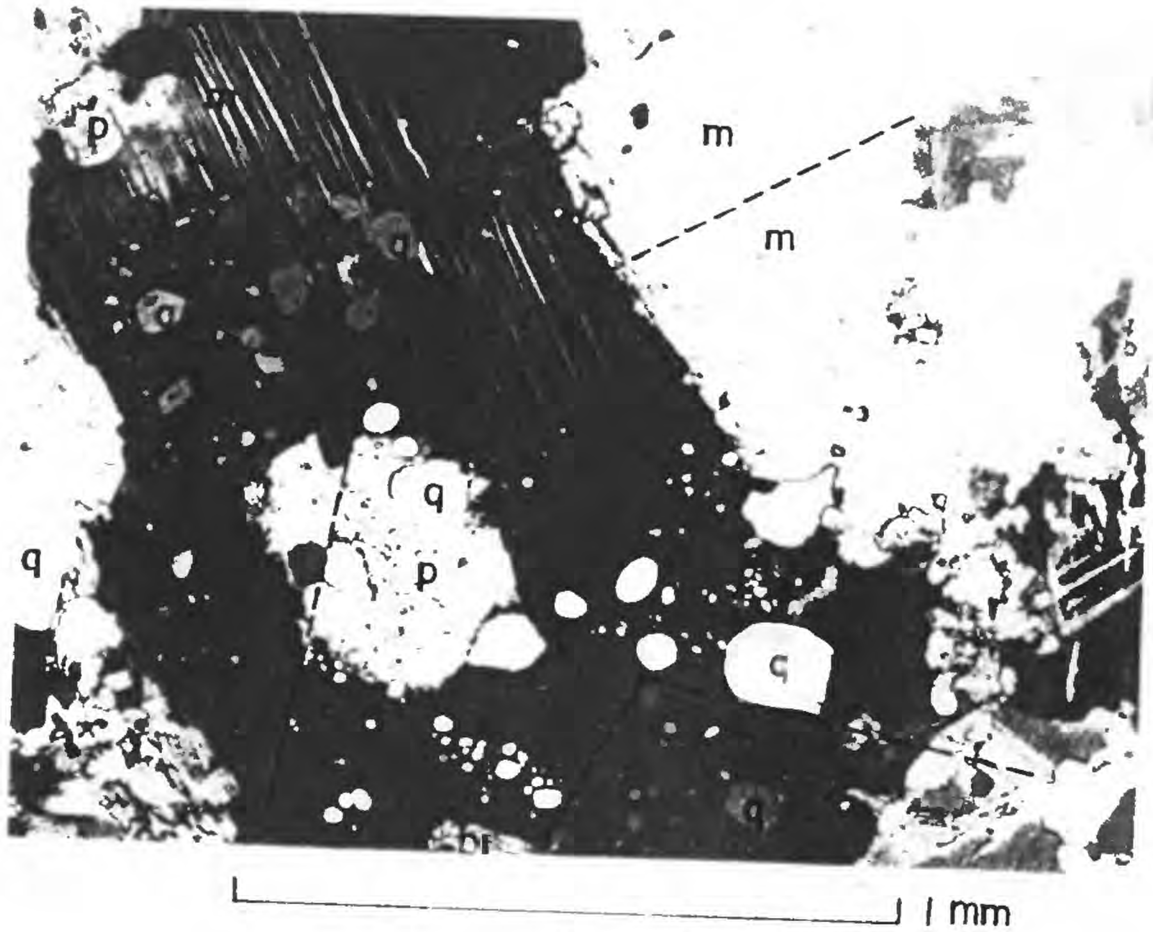
Plate 37

Photomicrograph of specimen from the binary granite facies of the Andover Granite exposed 900 feet west-southwest of Glen Rd.-Church St. intersection, Wilmington. q, quartz; p, plagioclase; m, microcline; mu, muscovite; bi, biotite; myrmekite at arrow. Note the uniformity in the orientation of quartz blebs within restricted parts of the large microcline crystal. Crossed nicols.

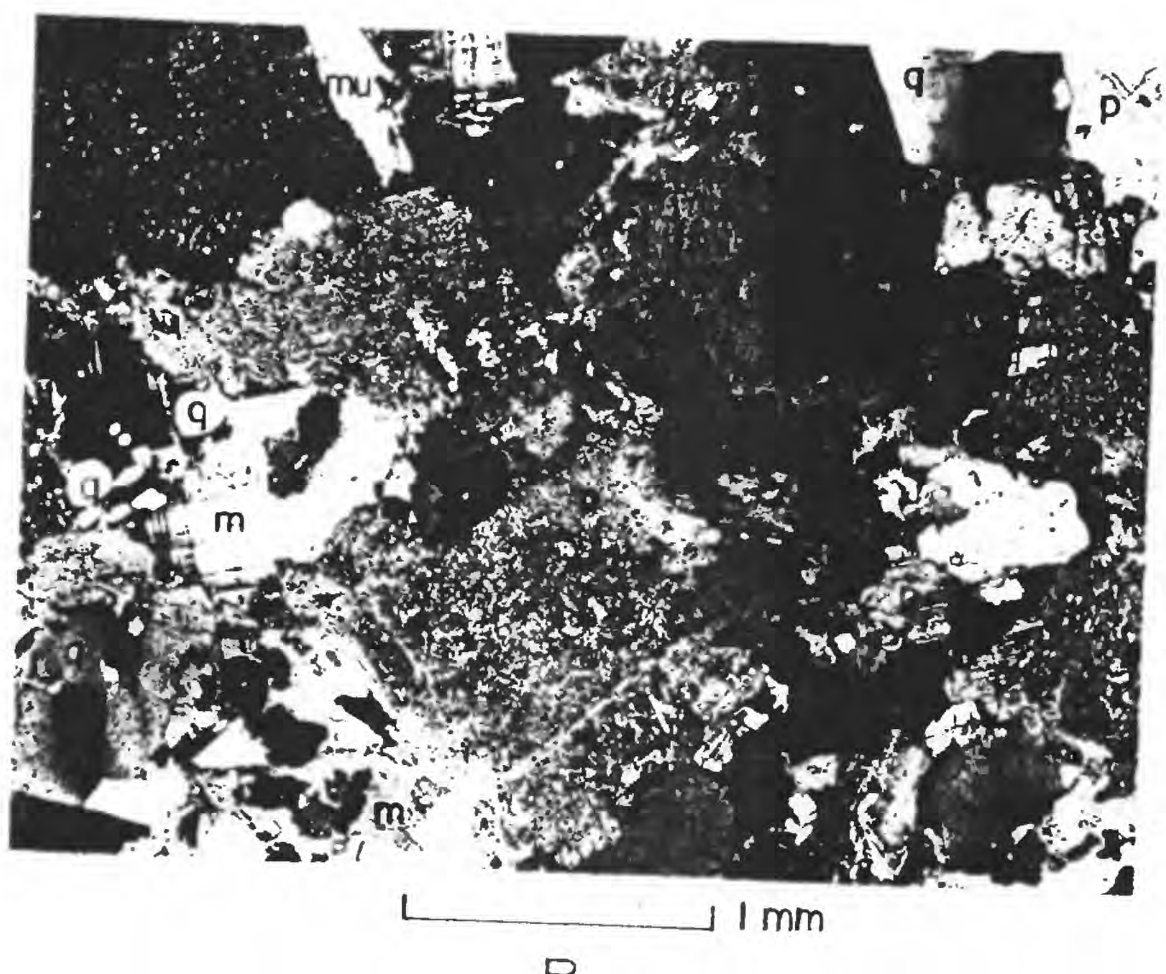

1 mm

Plate 38

Photomicrographs of specimen from the binary granite facies of the Andover Granite exposed 1200 feet south of Salem St.-Woburn St. intersection, North Wilmington. q, quartz; p, plagioclase; m, microcline; bi, biotite largely altered to chlorite. Crossed nicols. A. Broken lines may represent in a gross way pre-recrystallization feldspar grain boundaries. B. Note the uniformly oriented quartz blebs along left side of photo and extremely irregular plagioclase-microcline grain boundaries.




A

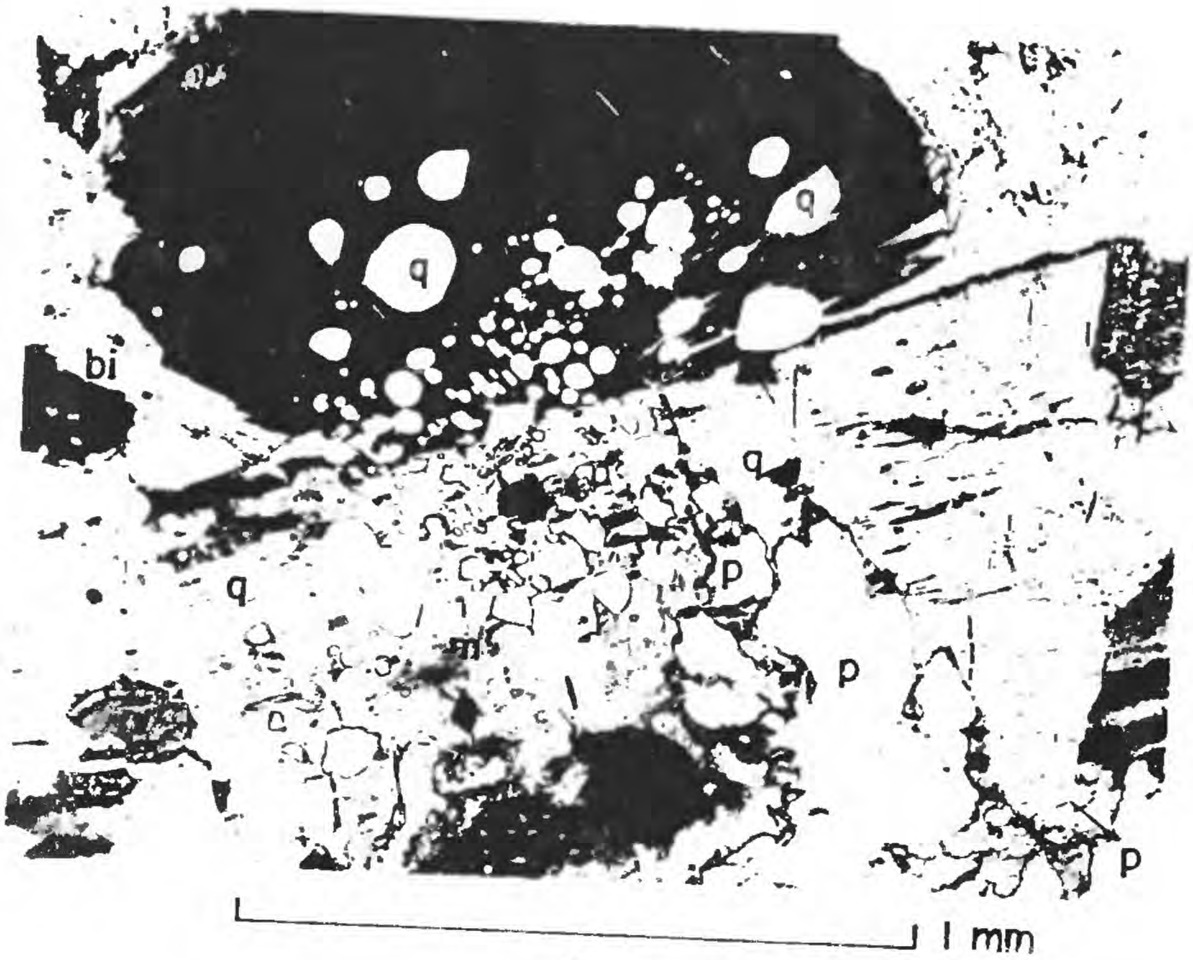



B

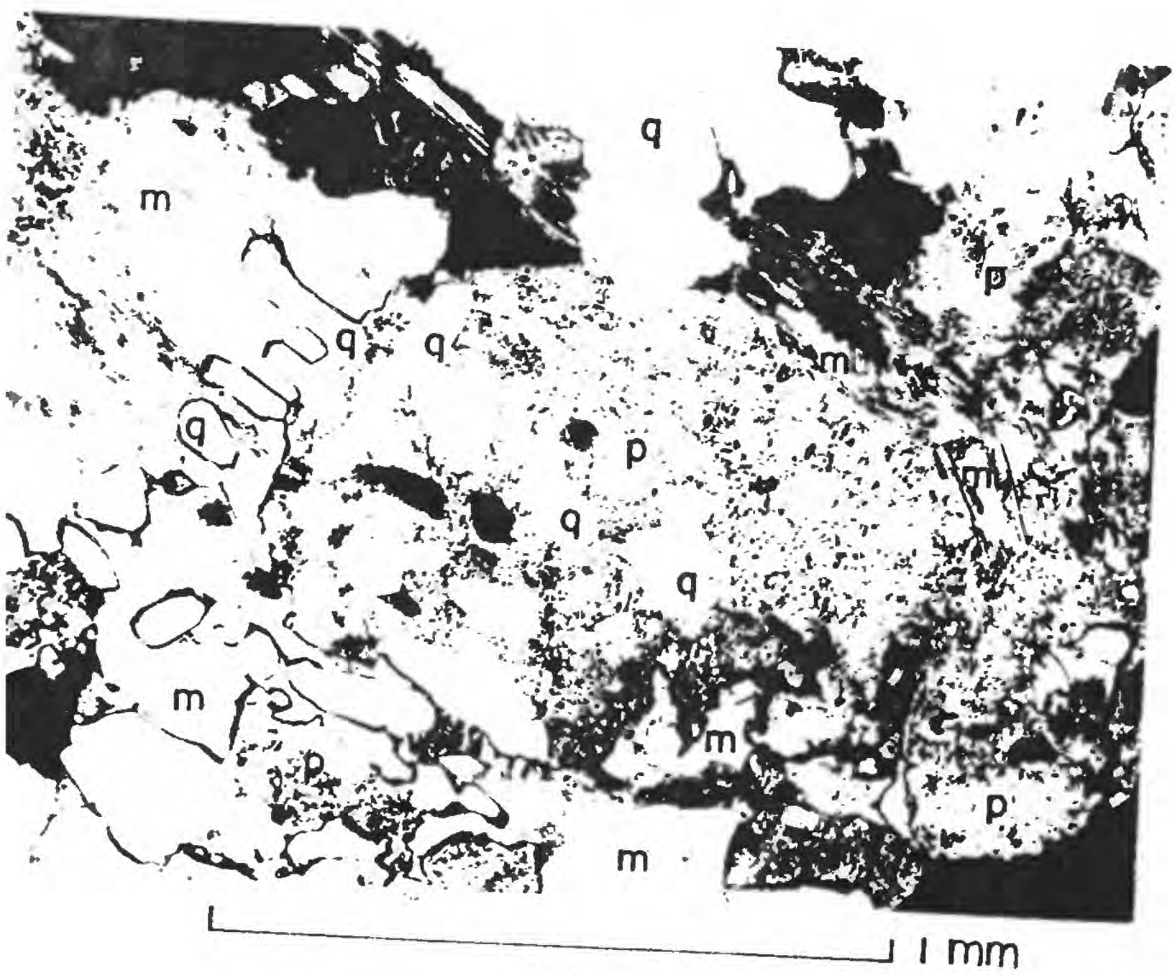
Plate 39

A. Photomicrograph of biotite granite from the Andover Granite exposed 600 feet north-northeast of Bedford St.-Winter St. intersection, Lexington. q, quartz; p, plagioclase; m, microcline; bi, biotite. Note the oriented quartz blebs within the microcline and intricate intergrowth between plagioclase and microcline in lower right quarter of photograph. Crossed nicols.

B. Photomicrograph of granite from the pegmatitic granite facies of the Andover Granite exposed 5000 feet north-northeast of Hill St.-South St. intersection, Tewksbury. q, quartz; p, plagioclase; m, microcline; bi, biotite altering to chlorite; mu, muscovite. Note that the field of the optically oriented quartz blebs in the center of the photograph extends across the feldspar grain boundaries. Crossed nicols.




A




B

demonstrate either a present or previous connection between the apparently separate parts of the crystal. However, the occurrence of "islands" of the type shown in figure 9B does not necessarily demonstrate a real break between the two parts of the crystal; inasmuch as a single thin section provides but a two-dimensional view, it is not unlikely that the separate sections of a particular crystal may be (or may have been) connected through an unseen part of the rock. "Island" and "peninsular" texture is illustrated in plates 30B, 31, and 32A as well as in figure 9B.

Although it was observed in no more than six or seven slides, the most interesting textural relationship between quartz and feldspar is one illustrated in plates 36-39. In addition to its more usual occurrences, quartz occurs here as uniformly oriented, generally more or less rounded but locally angular blebs within feldspar. The uniformly oriented quartz may be confined essentially to a single feldspar crystal (see plates 38B and 39A), or it may cut across grain boundaries with an apparent indifference to their existence (see plates 36, 38A, and 39B). A few examples were discovered in which several clearly separable orientation fields occupied the same host crystal (see plates 37 and 38A). That these uniformly oriented quartz blebs are distinct from myrmekitic quartz is illustrated in plate 36 where the habit or style of the larger quartz blebs is clearly at variance with that of the myrmekite. The spatial arrangement and configuration of the non-myrmekitic quartz blebs in plates 36, 37, and 39B, moreover, impart a granophyric or graphic appearance to the rock.

Both biotite (along with its chloritic derivative) and muscovite occur throughout most of this facies, where together they compose from 2 to 13 percent of the granite. Biotite, however, commonly is absent from the granite cropping out in the southern half of the Wilmington quadrangle and northwestern quarter of the Reading quadrangle, whereas the granite found along the South Groveland-Reading quadrangle boundary is locally devoid of muscovite. Both muscovite and biotite occur chiefly as anhedral to subhedral grains uniformly disseminated through the granite. Muscovite also occurs as oriented inclusions in feldspar, and it in turn is intergrown locally with uniformly oriented, vermicular or runiform quartz stems. Euhedral to subhedral crystals of pink garnet were found in about one-half the specimens examined from the binary granite; they generally compose no more than a fraction of 1 percent of the rock. Garnet is rare or absent in many of the granitic dikes, and its most conspicuous occurrence is in the relatively leucocratic rocks exposed along the main belt of the binary granite. Apatite is a ubiquitous phase within the binary granite, but it occurs only in trace amounts. Epidote, sericite, and chlorite are commonly developed in the binary granite; epidote and sericite occur chiefly as alteration products in plagioclase, whereas the chlorite is generally associated with biotite. Other accessory minerals include ilmenite, magnetite, calcite, sphene, and zircon or thorite.

A chemical analysis and norm of a specimen from the binary granite are presented in table 25.

### Pegmatitic granite facies

The pegmatitic granite facies is distinguished by the presence of an enormous volume of pegmatite; it is this profuse development of pegmatite more than any other feature that imparts such a unique aspect to the Andover Granite. The pegmatitic granite crops out over 30-35 square miles of the map area and is thus the most widespread of the separately mapped facies of the Andover. It occurs chiefly in the southeastern and southwestern quarters of the Lawrence and South Groveland quadrangles respectively, and in the northeastern quarter of the Wilmington quadrangle; it also crops out in a number of relatively small pockets scattered widely over the area of plate 1. The best exposures occur along a wide, northeast-trending zone through the center and northeastern part of the Wilmington quadrangle. The pegmatitic granite is transitional with the binary granite on both map and outcrop scale, but it is apparently non-transitional with the other facies of the Andover. Pegmatite dikes locally post-date the several granite-gneiss facies, but age relationships between pegmatite and binary granite are

Table 24. Modal analyses of rocks from pegmatitic granite facies of the Andover Granite[1/]

| | A. | B. | C. | D. | E. | F. | G. | H. | I. |
|---|---|---|---|---|---|---|---|---|---|
| Quartz | 35.2 | 31.0 | 31.2 | 32.8 | 29.2 | 37.6 | 38.6 | 24.6 | 30.7 |
| Plagioclase | 34.0 | 37.2 | 33.6 | 40.0 | 48.8 | 31.8 | 39.4 | 67.4 | 33.0 |
| Microcline | 20.2 | 24.8 | 32.6 | 7.8 | 17.0 | 26.0 | 10.8 | | 31.6 |
| Perthitic albite | | | | | | .2 | | | |
| Biotite | 2.6 | 2.0 | .4 | | .2 | 4.0 | | | 2.1 |
| Chlorite | 4.2 | .6 | .1 | | .6 | .2 | | | .4 |
| White mica | 3.8 | 4.4 | 1.6 | 16.8 | 4.1 | .2 | 9.2 | 6.0 | 2.1 |
| Apatite | | | | | .1 | tr. | | .1 | .1 |
| Rutile | | | | .4 | | | | | |
| Garnet | tr. | tr. | .3 | 2.6 | tr. | | 2.2 | 1.9 | |
| Carbonate | | | | | | | .2 | | |
| Epidote | | .4 | .1 | | | | | | |
| Zircon | | | | | | tr. | | | |
| Opaque | | | .1 | .2 | | | | | |

Table 24. (cont.)

A(C-6). Granodiorite 800 ft. S74°W of Salem Turnpike-Railroad Ave. intersection, Den Rock Park, Lawrence. Points counted: 500. Plagioclase composition $An_{15\pm4}$

B(L-971). Granodiorite 3100 ft. N43°E of Elm St.-Summer St. intersection, Andover. Points counted: 500. Plagioclase composition $An_{12\pm4}$

C(L-984). Adamellite 2900 ft. S10°E of Haverhill St.-Main St. intersection, Andover. Points counted: 1000. Plagioclase composition $An_{13\pm4}$

D(L-987). Pegmatitic granodiorite, small quarry 1150 ft. east of Cutler Rd.-Lowell St. intersection, Andover. Points counted: 500. Plagioclase composition $An_{10\pm4}$

E(C-5). Pegmatitic granodiorite along Andover Bypass 650 ft. south of Andover Bypass-Vine St. intersection, Andover. Points counted: 1000. Plagioclase composition $An_{7\pm4}$

F(G-72). Granodiorite 1800 ft. N50°E of Great Pond Rd.-Marbleridge Rd. intersection, North Andover. Points counted: 500. Plagioclase composition undetermined

G(G-80). Granodiorite along north side of Great Pond Rd. 1000 ft. northeast of Great Pond Rd.-Marbleridge Rd. intersection, North Andover. Points counted: 500. Plagioclase composition $An_{5\pm4}$

Table 24. (cont.)

H(G-843). Sodaclase tonalite 2800 ft. N85°W of Salem Turnpike-Johnson St. intersection, North Andover. Points counted: 1000. Plagioclase composition $An_{4 \pm 4}$

I(W-609). Adamellite 3650 ft. S53°E of Shawsheen St.-Lowe St. intersection, Tewksbury. Points counted: 1000. Plagioclase composition $An_{15 \pm 4}$

1/ All figures volume percent

Table 25. Chemical analyses, norms, and modal analyses of rocks from binary granite and pegmatitic granite facies of the Andover Granite

Chemical analyses[1/] [2/]

| | Binary granite facies | Pegmatitic granite facies | |
|---|---|---|---|
| | A. | B. | C. |
| $SiO_2$ | 72.9 | 72.3 | 74.7 |
| $Al_2O_3$ | 14.4 | 15.1 | 15.1 |
| $Fe_2O_3$ | .3 | .6 | .4 |
| FeO | 1.1 | 1.2 | .6 |
| MgO | .23 | .54 | .12 |
| CaO | .41 | .46 | .39 |
| $Na_2O$ | 3.3 | 3.6 | 4.3 |
| $K_2O$ | 5.0 | 4.0 | 3.2 |
| $TiO_2$ | .15 | .24 | .03 |
| $P_2O_5$ | .16 | .12 | .26 |
| MnO | .06 | .04 | .13 |
| $H_2O$ | .82 | 1.3 | .64 |
| $CO_2$ | .46 | <.05 | .14 |
| Sum | 99 | 100 | 100 |

Table 25. (cont.)

Norms[2/]

| | A. | B. | C. |
|---|---|---|---|
| Quartz | 34.52 | 34.42 | 37.28 |
| Corundum | 3.67 | 4.38 | 4.59 |
| Orthoclase | 30.06 | 23.92 | 18.88 |
| Albite | 28.32 | 30.93 | 36.66 |
| Anorthite | | 1.39 | |
| Enstatite | | 1.41 | |
| Ferrosilite | 1.72 | 1.45 | .92 |
| Magnetite | .46 | .93 | .69 |
| Ilmenite | .30 | .46 | .67 |
| Apatite | .34 | .34 | .25 |
| Calcite | .40 | | |
| Magnesite | .51 | | |
| Sum | 100.30 | 99.63 | 99.94 |

Table 25. (cont.)

Modal analyses[3/]

| | A. | B. | C. |
|---|---|---|---|
| Quartz | 31.4 | 35.2 | 29.2 |
| Plagioclase | 30.6 | 34.0 | 48.8 |
| Microcline | 29.9 | 20.2 | 17.0 |
| Biotite | .3 | 2.6 | .2 |
| Chlorite | 1.5 | 4.2 | .6 |
| White mica | 5.3 | 3.8 | 4.1 |
| Apatite | tr. | | .1 |
| Epidote | .2 | | |
| Garnet | .2 | tr. | tr. |

A(C-12). Adamellite from roadcut along west side of Haverhill St. 600 ft. south of Haverhill St.-Marblehead St. intersection, North Reading. Points counted: 1000. Plagioclase composition $An_{10\pm4}$

B(C-6). Granodiorite 800 ft. S74°W of Salem Turnpike-Railroad Ave. intersection, Den Rock Park, Lawrence. Points counted: 500. Plagioclase composition $An_{15\pm4}$

C(C-5). Pegmatitic granodiorite along east side of Andover Bypass 650 ft. south of Andover Bypass-Vine St. intersection, Andover. Points counted: 1000. Plagioclase composition $An_{7\pm4}$

Table 25. (cont.)

1/ U. S. Geological Survey Rapid Rock Analysis Laboratory

2/ All figures weight percent

3/ All figures volume percent

generally indeterminate. Dikes or sills of pegmatite commonly occur within the Nashoba and Boxford Formations and the Sharpners Pond Tonalite; the pegmatitic granite, moreover, is the only facies of the Andover thought to invade the Merrimack Group.

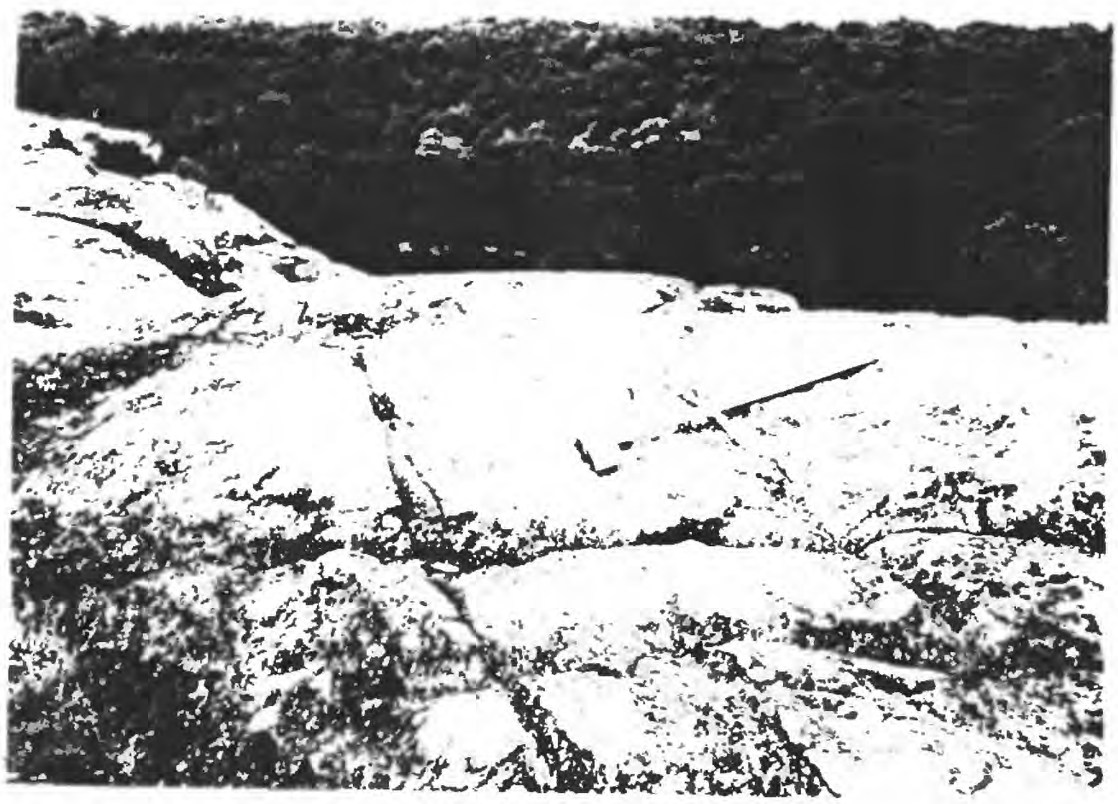
Pegmatites, according to Jahns (1955, p. 1030), are "holocrystalline rocks that are at least in part very coarse grained, whose major constituents include minerals typically found in ordinary igneous rocks, and in which extreme textural variations, especially in grain size, are characteristic." It is this variation or departure from "normal" textural characteristics that provides the principal basis for mapping the pegmatitic granite facies. Inasmuch as the binary and pegmatitic granite are grossly similar in their mineralogical composition, differences in texture afford the chief, and in many cases the only means of distinguishing between these two generally transitional facies. Accordingly, exposures of the Andover Granite composed of at least 50 percent pegmatite (as defined above) have been mapped with the pegmatitic granite. The coarser-grained pegmatite of the pegmatitic granite occurs mainly in moderate-sized, irregularly to tabularly shaped masses within a more granitic or aplitic "host" with which it is generally transitional (the occurrences illustrated in plate 40 display some of these features; they are atypical, however, in the sense that the pegmatite is more regularly layered here than in

Plate 40

A. Exposure within the pegmatitic granite facies of the Andover Granite 2700 feet north-northwest of pumping station, Wilmington. Crudely layered appearance is common within this facies.

B. Interlayered granite and pegmatite within the pegmatitic granite facies of the Andover Granite exposed in Den Rock Park, Lawrence. Variations from layer to layer are chiefly textural and mineral content apparently varies little. In this exposure the layers form a crude synclinal structure only partly discernible in the photograph.

A



B

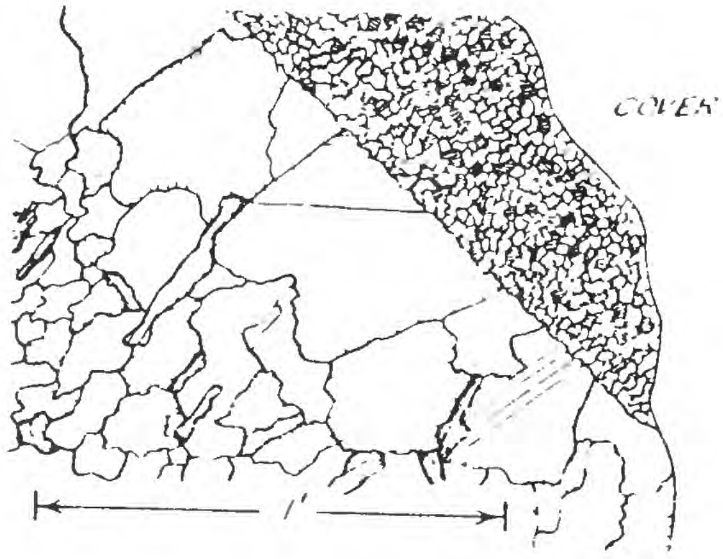
the general case). It also occurs within a number of broad, vaguely defined zones up to a square mile or more in extent (confined chiefly to the town of Andover), that are apparently devoid of typically granitic or aplitic rocks.

Contact relations between the pegmatitic granite and surrounding rocks differ somewhat from those that exist among other facies of the Andover and their contact rocks. Where pegmatite is in contact with more typically granitic rocks it generally ranges transitionally from a very coarse-grained pegmatitic facies into a medium-grained facies more characteristic of the surrounding granite (see plate 40A). This is not everywhere true, however, and at least a few exposures have been discovered in which the granitic rocks occur in contact with the coarser pegmatite crystals (see figure 10A). Where the pegmatite invades distinctly older rocks, contacts between the two commonly are sharp and devoid of mixed zones. Locally within the Nashoba Formation, however, diffuse, mixed zones up to 3 or 4 feet wide occur between the biotite gneiss and the pegmatite. Another somewhat unusual contact phenomenon is illustrated in figure 10B where the pegmatitic granite is shown invading dioritic rocks of the Sharpners Pond Tonalite. The pegmatite in this exposure for the most part grades through a coarse-grained facies into typical, medium-grained granitic rocks, that in turn are separated from the diorite by a thin, micaceous selvage. However, neither a micaceous selvage nor a finer-

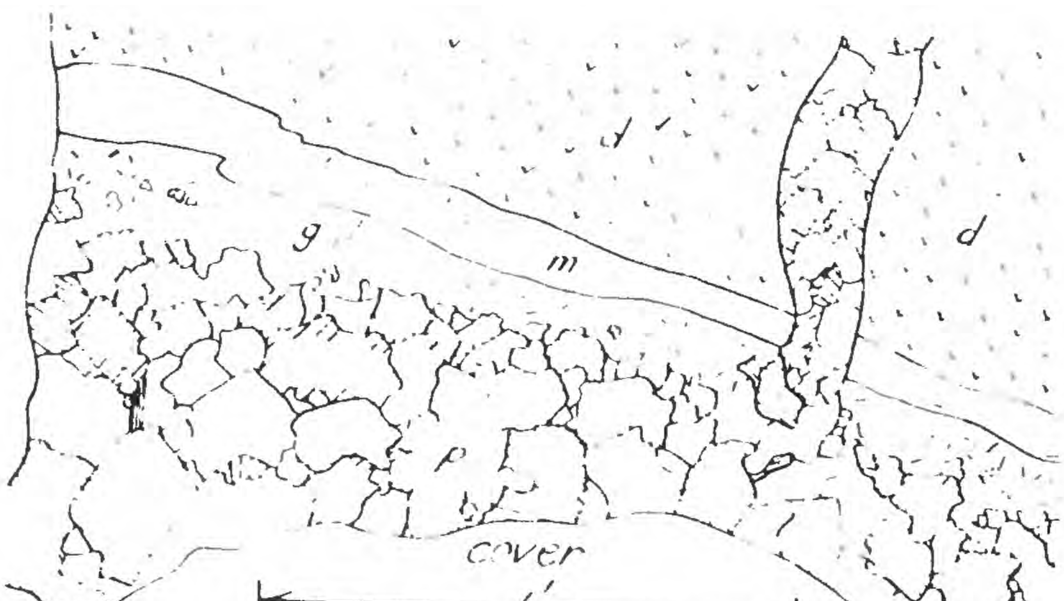
Figure 10

A. Diagrammatic sketch of pegmatitic granite of the Andover Granite (may not be in place) exposed in old railroad cut south of Martins Brook, North Reading. Note that the pegmatite is progressively coarser grained toward its contact with the muscovite granite in the upper-right section of sketch.

B. Diagrammatic sketch of outcrop approximately 600 feet east of Park St.-Woburn St. intersection, Wilmington. In this exposure a diorite (d) facies of the Sharpners Pond Tonalite has been intruded by granite (g) and pegmatite (p) of the Andover Granite. Note the development of the essentially biotitic, micaceous selvage (m) between granite and diorite. Note also the development of generally finer-grained pegmatite toward the diorite, except where pegmatite crosscuts the micaceous selvage and diorite.




A




B

grained margin are associated with the small pegmatite apophysis cross-cutting the diorite.

The rocks of the pegmatitic granite facies are uniformly leucocratic, whether they be essentially pegmatitic or granitic. Fresh specimens are generally pearly white to very light gray. Relatively coarse grained potassium feldspar crystals commonly show a blue-gray iridesence, and concentrations of garnet locally impart a slight pinkish cast to the rock. Staining by iron oxides and an unidentified, but probably manganiferous black phase occurs locally. Weathering commonly intensifies the leucocratic nature of the pegmatitic granite, bringing it to the chalk-white color characteristic of the prominently exposed parts of the Andover Granite.

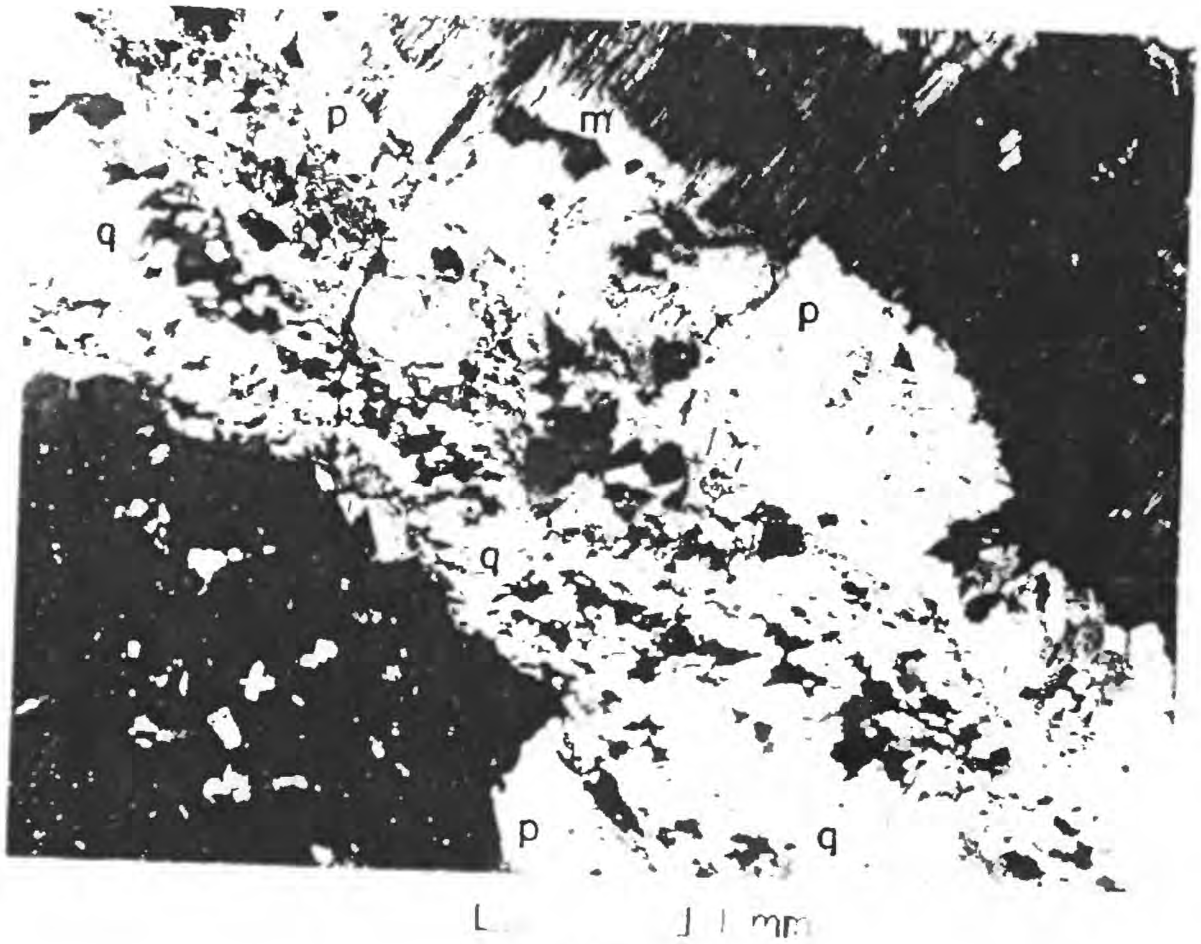
The granitic rocks within the pegmatitic granite facies are slightly foliated in part, but the pegmatite itself generally lacks any consistent penetrative structure. A crude foliation is manifested locally by the development of mortar structure in the pegmatite (see plate 41A), but it is not ordinarily detectable in outcrop. The layering within some of the more regularly layered pegmatites may mimic pre-existing structures, but it is generally too poorly defined for one to attempt to measure and in turn compare its attitudes with the regional structure.

As might be expected, textural variations within the pegmatitic granite are extreme. The range is from typically

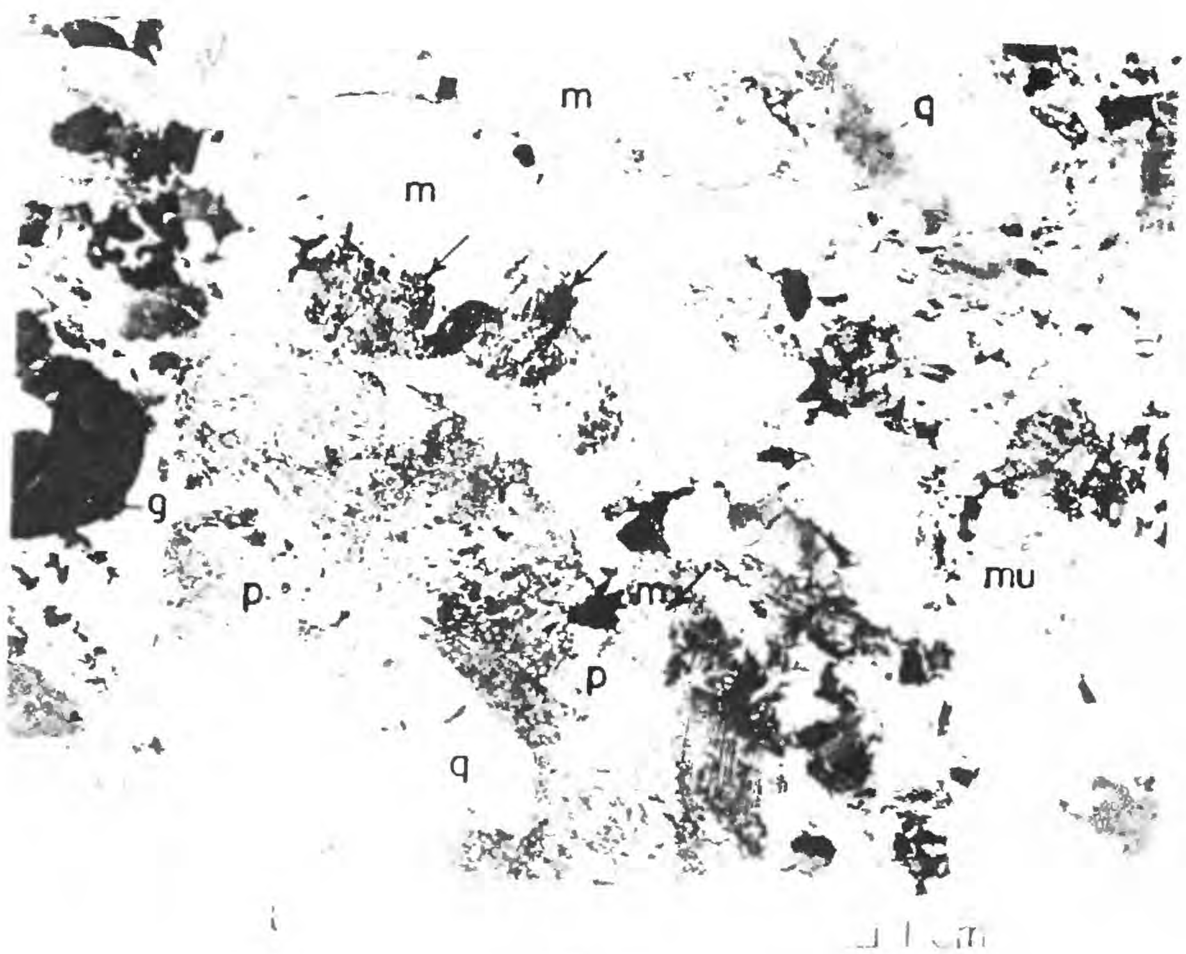
Plate 41

A. Photomicrograph of pegmatite from the pegmatitic granite facies of the Andover Granite exposed at Main St.-Hidden Rd. intersection, Andover. q, quartz; p, plagioclase; m, microcline. Note the mortared quartz and rutilated plagioclase. Crossed nicols.

B. Photomicrograph of specimen from the pegmatitic granite facies of the Andover Granite exposed in quarry north of Cutler Road, West Parish Cemetery, Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite; g, garnet. Note the idiomorphic development of garnet and quartz in lower left section of photo. Myrmekite at arrows. Crossed nicols.




A



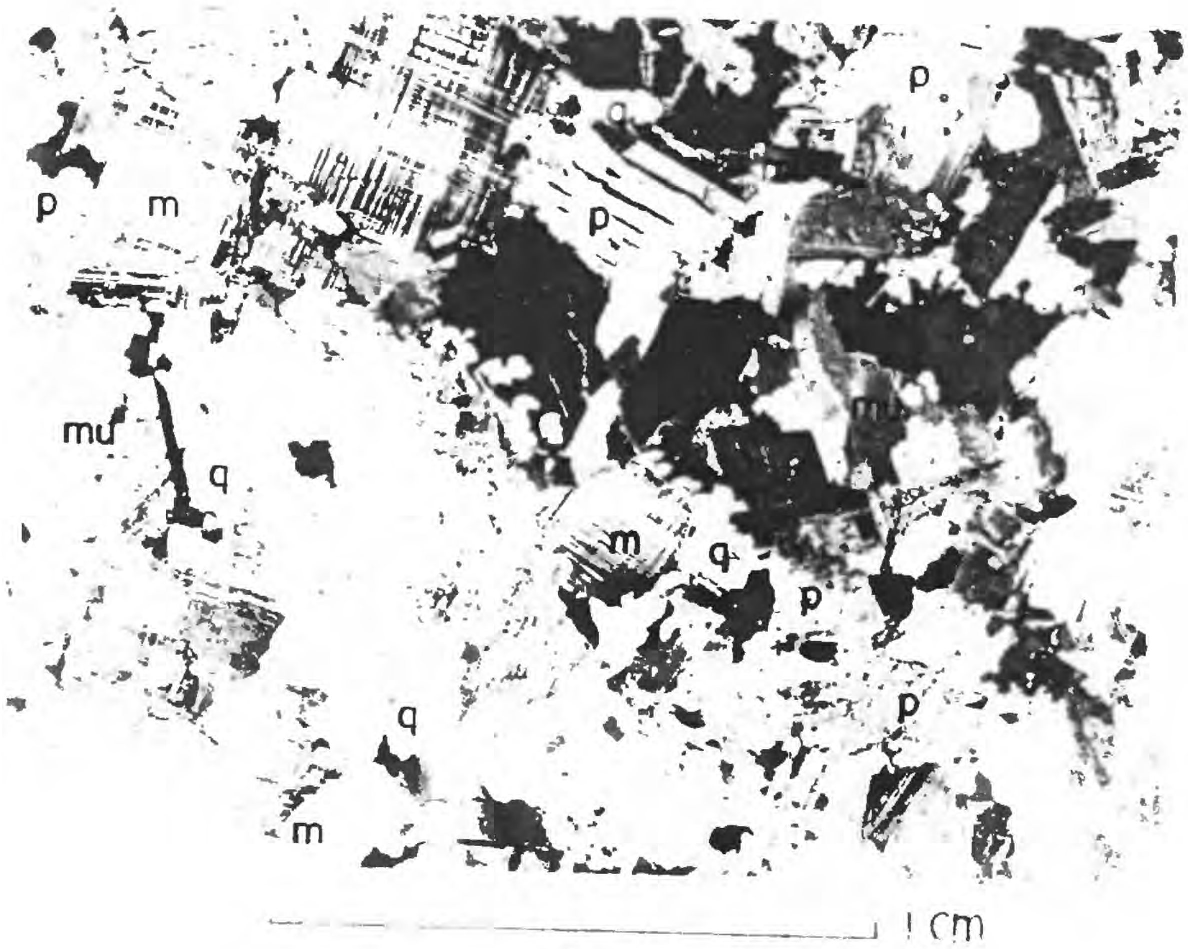

B

granitic, essentially medium- to coarse-grained, allotriomorphic, more or less equigranular textures to extremely coarse-grained, hypidiomorphic, generally inequigranular, typically pegmatitic textures. Aside from the substantial differences in grain size, the textures of this facies contrast with those of the binary granite chiefly in the local tendency toward idiomorphism shown by the major mineral constituents of the pegmatitic granite. The degree of idiomorphism shown in some of the finer-grained specimens of the pegmatitic granite is illustrated in plates 41B-43A. Transitions in grain size are in part gradational (see plate 40A) and in part abrupt (see figure 10A); close examination has revealed, however, than many apparently abrupt breaks are transitional through zones two or three crystals wide. Grain size within the exclusively pegmatitic zones in the town of Andover ranges from extremely coarse to relatively fine, but there is little regularity or consistency in this grain size variation. Pegmatite cropping out over Rattlesnake Hill, for example, is transitional over distances of a few feet from rocks containing feldspar crystals over 30 inches long, to ones in which the average grain size is less than an inch; yet there is no apparent zoning, textural or otherwise, over even this very large exposure. Many of the smaller pegmatite bodies, however, do show textural zoning of the sort illustrated in plate 40A. Textural relationships among specific phases are discussed with the mineralogy

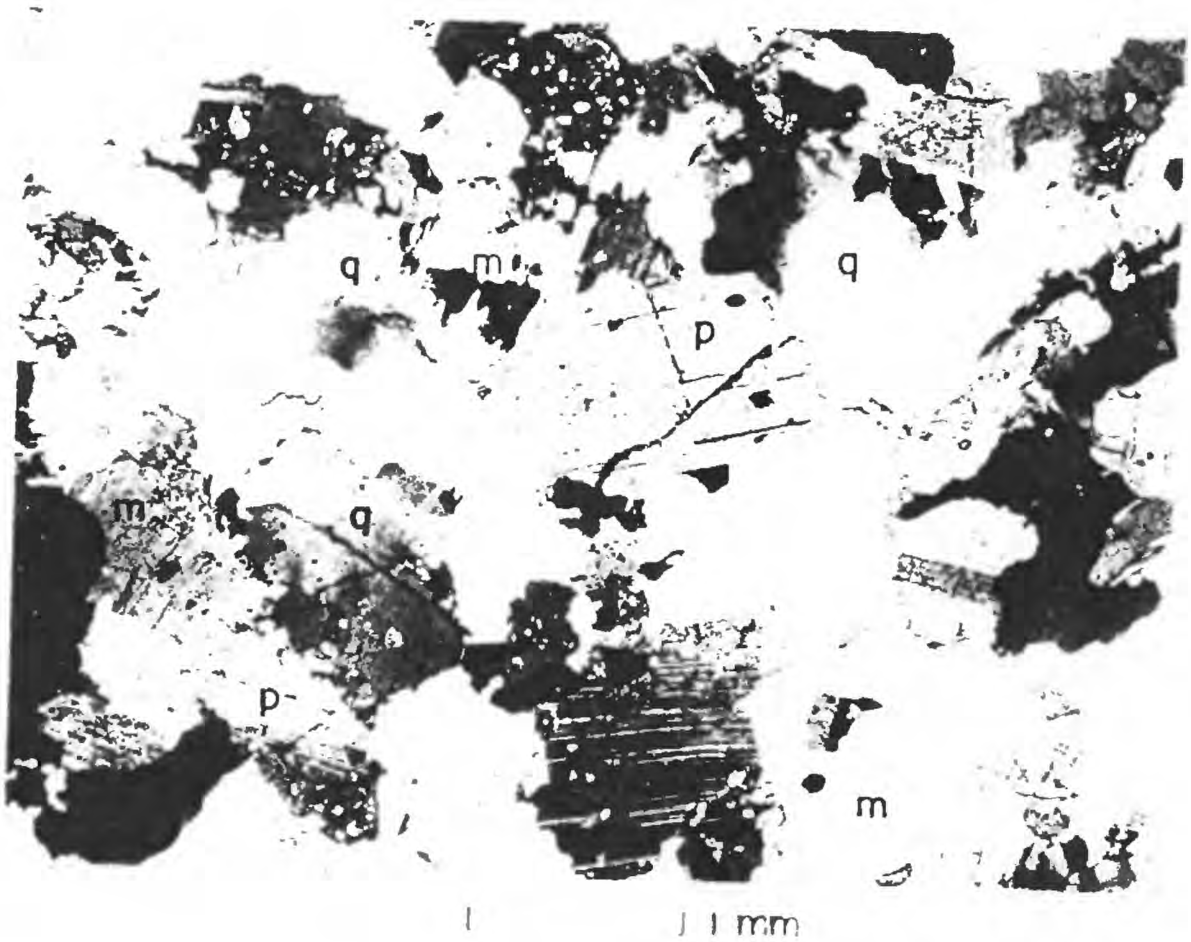
Plate 42

A. Photomicrograph of specimen from the pegmatitic granite facies of the Andover Granite exposed 2200 feet west of South St.-Dale St. intersection, North Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite. Note the relatively pronounced idiomorphism of the plagioclase. Crossed nicols.

B. Photomicrograph of granite from the pegmatitic granite facies of the Andover Granite exposed in railroad cut 2300 feet east-southeast of Haverhill St.-Main St. intersection, Andover. q, quartz; p, plagioclase; m, microcline. Note the high degree of idiomorphism and partly zoned character of the generally albitic plagioclase in this non-myrmekitic rock. The plagioclase crystals are locally fractured whereas the microcline shows no evidence of deformation. Crossed nicols.




A

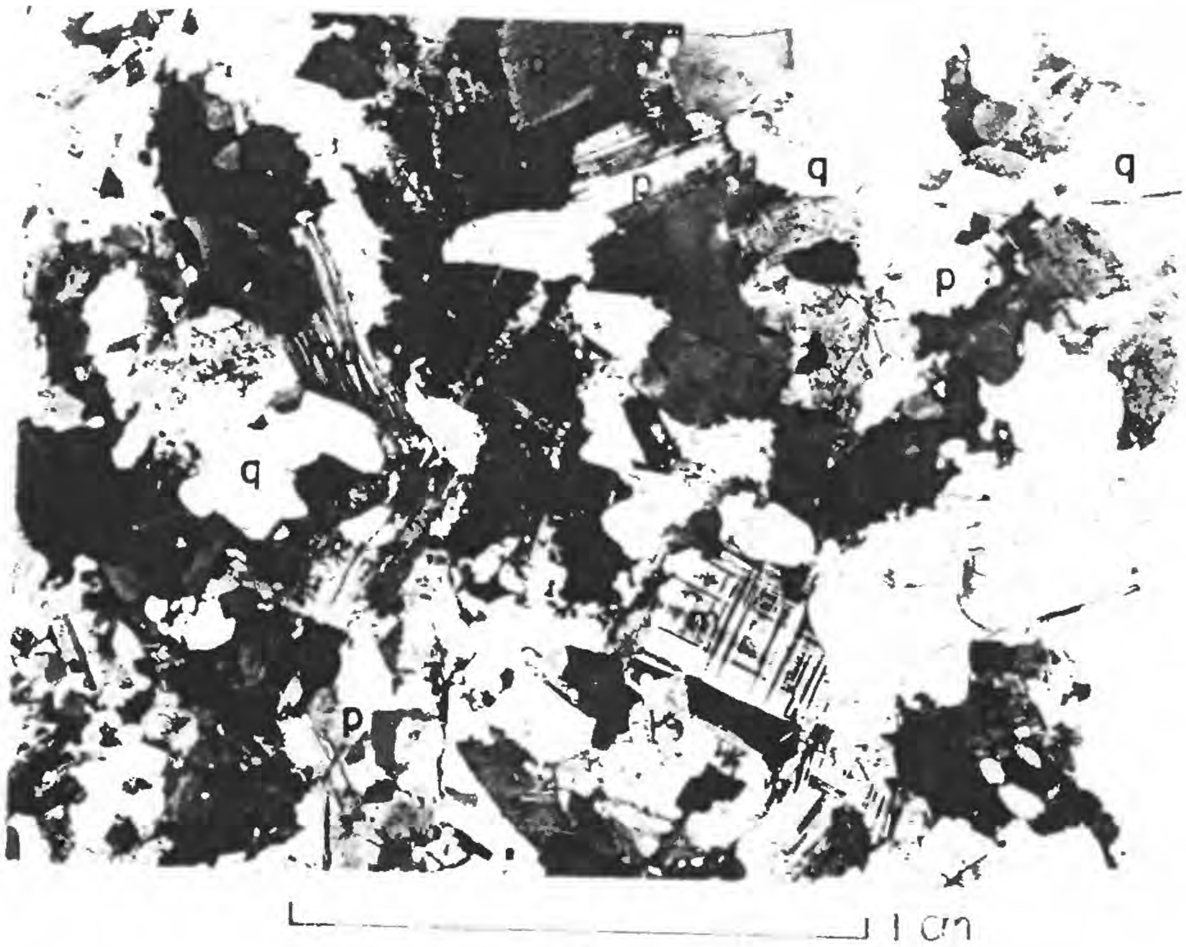



B

Plate 43

A. Photomicrograph of fine-grained specimen from the pegmatitic granite facies of the Andover Granite exposed 800 feet south of Andover Bypass-Vine St. intersection, Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite. The plagioclase here is zoned in part and shows a higher degree of idiomorphism than is generally manifested within the Andover Granite. Crossed nicols.

B. Photomicrograph of specimen from finer grained facies of pegmatite dike cross-cutting hornblende-biotite tonalite exposed in abandoned railway cut, 2100 feet east of Mt. Vernon St.-Park St. intersection, North Reading. q, quartz; p, plagioclase; m, microcline; bi, biotite. Note the development of myrmekite in central part of photograph. Crossed nicols.




A


B

of the pegmatitic granite facies.

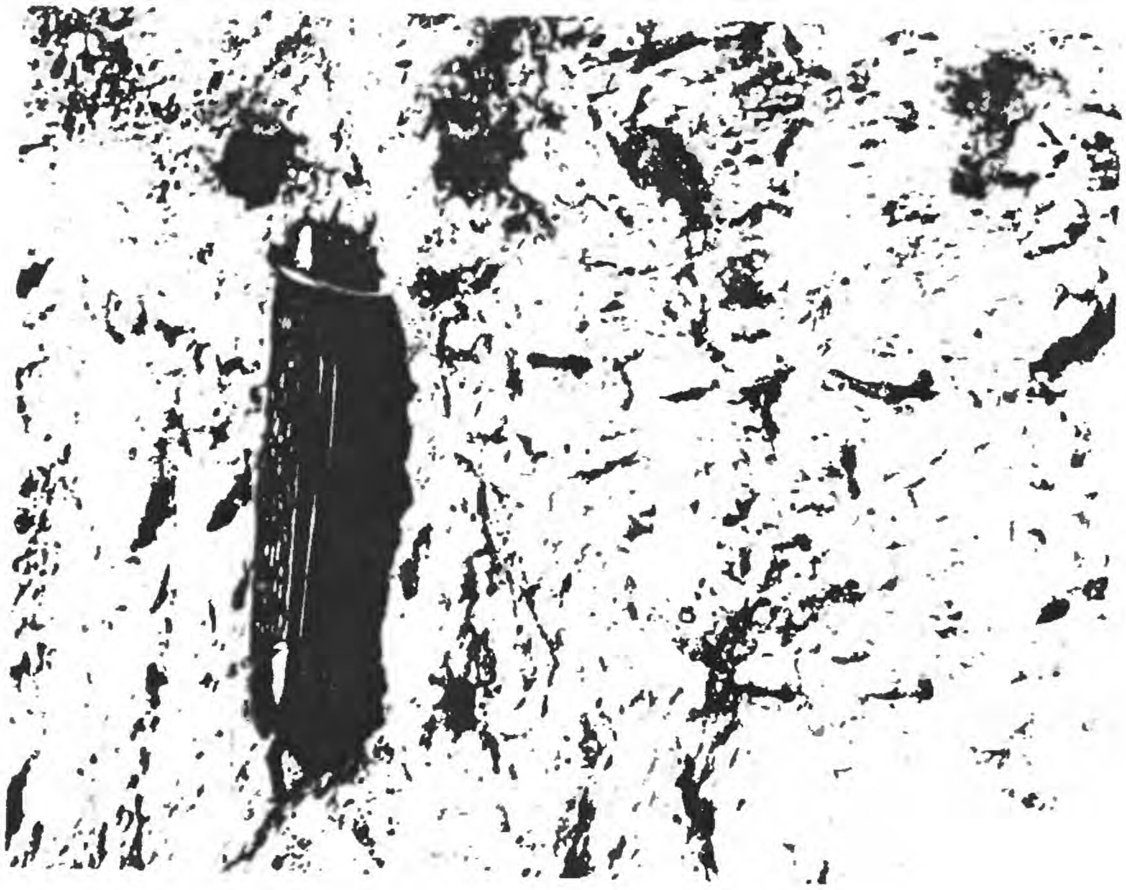
The mineralogical composition of the pegmatitic granite is thought to parallel closely that of the binary granite. The pegmatite itself, moreover, is, in the idiom of Turner and Verhoogen (1960, p. 423-424), a "simple" type, in that it is generally devoid of rare, exotic phases not ordinarily found in granite. Accurate sampling of the pegmatite is no less a problem here than elsewhere; where the grain size ranges above a few inches it is almost impossible to obtain a "representative" specimen. In this study modal analyses (see table 24) of the pegmatitic granite are restricted to the relatively fine-grained, "interstitial" material between masses of coarser-grained pegmatite. Whether these modes are reflective of the pegmatite itself is moot.

Microcline composes up to 35 percent of the pegmatitic granite, but its average content within this facies is probably between 25 and 30 percent. Much of the microcline is slightly perthitic (see plate 43B), especially along plagioclase contacts, but the albitic intergrowths generally occupy less than 1 or 2 percent of the host crystals. Microcline(?) found within the very coarse pegmatite is characterized locally by graphic intergrowths of quartz (see plate 44A); good runiform textures, however, are relatively uncommon. The microcline is relatively clear, but it is clouded in part with fine-grained inclusions or alteration products. Its occurrence in the fine-grained granitic rocks

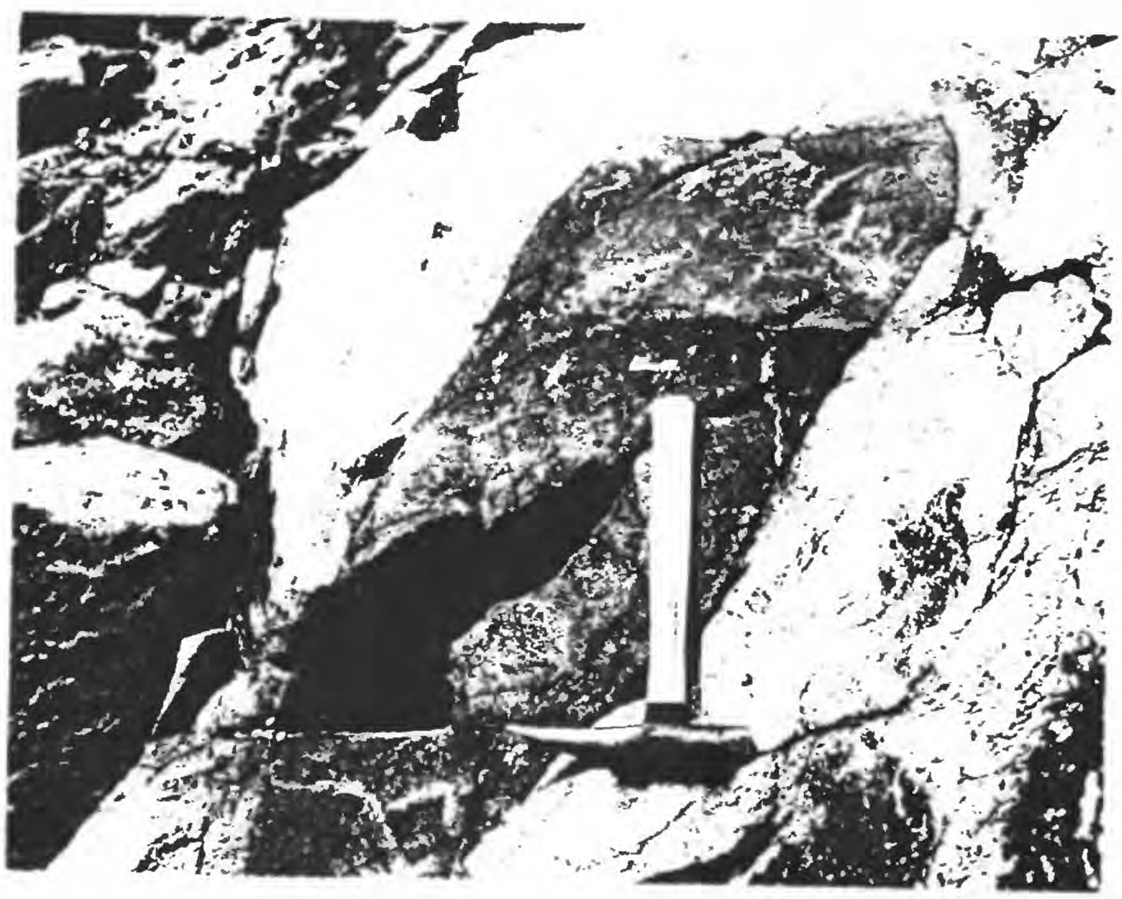
Plate 44

A. Pegmatite within the Andover Granite exposed about one-half mile west-southwest of Dascomb Rd.-Osgood St. intersection, Andover. The graphic texture developed in this exposure is the best observed within the Andover Granite.

B. Inclusion of amphibolite gneiss in foliated binary granite of the Andover Granite exposed approximately 500 feet west-southwest of Burlington Rd.-Crosby Rd. intersection, Bedford. Note that the foliation in the inclusion is at a large acute angle with that in the granite. Dark patch to left of hammer is shadow cast by overhang.



A



B

is about the same as in the binary granite; in the coarser pegmatitic facies, however, microcline commonly occurs as giant crystals enveloping hordes of smaller crystals, particularly mica. Its homogenized composition has been evaluated according to a method devised by Ernst (1960, p. 292-296); two specimens, one medium grained and the other very coarse-grained, yielded values of $Or_{79.5}$ and $Or_{79.0}$ respectively.

Plagioclase composes from 30 to about 70 percent of the finer-grained pegmatitic granite, and its average content seems to be above 35 percent. The plagioclase, particularly that within the coarser facies, is relatively sodic; the maximum An content of any of the plagioclase studied from this facies was about $An_{20}$ and the average plagioclase composition is estimated to fall between $An_8$ and $An_{10}$. The most albitic plagioclase occurs in an ill-defined zone extending south-southeast from North Andover center to the Lawrence-Wilmington quadrangle boundary. The plagioclase locally is normally but obscurely zoned and more conspicuously altered and strained than adjacent microcline (see plates 41A and 42B). Myrmekite occurs within much of the finer-grained platioclase (see plates 34, 35, and 43B), but it is not generally found within the coarser-grained rocks.

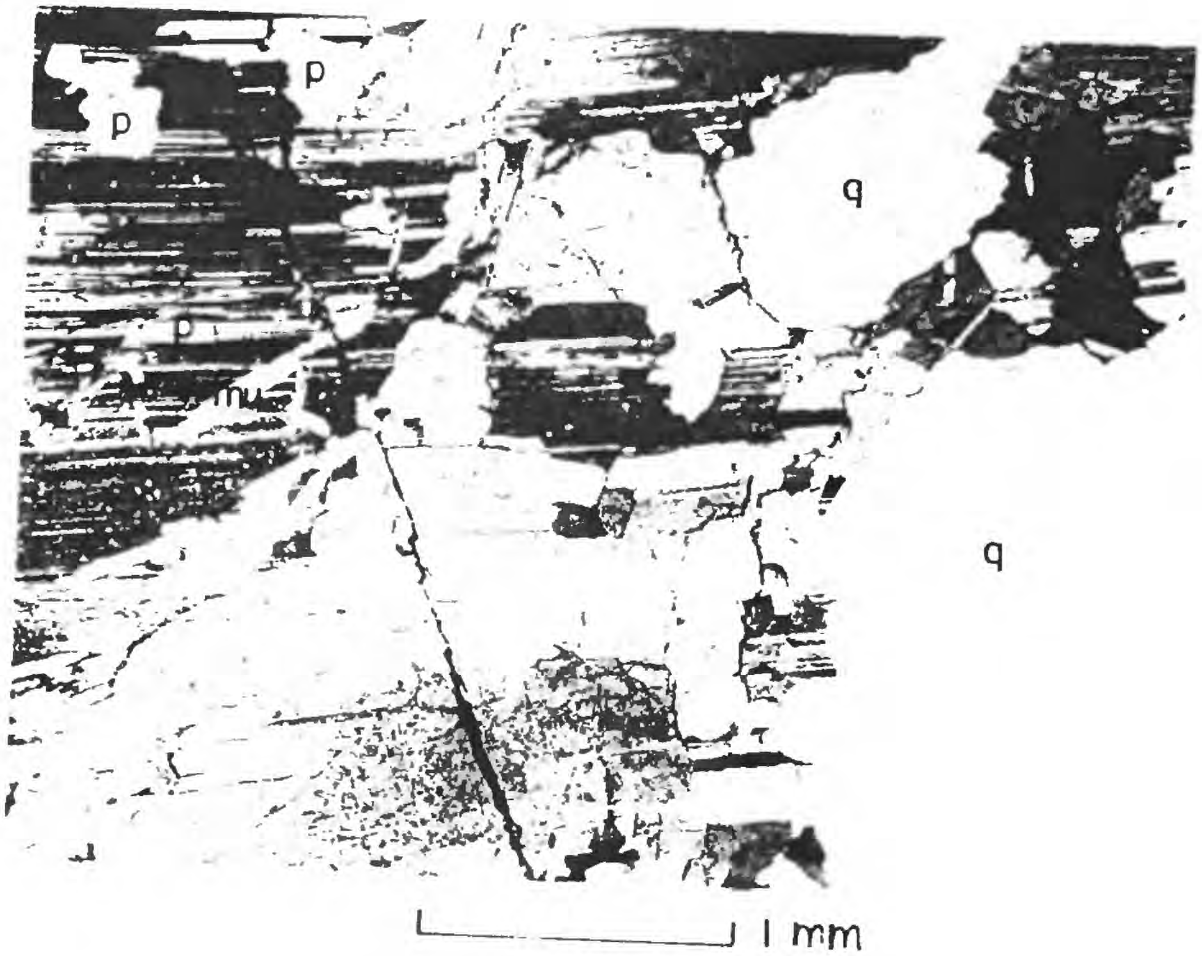
Grain boundary configurations between microcline and plagioclase are less intricate here than they are within the other facies of the Andover (see plates 41B-43). Irregular blebs of uniformly oriented microcline, however, commonly are scattered randomly through plagioclase crystals (see plate 43B); some are distributed more or less uniformly through the host plagioclase, whereas others occur as irregularly shaped patches concentrated in limited parts of the host crystals. "Peninsular" and "island" texture is not uncommonly developed in the rocks of this facies (see plates 35B and 45), but it is far less conspicuous than in the binary granite facies. In addition to its occurrence between plagioclase and microcline, moreover, "island" texture also is developed between grains of the same feldspar species (see figure 11B).

Quartz is a prominent constituent of both the pegmatite and granite of this facies, and it generally makes up about one-third of the finer-grained rocks. It occurs as inclusions and intergrowths, but it is disposed chiefly in the interstices between feldspar grains. Great, irregularly shaped masses of white, barren quartz occur in association with some of the coarse-grained pegmatite, but it is as yet unclear whether these large volumes of relatively pure quartz represent the "cores" of zoned pegmatites. Small irregular vugs lined with crystals of $\alpha$-quartz morphology were seen in exposures of pegmatite along the side of Rattlesnake Hill, but the vuggy quartz may be much younger than that in the surrounding pegmatite. A textural relationship noted between quartz and plagioclase is one in which quartz appears

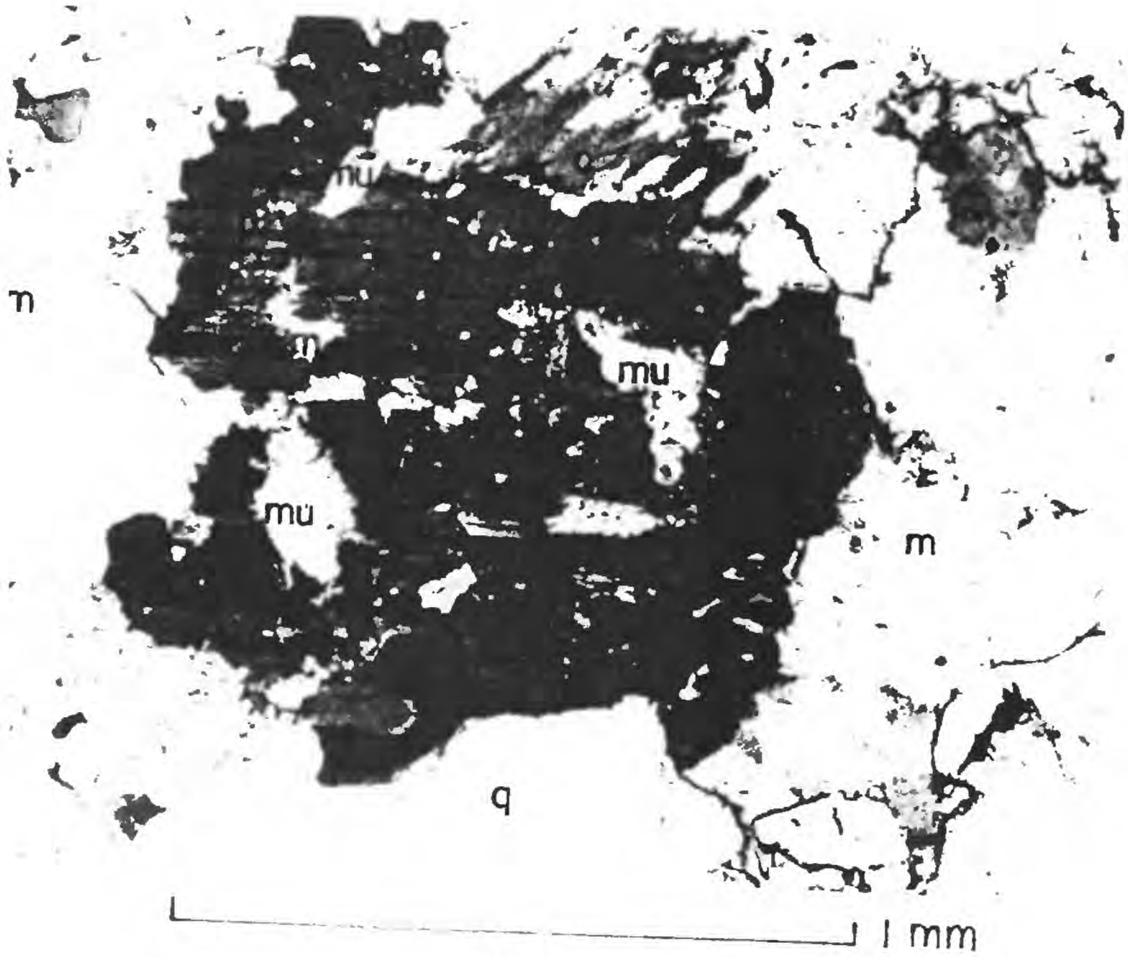
Plate 45

A. Photomicrograph of pegmatite from pegmatitic granite facies of the Andover Granite exposed 2500 feet east of Main St.-Haverhill St. intersection, Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite. Note the development of "island" texture between plagioclase and microcline, where the large plagioclase crystal in the left hand part of the photo shows continuity of twinning as well as optical continuity with the smaller plagioclase grain contained within the microcline. Note in addition the "island" texture developed between plagioclase and plagioclase in upper left corner of photo. Crossed nicols.

B. Photomicrograph of fine-grained specimen from the pegmatitic granite facies of the Andover Granite exposed 2700 feet north of Indian Ridge School, Andover. q, quartz; p, plagioclase; m, microcline; mu, muscovite; c, chlorite. Note the embayment of plagioclase by microcline and slight development of myrmekite in lower right corner of large plagioclase grain. Crossed nicols.




A

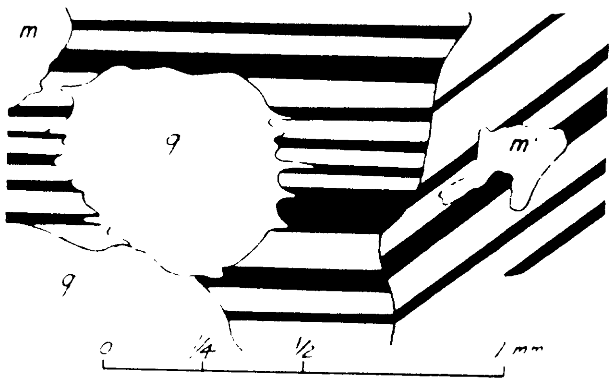



B

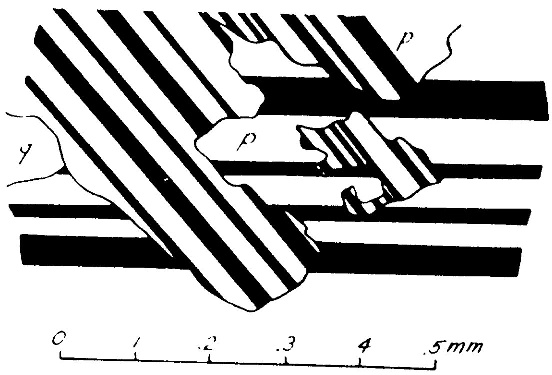
Figure 11

A. Diagrammatic thin section sketch of fine-grained ock from the pegmatitic granite facies of the Andover anite exposed 2500 feet east of Main St.-Haverhill St. tersection, Andover. Note in particular the preferred owth of quartz (q) apophyses along the plagioclase twins. all, irregularly shaped intergrowths are probably twinned microcline (m).

B. Diagrammatic thin section sketch of specimen from matitic granite facies of the Andover Granite exposed 0 feet west of Salem Turnpike-Johnson St. intersection, th Andover. This particular specimen is composed almost rely of albitic plagioclase (p) and quartz (q) and is rently devoid of potassium feldspar. Note the develop- of the apparent "island" texture in which the twinning optical orientation in the small crystal in the center ketch is continuous with that in the large crystal in upper left section of sketch.




A




B

to be selectively intergrown with specific plagioclase twins (see figure 11A). Much of the pegmatitic quartz shows undulatory extinction and in places it is highly granulated (plate 41A).

Rutilation of quartz and feldspar is apparently less pervasive in the pegmatitic granite than it is within the binary granite facies. Where it does occur, however, it is commonly very conspicuous and generally coarser grained than it is within the other facies of the Andover. Examples of rutilation are shown in the photomicrographs in plates 41A and 45A.

Both muscovite and biotite occur throughout much of the pegmatitic granite facies, and together they compose from 2 to 18 percent of these rocks. Muscovite is found in essentially all the rocks of this facies and locally makes up over 16 percent of the pegmatitic granite. It occurs generally in an anhedral to subhedral habit in the finer-grained granitic rocks and as essentially euhedral books up to 6 inches across in the coarser-grained pegmatites. Here and there within the pegmatite, muscovite is intergrown with quartz in a graphic or vermicular style. The average biotite (plus chlorite) content of the pegmatitic granite is no more than 2 or 3 percent, and biotite is totally absent from about one-third of the rocks of this facies. Although it occurs locally as relatively coarse-grained books, it is generally much finer grained than the muscovite.

Biotite is found both interlayered with muscovite and as individual grains uniformly scattered through the rock. Within a given outcrop, such as the one illustrated in plate 40A, the muscovite-biotite ratio generally seems to differ little from the more pegmatitic to the more aplitic facies. The writer has found, however, that much of the granite associated but not specifically interlayered with the pegmatite tends to be richer in biotite. Cuppels (1963, written communication), moreover, has described interlayered pegmatite and granite in the Concord quadrangle in which the ratio of muscovite to biotite in the pegmatite is about 4:1, whereas the same ratio in the adjacent granite is about 1:4. The abundance of a particular mica is apparently independent of the microcline-plagioclase ratio, but biotite seems to occur more commonly in those rocks containing relatively calcic plagioclase.

Garnet, tourmaline, apatite, zircon, magnetite, and beryl(?) all occur as accessory minerals in the pegmatitic granite. Garnet is the most abundant of these accessories and comprises from 2 to 3 times the total of all the others put together. It is absent from only a small fraction of the rocks of this facies and locally composes up to 6 or 8 percent of the rock. Garnet commonly is retrograded in part to sericite and chlorite, and a few pseudomorphs were discovered in which the garnet had been completely replaced by a mat of alteration products. Fractured, greenish-black tourmaline crystals were seen in a few thin sections, but tourmaline is rarely developed here. Tiny, euhedral apatite crystals are moderately common throughout the pegmatitic granite, but they generally compose much less than 1 percent of the rock. The beryl(?) was not positively identified by the writer, and beryl-green crystals of apatite may have been mistakenly identified in hand specimen as beryl. Zircon and thorite(?) were observed in several thin sections from the pegmatitic granite, but both are relatively uncommon. Zircon is found in part as isolated grains, but it is most evident as "core" crystals within the pleochroic haloes in biotite. Magnetite is locally prominent but nowhere composes more than a fraction of 1 percent of the pegmatitic granite. Small amounts of epidote and sericite are scattered throughout this facies, where they occur almost exclusively as alteration products in plagioclase.

Chemical analyses and norms for two relatively fine-grained specimens from the pegmatitic granite are presented in table 25.

## Origin

A discussion of the origin of the Andover Granite should consist basically of a description of the historical evolution of this unit from its magma or other immediate precursors to its present state. It should be concerned, therefore, not only with the source and nature of the materials from which the granite originated, but should include as well a description of the physical environment under which crystallization took place. Moreover, it should consider the origin of the granite in the light of any other geologic events proceeding concurrently.

Although there are understandably points of similarity between the Andover and other granites around the world, no attempt is made here to examine the merits of the several general hypotheses on the origin of granite except as they apply specifically to the Andover. For purposes of this discussion the origin of the granite is divided into two separate but related chapters on early and late crystallization. The first chapter deals with the primordial crystallization of the granite and the second with a period of recrystallization that may have begun even before the events of the first chapter ended.

## Early crystallization history

### Metasomatic versus magmatic hypotheses

Two general hypotheses currently are invoked to explain the origin of granite. One school has attributed the formation of granite to a more or less solid state metasomatic transformation of preexisting sedimentary or metamorphic rocks; this process has come to be known as "granitization." Other students, however, have preferred to explain granites as the crystalline precipitates of silicate melts or magmas.

A number of nuances have been attached to both hypotheses by various writers and some have even combined elements of both in explaining the origin of particular granites; there remain, nevertheless, these two very distinct schools of thought.

## The metasomatic argument

It is appropriate that the possibility of a metasomatic or granitized origin for the Andover Granite be considered first, for granitization recently has been called on to explain the undifferentiated granite-gneiss facies (Gospel Hill Gneiss) cropping out in the Hudson and Maynard quadrangles (Hansen, 1956, p. 39-41). The following paragraphs, then, are devoted to an examination of those features developed within the Andover that are commonly employed in demonstrating the supposed efficacy of the metasomatic process in the formation of granite.

Granitization, if operative at all, most likely has figured in the formation of the several granite-gneiss facies. The common gradational relationship (at least on outcrop scale) between the rocks of the granite-gneiss facies and the Nashoba Formation might be construed as reflective of the "soaking" of the Nashoba by an advancing metasomatic fluid (it should be pointed out, however, that gradational contacts are no better developed around the granite-gneiss than the several other facies of the Andover).

A far stronger suggestion of granitization within the granite-gneiss facies, however, derives from their generally foliated character and structurally conformable relationships with the surrounding metasediments, for structural features of this sort are conceivably palimpsest. Inclusions of Nashoba within the undifferentiated granite-gneiss facies, moreover, are oriented in such a manner that not only is the foliation conformable with that of the country rock, but the linear elements as well tend to parallel those in the surrounding rocks (see description of the undifferentiated granite-gneiss facies). The vague continuity between the muscovite granite-gneiss and the Brimfield-type schist on the one hand and the biotite granite-gneiss and the Nashoba Formation on the other hand, provides still another suggestive piece of field evidence; both the biotite granite-gneiss and the Nashoba Formation are characterized by the presence of biotite, whereas the muscovite granite-gneiss and Brimfield-type schist are typically muscovitic.

There is abundant textural evidence throughout the Andover Granite apparently compatible with the notion of at least local replacement of preexisting plagioclase through the action of a metasomatic, potassic "wave." The extension of myrmekitic quartz stems into microcline beyond the plagioclase-potassium feldspar grain boundaries (see plates 32B and 33A) is very suggestive of potassium metasomatism; this unusual relationship virtually demands that the myrmekitic plagioclase has been replaced at least in part by microcline. The "peninsulas" and "islands" of plagioclase in microcline (see figure 9B and plates 25A, 26A, 27B, 30B, 31, and 32A), moreover, provide an additional, but somewhat ambiguous textural argument in support of potassium metasomatism.

There is seemingly, then, a moderate amount of evidence tending to support a granitized origin for at least a part of the Andover. However, almost all the features suggestive of metasomatism may be explained equally well by other processes.

The field evidence suggestive of granitization is less convincing when considered in connection with all the available evidence. For example, although the Nashoba and Andover are in part gradational with each other, there exist as well sharply cross-cutting relationships of the sort illustrated in plate 18. Parallelism between the foliation in the granite-gneiss and country rock, moreover, becomes a much less impressive argument in favor of metasomatism when it is recognized that the foliation in the granite-gneiss is not generally an inherited structure, but is attributable instead to the effects of shearing (see plates 24A, 25A and 28). Furthermore, although there exists a strong tendency toward parallelism between the gneissic foliation in the host granite-gneiss and inclusions within the undifferentiated granite-gneiss, this is not true everywhere. The exposure shown in plate 44B crops out several miles east of, but on strike with rocks mapped with the undifferentiated granite-gneiss; the position and composition of the leucocratic "host" rock shown here leave little doubt that it belongs to the same general group of rocks (i.e., the Andover Granite) as does the granite-gneiss. In this outcrop the longer axis of the amphibolite xenolith is approximately conformable with the planar structure of the granite. However, the laminar structure within the amphibolite is at a generally large angle to that of the granite; it seems improbable, then, that the granitic foliation has been inherited from the rock initially adjacent to the amphibolite. That linear elements within inclusions in the granite-gneiss parallel those of the surrounding host may reflect one of two phenomena unrelated to any granitization process. The inclusions, so-called, may be simply roof pendants of the Nashoba Formation. It is equally possible that the linear features within the granite-gneiss were developed under the same stress system as those outside; the granite-gneiss, in other words, may be either syn- or pretectonic.

Regardless of the apparent suggestion of potassium metasomatism shown by the peninsular and island textures between plagioclase and potassium feldspar, it is likely that these textures are nothing more than very intricate intergrowths between contemporaneously crystallized grains. This is surely the case, for example, in the specimen illustrated in figure 11B, where a comparable texture exists between grains of the same feldspar species. Where the myrmekitic quartz stems invade potassium feldspar grains, no alternative to at least local migration of potassium can be offered. It is worth pointing out, however, that this feature extends over no more than a small fraction of a millimeter; considerable temerity should be required to extrapolate from a phenomenon of this scale to one the size of a pluton.

Lastly, if as Hansen has suggested, the undifferentiated granite-gneiss facies (Gospel Hill Gneiss) has arisen in response to a potassic wave sweeping through the gneissic Nashoba Formation, the invaded Nashoba should become progressively less potassic away from its contact with the Andover. The Nashoba Formation cropping out adjacent to the main mass of the biotite granite-gneiss, however, is completely devoid of potassium feldspar. Moreover, although the writer has examined only three thin sections across the strike of the Nashoba Formation cropping out in the Hudson quadrangle, these three sections at least, also convey precisely the opposite impression. The specimen from nearest the granite contact (approximately 1½ miles away) was devoid of potassium feldspar, whereas specimens 3¼ and 4½ miles away carried 35 and 10 percent microcline respectively.

The magmatic argument

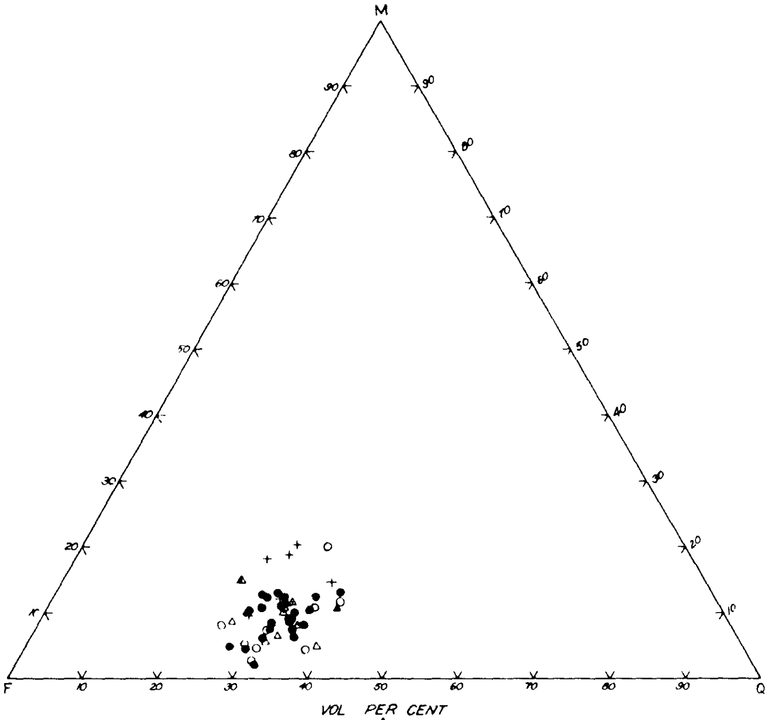
Arguments tending to support a magmatic origin for the Andover Granite are partly negative, in that they depend (as outlined in the preceding paragraphs) on a refutation of a metasomatic origin for these rocks. There are in addition such positive evidences of fluid intrusion as knife edge contacts between granite and country rock and well-defined cross-cutting relationships that occur at both map and outcrop scale. Moreover, locally developed features, such as the parallelism between the longer direction of the roughly tabular xenolith and the faintly defined foliation of the granitic host in plate 44B, are consistent with the notion that platy elements tend to orient themselves parallel to the direction of magma flow (and, thus, each other).

The most convincing positive arguments in support of a magmatic origin for the Andover Granite relate to various aspects of its composition. The chemical and mineralogical composition of the presently observable granite is hardly independent of the mechanism that brought it into being; yet, as Chayes (1952, p. 209) has pointed out, this obvious and fundamental property of granite generally has played "at most a minor role in many theories concerning its origin."

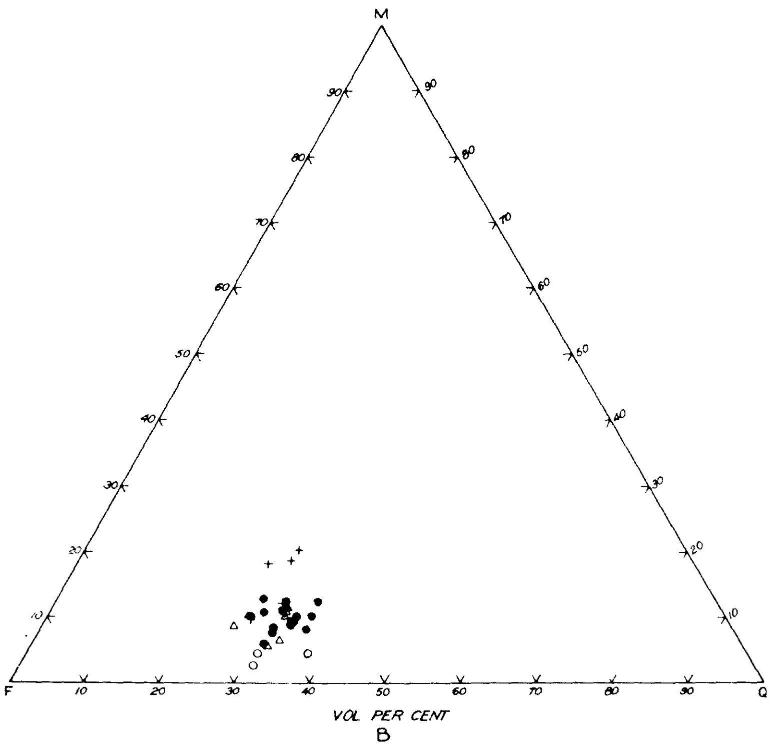
Compositional features of the Andover Granite have been tabulated in tables 21-25 in the form of chemical and modal analyses. Major compositional characteristics, however, are represented more meaningfully diagrammatically. Diagrams reflective of various aspects of the bulk mineralogical composition of the Andover are presented in figures 12 and 13. Modal analyses employed in the construction of these figures are based on point counts of standard size thin sections and their statistical value probably ranges widely. A group of randomly selected specimens has been used for the preparation of the diagrams in figures 12A and 13A. In figures 12B and 13B, however, only those specimens have been employed that are less likely to reflect compositional aberrations; samples from contact zones (and thus more subject to contamination) generally have been removed as have those that have been sheared highly or are of relatively coarse grain size. However, an attempt has been made to retain at least one or two specimens from each facies of the granite, even though retention of the mode might distort the "average" composition. Although the selected group may be poorly reflective of a good statistical sample of the Andover, in no case has selectivity been consciously exercised on the basis of composition itself. (There probably exists a correlation between coarseness and the occurrence of a particular mica <u>species</u>, but as both biotite and white mica are grouped together in the diagram, this factor does not enter into the ensuing arguments.) In both figures 12 and 13 employment of the selected as opposed to the random sample results in a more restricted compositional field, but

Figure 12

Volume percent of quartz (Q), total feldspar (F), and
rally mafic varietal minerals (M) in thin sections of
Andover Granite and biotite tonalite facies of the
rpners Pond Tonalite. ▲, muscovite granite-gneiss
ies; △, biotite granite-gneiss facies; △, undiffer-
iated granite-gneiss facies; ◭, fine-grained granite-
iss facies; ●, binary granite facies; ○, pegmatitic
ite facies; +, biotite tonalite facies. Data from
les 18, 21, 23, and 24 (after the method of Chayes, 1952).
Random sample composed of 49 specimens. B. Selected
le composed of 29 specimens.



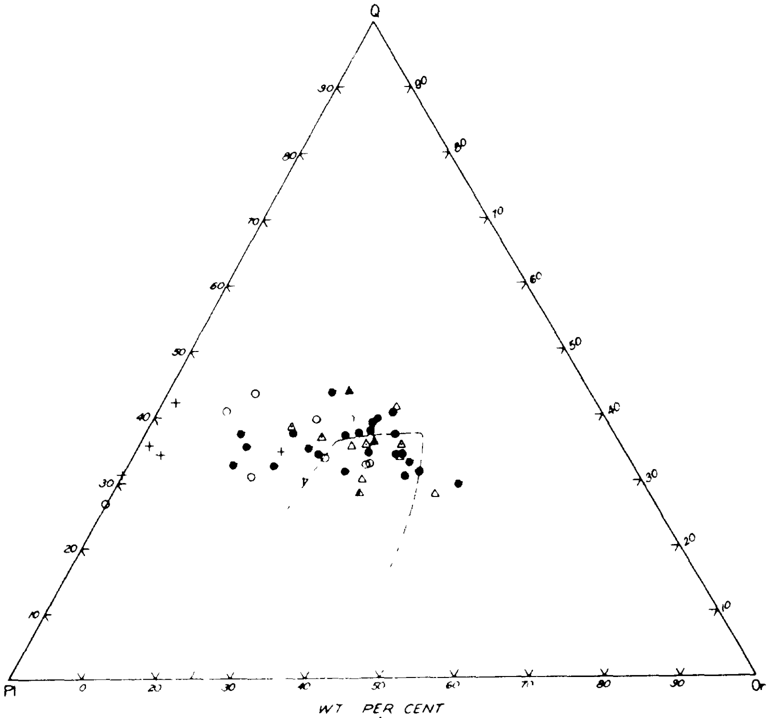
A



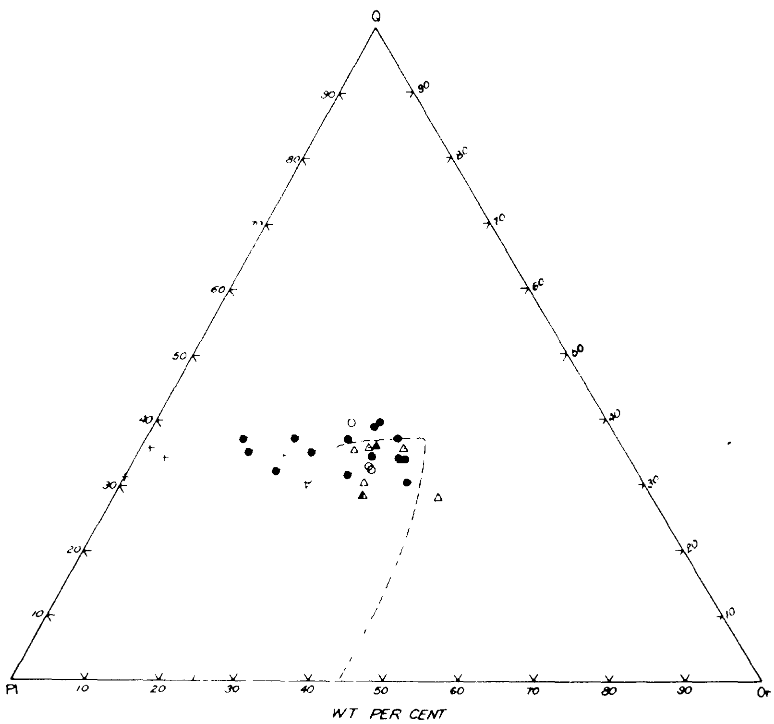
B

Figure 13

Q (quartz) -- Pl (plagioclase) -- Or (potash feldspar) diagrams for the Andover Granite and biotite tonalite facies of the Sharpners Pond Tonalite. Weight percent recalculated to 100. ▲, muscovite granite-gneiss facies; △, biotite granite-gneiss facies; △, undifferentiated granite-gneiss facies; ▲, fine-grained granite-gneiss facies; ●, binary granite facies; ○, pegmatitic granite facies; +, biotite tonalite facies. Data from tables 18, 21, 23, and 24. Dashed lines define the thermal valley outlined by Bowen for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$ (after the method of Chayes, 1952). A. Random sample composed of 49 specimens. B. Selected sample composed of 29 specimens.


Q
90
80
70
60
50
40
30
20
10
Pl
Or
WT PER CENT

A


Q
90
80
70
60
50
40
30
20
10
Pl
Or
WT PER CENT

B

both the position and form of the plots remain essentially unchanged. Thus, in spite of the admittedly crude nature of the analyses represented in these plots, it is felt that the diagrams in figures 12 and 13 have at least conceptual significance.

Quartz-mafic (i.e., phases other than quartz and feldspar)-feldspar (QMF) diagrams prepared according to the method of Chayes (1952, p. 220-221) are presented in figure 12. The chief significance of these diagrams lies in the very limited compositional spread they show for the rocks that have been mapped with the Andover Granite. Even the random, statistically suspect sample fails to show a very wide range in QMF values. If the selected sample (12B) is employed, and if furthermore the less reliable pegmatitic modes are excluded, the compositional uniformity of the formation is seen to be pronounced. Another measure of the homogeneity of the Andover is provided by the chemical analyses and calculated norms tabulated in tables 22 and 25. The percentage range in the major oxides is remarkably small and the occurrence of such normative phases as corundum is surprisingly consistent among these six widely distributed samples. Still another manifestation of the compositional uniformity of the Andover is the ubiquity of minor, accessory phases, particularly garnet. As shown by the modes in tables 21, 23, and 24, small amounts of garnet occur in the great majority of specimens from the Andover, but in only a very few specimens does garnet occur in excess of 1 percent.

The compositional features cited in the preceding paragraph are such that (1) a genetic unity is fairly well demonstrated, and (2) "the existence of a homogeneous parent-material...may be inferred" (Chayes, 1952, p. 239) for the several facies of the Andover Granite. The writer can conceive of no mechanism that might account for such a thorough homogenization that did not involve at least partial liquefaction of the granite parent. Granitizationists would argue that the granitizing agent itself was responsible for this homogenization; the reader is referred to Chayes (1952, p. 239-241), however, for an effective rebuttal to the selective feldspathization argument that granitization demands.

The relative proportions of quartz, plagioclase, and potassium feldspar in specimens from the Andover Granite have been plotted in figure 13. The graphic representation adopted in figure 13 again is one that has been employed by Chayes (1952, p. 224-225) to describe the compositional characteristics of a series of calcalkaline granites from New England. The Andover differs from the plutons examined by Chayes (1952, p. 227-228) in that it manifests a wider, more erratic range in Q-Pl-Or values. However, although there exist several real differences between the Andover and the granites described by Chayes, the apparently wider range of values shown here may be in part a function of the lower degree of selectivity exercised in the choice of specimens and in part attributable to the less meticulous care given to modal analyses carried out by the writer. Accordingly, several of the compositional nuances noted by Chayes are much less conspicuous in the Andover.

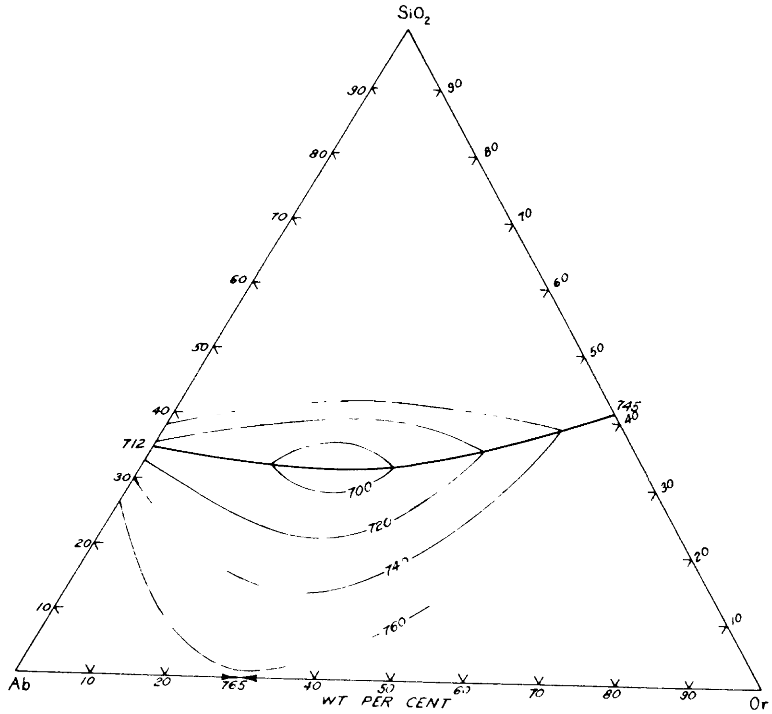
In both figures 13A and 13B the points are disposed linearly through the center of the diagram, parallel to the Pl-Or axis. The probable significance of this compositional feature is demonstrated by a comparison of figure 13 with: (1) the normative distribution of quartz, plagioclase, and potassium feldspar in salic extrusive rocks; (2) equilibrium diagrams for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$-$H_2O$, an example of which is illustrated in figure 14A.

Tuttle and Bowen (1958, p. 78) have plotted on a single triangular diagram the distribution of normative albite, orthoclase, and quartz for 362 analyzed extrusive rocks carrying 80 percent or more normative Ab + Or + Q; the distribution accords very well with that of the points in figure 13, particularly as regards the concentration of points toward the center of the diagram. Inasmuch as it may be presumed that the analyzed extrusive rocks have passed through a magmatic stage, the concordance between the analyzed volcanics and the Andover rocks provides circumstantial evidence of the magmatic derivation of the latter group.

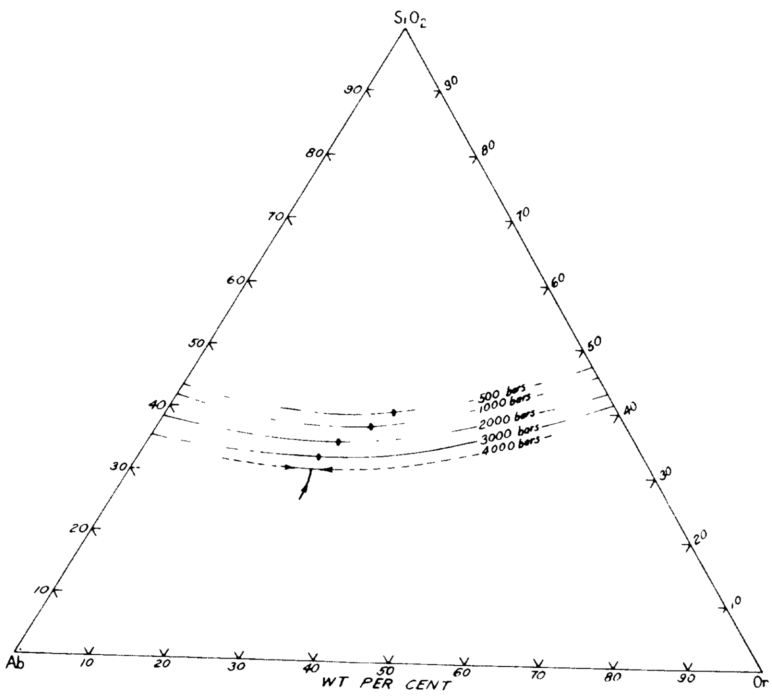
Figure 14

A. 3000 $kg/cm^2$ ($H_2O$) isobaric equilibrium diagram for system $NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$-$H_2O$ (after Tuttle and Bowen, 1958, p. 56).

B. Effect of water-vapor pressure on the isobaric minimum in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$-$H_2O$. The minimum becomes a ternary eutectic at pressures above approximately 3600 $kg/cm^2$ (after Tuttle and Bowen, 1958, p. 75).


SiO2
90
80
70
60
50
40
30
20
10
745
712
700
720
740
760
765
Ab
Or
WT PER CENT

A


SiO2
90
80
70
60
50
40
30
20
10
500 bars
1000 bars
2000 bars
3000 bars
4000 bars
Ab
Or
WT PER CENT

B

A second suggestive comparison may be made between figure 13 and equilibrium diagrams for the experimentally investigated system $NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$-$H_2O$. An example of an isobaric equilibrium diagram for this system is illustrated in figure 14A where $P_{H_2O}$= 3000 bars. Although, as shown in figure 14B, the quartz-feldspar boundary migrates somewhat with decreasing water pressures, the general form of the liquidus surface remains about the same as that shown in figure 14A. Perhaps the major, petrologically significant feature of this system, as noted by Tuttle and Bowen (1958, p. 73) is the minimum along the quartz-feldspar cotectic trough (the so-called "granite minimum"); it is this minimum toward which liquids move as they crystallize. The essential restriction of the Q-Pl-Or values of figure 13 to the area around the minima of figure 14 is a coincidence not likely attributable to pure chance. The dashed lines shown in figure 13 are intended to outline crudely the "thermal valley" described by Bowen for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$ (see Chayes, 1952, p. 241-242); thus they roughly embrace the thermal trough on the liquidus surface within the feldspar field shown in figure 14A. It will be noted that all the points in figure 13B (with one aberrant but explainable exception) lie distinctly to one side of this thermal valley, i.e., toward the plagioclase-quartz sideline. This is of course to be expected if the granite has descended from a liquid parent for, as Chayes (1952, p. 243) has pointed out, "crystallization of a liquid whose initial composition lies in the (Q-Pl-Or) diagram generates a liquid residue which approaches and finally enters the thermal valley; and, unless heat is added, the liquid cannot escape from the valley once it has entered. The composition of adequate samples of such a crystallizing mass would necessarily fall either in the valley or outside it on the side nearest the initial composition." Considering the crude nature of the modal analyses, and the fact that the positions of the quartz-feldspar cotectic and minimum may have shifted somewhat during crystallization, it is remarkable how close the Q-Pl-Or values of figure 13B match with the trough and minimum of the experimentally investigated systems; in the writer's view, Chayes perceptive analysis provides the best explanation for this correspondence.

All the compositional features described in the preceding paragraphs, then, are compatible with a magmatic origin for the Andover Granite. Non-magmatic hypotheses, moreover, in general fail to explain not only the compositional, but almost all the major features of the Andover.

Needless to say, the essentially magmatic origin of the Andover Granite does not in itself preclude the existence of metasomatic phenomena accompanying intrusion. There is in fact some evidence that almost certainly demonstrates a limited amount of metasomatic activity around the periphery or apophyses of the pluton.

An example of a metasomatic effect related to the invasion of pegmatite is shown in figure 10B. The development of the micaceous selvage between the pegmatite and the diorite doubtlessly is attributable to reaction between a highly charged aqueous and potassic residuum of the pegmatitic magma with the invaded diorite. The absence of a comparable selvage along the margin of the crosscutting pegmatite, however, cannot be explained.

## Environment of crystallization and paragenesis

### Pressure-temperature conditions

Determination of the depth (confining pressure) of intrusion and crystallization is a no less difficult problem with the Andover than it is with most plutonic rocks. The maximum confining pressure may be inferred, as was done with the Sharpners Pond Tonalite, from the presence of andalusite in the intruded metasediments of the Boxford Formation. Its coexistence with sillimanite that has almost certainly been derived from the andalusite, strongly suggests that the Andover was intruded under confining pressures no greater than 8 kilobars (see figure 3) or at depths no greater than approximately 28 kilometers. The assumption is made, of course, that the andalusite could not have been maintained for long both within the stability field of sillimanite and far removed from the andalusite-sillimanite phase boundary. Establishing the probable minimum confining pressure is an even greater problem; however, a rough approach to the solution of this problem is available. The large volume of pegmatite within the Andover demands that the confining pressure was at one time great enough to maintain in solution the high concentration of water required to promote the crystallization of this pegmatite. It is reasonably certain, moreover, that crystallization of the pegmatite took place well within the two-feldspar field, for the hypidiomorphic textures and giant plagioclase and potassium feldspar crystals associated with this facies are hardly the products of feldspar unmixing. Accordingly, the magmatic water content and attendant pressures must have been great enough to depress the alkali feldspar solidus well below the crest of the solvus. If, then, the following points are conceded the minimum confining pressure becomes crudely determinate: (1) the potassium feldspar compositions ($Or_{79.0}$ and $Or_{79.5}$) determined through x-ray investigation of homogenized specimens from the pegmatitic granite facies are the same as those initially crystallized from the pegmatitic melt; (2) the coexisting plagioclase and potassium feldspar occuring in these rocks represent an equilibrium pair; (3) the very small percentage of An in the system has not raised the feldspar solvus sufficiently to make the experimentally determined Ab-Or solvus curves inapplicable to the problem at hand; (4) silica saturation of a pure alkali feldspar melt will depress the solidus-liquidus trough no more than 85°; it is depressed by approximately this amount at $P_{H_2O}$ = 3000 $kg/cm^2$ (Tuttle and Bowen, 1958, p. 56). If the preceding assumptions are admitted, extrapolation of the phase relations deduced by Tuttle and Bowen (1958, p. 40) and Yoder, Stewart and Smith (1957, p. 208) for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$H_2O$ indicate that crystallization almost certainly took place under confining pressures greater than 6 kilobars and perhaps as high as 7 kilobars. (At $P_{H_2O}$ = 5000 $kg/cm^2$ the alkali feldspar solidus should be depressed by silica saturation to an intersection with the solvus at a potassium feldspar composition of $Or_{70-}Ab_{30+}$ and a temperature of about 620°C. An increase in $P_{H_2O}$ from 5000 $kg/cm^2$ to 6000 $kg/cm^2$ will depress the solidus an additional 30°± -- it is depressed approximately 40° in the 3000-4000 $kg/cm^2$ interval -- to an intersection with the solvus at a potassium feldspar composition of about $Or_{75}Ab_{25}$ and a temperature of about 585°C; a further increase in $P_{H_2O}$ from 6000 $kg/cm^2$ to 7000 $kg/cm^2$ will depress the solidus to an intersection with the solvus at a potassium feldspar composition of $Or_{80}Ab_{20}$ and a temperature of about 550°C.) It is tentatively concluded, therefore, that the Andover Granite was crystallized at a depth of between 20 and 25 kilometers and probably between 22 and 24 kilometers.

Attempts to establish the probable temperature or, more specifically, the range of temperatures of magmatic crystallization, have been generally frustrated. In theory, however, a maximum limit on the minimum temperature of pegmatitic crystallization may be deduced in a manner analogous to that by which the minimum confining pressure was crudely determined. The same assumptions must be made, of course, regarding the composition of the potassium feldspar, the effect of An on raising the solvus, etc. Accordingly, if the pegmatitic potassium feldspar carries no more than 20 percent by weight Ab, the temperature of crystallization at 6 kilobars should have been about 585$^{o}$C.; at 7 kilobars the maximum temperature might have been 30-35$^{o}$C. below this figure. The effect of any An in the system, of course, would be such as to raise these temperature estimates. The quartz of $\alpha$-quartz morphology associated with the pegmatite contributes little toward a solution of the probable minimum crystallization temperature, even if it is admitted that the formation of the quartz accompanied the primary crystallization of the pegmatite. Unfortunately for the purpose at hand, low temperature quartz would be stable at temperatures as high as 700$^{o}$ at pressures no greater than 5 kilobars.

The maximum temperature that prevailed during the crystallization of the Andover cannot be ascertained. However, it may be possible to determine the lowest possible maximum temperature of crystallization. Textural considerations brought out in the section on late crystallization history strongly imply that at least a part of the magmatic crystallization of the binary granite facies took place above the feldspar solvus. Figures for the crest of the alkali feldspar solvus of 685° at 2000 bars (Orville, 1963, p. 221) and 715° at 5000 bars (Yoder, Stewart, and Smith, 1957, p. 208) suggest that the top of the solvus rises at about 10°/kilobar. For the lowest reasonable pressure of 6 kilobars, then, a maximum crystallization temperature of 725° or above is indicated for the Andover; if the pressure were as great as 8 kilobars, the corresponding temperature should have to have been at least 745°. Inasmuch as the presence of any An in the system would have the effect of raising isobarically the solvus crest to even higher temperatures, it is concluded that the maximum temperature of crystallization was certainly above 725° and probably above 750°.

## Paragenesis

The several facies of the Andover Granite probably are roughly contemporaneous. Crosscutting relationships fail to occur among the seemingly transitional granite-gneiss facies, but age relationships between the granite-gneiss facies and the binary granite are slightly less clear. Discounting the evidence of a single exposure in the north-central part of the Wilmington quadrangle, the granite-gneiss facies are nowhere known to be transitional with either the binary granite or pegmatitic granite facies. However, dikes of binary granite have never been found crosscutting the granite-gneiss nor vice-versa, and the approximate contemporaneity of the two groups seems highly probable. Pegmatite dikes locally crosscut all facies of the Andover Granite; the pegmatitic granite, on the other hand, is clearly transitional with parts of the binary granite and locally appears to be crosscut by it (see figure 10A). Thus, although the pegmatitic granite apparently extended its period of intrusion and crystallization somewhat beyond that of the other facies of the Andover, its general contemporaneity with the remainder of the formation is clearly indicated. That the several facies of the Andover should be essentially contemporaneous is of course expectable, for the compositions of all the facies closely approach that of the granite minimum.

The mineral paragenesis associated with the magmatic crystallization of the Andover has been deduced in only a general way. Textural relationships among the major mineral phases fail to show definitively their order of crystallization, but it is likely that the quartz and feldspar of the non-pegmatitic facies were precipitated essentially simultaneously. Within the pegmatite, however, the widely scattered euhedral to subhedral quartz crystals, together with the local occurrence of large expanses of barren quartz, suggest that its depositional range extended beyond that of the other pegmatite phases. The relatively coarse-grained, intergranular mica, particularly biotite, shows a somewhat greater tendency toward idiomorphism than does either quartz or feldspar; its crystallization, accordingly, may have begun earlier and/or have been of shorter duration. The generally idiomorphic habit of the garnet suggests that its crystallization probably terminated somewhat earlier than the other prominent phases of the granite; the common occurrence of quartz inclusions within the garnet, however, indicates that it did not necessarily begin crystallizing appreciably earlier than the associated phases.

The distribution of points in figure 13 suggests that crystallization of the Andover began along or near the quartz-feldspar cotectic, and that as it proceeded the composition of the magma shifted away from the plagioclase-quartz sideline toward the ternary (granite) minimum. Moreover, as the composition of the magma moved toward the minimum the $H_2O$ content probably rose, such that the minimum itself must have shifted in the manner shown in figure 14B. The combined effect suggests that the changing composition of the magma must have followed a path that curved back toward the Pl-Or sideline; confirmation of this conclusion regretably is poorly reflected in figure 13B. Magmatic activity concluded near the granite minimum with the crystallization of great quantities of pegmatite. The locally developed graphic textures suggest eutectoid crystallization of the pegmatite; the possibly continually shifting position of the minimum, [illegible]ver, may have precluded the maintenance of eutectoid conditions over long periods.

During the early stages of crystallization of the pegmatitic granite facies the concentration of fugitive constituents (chiefly $H_2O$) probably was sufficiently low that "normal" granites or aplites were precipitated. With rising $H_2O$ content, however, the crystallizing granitic materials took on more pegmatitic characteristics; the ultimate result was a number of locally large, generally irregularly shaped and diffusely bounded pegmatite bodies within the granite host. The presence of tabularly shaped and layered pegmatite bodies within the Andover pluton may be in part attributable to simple late stage intrusion along joints. However, some of these tabular bodies, particularly those showing the rather indefinite diffuse contact relations of the sort illustrated in plate 40A, may reflect the tectonic environment in which they were formed. Within a large, semiconsolidated pluton, shearing might have been initiated during the final stages of crystallization; the residual magma might then have been concentrated along these shear zones such that the resultant pegmatites would be distributed along a series of roughly parallel, planar zones.

## Derivation of the magma

The Sharpners Pond Tonalite and Andover Granite almost certainly belong to the same plutonic series; it is also thought that there formerly existed an actual fluid continuity between the two. Several lines of evidence point to this probable continuity. (1) As the binary granite facies is traced eastward at the relatively broad scale of the geologic map, particularly in the northwest quarter of the Reading quadrangle, it is seen to be smoothly transitional with the biotite tonalite facies of the Sharpners Pond. A comparable transitional relationship involving the binary granite exists with neither the other facies of the Sharpners Pond nor the surrounding country rock; it is unlikely then, that the vaguely defined transition with the biotite tonalite can be attributed to either metasomatism or mixing and assimilation of invaded country rock. (2) Rocks clearly identifiable with the binary granite facies grade imperceptibly into the biotite tonalite of the Sharpners Pond over the width of a single outcrop. (3) That the two formations are actually and not simply apparently transitional may be seen by comparing in order the modal analyses given in tables 16, 18, and 23. This compositional intergradation is illustrated more effectively, perhaps, in figures 12 and 13. (4) The modal analyses show that there is not only chemical continuity between the Andover and Sharpners Pond, but continuity in phase composition as well. It is inferred, therefore, that both igneous units have had similar histories and have been emplaced and crystallized under similar conditions. A comparable suggestion of genetic continuity is provided by the fact that compositionally similar rocks from the separate formations are characterized by similar textural features. This similarity is illustrated by a comparison of plates 21B, 23, 29, 30B, and 31.

The natural split between the Sharpners Pond and Andover magmas was conditioned by the appearance of melt compositions that might coexist (in equilibrium) with potassium bearing feldspar. These compositions may have been ones in which crystallization either had joined a plagioclase-potassium feldspar cotectic, or the An content of the plagioclase had been reduced to the point that significant amounts of potassium could be held in solid solution in the now essentially alkalic plagioclase feldspar.

Although it is virtually certain that the Andover Granite and the Sharpners Pond Tonalite both belong to the loosely defined but genetically connected, continuous subalkaline intrusive series, this does not imply that they necessarily descended from a single, parent magma. There is in fact evidence suggesting just the opposite conclusion. The modal analyses in tables 16, 18, 21, 23, and 24, coupled with the volumetric totals of the several mapped facies as reflected by their areal distribution, show that the Sharpners Pond is predominantly tonalitic, whereas the composition of the Andover groups closely around that of the average adamellite. Within the range of the subalkaline series represented locally, then, it is clearly bimodal and is characterized by a general, though far from total absence of rocks of granodioritic composition. The very limited development of granodiorite, moreover, is confined _entirely_ to the area in and around the biotite tonalite facies of the Sharpners Pond Tonalite. Thus, had the Sharpners Pond Tonalite and Andover Granite descended from a common parent through some simple fractionation process, it is difficult to see how this compositional discontinuity could have been imposed upon the subalkaline series (assuming, of course, that the compositions of the resultant rocks reflect the changing composition of the magma from which they crystallized). The implication remains that the Sharpners Pond Tonalite and Andover Granite may have been precipitated from partly mixed but separately derived magmas.

The composition of the Sharpners Pond Tonalite is such that it might reasonably be explained through fractionation of a "primary" basaltic magma. On the other hand, the large volume and generally peraluminous character of the Andover Granite, coupled with the absence of a complementary mafic fraction (assuming such a fraction is not represented by the Sharpners Pond), point to its probable palingenetic derivation. In any event, both magmas arose through processes of either fractional cyrstallization or fractional melting; as the mean melting temperatures for the Sharpners Pond and the Andover may differ substantially, it seems unlikely that both magmas were generated within the same region of the earth's crust or subcrust. It is at least conceivable, therefore, that the Andover magma arose through palingenesis or anatexis of a metasedimentary-metavolcanic sequence well within the crust, whereas the Sharpners Pond may reflect the tapping of "virgin" rock at least a short distance into the mantle.

## Late crystallization history

Subsequent to its emplacement and initial crystallization the Andover Granite underwent at least partial recrystallization and may have undergone minor reconstitution. Although the effects to be described are in a strict sense metamorphic, they are thought to be tied closely to the cooling history of the pluton; there is as a consequence no clear division between the magmatic and post-magmatic history of the granite. For purposes of presentation the late crystallization history is roughly divisible into sections on (1) autometamorphism or deuteric activity and (2) unmixing and simple recrystallization; this does not, however, imply a sequential relationship between the two.

### Autometamorphism

Autometamorphic or deuteric effects pervade the entire plutonic complex, yet they generally are limited to small scale phenomena of presumably local origin.

The locally intense sericitization of plagioclase is perhaps the most widespread autometamorphic (or in a certain sense, metasomatic) effect present. It seems clear, moreover, that the sericitization is indeed an intraplutonic, deuteric phenomenon and not the result of a regional metasomatism; were this not the case it should be difficult to explain the general absence of a comparable effect in similarly constituted plagioclase contained within the country rock. Chayes (1952, p. 245) concluded that the preferential sericitization of plagioclase in the Barre Granite of Vermont was somehow related to the cooling rate. According to Chayes, slow cooling (of the Barre Granite) promoted instability in the plagioclase such that the potash "which might otherwise have appeared in...feldspar went to form muscovite." This simply begs the question, however, for Chayes has made no attempt to relate the postulated instability of plagioclase to slow cooling (nor the stability of potassium feldspar to rapid cooling). P. M. Orville (1963, oral communication) has suggested what appears to be a sounder explanation for this omnipresent feature. He has postulated that $(K^{+})/(Ca^{++})$ in a vapor phase coexisting with plagioclase feldspar may fall off with declining temperature. Thus maintenance of equilibrium in a falling temperature field would require ionic exchange between the potassium of the vapor phase and the calcium of the plagioclase. Under the proper cooling conditions, then, a reaction of the sort

$$\begin{array}{l} \text{An in plagioclase} \\ \overset{\text{solu}}{4H^+ + 2K^+} + 3CaAl_2Si_2O_8 \rightleftharpoons \overset{\text{muscovite}}{2K(Al)_2AlSi_3O_{10}(OH)_2} + \overset{\text{solu}}{3Ca^{++}} \end{array}$$

should be driven to the right with the consequent production of sericite. Whether or not sericitization would ensue with falling temperature, then, should be a function, among other things, of the An content (alumina supply) of the plagioclase. The probable dependence of sericitization on the initial An composition of the plagioclase is shown in several ways. (1) In those relatively rare situations in the Andover where plagioclase zoning may be recognized, sericitization commonly is developed preferentially in the presumably more calcic and aluminous cores (see figure 8A and plates 25B and 31). (2) Plagioclase sericitization is noticeable to some degree throughout the rocks of the pluton, but it is least conspicuous in the more albitic rocks of both the granite and pegmatite.

There are several textural relationships suggestive of local potassium metasomatism or autometamorphism. The most widespread of these are the peninsular and island textures in which irregular blebs of plagioclase seem to be partly or completely surrounded by potassium feldspar. As noted earlier, however, these textures may represent nothing more than very intricate intergrowths between the two feldspars. A somewhat more convincing textural expression of local potassium metasomatism (autometamorphism) is provided by the anomalous extension of myrmekitic quartz stems into the adjacent microcline (see plates 32B and 33A). The results of experimental investigations by Orville (1963, p. 223-224) tend to accord with this conclusion: with falling temperature, $(K^+)/(Na^+)$ in a vapor phase coexisting with two alkali feldspars may fall off in such a manner that not only will the potassium feldspar become less sodic, but the plagioclase as well may be replaced by potassium feldspar.

## Unmixing and simple recrystallization

The effects of unmixing and simple recrystallization are shown by all the major or essential phases of the Andover Granite. As used here, the terms "unmixing" or "exsolution" refer to the process of segregation into two or more phases from an initially homogeneous phase; whether or not this process is essentially intergrain or intragrain (i.e., involves reaction among as well as within individual grains) is not stipulated by the use of these terms. "Recrystallization," on the other hand, is the more inclusive term and refers simply to the creation of new crystals in the solid state by whatever means. Unmixing necessarily will involve recrystallization, but the converse need not be true.

The only specific evidence of the recrystallization of quartz is provided by the common rutilation of this phase. Although rutilated quartz is apparently absent from many specimens (and its occurrence seems to range widely even within the field of an individual thin section), it is nevertheless common to every facies of the Andover and it is unlikely that quartz anywhere has escaped *in situ* recrystallization of this sort.

It is the feldspars that are thought to show the greatest effects of recrystallization. The local rutilation of feldspar and the inclusion in potassium feldspar of albitic perthite lamellae of varying configuration are pervasive and generally good evidences of limited unmixing. It is probable, however, that unmixing has gone far beyond that suggested by the rutilated and perthitic feldspar.

Tuttle (1952) and Tuttle and Bowen (1958, p. 98-116, 137-141) have outlined natural and experimental evidence which suggests that some alkali to calcalkali two-feldspar granites may have evolved through unmixing of an initially homogeneous single feldspar beyond the perthite stage. In other words, as the granite slowly cooled in the sub-solvus region, plagioclase and potassium feldspar may have been segregated into discrete grains through exsolution fluxed by $H_2O$. There is considerable evidence within the Andover pluton that tends to support this explanation for the present phase composition of much of the granite.

The grain boundary configuration between the separate feldspar phases provides an almost omnipresent suggestion of unmixing into discrete grains. If the grain boundary characteristics of the feldspars throughout the subalkaline intrusive complex are compared, several relations stand out with respect to the degree of idiomorphism shown by these phases and the modal compositions of the rocks in which they occur. It was pointed out in the description of the Sharpners Pond Tonalite that its textures are characteristically hypidiomorphic; the feldspars of the Sharpners Pond tend to lose their limited idiomorphism, moreover, only among those rocks that carry substantial potassium feldspar. Within the binary granite and granite-gneiss facies of the Andover the plagioclase and microcline are characterized by the irregular and intricate mutual grain boundaries that have been described in detail in the sections devoted to the descriptions of the individual facies of the Andover. The almost exclusively xenomorphic textural characteristics of the Andover give way to a more hypidiomorphic habit only within the pegmatitic granite facies. This range in crystal habit in the feldspars is compatible with an essentially unmixed or exsolved origin for the two feldspars of the finer-grained rocks of the subalkaline intrusive series. Those granitic rocks largely devoid of potassium feldspar (in both mode and norm) are thought to have retained the relatively idiomorphic habit implicit in their crystallization from a melt simply because they have not been subjected to the extensive recrystallization induced by the unmixing of feldspar into discrete grains. The individual grains of plagioclase and potassium feldspar within the granodioritic and adamellitic rocks, on the other hand, are thought to have evolved largely through exsolution from a single ternary feldspar with the concomitant destruction of the possibly hypidiomorphic primary fabric. The relatively hypidiomorphic textures manifested by the two-feldspar rocks of the pegmatitic granite facies are thought to reflect the elevated $P_{H_2O}$ attendant upon crystallization of the pegmatite; this $P_{H_2O}$ probably depressed the feldspar solidus well below the crest of the solvus, thereby promoting the primary crystallization of separate plagioclase and potassium feldspar phases of relatively idiomorphic habit.

The granophyre-like textures developed in the binary granite facies (see plates 36-39) provide substantial evidence of exsolution into discrete plagioclase and potassium feldspar grains. The locally almost runic, idiomorphic habit (see plate 36) and spatial configuration (see plates 36 and 39A) of the quartz blebs are particularly remeniscent of graphic textures; moreover, as shown particularly well in plate 36A, these uniformly oriented quartz grains clearly are non-myrmekitic. The described textures differ from "true" granophyres chiefly in (1) the absence of a mutually limited, uniformly oriented single feldspar over the field of the oriented quartz, and (2) the generally anhedral habit of quartz. It is postulated, nevertheless, that each uniformly oriented quartz field was originally coincident with a single, alkali to calcalkali feldspar mix crystal in a true granophyric texture. If this is the proper interpretation of this texture (and possible alternatives seem highly contrived), both quartz and feldspar probably were precipitated under the eutectoid conditions that are thought to have obtained at the granite minimum; the feldspar crystallization, moreover, must have gone on either above the crest or well toward the top of the solvus. As the pluton slowly cooled, the initially homogeneous feldspar apparently unmixed and recrystallized into discrete plagioclase and potassium feldspar grains.

(If it is accepted that the textures shown in plates 36-39 are indeed muted granophyric phenomena, metasomatic replacement seems the only alternate explanation to exsolution for the present feldspar distribution. Metasomatic replacement is an unlikely if not impossible explanation of the resultant textures for the following reasons: (1) If the primary granophyre consisted of an intergrowth between potassium feldspar and quartz, the occurrence of several quartz fields within a single microcline crystal (see plate 37) should be difficult to explain. It should require specifically that potassium feldspar replaced itself. (2) If the original intergrowth were between plagioclase and quartz, it should prove equally difficult to explain the several plagioclase orientations within a single quartz field (see plate 36) or the extension of a single plagioclase grain into two or more quartz fields (see plate 38A). (3) Metasomatic replacement would be completely at variance with the demonstrated relationship between the modal composition of the granite and its probable magmatic origin. Had metasomatism been operative to any significant extent, this relationship should have been impossible to deomonstrate.)

Several theoretical objections have been raised against exsolution as an explanation for the origin of the feldspars in many two-feldspar granites. A major criticism stems from the common appearance of two feldspars in rhyolites and other salic extrusives. Tuttle and Bowen (1958, p. 130-134) have considered this objection in detail, however, and have shown that it neither proves nor even suggests that one-feldspar rocks could not have been precipitated from comparable magmas under conditions of slow cooling. It might be added parenthetically, that even should two feldspars have been precipitated under near-equilibrium conditions, this does not in itself invalidate the general applicability of the exsolution hypothesis proposed by Tuttle; two coexisting feldspars of compositions $Or_{25}Ab_{60}An_{15}$ and $Or_{59}Ab_{40}An_{6}$, for example, shoud retain considerable potential for unmixing. There may be, in fact, all gradations between recrystallized hypersolvus granites and two-feldspar granites whose phase composition and textural configuration have changed very little since their primary magmatic crystallization. The purity of either mechanism (exsolution or direct precipitation) may be to a large extent a function of the degree of fractionation in the melt (which might promote the development of a less calcic, more alkalic magma) and its approach to equilibrium during cooling (maintenance of equilibrium may tend to promote the resorption of earlier crystallized plagioclase and potassium feldspars). However, it may be that fractionation and maintenance of equilibrium do not necessarily tend toward the production of a single ternary (or binary) feldspar. In certain situations fractionation and equilibrium cooling might generate (1) more anorthitic liquids and (2) feldspars of more disparate compositions (Stewart and Roseboom, 1962, see in particular figure 2b, p. 286).

A second, more serious objection to the exsolution hypothesis is based upon the supposed impossibility of crystallizing a single feldspar granite at great depth. Stewart and Roseboom (*op. cit.*, p. 308) have suggested, for example, that in the "more deeply seated magmatic rocks with higher vapor pressure of volatiles and with large amounts of additional components, the solidus would be depressed in temperature sufficiently to intersect the solvus along the Or-Ab sideline" of the ternary feldspar system. This argument may be misleading, however, in the sense that it specifically associates higher confining pressures with higher vapor pressures; it is significant only to the extent that the magma is "volatile" saturated. Were the "volatile" content below saturation levels, however, the effect of total pressure ($P_{total}$) should be exactly opposite to that of vapor pressure. As shown schematically in figure 15, an increase in $P_{total}$ would tend to raise the feldspar solidus (and liquidus) above the solvus; although the crest of the solvus is thought to rise at about 10°/kilobar, the liquidus probably rises at an even faster rate, for Tuttle and Bowen (1958, p. 122) have indicated that the melting temperature of granite in a system of fixed $H_2O$ content climbs at about 14°/kilobar (see figure 16). Figures on the $H_2O$ contents of actual granite magmas are generally lacking; Tuttle and Bowen (1958, p. 78-79), however, have shown that the normative compositions of most granites suggest that they either crystallized at shallow depths or, more likely, that their magmas were rarely water saturated. Knowledge at this point, then, is such that it would seem unwise to adopt the *prima facie* notion that the depth of plutonism in itself will limit the extent of solid solution in the feldspars.

Still another objection relates to the presence of zoned plagioclase within some two-feldspar granites. (Plagioclase within the Andover Granite is generally unzoned, but it tends to be diffusely zoned locally.) The preservation of this zoning, however, may reflect one of several phenomena, none of which are incompatible with the general thesis of

Figure 15

Schematic phase equilibrium diagrams for $NaAlSi_3O_8$(Ab)-$KAlSi_3O_8$(Or) in system of constant $H_2O$ content. A. $P_{total} = 5{,}000$ bars $= P_{H_2O}$. B. $P_{total} = 10{,}000$ bars. C. $P_{total} = 20{,}000$ bars.

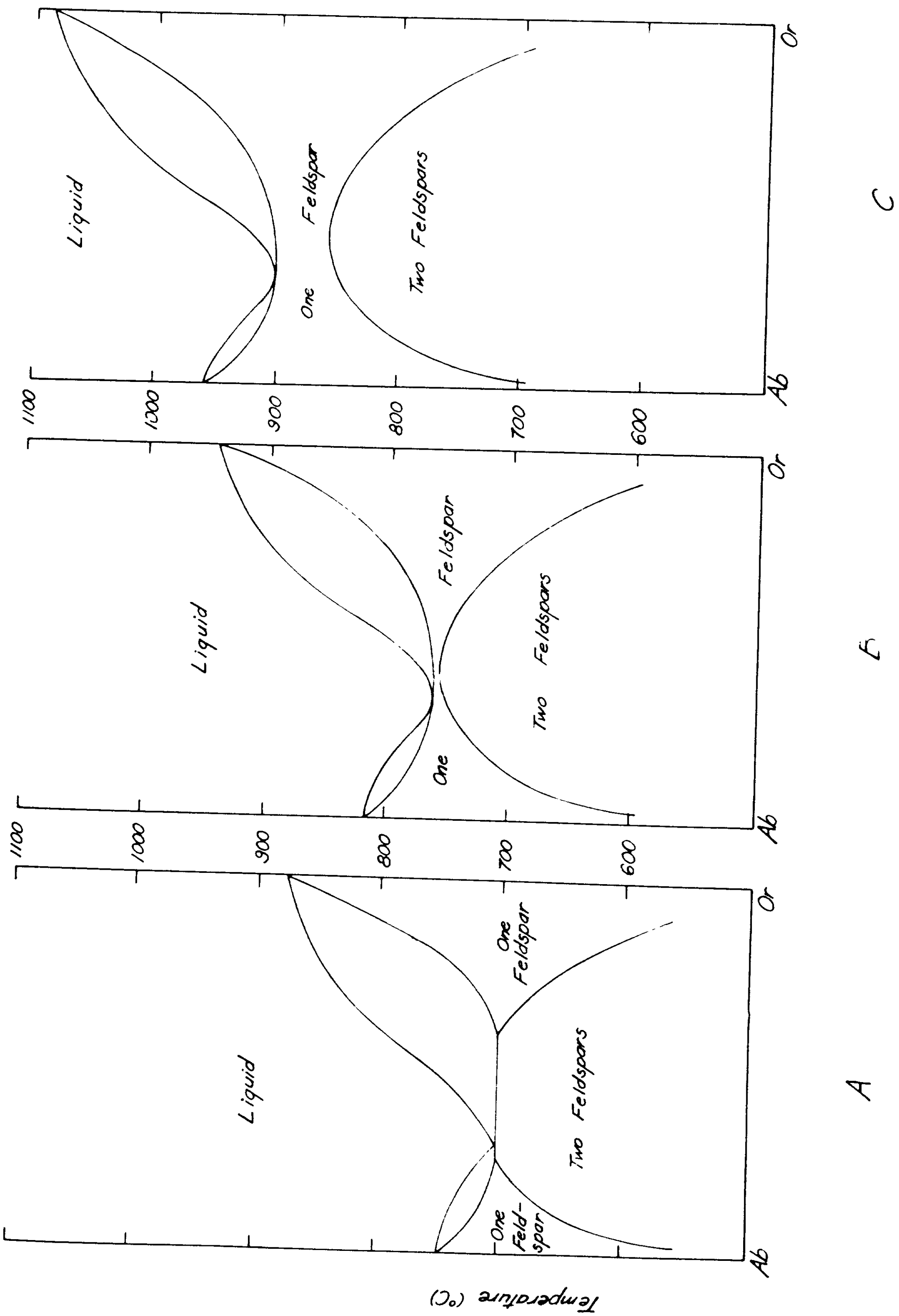
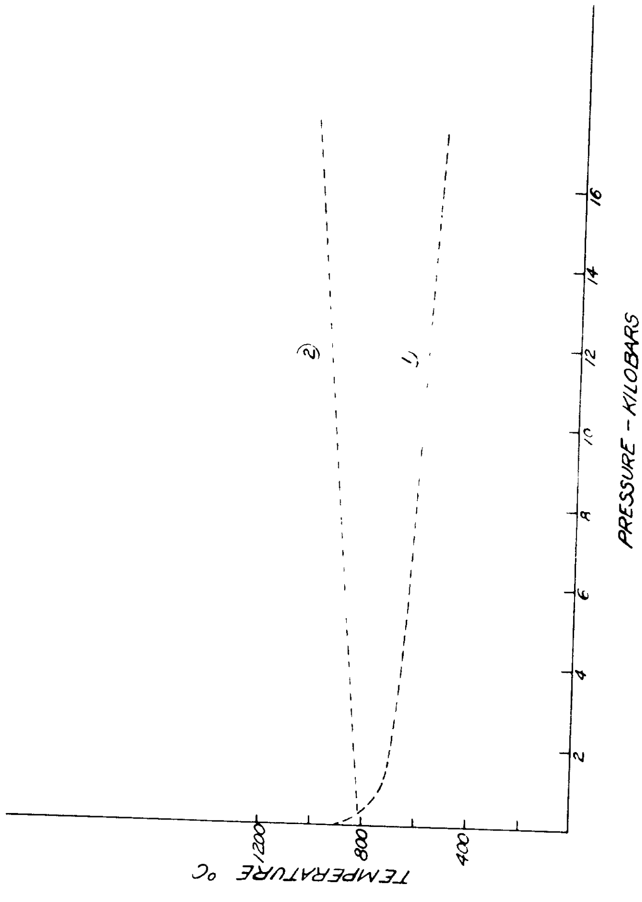

Liquid
One Feldspar
Two Feldspars
Or
Ab
C
Liquid
One Feldspar
Two Feldspars
Or
Ab
B
Liquid
One Feldspar
One Feld-spar
Two Feldspars
Or
Ab
A
1100
1000
900
800
700
600
Temperature (°C)

Figure 16

Schematic P-T diagram showing melting temperatures and pressures for granite where: (1) melt is $H_2O$ saturated for all pressures and temperatures and (2) melt contains 2 percent $H_2O$ by weight (after Tuttle and Bowen, 1958, p. 122).



TEMPERATURE °C
1200
800
400
PRESSURE - KILOBARS
2
4
6
8
10
12
14
16
1)
2)

discrete unmixing: (1) The zoned plagioclase may have been precipitated during an early magmatic, two-feldspar stage and subsequently failed to be resorbed. (2) The zoning may have been inherited from the original mix crystal. (3) The zoning may be the product of the unmixing process itself; that is, its presence may simply reflect a minor disequilibrium initiated during cooling.

Even should the theoretical objections to the occurrence of binary and ternary feldspar solid solutions of appropriate composition ($Or_{30-60}Ab_{30-60}An_{0-10}$) be dismissed, this would not in itself provide positive evidence of their existence. Tabulations of feldspar analyses by several writers indicate that somewhat calcic, intermediate alkali feldspars actually do occur; whether or not these feldspars crystallize in profusion under plutonic conditions is less certain.

Tuttle and Bowen (1958, p. 132) have plotted the compositions for a large number of ternary feldspars in order to outline the maximum limits of solid solution in the feldspars. The compositions of these feldspars have not been plotted by coexisting pairs, nor have they been segregated according to occurrence; a wide range of crystallization environments accordingly may be represented. Nevertheless, this plot does place limits on speculation regarding possible ternary compositions. A great number of the analyses considered by Tuttle and Bowen fall within the critical range Ab/Or = 0.5-2.0; within this same range, moreover, one specimen reportedly contained 20 percent by weight An, many carried up to 12 percent, and fully half contained 5 percent or more An. Carmichael (1960, p. 597) has analyzed the feldspar phenocrysts from a variety of felsic glasses. Many of the essentially sodic feldspars from this group carried substantial amounts of both An and Or and one specimen within the critical range was analyzed as $Or_{42.4}Ab_{51.5}An_{6.1}$. The sanidine and orthoclase phenocrysts from a suite of hypabyssal rocks have been analyzed by Emeleus and Smith (1959, p. 1193). The An content of this group ranged up to a maximum of 4.6 percent by weight. Smith and MacKenzie (1959, p. 1171) have tabulated the ternary compositions for a broad group of orthoclase and microcline perthites. The maximum An content of any specimen in which Ab $<$ 30 percent, was 4.3 percent.

Although relatively calcic alkali feldspars seem common to some environments, it would appear at first glance that the An content of the typically plutonic intermediate alkali feldspars rarely ranges above 5 percent. The only data known to the writer that seems to refute this conclusion derives from studies of intraperthitic plagioclase compositions by Gates (1953). Gates (op. cit., p. 130-131) has ascertained the plagioclase compositions for a small group of microcline microperthites in which Ab/Or is approximately 1; the plagioclase An content of this group ranges up to a maximum of about $An_{18}$ (which suggests a homogenized An content of about 9 percent).

## Origin of the myrmekite

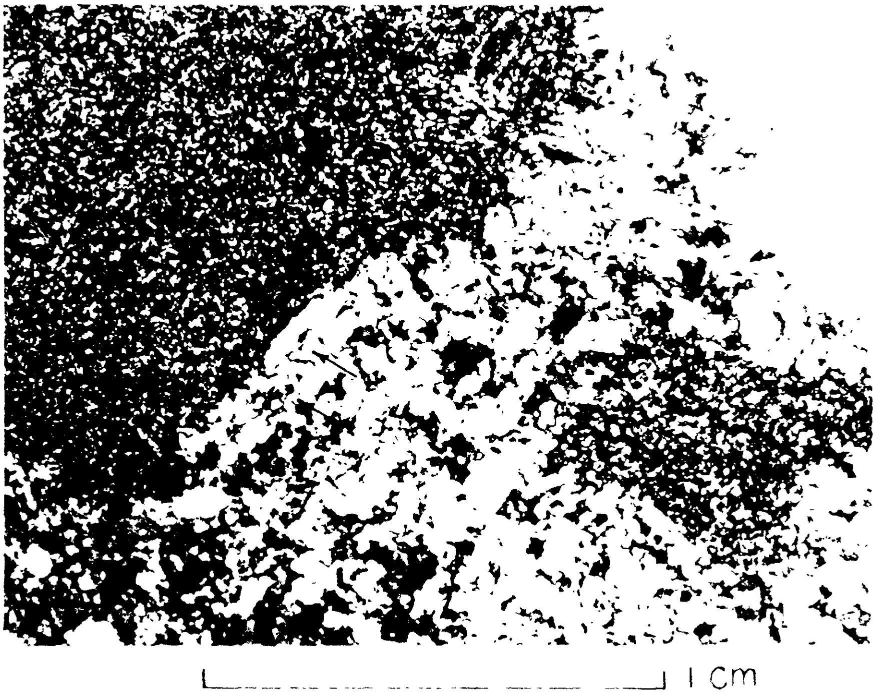
The generally microscopic mineral assemblage characterized by the unique occurrence of vermicular quartz in a plagioclase host is known as myrmekite; it is prominently developed in the Andover Granite (see plates 27, 30B, 32-36, 41B, and 43B) and probably occurs to some degree in almost all two-feldspar granites. The characteristics and occurrences of this interesting mineral association have been tabulated by a number of writers (Tronquoy, 1912; Sederholm, 1916; Drescher-Kaden, 1948); inasmuch as any hypothesis purporting to explain the origin of myrmekite must account for these features (both as they occur within the Andover and elsewhere), they are considered below in detail.

1. Myrmekite is found in fresh rocks and is neither specifically nor even preferentially associated with zones of weathering or alteration (Tronquoy, 1912, p. 217). In other words, any thought that myrmekite may have arisen through processes of weathering or even hydrothermal alteration may be immediately dismissed.

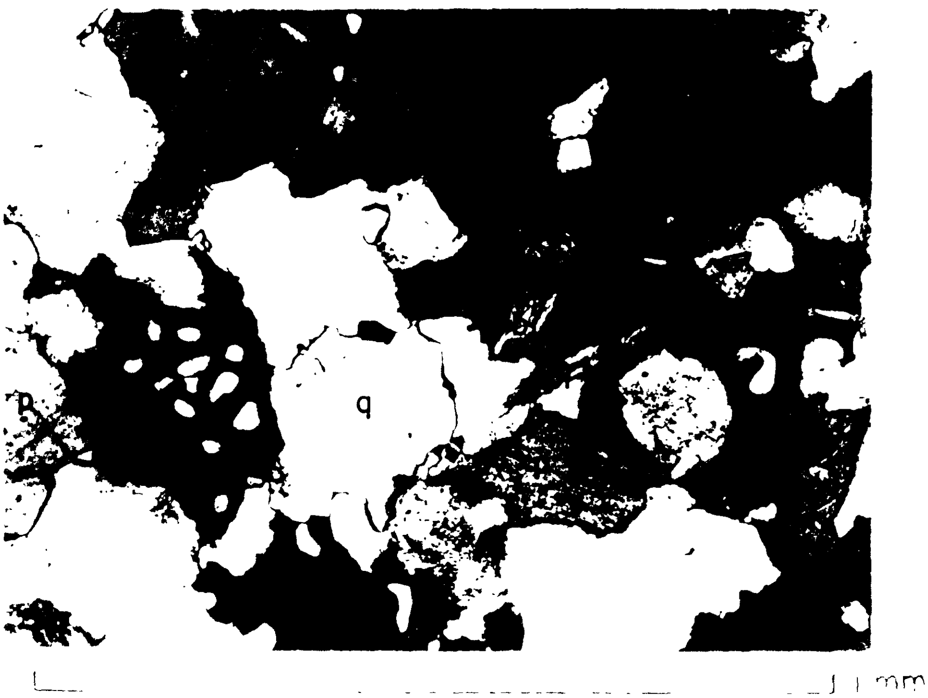
2. Myrmekite is found in a wide variety of more or less salic, deep-seated rocks, including feldspathic paragneisses (see plate 47B) as well as granites. It has been found in neither volcanic rocks (Roques, 1955, p. 189) nor, to the writer's knowledge, low-grade metamorphic rocks.

Plate 46

Photomicrographs of specimen from xenolith bearing dike
posed 1300 feet north of knob 285, Bruin Hill, North
over. Crossed nicols. A. The relatively coarse-grained
t is a biotite tonalite and the darker inclusions are
posed of chloritic biotite (40 percent) and plagioclase
percent). Myrmekite (at arrows) is developed in a zone
g the inclusion boundary. No potassium feldspar could
etected in this thin section. B. Closeup of myrmekitic
shown at arrow in left central section of photograph
late 46A. q, quartz; p, plagioclase; bi, biotite.




A

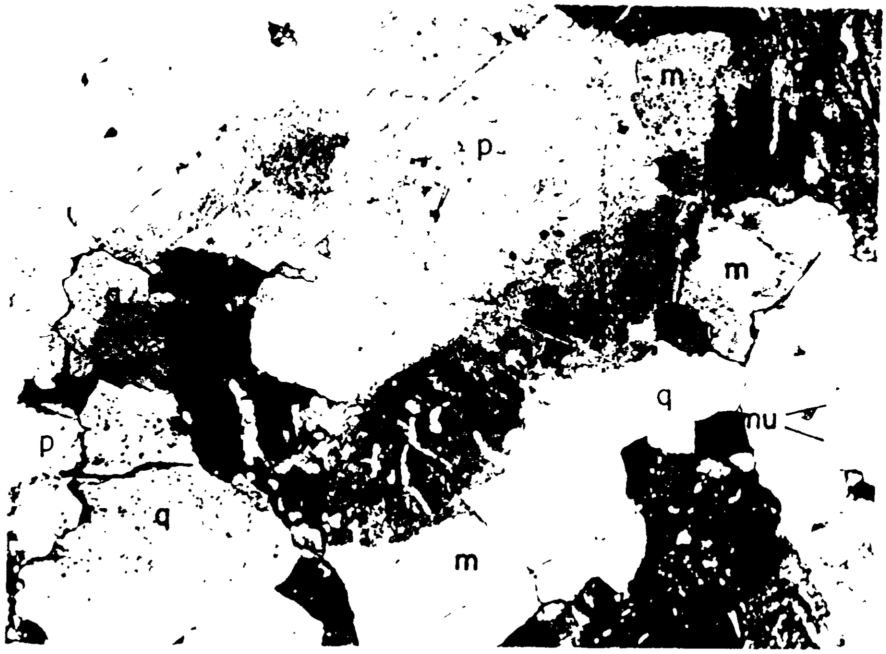



B

Plate 47

A. Photomicrograph of specimen from granitic dike ithin the hornblende diorite facies of the Sharpners Pond onalite exposed 5000 feet south of south tip of Stiles ond. q, quartz; p, plagioclase; m, microcline; mu, musco-ite; c, chlorite; e, epidote. Note the zoned plagioclase which myrmekite is confined to the irregularly margined ter zone (there is no grain boundary between gray and ite portions). Crossed nicols.

B. Photomicrograph of specimen from a prominently dded facies of the Nashoba Formation exposed 1500 feet t of Finns Rd.-Stow Rd. intersection, Harvard. Not in area. q, quartz; p, plagioclase; m, microcline; mu, covite; bi, biotite. Note the development of myrmekite central part of photograph. Crossed nicols.




A


B

Reports of its occurrence in "one-feldspar" (perthite) granites are unknown to the writer, but it does occur in those "one-feldspar" granites carrying even small amounts of extraperthitic plagioclase (see plate 49B).

3. According to Tronquoy (1912, p. 217) myrmekite is never found in granulated rocks. Although it may fail to occur in true mylonites, cataclasites, or even flaser gneisses, Futterer (Sederholm, 1916, p. 68) has observed myrmekite in association with granulated feldspars and the writer has discovered it in a number of deformed specimens from the granite-gneiss facies of the Andover.

4. According to Roques (1955, p. 189) "le quartz vermiculé est toujour localisé dans les plagioclases." This statement should be modified, however, to the extent that it is recognized that many granophyres contain vermicular or myrmekite-like (as well as runic) intergrowths of quartz in a potassium feldspar host. Moreover, the writer has discovered quartz stems within microcline optically continuous with myrmekitic quartz (see plates 32B and 33A), and Drescher-Kaden (1948, p. 104) has noted that "Reste der Quartzstengel in (Kalifeldspat) nicht selten zu beobachten sind."

5. To the writers knowledge, myrmekite is developed only in rocks that contain quartz in excess of that contained within the myrmekite. Spencer (1945, p. 91) has alluded to the presence of myrmekite in syenites, but it may be that

these are quartz bearing varieties.

6. In most cases myrmekite is intimately associated with discrete grains of potassium feldspar, generally microcline (see plates 23, 27, and 32-36). According to Petraschek (Roques, 1955, p. 190), the "myrmékite se trouve sur les bords des cristaux de plagioclase, là où ils sont en contact avec du microcline." Tronquoy (1912, p. 219), on the other hand, has pointed out that myrmekite may occur in parts of the rock besides those immediately adjacent to potassium feldspar grains; when it is recalled, however, that a thin section provides but a two dimensional view, it is not improbable that the "adjacent" microcline may occasionally occur just above or below the plane of the slide. Nevertheless, in those occurrences of myrmekite that are indisputable, i.e., where the material in question could not be just as easily described as an irregular or graphic intergrowth between quartz and plagioclase, there is almost always some potassium feldspar in the rock. According to Raquin (1957, p. 20), Drescher-Kaden has reported myrmekite from rocks devoid of potassium feldspar, but this is contradicted by Drescher-Kaden (1948, p. 104) himself who has stated that "Myrmekit ist genetisch immer an Kalifeldspat gebunden." (Previous authority to the contrary, the writer has examined a myrmekite bearing specimen from this region in which no potassium feldspar could be detected in the rock. The myrmekite in question occurred within a tonalite and was

localized along a contact with a xenolith composed chiefly of plagioclase and chlorite -- see plate 46. The significance of this particular specimen, however, currently is considered doubtful.)

7. Certain generalizations can be made regarding the spatial arrangement of the quartz stems or vermes within the myrmekitic plagioclase (see plates 23, 27, and 32-36 and the illustrations of Drescher-Kaden (1948) and Sederholm (1916)). The long dimensions of the quartz stems generally are directed toward a contact with microcline; where this contact is formed by a curved or rounded reentrant of plagioclase in the adjacent microcline, a fan shape distribution is imparted to the quartz stems (Tronquoy, 1912, p. 217 and plates 23A, 33A, and 35A). There is a common tendency for the quartz stems to (1) attenuate and (2) increase in number adjacent to the microcline contact (see plates 23A, 34A, and 35A). As a corollary, quartz blebs away from the contact tend to be less spindly, more rounded, discrete grains, such that the mineral assemblage isolated from the contact might not always be described as "myrmekite."

8. The quartz stems within an individual myrmekite grain commonly possess a single optical orientation, but, as noted by Tronquoy (1912, p. 219) and confirmed by the writer, "les extinctions des parties concentrique ne sont pas (toujours) simultanées." The number of extinction

positions, nevertheless, is always small.

9. Where myrmekitic plagioclase abuts against non-myrmekitic plagioclase, the myrmekitic material commonly is crystallographically continuous with the non-myrmekitic phase (see plates 23, 27, and 32-36). There seems to be no systematic crystallographic relationship between myrmekitic plagioclase and any adjacent microcline, but this possibility never has been seriously investigated.

10. Several important relationships exist between the occurrence of myrmekite, composition of the host plagioclase, and composition of the plagioclase in the rock as a whole (i.e., non-myrmekitic as well as myrmekitic plagioclase). About the only completely valid generalization that can be made at this time is one attributable to Tronquoy (1912, p. 218): "Le plagioclase qui entre dans la constitution de la myrmekite est d'autant plus basique que la roche consideree l'est davantage." Many early workers recognized that myrmekitic plagioclase commonly fell within the oligoclase range, but it remained for Becke (Sederholm, 1916, p. 90), to carry out a more or less statistical study relating the volume of contained quartz to plagioclase composition. Becke compiled the following table in which index is defined as the ratio between volume of plagioclase and volume of quartz (presumably limited to the myrmekitic zone of any given plagioclase crystal).

| | Anorthitgehalt % | Index |
|---|---|---|
| Albite | 0--- 5 | -- 17.0 |
| Oligoklas-Albit- | 5-- 16 | 17.0 -- 5.0 |
| Sauer Oligoklas- | 16-- 22 | 5.0 -- 3.8 |
| Basischer Oligoklas- | 22-- 30 | 3.8 -- 2.7 |
| Sauer Andesin- | 30-- 41 | 2.7 -- 1.9 |
| Basischer Andesin- | 41-- 48 | 1.9 -- 1.6 |

Becke's observations, however, suggest nothing regarding the volume of myrmekite expectable for the rock as a whole.

11. According to Tronquoy (1912, p. 217) there is no relation between the volume of a microcline crystal and the volume of myrmekite found at its border. In the writer's experience, however, there is a definite relationship between the total volume of potassium feldspar and the total amount of myrmekite in a rock. Other things being equal, the less potassium feldspar, the less myrmekite.

12. A number of writers have indicated that where myrmekitic plagioclase adjoins non-myrmekitic plagioclase, the former is always the more albitic of the two. (It has not always been clear from the writings whether the plagioclase crystals in question were in crystallographic continuity, but where such statements have been made this seems to be implied.) Roques (1955, p. 191), for example, has described a specimen from a "migmatite" of the Massif Central in which the "plagioclase non myrmékite est un oligoclase $An_{20}$" and "les plages myrmékitiques sont constituées

par une albite $An_5$." Drescher-Kaden (1948, p. 104), moreover, has noted that "Die Auslaugungarander sind in den bisher bekannten Vorkommen immer saurer als die inneren noch anangegriffenen Schichten des Kristalls," but he has refrained from even suggesting any limit on the range of compositional differences between inner and outer zones. Raguin (1957, p. 19), on the other hand, has observed that "La matière du bourgeon (myrmekite) est faite du prolongement direct du plagioclase avec légère modification de sa composition chimique devenue plus sodique" (italics added). Observations by the writer tend to support the view that these "modifications" are indeed slight, to the point that compositional differences between the myrmekitic and non-myrmekitic parts of the plagioclase commonly are undetectable.

13. Specific age relationships among the quartz stems, host plagioclase, potassium feldspar, and other mineral phases have been alleged by a number of writers. Conclusions, however, are sharply conflicting and the writer is of the view that valid generalizations cannot be made at this time. Evidence suggesting replacement of plagioclase by potassium feldspar locally accompanies the presence of myrmekite, but it is by no means omnipresent.

Attempts to explain the origin of myrmekite are legion; they date from at least as early as 1874. The writer has made no effort to review all the original sources on this subject, but detailed summaries of the many hypotheses on the origin of myrmekite are contained in works by Tronquoy (1912), Sederholm (1916), and Drescher-Kaden (1948), and much of the following is based on the historical compilations of these three.

Prior to the turn of the century a variety of explanations were advanced to explain the occurrence of the assemblage that subsequently came to be known as myrmekite. Fouqué and Michel-Lévy (Sederholm, 1916, p. 64) felt that it could be attributed to magmatic corrosion of feldspars followed by the crystallization of quartz. Becke (Sederholm, 1916, p. 67) concluded as a consequence of his earlier investigations that myrmekite somehow arose through a reaction between microcline and plagioclase, probably at a late stage of crystallization. Futterer (Sederholm, 1916, p. 68) suggested that myrmekite evolved through a process of dynamal metamorphism, for he commonly observed it in association with mortar structure and other evidences of granulation.

In considering the results of some of Becke's researches, Schwantke developed the notion of unmixing to explain myrmekite. According to Tronquoy (1912, p. 216), Schwantke felt that the "microcline, au moment de sa formation, contient une certaine proportion d'un silicate de formule $CaO \cdot Al_2O_3 \cdot 6SiO_2$ formant un mélange avec $K_2O \cdot Al_2O_3 \cdot 6SiO_2$, mais il tend par la suite à se séparer en se dedoublant on $CaO \cdot Al_2O_3 \cdot 2SiO_2 + 4SiO_2$ en donnant naissance à la myrmékite." Luczizky (Sederholm, 1916, p. 95), on the other hand concluded that myrmekite was "most closely connected with the alteration and dissolution of the primary isomorphous mixture of potash-sodium-lime-feldspar." Luczizky, unlike Schwantke, considered it unnecessary to call upon an abnormally silica rich primary phase, but he neglected to explain the source of the excess silica characteristic of myrmekite.

In recent years direct unmixing hypotheses again have received serious consideration. Spencer (1945, p. 94), for example, has been driven to the conclusion "that there may be some truth in Schwantke's hypothesis of a high silica-lime-felspar for that portion held in solid solution in potash-felspar," for he has noted that most analyses of alkali feldspar "show a definite excess of silica and a deficiency of total felspars when the anorthite formula is used in felspar calculations." Tuttle (Roques, 1955, p. 194) has suggested still more recently, "that the myrmekitic quartz and plagioclase were in solid solution in the potash feldspar at a higher temperature and subsequently entirely separated from potash feldspar." Tuttle (1962, written communication) takes the view that the primary, unmixed calcalkali feldspar may have been stoichiometrically enriched in silica through substitution of a single calcium ion for two alkali ions; experimental work by Carman and Tuttle

(1963) tends to support this possibility.

A number of objections might be raised to those hypotheses based on direct unmixing. If myrmekite has evolved through simple exsolution of excess silica from an alkali-lime feldspar, it would seem that myrmekite and perthite should commonly or at least occasionally occur together; they apparently do not. Unlike much perthite, moreover, myrmekite generally does not display the more or less uniform distribution of its component parts that one might expect from the unmixing of an initially homogeneous crystal. Furthermore, if an explanation is sought in simple unmixing, why is it that the appearance of myrmekite generally is so dependent on the presence of discrete grains of potassium feldspar in the same rock? Somewhat ad hoc reasoning should be required to show why silica enrichment should be limited to a specific feldspar structural state involving rather definite proportions of Or, Ab, and An. In contradistinction to the experimental observations of Carman and Tuttle, moreover, Stewart (1962, written communication) has advised the writer "that no one has made measurements of cell dimensions to the requisite accuracy that would be needed to prove very minor amounts of silica solid solution (less than a fraction of a percent $SiO_2$)" in calcalkali feldspars, but he is nevertheless of the opinion "that the evidence from feldspar synthesis in a variety of silica-rich and silica-poor environments argues against any silica solid solution in synthetic feldspar."

Several students have argued that there is no basic mechanistic difference between the origin of myrmekite and the origin of granophyre or graphic granite. This possibility deserves further discussion. Most observers probably would agree that some "graphic" granite consists of irregular blebs or vermes of quartz set in a potassium feldspar host, and that well developed runiform textures are perhaps the exception. The textural characteristics of myrmekite and graphic granite then, are sufficiently similar that it is conceivable that the two may have a common origin. If one accepts the view that the "graphic" texture of a granophyre reflects a eutectic composition, it follows that the origin of myrmekite might be explained in similar fashion. Thus if the strictly operational definition adopted at the beginning of this section is adhered to, it seems probable that at least some myrmekite (or myrmekite-like material) is of eutectic origin, for an $SiO_2$-plagioclase eutectic certainly is demonstrable. Indeed, Stewart (1962, written communication) has pointed out to the writer that the eutectic composition shifts toward the silica end with increasing An content, a very suggestive observation in accord with the generally accepted view that the higher the An content of the myrmekitic plagioclase, the denser the mat of contained quartz. Nevertheless, if one is reduced to reasoning by analogy, there are several notable differences between graphic granite (which is assumed to represent a eutectoid composition) and most myrmekite. Whereas good runic textures are commonly developed in graphic granite, they are extremely uncommon in myrmekite. Where both granophyric textures and myrmekite occur together, moreover, the styles of the two are so completely dissimilar (see plate 36) that it should be difficult to postulate a common explanation for their occurrence. Furthermore, most petrographers would admit that the arrangement and form of the quartz stems in myrmekite somehow are controlled by the configuration of and distance from the feldspar grain boundary; a corresponding relationship is absent in graphic granite. Again, there is nothing in graphic granite that corresponds to the two-feldspar requirement connected with the occurrence of most myrmekite. Analogies aside, the fact that seems to mitigate most strongly against a eutectic origin for myrmekite is its conspicuous absence in plutonic rocks devoid of potassium feldspar.

In 1948 Drescher-Kaden published an entire text devoted to myrmekite and graphic granite. He (1948, p. 38-89) concluded that there are actually two types of myrmekite that he described as "prämikrokliner" or "Grosskornmyrmekit" and "postmikrokliner" or "Kleinkornmyrmekit." Of the two types, type I ("prämikrokliner") is by far the more prominent (in the writer's view "Kleinkornmyrmekit" may actually represent a late stage eutectic mixture, and will not be discussed further at this time). Drescher-Kaden (op. cit., p. 102-104) apparently envisaged a complicated mechanism, whereby potassium rich solutions attacked the supposedly rhythmically arranged "Lockerstellen" of disordered plagioclase crystals. Thus, as Drescher-Kaden would have it, the various cations (including Al) would be eliminated from the "loose positions" leaving free silica behind. At least some of the cations would then be redeposited in "Lockerstellen" farther inside the crystal creating "Lösungsschutz" that would inhibit further attack by the percolating solutions.

The most recently published hypothesis known to the writer is that of Roques (1955). On the basis of a volumetric study, Roques concluded that the formation of myrmekite could be explained simply through fixation of silica and elimination of alumina, lime, soda and, on occasion, potash. Roques' hypothesis fails to explain almost completely the several most commonly observed characteristics and associations of myrmekite.

Becke published the first thorough petrographic study of myrmekite in 1908; he summarized his views on this subject as follows (Sederholm, 1916, p. 89-90): "Was mich bei diesen Gebilden am meisten gefesselt hat, ist aber die Beziehung zwischen Quarzmenge und Anorthitgehalt des Feldspatgrundes. Dieses Abhangegkeitsverhaltnis in Verbindung mit den ubrigen Eigenschaften und dem Aufreten des Myrmekits legt die Auffassung nahe, dass sich Myrmekit aus Kalifeldspat unter Ersatz des K durch die aquivalente Menge Na, beziehungsweise Ca bilde. Diese Hypothese gestattet die Quarzmenge im Myrmekit mit dem Anorthitgehalt des Plagioklasgrundes in eine quantitative Beziehung zu setzen, die durch die Beobachtung geprüfte werdan kann... Die Bildung des Myrmekits auf Kosten des Kalifeldspats bindet Na und Ca in einer bestimmten Entwicklungsphase des Gesteins und macht K frei." Although not specifically stated, Becke apparently envisaged some such reaction as the following:

$$4KAlSi_3O_8 + Ca^{++} + 2Na^+ \longrightarrow CaAl_2Si_2O_8 \cdot 2NaAlSi_3O_8 + 4SiO_2 + 4K^+$$

This ingenious hypothesis, then, very logically correlates the quartz and plagioclase composition of the myrmekite.

Sederholm (1916, p. 134-140), more or less in accordance with Becke's views, agreed that myrmekite developed through some reactive process between potassium feldspar and Na and Ca rich solutions, probably at the deuteric stage of crystallication. Sederholm felt that Becke's explanation was over-simplified, perhaps, for he (op. cit., p. 137) had apparently discovered "many cases where certain portions of myrmekite rims contain much more quartz than neighboring parts in which felspar certainly has the same composition." Sederholm believed, however, that he could postulate a reasonable source for the Na and Ca allegedly introduced during myrmekitization, for he (1916, p. 123) claimed that myrmekite commonly was most conspicuously developed near basic inclusions. Following up on this line of reasoning, Sederholm concluded that great amounts of potassium should be discharged with the formation of myrmekite; considerable secondary mica in plutonic rocks or their contact aureoles, might then be explained as a consequence of the metasomatic introduction of the liberated potassium.

Of all the earlier theories developed to explain the origin of myrmekite, the writer finds the views of Becke and Sederholm the most convincing. There remain, nevertheless, several unexplained features. The most conspicuous deficiency of the Becke replacement theory, relates to the 50-year old observation of Tronquoy: the An content of the myrmekitic plagioclase is a direct reflection of the "basicity" of the host rock. Rather circuitous reasoning should be required to explain this neat compositional correspondence if Ca-Na rich solutions were called upon to explain the formation of myrmekite. Secondly, the writer would agree with Spencer (1945, p. 93) that a strong objection to the replacement explanation "lies in the strictly limited size of these structures and the limited amount of local 'replacement' which they represent. As Sederholm has pointed out, these myrmekite structures never exceed about [illegible] millimetre in diameter yet they usually occur scattered fairly evenly through very large rock masses, without completely 'replacing' the potash-felspar present, even in the small localized area of a hand-specimen. This itself points to a very local source for the 'invading' plagioclase and to a 'closed system'." Thirdly, both Drescher-Kaden and the writer have noted that there is some evidence suggesting that the associated potassium feldspar commonly post-dates the myrmekitic plagioclase. Lastly, there are the objections to Becke's theory noted and never fully explained by Sederholm himself.

The possibility (or probability) that the Andover Granite may have evolved through a period of calcalkali feldspar unmixing suggests still another explanation for the origin of myrmekite; for lack of a better name, it might be described as the indirect unmixing hypothesis.

The indirect unmixing hypothesis is explained most easily by reference to figure 17. This illustration is designed to show various trends in the exsolution of alkali and calcalkali feldspars; exsolution is represented as proceeding both in an isolated system and under the influence of a matrix silica reservoir. The nature of this silica reservoir is deliberately unspecified; it might be simply a silica-enriched, aqueous solution, or it might even exist as a crystalline solid. The several hypersolvus feldspar compositions employed in figure 17 have been adopted primarily to demonstrate the effects of various alkali and alkali to An ratios on the production of myrmekite; they have been selected secondarily for ease of arithmetic manipulation and not because they are felt to be particularly representative hypersolvus compositions. The separate steps (A, B, C, etc.) in each column are not necessarily sequentially arranged, but the bottom step in each case is presented as the ultimate (and therefore the latest) stage in the unmixing process. Each column, then, is more in the nature of a listing of the possible cation exchanges that might accompany exsolution; the arrangement of steps within each column is reflective of nothing more than increasing complexity beyond simple alkali ion exchange, which is taken in turn as a point of departure for each case. In all probability the separately listed reactions may run more or less simultaneously or even in an order inverted from that presented in figure 17.

In each of the cases presented in figure 17, unmixing is assumed to take place either among or within feldspar grains of initially uniform, homogeneous composition. The dashed lines accordingly represent either actual or potential grain boundaries; the positions of the final grain boundaries thus might be determined by the unmixing process itself. It is assumed further that the primary, unmixed feldspar is initially set within a silica matrix in the presence of a water flux at an elevated, hypersolvus temperature. The indicated exchange reactions might then be induced through very slow reduction of temperature. Should the temperature drop to very low levels, and should infinite time be allowed for this drop, complete exsolution of potassium and plagioclase feldspar phases into discrete grains theoretically might result (although complete exsolution is never realized in nature, it is closely approached). With the above assumptions in mind, each of the five cases in figure 17 may be considered.

I. This example is designed to show how pure, alkali feldspar mix crystals might be transformed into discrete grains of potassium and plagioclase feldspar through simple alkali ion exchange. Simple cation exchange of this sort is such that the feldspar structure need not be disrupted; it should proceed, therefore, relatively easily, even at reduced temperatures.

II. The primary feldspar composition represented in case II is one in which unmixing again may operate in part through a process of simple alkali ion exchange. It may not proceed to completion, however, without a paired exchange between K-Si and Ca-Al. That paired reactions of this sort actually take place in nature is suggested by the calcic albite to andesine compositions of intraperthitic plagioclase lamellae set within a potassium feldspar host essentially devoid of An (Warren, 1915, p. 136-137, 142; Alling, 1938, p. 153-154). If the reaction is precisely balanced such that potassium and silicon and calcium and aluminum migrate as pairs, unmixing into discrete grains of potassium and plagioclase feldspar may take place as in case I. A major difference between these two examples, however, derives from the fact that unmixing in case II requires a disruption of the silica and alumina tetrahedra of the feldspar structure; this in turn implies the existence of proportionately higher temperature thresholds for the exsolution of ternary feldspars as contrasted with pure alkali feldspars.

III. This case is designed to show what might happen were the calcalkali feldspar of case II allowed to unmix in such a way that potassium and silicon did not necessarily migrate as a pair. If the silicon requirements of the evolving potassium feldspar were met by the matrix silica reservoir, the consequent stoichiometric surplus of silicon within the concomitantly developing plagioclase might remain imprisoned as myrmekitic quartz.

IV. Case IV is presented as an example of how a reduction in Or:Ab in the ternary feldspar system might inhibit the development of myrmekite (i.e., the molar ratio of myrmekitic quartz to unmixed plagioclase). Unmixing of the essentially potassic feldspar in steps C and D probably is oversimplified; however, whether the exsolved sodium feldspar will be incorporated in the main body of the plagioclase or will remain as perthite lamellae within the potassium feldspar, is not immediately significant. It should be noted, however, that had Ab:An been held at the same value (4:1; $Or_{40}Ab_{48}An_{12}$) as that obtaining in case III, the molar ratio of myrmekitic quartz to plagioclase should have been precisely the same as that in case III. In other words, where Or:An >1 and Or:Ab+An ≤1 in the ternary system, the development of myrmekite may be a simple, direct function of the unmixed plagioclase composition alone.

V. Case V is designed to show how an increase in Or: Ab+An above 1.0 might promote the production of myrmekite. The composition ($Or_{70}Ab_{24}An_6$) probably is the least realistic of any employed in this discussion (*i.e.*, it represents the most unlikely hypersolvus composition). A feldspar of this composition is more apt to occur as one member of a subsolvus, coexisting pair whose other member might be characterized by some such composition as $Or_{20}Ab_{55}An_{15}$. Needless to say, cation exchange between these two phases might proceed much as it does between or among mix crystals of uniform composition; it simply could not proceed so far. The two-stage unmixing process depicted in case V may be artificial; regardless, it is deliberately contrived to show the maximum amount of myrmekitic quartz that could be obtained through the unmixing of hypersolvus feldspars of this composition.

As presently formulated, the indirect unmixing hypothesis is simply a model; there is no implication that the actual process of myrmekitization is described by such a model. Whether the postulated reactions take place through solid diffusion, through the intermediary of an aqueous phase, or in some other way is not stipulated. Nor can it be stated what form the various atomic particles will take during reaction. It should be recognized, moreover, that this scheme does not require that myrmekite must form as a consequence of unmixing, but only that it may form.

The hypothesis presented above suggests in effect that two-feldspar, calcalkali granites (or granite-gneisses) initially crystallized as single-feldspar, hypersolvus granites, are precisely those rocks in which myrmekite should be most conspicuous. On the other hand, granites characterized by the presence of a "single" feldspar (perthite, cryptoperthite) should in general fail to develop significant amounts of myrmekite, for the limited unmixing expressed in perthite granites is more of an intragrain than intergrain phenomenon. By the same token, two feldspar rocks crystallized directly from a melt or lower temperature metamorphic assemblage, are less apt to contain myrmekite simply because their exsolution potential is sharply limited. Rapakivi granites, for example, are explained most reasonably as mineral assemblages precipitated directly from a melt with little if any subsequent modification; to the extent that this interpretation is valid, the development of myrmekite in rapakivis should be less conspicuous than in most other two-feldspar granites. This actually seems to be the case; Sederholm (1916, p. 114) has observed that myrmekite is "certainly much less common in the rapakivi granites than in the earlier granites of Fenno-Scandia," and Holmquist (Sederholm, 1916, p. 85) has found myrmekite almost totally absent from the rapakivi granites of Sweden. Any magmatic rock thought to have crystallized under relatively high vapor pressures should fail to carry significant amounts of myrmekite; high vapor pressures tend to depress the feldspar solidus to relatively low temperature intersections with the solvus such that primary crystallization of two feldspars is promoted. Pegmatites certainly are exemplary of rocks crystallized under elevated vapor pressures; they are characterized, moreover, by a general absence of myrmekite (it must be admitted, however, that the trivial development of myrmekite in pegmatite may reflect as well the generally lower An content of the magmatic residuum from which these rocks crystallized). The occurrence of muscovite provides another index of vapor pressure, for, as shown in figure 18, muscovite is unstable at low $P_{H_2O}$. Granites in which the percentage of muscovite or the ratio of muscovite to biotite is high, are more apt to be ones in which the feldspars were crystallized initially well below the crest of the solvus and are thus devoid of myrmekite. A crude, subjective test for this relationship was carried out on a group of rocks collected from the Andover Granite. Granting the limitations of this approach, the results tabulated in figure 19 indicate that the prominence of myrmekite tends to be inversely proportional to that

Figure 18

(1) Univariant equilibrium curve for the reaction scovite ⇌ sanidine (S) + corundum (C) + vapor (V) (after oder and Eugster, 1955, p. 242). (2) Univariant equilibrium curve for the reaction phlogopite ⇌ forsterite (F) + cite (L) + $KAlSiO_4$(K) + vapor (V) (after Yoder and gster, 1954, p. 163). (3) Incipient melting curve for anite" (after Turner and Verhoogen, 1961, p. 139).

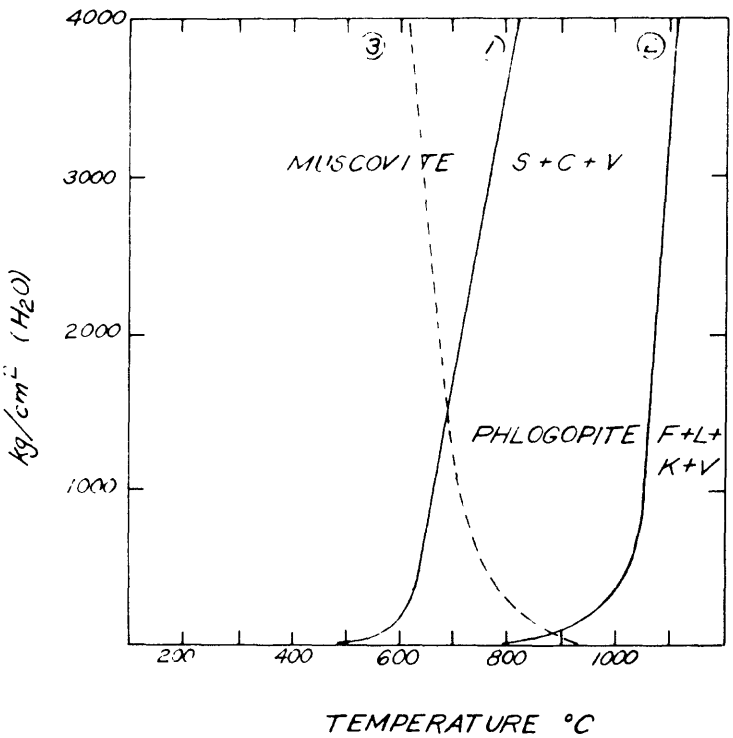
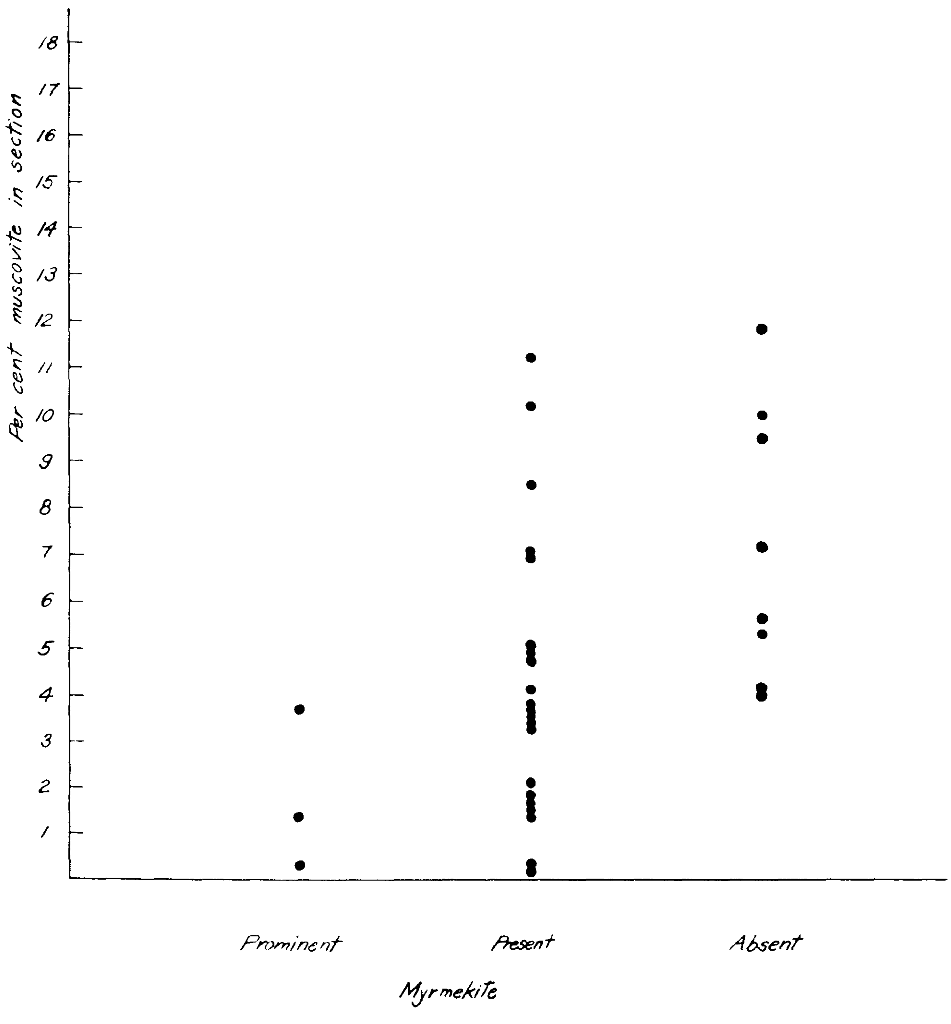

4000
3000
2000
1000
kg/cm² ($H_2O$)
3
1
2
MUSCOVITE
S + C + V
PHLOGOPITE
F + L +
K + V
200
400
600
800
1000
TEMPERATURE °C

Figure 19

Plot showing relationship between occurrence of dickite and occurrence of muscovite. Compiled from data tables 18, 21, 23, and 24.


Per cent muscovite in section
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Prominent
Present
Absent
Myrmekite

of muscovite; the converse certainly is not indicated.

Many of the textural characteristics of myrmekite and myrmekite-bearing rocks may be explained through indirect unmixing. Sederholm (1916, p. 136), for example, has described "plagioclases which are entirely surrounded by microcline, (that) as far as can be judged from the slides, may show no myrmekitic rims while such rims, on the other hand, occur at all other contacts between the two minerals in the same slide." This is entirely expectable, of course, where the exsolved plagioclase is nucleated in part toward the center and in part toward the edge (adjacent to a secondary silica source) of an essentially alkalic mix crystal. The tendencies toward the concentration of quartzose filaments along potassium feldspar contacts, and the development of coarser, more rounded quartz blebs away from these contacts (see plates 23A, 34A, and 35A) also are thought to be related to the mechanics of unmixing. Imagine that the figurative plagioclase grain developed in case III of figure 17 has grown through sinistral migration of the grain boundary; the earliest development of myrmekitic quartz should take place, therefore, well to the right of this grain boundary. A reduction in the free energy of the system represented solely by the myrmekite would be favored by a reduction in the surface area of the vermicular quartz; such a diminution in surface area could be most easily effected during a higher temperature, and therefore earlier stage of unmixing.

Recrystallization in the early stages of unmixing may have gone forward so much more easily, in fact, that any surplus silica accumulated in the core of the exsolved plagioclase may have been removed almost immediately.

The occasional zoning manifested by myrmekitic plagioclase may be attributable to one of several phenomena, none of which are incompatible with unmixing. Certain types of zoning may reflect nothing more than a condition inherited from the primary, unexsolved feldspar. Inheritance, for example, is thought to explain the zoning in the myrmekitic plagioclase shown in plate 47A. The plagioclase core shown in this photomicrograph probably crystallized as relatively pure plagioclase; the plagioclase rim, on the other hand, probably was enriched in Or to the point that unmixing promoted the growth of myrmekite. Zoning in the myrmekitic plagioclases illustrated in plates 27A, 33B, and 34A is less easily explained; it is presently thought to be a direct consequence of unmixing. Consider again the situation represented by case III in figure 17. The tendency of the An component to unmix from a highly potassic feldspar certainly is greater than that of the Ab component; the reaction represented by step B, then, might run to completion well before that of step A. This sequence of events is not at all improbable, for simple alkali ion exchange may continue well below the temperature threshold associated with the exchange of K-Si and Ca-Al. Thus continued unmixing of pure alkali feldspar beyond the reaction represented by step B, would promote a disequilibrium migration of the grain boundary to the left with the consequent development of an albitic rim around the more myrmekitic plagioclase. The outermost plagioclase zone (at arrow) of the large, central plagioclase grain shown in plate 33B is optically continuous with the nearby perthite lamellae. It seems likely, therefore, that this more sodic rim has arisen through simple exsolution from the adjacent microcline grain much as is shown in step C of case IV in figure 17.

The compositional characteristics of myrmekite and its associated feldspars seem to accord with the indirect unmixing hypothesis. The myrmekitic plagioclase of most rocks has about the same composition as the non-myrmekitic plagioclase. This is fully consistent with this scheme, for a comparison of cases II and III in figure 17 shows that the gross composition of the exsolved plagioclase should be unaffected by the development of myrmekite. Those rocks generally low in An, moreover, should contain little if any myrmekite; the absence of An will allow unmixing to proceed without any migration of Al or Si so that there simply will be no tendency for myrmekite to develop. On the other hand, alkali feldspar systems in which the An content is above a certain critical (small) value are more apt to fall within the two-feldspar field, such that the post-crystallization unmixing potential should be diminished sharply. For these reasons, then, the composition of myrmekitic plagioclase should (and does) tend to fall within the low oligoclase range. As a final point of comparison, the indirect unmixing hypothesis seems to be consistent with Becke's observations on the relationship between quartz content and plagioclase composition in myrmekite. If Or is held constant at 50 mol percent and unmixing is assumed to have progressed to completion, the effect of increasing An in the ternary feldspar system on the development of myrmekite may be calculated:

| Mol percent An in unmixed plagioclase | | Maximum volume percent of myrmekitic quartz in total volume of unmixed plagioclase |
|---|---|---|
| 5 | | .68 |
| 10 | | 1.36 |
| 15 | | 2.03 |
| 20 | (case III) | 2.76 |
| 25 | | 3.34 |
| 30 | | 3.97 |
| 35 | | 4.60 |
| 40 | | 5.22 |

A number of statistical procedures might be devised to test the validity of the indirect unmixing hypothesis. Most of these tests, however, should prove extremely tedious and the writer thus far has been unable to carry out an investigation of this sort. For the moment, then, the hypothesis can be considered no more than reasonable speculation.

## Deformation

The Andover Granite was subjected to deformation during and subsequent to its emplacement, and it is thought to have been deformed in part subsequent to major recrystallization. Demonstration of this deformation, however, is based chiefly on the fabrics of the rocks themselves and finds little corroboration from other sources. Nevertheless, the widespread, preferentially mortared quartz, the abundance of strained feldspar, and the prominent development of closely spaced, intensely mortared folia (see plates 24A, 25A, 26A, 28, 34B, 41, and 42B), provide fairly convincing evidence of the deformed nature of these rocks.

A query does arise, however, with respect to the chronology of this deformation. The emplacement of the granite must have been at least in part syntectonic; this is shown by the fact that the rocks of the granite-gneiss facies locally are intensely deformed (see plates 24A, 25A, and 28), yet are crosscut by apparently undeformed, clearly consanguineous pegmatite dikes. However, deformation must have continued at least briefly beyond the final stages of magmatic crystallization, for both the pegmatites and granites of the pegmatitic granite facies are locally deformed (see plates 34B, 41, and 42B).

The extent to which deformation postdated the recrystallization of the Andover is less clear. However, if it is assumed that the myrmekite evolved concomitantly with the unmixing and recrystallization of the feldspars, the presence of strained myrmekitic plagioclase (see plate 34B) would seem to demand that deformation extended beyond at least the beginnings of recrystallization. This conclusion tends to be corroborated within the granite-gneiss facies by the presence of porphyroclasts which are composed of irregularly and intimately intergrown plagioclase and potassium feldspar, yet are at the same time smoothly bounded by folia of intensely sheared quartz and feldspar (see plate 25A).

The intensity of deformation apparently ranged widely across the pluton. The greatest deformation is shown by the several granite-gneiss facies and is related in part to protracted movement along one of more shear zones (see figure 22). The binary and pegmatitic granite facies have been deformed much less intensely than the granite-gneiss, but the effects of crushing and shearing are by no means totally absent in these rocks.

## Correlation

A detailed consideration of the supposed correlatives of the Andover Granite is beyond the scope of this report. Nevertheless, a few general comments are in order regarding its possible equivalents among the nearby igneous rocks of northeastern Massachusetts and southeastern New Hampshire. Disregarding the several small plutons thought to be related to the Andover within the map area of plate 1, possible correlatives of the Andover Granite fall into three separate, but partly overlapping groups: (1) the granitic rocks included locally with the Dedham Granodiorite; (2) the Fitchburg Granite (together with its presumed correlatives in New Hampshire); (3) the binary granites cropping out within a number of smaller stocks and bosses southeast of the northwest boundary of the Fitchburg pluton.

Descriptions of the Dedham Granodiorite cropping out in Essex County (Emerson, 1917, p. 172-177; Clapp, 1921, p. 24-25, 44-49) differ from those of the Andover chiefly in the generally less salic character ascribed to the Dedham as contrasted with the Andover. However, at least parts of the Dedham are lithologically similar to parts of the Andover (Emerson, 1917, p. 173, 176-177), and both occupy roughly the same position in time in that both are thought to be transitional with the same general group of dioritic to tonalitic rocks (Salem Gabbro-Diorite of Emerson and Clapp; Sharpners Pond Tonalite of this report). Schneer (1957, written communication), moreover, has described a rock similar to the muscovite granite-gneiss from one of the "Dedham" plutons cropping out in the Newburyport West quadrangle. Not only is the rock similar in appearance to the muscovite granite-gneiss, but it occupies a corresponding position in space as well, in that it is bordered on the north by the Merrimack Group and on the south by rocks of the subalkaline intrusive series.

The Fitchburg Granite and its New Hampshire correlatives display a strong compositional resemblance to the Andover Granite; moreover, they invade apparently equivalent rocks and show the same range in fabric (Emerson, 1917, p. 231-232, pl. X; Billings, 1956, p. 67, geologic map). According to Emerson (1917, p. 231-232), the Fitchburg Granite of Massachusetts is a massive and uncrushed, "light-colored medium-grained muscovite-biotite microcline granite"; its plagioclase is apparently myrmekitic in part and both quartz and feldspar are prominently rutilated. Irregular masses and dikes of pegmatite occur in and adjacent to the main granite body. Billings (1956, p. 67) has pointed out "that the Fitchburg granite on the geological map of Massachusetts and Rhode Island (Emerson, 1917, p. 232-233) includes two very different rocks." Thus the binary granite described above is apparently atypical of the Fitchburg pluton in New Hampshire which apparently consists chiefly "of the granodiorite that was included with the Fitchburg on Emerson's map" (Billings, 1956, p. 67, geologic map). Detailed descriptions for the New Hampshire rocks correlated with the Fitchburg (as originally mapped by Emerson) by Billings exist only for the area around the Pawtuckaway

Mountains (op. cit., p. 67). The rocks in this area are generally medium- to coarse-grained and weakly to locally strongly foliated. They consist chiefly of biotitic and partly hornblendic quartz monzonite, biotite-muscovite granite, microcline granite, and garnetiferous pegmatite. The above descriptions of the Fitchburg Granite and its New Hampshire equivalents accord particularly well with those of the binary granite and biotite granite-gneiss facies of the Andover. It is possible or probable then, that both the Fitchburg and the Andover belong to the same plutonic series.

The third group of rocks that might include correlatives of the Andover Granite has been mapped under several different names. Rocks in southeastern New Hampshire mapped simply as "granite" (Billings, op. cit., p. 68, geologic map) bear the same relationship to the surrounding metasedimentary rocks as do the rocks of the Fitchburg pluton. Moreover, they consist of both massive and foliated medium-grained binary granite and quartz monzonite and are consequently at least roughly similar to the Andover. Billings (op. cit., p. 69), however, has indicated that these rocks are "certainly younger than the rocks of the Fitchburg pluton that are mapped as granite, quartz monzonite, and granodiorite." This point is debatable or at least subject to modification. The "granite" around Milford, New Hampshire, for example, although clearly younger than the adjacent plutonic rocks (Billings, op. cit., p. 69) is not necessarily younger than the Fitchburg Granite itself; Billings himself carefully noted that the true Fitchburg Granite is sparsely developed in the New Hampshire part of the pluton, and thus there is no way of showing that this "granite" is not simply a somewhat younger member of the same plutonic series it intrudes. Rocks mapped as "binary granite" by Jahns (1952, p. 110) crop out in Dunstable, Massachusetts and Pelham, New Hampshire. They apparently belong to the same group of rocks mapped as "granite" by Billings and correspondingly bear the same relationship to the Andover. A group of rocks crops out in the Maynard and Westford quadrangles that formerly was included with the Andover (Emerson, 1917, pl. X; pl. 2, this report), but subsequently was mapped as the Acton Granite (Hansen, 1956, p. 48-50; Willard, 1951, oral communication). The Acton Granite is intrusive into the Nashoba Formation, but its relationships to other nearby units are unknown. According to Hansen (1956, p. 48-49) the Acton is a fine-grained, moderately foliated rock composed chiefly of quartz and feldspar in which the ratio of potassium feldspar to plagioclase is more than 2:1 (modal analyses were not presented). Biotite and muscovite occur as major accessory minerals, and apatite, zircon, and garnet are less prominent accessories. The description of this rock is such that the probability exists (as Emerson originally suspected) that the Acton is simply an isolated facies of the Andover.

The Ayer Granite of eastern Massachusetts occupies a position in time comparable with that of the Andover (Emerson, 1917, p. 224). However, neither its contact relations with surrounding rocks nor its petrography accord with that of the Andover (Emerson, 1917, p. 224; Jahns, 1952, p. 112; Hansen, 1956, p. 47-48). Moreover, Jahns (1952, p. 110) has noted that the binary granites of Dunstable, Massachusetts and Pelham, New Hampshire "are younger than the rocks of the Ayer complex"; if the equivalence of the binary granite and the Andover is conceded, the Ayer almost surely predates the Andover.

Clapp (1921, p. 27-29) assigned the Andover Granite to the "alkaline group" of Essex County, implying its equivalence with what is mapped here as the Peabody Granite (see discussion on the "alkalic" intrusive series). There is a gross chemical similarity between the Andover and the Peabody, but the two are completely dissimilar in terms of their phase composition and petrogenesis. In addition, the emplacement of the Andover Granite and the other rocks of the subalkaline group was generally synkinematic, whereas the Peabody Granite is essentially post orogenic and clearly post-dates the subalkaline intrusive series. The two granites are certainly non-equivalent.

## Adamellite at Johnsons Pond

A singular, essentially adamellitic rock crops out along the southeastern shore of Johnsons Pond in the South Groveland quadrangle. The southeastern contact of the adamellite is moderately well defined by abundant nearby exposures of the Boxford Formation, but Johnsons Pond and a heavy cover of glacial drift conceal the northwestern contact. Actual exposures are limited to a narrow zone between Washington Street and Johnsons Pond and to a few dikes intrusive into the Boxford Formation. The adamellite appears on Emerson's map (see plate 2) as Dedham Granodiorite that was thought to be continuous with a large mass of Dedham(?) cropping out in the Newburyport West quadrangle.

The adamellite ranges from light gray to pearly white, but it is characterized by a faint blue-green tinge. A unique appearance is imparted to the rock by its dark smoky quartz and commonly pitted, almost gnarled, weathered surface. It is faintly foliated, and generally coarse grained. Effects of cataclasis, including strained and granulated quartz and broken and bent feldspar (see plate 48), are clearly evident in the main mass of the adamellite (i.e., toward its contact with the Merrimack Group).

The adamellite is composed of plagioclase, microcline, and quartz with accessory amounts of muscovite, chlorite, and limonite. Microcline and plagioclase are approximately equal in amount and together compose from 70 to 80 percent

## Plate 48

Photomicrograph of adamellite exposed along the south shore of Johnsons Pond. Note the shattered appearance of the rock. q, quartz; p, plagioclase; m, microcline. Crossed nicols.


m
p
1 mm

of the rock. The microcline is slightly perthitic and somewhat altered. The plagioclase is albitic and characterized by sericitic alteration along its cleavages. Chlorite and limonite together account for less than 3 percent of the rock.

The unmapped dike rocks, tentatively correlated with the adamellite, are similar in appearance to those of the main adamellite mass. However, they are finer grained and compositionally distinct. The dike rocks are essentially trondhjemitic in composition, largely or entirely devoid of potassium feldspar, and carry up to 5 percent accessory garnet.

## Correlation

The adamellite has been discussed separately here because of its unique appearance in outcrop and previous inclusion by Emerson with the Dedham Granodiorite. However, there presently seems little basis for assigning the adamellite to the Dedham if only because of its limited extent, isolated occurrence, and great distance from the type locality. Moreover, its composition and areal relationships accord with those of the Andover Granite, and it seems likely that the two are correlative. The adamellite at Johnsons Pond accordingly is assigned to the subalkaline intrusive series.

## Adamellite near Middleton Pond

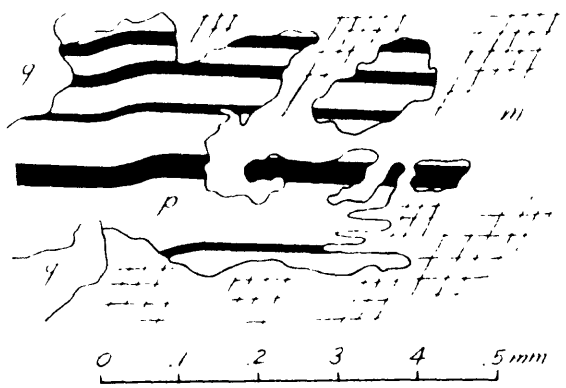
A poorly defined belt of generally adamellite rocks occurs south of Middleton Pond and north of the Ipswich River in the Reading quadrangle. The adamellite extends from Strawberry Meadow on the west to the quadrangle boundary on the east, but it is poorly exposed throughout the entire area. Accordingly, this adamellite "belt" subsequently may prove to be a discontinuous series of dikes and small, irregular bosses. Unmapped apophyses intrude much of the Sharpners Pond Tonalite cropping out north of the main adamellite body, and few exposures were discovered that did not contain xenoliths of older rocks.

The adamellite near Middleton Pond is characterized by its reddish color. The feldspar was a deep, chinese red in about half the outcrops examined by the writer, and no exposures were mapped with this unit that were not conspicuously pink or orange. The rock is uniformly massive, and it is generally allotriomorphic and fine to medium grained. The texture is characterized by intricate intergrowths between potassium and plagioclase feldspar (see figure 20), rather like those developed in the Andover Granite.

The adamellite is composed chiefly of feldspar and quartz. Viewed in hand specimen, the rock seems to contain but a single feldspar, but the discrete occurrence of microcline and plagioclase is clearly evident in this section. Between 25 and 40 percent of the adamellite is composed of

Figure 20

Composite thin section sketch of specimen from the mellite near Middleton Pond exposed 800 feet north of erside Cemetery, North Reading. q, quartz; p, plagio- se; m, microcline. Note the development of "island" ture in which the twinning in the isolated plagioclase ands" is continuous with that in the larger plagioclase tal.


q
m
p
q
0 .1 .2 .3 .4 .5 mm

clear, unaltered and slightly perthitic microcline. From 20 to 40 percent is made up of altered and somewhat deformed sodic plagioclase (see figure 20). Quartz composes from 25 to 30 percent of the rock and is characterized by pronounced strain shadows and highly serrated contacts. White mica occurs in part as discrete grains, but it is found primarily as an alteration product of plagioclase. Up to 4 or 5 percent of the adamellite is composed of chlorite, apparently derived from biotite. Epidote and apatite occur in accessory amounts. A modal analysis is presented in table 26.

Correlation

The generally red color of the adamellite near Middleton Pond is its most unique characteristic and affords a convenient basis for mapping this unit. The only other similarly colored granitic rocks in this area occur around the periphery of a small pluton assigned to the so-called "alkalic" intrusive series. However, Toulmin (1961, written communication), has correlated the Middleton Pond adamellite in the Salem quadrangle with what he defines as the Topsfield Granodiorite, a rock that seems to be clearly unrelated to the "alkalic" group. Moreover, the writer's studies of the adamellite point to a mineralogical and textural kinship with the Andover Granite. It seems reasonable, therefore, that the adamellite near Middleton Pond tentatively be included with the subalkaline intrusive

Table 26. Modal analysis of rock from adamellite near Middleton Pond[1/] [2/]

| | |
|---|---|
| Quartz | 30.4 |
| Plagioclase | 32.8 |
| Microcline | 28.2 |
| Perthitic albite | .8 |
| Chlorite | 2.0 |
| White mica | 5.8 |
| Epidote | .4 |
| Opaque | .2 |

1/ (R-109). Adamellite 800 ft. north of northernmost point in Riverside Cemetery, North Reading. Points counted: 500. Plagioclase composition $An_{8\pm4}$

2/ All figures volume percent

## Age of the subalkaline intrusive series

Rocks included here with the subalkaline intrusive series have been assigned ages ranging from Precambrian to post-Carboniferous. The precise age of the series is still in doubt, but considerable evidence now indicates that it almost certainly evolved during the middle or late Paleozoic.

The minimum age of the subalkaline series may be fixed fairly accurately by its relation to the Peabody Granite of the "alkalic" intrusive series (see discussion on the age of the "alkalic" intrusive series). The Sharpners Pond Tonalite clearly is intruded by the Peabody Granite, and the Peabody in turn is very doubtfully younger than earliest Pennsylvanian; the subalkaline series accordingly must be at least as old as Early Carboniferous. Earlier suggestions of a younger age for this series (Emerson, 1917, p. 86-87, 221; LaForge, 1932, p. 44) were based chiefly on the presumption that both the Nashoba Formation and Merrimack Group were Carboniferous.

The establishment of a maximum age for the subalkaline series is a difficult problem. Field criteria afford the best means of determining its maximum age, but they are far from unambiguous; available radiometric dates do little more than corroborate the probable minimum age of the series.

Billings (1956, p. 105-106) has assigned the Newburyport Quartz Diorite to the Precambrian. This age assignment, ...er.. is based on a series of highly speculative correlations among the igneous rocks of Essex County and granodiorites in southeastern Massachusetts that are overlain unconformably by fossiliferous Cambrian strata; this suggested Precambrian age is accordingly of doubtful validity. The entire series of subalkaline rocks intrudes the Marlboro, Boxford, and Nashoba Formations. If these metasedimentary and metavolcanic rocks are actually no older than Ordovician, the subalkaline series as well can be no older than Ordovician. Still another approach to the maximum age of the subalkaline series derives from the presence of pegmatitic rocks assigned to the Andover Granite within the Merrimack Group cropping out north of Lawrence. Granting the validity in correlation of both the pegmatite with the Andover and the Merrimack with Middle Silurian rocks in Maine, the subalkaline series must be no older than Silurian.

Perhaps the best and most sharply limiting field evidence pertaining to the maximum age of the subalkaline series stems from its relationships with the Upper Silurian Newbury Formation. According to Clapp (1921, p. 31), the volcanics of the Newbury Formation cropping out in the Parker River Basin (northeast of the map area of plate 1) have been deposited on an eroded surface of subalkaline rocks, presumably correlative with the subalkaline series of this area. Emerson (1917, p. 162), however, has noted that where the subalkaline rocks surround the Newbury Formation in the Parker River Basin, the "form of the boundary of the basin,...at least along its southeast side, indicates, though not conclusively, that the surrounding rocks are younger and have been intruded against the volcanic (Newbury) rocks." It was pointed out earlier that the adamellite near Middleton Pond is a compositional, but essentially contemporaneous variant of what has been mapped by Toulmin as the Topsfield Granodiorite. Toulmin (1961, written communication) has indicated, moreover, that the Topsfield "transects the structure of the Newbury Formation and separates the body of the Newbury Formation" in such a way as to suggest intrusion by the Topsfield. In addition, where the Newbury Formation crops out in the eastern Reading quadrangle it apparently is interrupted by the Newburyport(?) Quartz Diorite, and a locally exposed contact between the two is more suggestive of intrusion than faulting. Nevertheless, the sharp break in metamorphic grade between the Newbury Formation and the nearby Marlboro Formation is not easily explainable except through faulting (or a pre-Newbury metamorphism). Although the evidence, then, is somewhat ambiguous it is tentatively concluded that the subalkaline series post-dates the Upper Silurian Newbury Formation.

There are no radiometric dates for the subalkaline rocks exposed in this area. A few determinations are available, however, for several rocks from the more or less contemporaneously emplaced Fitchburg pluton. Unfortunately, age determinations for the granitic rocks of the Fitchburg [illegible] are not in particularly good agreement with each other and their value is limited accordingly. Most recently reported is a lead-alpha age of 286 million years for a binary granite from the Fitchburg pluton cropping out in southeastern New Hampshire (Lyons *et al.*, 1957, p. 535). This age is slightly less than the mean age (294±12 million years) as reported by Lyons et al. (*op. cit.*, p. 535) for the dated granitic rocks throughout southeastern New Hampshire. An age determination of 340 million years has been reported for a uraninite in the granite at Fitchburg, Massachusetts (Rodgers, 1952, p. 419), and a total lead-zircon age of 230±25 million years for a "mica diorite" from the Fitchburg Granite cropping out 2 miles west of Leominster, Massachusetts, has been reported by Webber, Hurley, and Fairbairn (1956, p. 58). According to Lyons *et al.* (1957, p. 536), ignorance of the original lead content vitiates the value of the uraninite determination; if the equivalence of the Andover and Fitchburg is conceded, however, the reported age of the uraninite is more in agreement with the facts than are the other ages from this pluton.

The evidence cited above is inconclusive, but the age of the subalkaline series probably falls between latest Silurian and Early Carboniferous. It is not unlikely, therefore, that the subalkaline series is essentially syntectonic with Acadian orogeny of early to middle Devonian age.

## Rocks of doubtful late Paleozoic age

Rocks considered under this heading are confined to a single formation: the Straw Hollow Diorite. There are few controls on the geologic age of this unit, and it is described at this point simply to conform with the order of presentation set forth by Hansen (1956, p. 45-47).

### Straw Hollow Diorite

Dioritic rocks cropping out adjacent to the westernmost salient of the Andover Granite in Hudson and Marlboro have been assigned to the Straw Hollow Diorite by Emerson (1917, p. 219-220) and Hansen (1956, p. 46-47). The unit is poorly exposed within the map area, and neither its relationships to surrounding rocks nor its geologic age have been clearly established. The Straw Hollow has not been studied by the writer and the following has been taken chiefly from Hansen's (op. cit., p. 46-47) description of the formation.

Emerson (1917, p. 219) noted that the rocks of the Straw Hollow "display a marked tendency to occur in, alongside of, or near lenses of Brimfield schist." Contacts between the Straw Hollow and adjacent units apparently are unexposed in the Hudson area, but the Straw Hollow does crop out in close proximity to the Andover Granite, and there is no apparent gradation between the two (Hansen, 1956, p. 47).

According to Hansen the Straw Hollow Diorite cropping out in Hudson is a medium-gray, generally massive and locally lineated, medium-grained rock. Emerson (1917, p. 220) discovered gneissose and schistose facies beyond the map area, and Hansen (1956, p. 47) has observed a foliation within the Straw Hollow near its borders. According to Emerson (1917, p. 220) the "rock is everywhere fresh and uncrushed," but Hansen (1956, p. 47) has found that it is locally sheared and fractured "as if to suggest deformation and movement within the mass after at least part of it had consolidated." The Straw Hollow exposed in Hudson is composed chiefly of plagioclase, hornblende, and biotite, together with lesser amounts of apatite and sulfides and local veinlets of quartz. Emerson (1917, p. 220) has found that it locally contains in addition small amounts of diopside and actinolite.

### Correlation and age

Judging from its lithology and association with the Brimfield Schist (and Nashoba Formation), it is conceivable that the Straw Hollow Diorite is the temporal equivalent of the hornblende gneiss contained within the Nashoba Formation exposed in Billerica. To the extent that this speculation is valid, the Straw Hollow may be considerably older than most of the other igneous rocks in the area. Emerson (1917, p. 220) assigned the Straw Hollow to the Carboniferous, for he thought it "a border variant or differentiate of the (Carboniferous) Andover granite magma." However, Hansen's observations on the absence of a gradational contact between the two formations would seem to refute this suggested age equivalence. Hansen (1956, p. 45-47) felt that the Straw Hollow Diorite was of late Paleozoic age, probably post-dating the Andover, for its foliation "appears to cut across that of the Gospel Hill gneiss (Andover Granite) at an angle of about 40°." Hansen's conclusion may be vitiated in part by the facts that this relationship does not hold true all along the contact, and foliation within the Andover at least is attributable chiefly to synkinematic intrusion or post-intrusion tectonism. Owing to the general absence of positive criteria, Hansen's views are adhered to here and the Straw Hollow Diorite is assigned to the upper Paleozoic.

### Carboniferous(?) igneous rocks
### ("Alkalic" intrusive series)

Clapp (1921) and others have observed that the igneous rocks of Essex County fall into two natural groups, to which Clapp gave the names "alkaline" and "subalkaline." Toulmin (1961, written communication) has renamed the alkaline group the "alkalic" intrusive series; the general term has been retained "because many of the rocks in the series contain peralkaline minerals." He has used the name between quotation marks, however, for "chemical analyses of the rocks do not support a peralkaline character for the series as a whole." The petrography and petrogenesis of the "alkalic" intrusive series cropping out in the adjacent Salem quadrangle have been discussed in detail by Toulmin (1960; 1961, written communication). For this reason and because but one member of the series is exposed locally to any significant extent, the "alkalic" series is discussed here only in detail sufficient to contrast its rocks with those of the subalkaline series.

According to Toulmin (1961, written communication) the "alkalic" rocks (of Essex County) are generally less calcic, have a higher ratio of alkalies to alumina, a higher ratio of iron to magnesium, and are less altered and deformed than the subalkaline rocks. In a chemical sense, the "alkalic" rocks of this area are most uniquely differentiated from the subalkaline group by a notably higher alkali-alumina ratio (and a correspondingly more peralkaline character). They do not, however, seem to be significantly less calcic than comparable subalkaline rocks. Regardless, differences in phase composition are perhaps of greater significance than chemical differences between the two intrusive series. Alkali feldspar tends to occur as discrete plagioclase and potassium feldspar phases in the subalkaline group, whereas microperthite is the characteristic alkali feldspar of the "alkalic" series. The predominant mafic phase in the "alkalic" granites is hornblende (a mineral totally absent from the subalkaline granites); biotite is the normally developed mafic mineral in the subalkaline granitic rocks.

The Peabody Granite and a few related dike rocks comprise almost the entire "alkalic" series in this area. A single outcrop of sodic trachyte or keratophyre is the only other locally occurring rock identified with the "alkalic" series.

## Peabody Granite

Rocks mapped with the Peabody Granite in this area formerly were mapped as Quincy Granite and consanguineous quartz syenite (see plates 1 and 2). However, Toulmin (1961, written communication) has concluded that in spite of their similarities, the differences between the Quincy Granite and the "alkalic" granites of Essex County "are sufficient to distinguish them." Toulmin accordingly has revived the name Peabody Granite, originally proposed by Clapp, for the "alkalic" granite cropping out in the southeast corner of the Reading quadrangle. The writer has applied this name to the so-called "quartz syenite" as well, for it is indistinguishable in outcrop from the type Peabody and seems very similar to the Peabody in its modal composition.

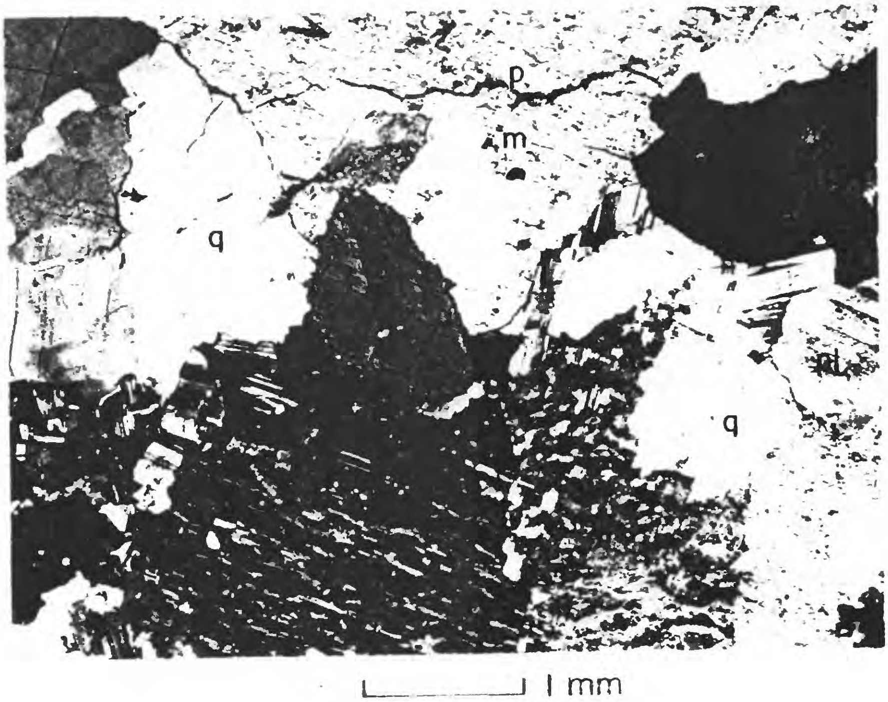
Most of the rocks assigned to the Peabody Granite are confined to two small stocks. The larger of these plutons, referred to here as the Peabody stock, occupies about 5 square miles of the southeast corner of the Reading quadrangle, where it intrudes the Marlboro Formation and Sharpners Pond Tonalite. The smaller intrusive is known as the Reading stock and occurs as a gourd-shaped body extending south from Reading center to the town of Wakefield. The Reading stock crops out over an area of about 2 square miles and clearly intrudes the Westboro-type quartzite as well as the Marlboro and Sharpners Pond. The Peabody Granite is very well exposed in the area south of Suntaug Lake and Pillings Pond, and moderately well exposed around Reading center and south of Lake Quannapowitt. Exposures of the Peabody Granite elsewhere are very limited.

Fresh exposures of the Peabody Granite are generally very light gray to bluish white and spotted with black hornblende crystals. On weathering the granite takes on a green to light-resinous-brown color, and in several intensely weathered parts of the Reading stock it has turned to a deep red brown. The granite of both stocks is characteristically massive. However, rocks exposed near the Bear Hill Golf Club in the Reading stock have been sheared extensively and presently are manifested as augen- or flaser-gneisses. Jointing is fairly common, and consistently oriented but widely spaced joint sets are particularly conspicuous in the Peabody stock. The texture of the Peabody Granite is uniformly coarse grained and ranges from hypidiomorphic to allotriomorphic. Idiomorphic habit is much more pronounced in the Peabody than it is in the granites of the subalkaline group (compare plates 29-32 with plate 49A). Finer-grained material commonly fills interstices between the generally coarse crystals, but the rock is nowhere truly porphyritic.

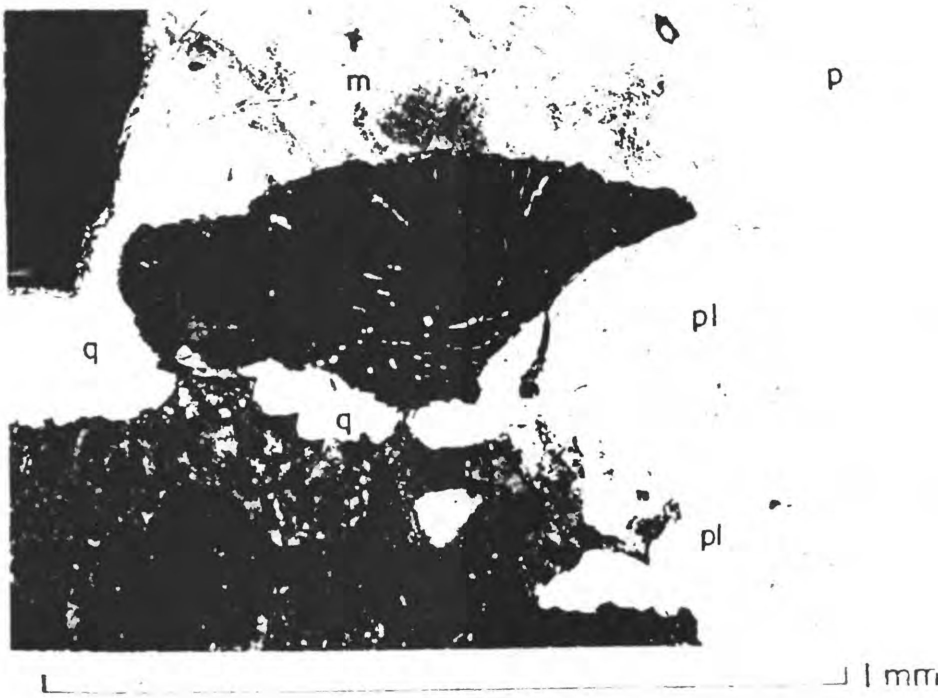
The mineral assemblage is consistent throughout both stocks and is characterized by the presence of microperthite, hornblende, and abnormally high amounts of zircon. Microcline-microperthite is the most prominent constituent of the Peabody and composes from 45 to 75 percent of the granite. It occurs chiefly as very coarse subhedral crystals that commonly show carlsbad twinning. Intraperthitic plagioclase lamellae locally comprise up to 50 percent of the microperthite and nowhere seem to compose less than 25 percent of this mineral. According to Toulmin (1961, written communication), "the bulk composition of microperthites from the Peabody Granite, as determined by chemical analysis and by x-ray diffraction methods on thermally homogenized samples, ranges from 47 to 52 weight percent Or. The plagioclase phase is albite, rarely sodic oligoclase." Plagioclase that occurs as discrete grains, optically discontinuous with adjacent intraperthitic plagioclase, has been designated "extraperthitic" by Toulmin (1961, written communication). Toulmin has reported extraperthitic plagioclase as sparingly developed in the Peabody Granite, but it composes from 5 to 10 percent of the specimens examined by the writer. It is generally albitic, ranging up to about

Plate 49

Photomicrographs of specimen from the Peabody Granite exposed 3300 feet south of Winona St.-Lake St. intersection, Peabody. q, quartz; p, perthitic plagioclase; m, perthitic microcline; pl, extraperthitic plagioclase; h, hornblende; a, allanite(?). Crossed nicols. A. Note the generally smooth crystal outlines. B. Note the development of myrmekite in extraperthitic plagioclase in the center of photograph. Note also that the perthite contains less plagioclase near its contact with the myrmekitic plagioclase than it does away from contact.




A




B

$An_{10}$. The extraperthitic plagioclase occurs mainly with quartz as a relatively fine-grained "groundmass" fringing coarse microperthite crystals (see plate 49A), and as discrete inclusions surrounded by microperthite. From 20 to 30 percent of the granite is composed of quartz. Quartz may compose considerably less than 20 percent of the rocks exposed south of Lake Quannapowitt in the Reading stock, but exposures are too few to consider the separation of a quartz syenite facies.

Very dark green hornblende is the chief mafic constituent in both the Peabody and Reading stocks, where it composes up to 8 or 10 percent of the granite. According to analyses supplied by Toulmin (1961, written communication), the hornblende is abnormally rich in iron and contains about "10 percent of the arfvedsonite component in solid solution." Dark-green clinopyroxene (of undetermined species) was seen in a single section from the Reading stock; Clapp (1921, p. 76) has reported hedenbergite and Toulmin has identified iron-rich augite from the Peabody stock. Tiny euhedral crystals of zircon were present in every section of the Peabody Granite examined. It generally composes one percent or less of the rock, but Toulmin (1957, oral communication) has discovered specimens containing several percent zircon. Accessory amounts of biotite and apatite occur locally.

Secondary minerals are best developed in the highly sheared rocks along the southern end of the Reading stock;

they include chlorite, epidote, and sericite. A mineral whose optical properties match those of allanite was seen in one section (see plate 49A).

Modal and chemical analyses of rocks from the Peabody stock cropping out east of this area are given in tables 27 and 28.

## Dike rocks

Dikes of the Peabody Granite fall into three general categories. The first consists of rocks indistinguishable in outcrop and thin section from those of the plutons. Examples occur along the southwest shore of Hawkes Pond and in the town of Stoneham west of the Bear Hill Golf Club. A second category is composed of seemingly hybrid rocks that are discussed in a subsequent section. The third type is described below and consists of rocks similar in appearance, but mineralogically unlike the normal granite. All three facies are probably transitional with each other, and none have been differentiated from the normal granite on the geologic map.

Dikes of the third category listed above are prominent in the area between the Peabody and Reading stocks. Most of these minor intrusives are unmapped, but in the area west of the Saugus River they attain moderate, mappable size. A leucocratic tonalite similar in appearance to some of the granitic dike rocks was discovered in this same zone.

Table 27. Modal analyses of rocks from the Peabody Granite[1/] [2/]

| | A. | B. |
|---|---|---|
| Quartz | 28.2 | 27.3 |
| Feldspar | 62.1 | 66.3 |
| Ferrohornblende | 7.7 | 3.7 |
| Pyroxene | | 1.4 |
| Biotite | .3 | .3 |
| Riebeckite(?) | | .2 |
| Opaque | 1.4 | .2 |
| Nonopaque accessories | .3 | .6 |

A. Average of two analyses. Granite from quarry along Route 128, Peabody, about one and one-half miles east of Reading-Salem quadrangle boundary

B. Granite from hill south of Lynnfield St., Lynn, about .9 mile east of Reading-Salem quadrangle boundary

1/ All figures volume percent

2/ Analyses supplied by Toulmin (1961, written communication)

Table 28. Chemical analyses and norms of rocks from the Peabody Granite

Chemical analyses[1/]

| | A. | B. |
|---|---|---|
| $SiO_2$ | 71.90 | 72.26 |
| $Al_2O_3$ | 12.98 | 13.18 |
| $Fe_2O_3$ | .81 | .24 |
| FeO | 2.85 | 2.77 |
| MgO | .02 | .20 |
| MnO | .08 | .10 |
| CaO | 1.04 | 1.10 |
| $Na_2O$ | 4.19 | 3.99 |
| $K_2O$ | 5.60 | 5.01 |
| $H_2O+$ | .20 | .20 |
| $ZrO_2$ | .12 | n. d. |
| $TiO_2$ | .34 | .36 |
| Sum | 100.13 | 99.41[2/] |

Table 28. (cont.)

Norms[1/]

| | A. | B. |
|---|---|---|
| Quartz | 22.95 | 25.60 |
| Zircon | .18 | |
| Orthoclase | 32.85 | 30.07 |
| Albite | 35.61 | 34.05 |
| Anorthite | | 3.06 |
| Wollastonite | 2.21 | 1.04 |
| Enstatite | | .50 |
| Ferrosilite | 4.48 | 4.35 |
| Magnetite | 1.16 | .46 |
| Ilmenite | .61 | .76 |
| Sum | 100.05 | 99.89 |

A. Granite, old quarry, South Lynnfield. Precise location unknown. M. F. Connor, analyst (Clapp, 1921, p. 78)

B. Granite from quarry along Route 128, Peabody about one and one-half miles east of Reading-Salem quadrangle boundary (Tuttle and Bowen, 1958, p. 81) Designated "Quincy granite" by Tuttle and Bowen. Location of quarry ascertained by Toulmin (1961, written communication)

Table 28. (cont.)

1/ All figures weight percent

2/ .07 $P_2O_5$, .04 $CO_2$, .08 $H_2O$ not included

It is possible, then, that some of the dikes correlated with the Peabody Granite actually belong to the Sharpners Pond Tonalite.

The coarse-grained dike rocks of the third category tend to be somewhat more quartzose than the normal Peabody, and the major mafic constituent is altered biotite rather than ferrohornblende. The feldspar of the more pegmatitic rocks has a distinct pinkish cast, and in some places it is deep orange red. The feldspar content differs somewhat from the normal granite in that there is considerably less microperthite and more extraperthitic plagioclase. The fine- to medium-grained dikes of this group were not studied microscopically, but they appear to be compositionally similar to the coarse-grained facies.

## Hybrid rocks

A zone of hybrid or mixed rocks commonly is developed where the Peabody Granite intrudes diorite or tonalite of the Sharpners Pond Tonalite. Good exposures of these hybrid zones are confined to roadcuts south of the Colonial Golf and Country Club in Lynnfield and south of Bear Hill near the Reading-Stoneham town line. The mixed zones range from a fraction of an inch to tens of yards in width and may surround the Peabody and Reading stocks. However, they have been observed only in those areas in which exposures are continuous, and no attempt has been made to delineate the hybrid rocks on the accompanying geologic map.

The hybrid zone exposed south of the Colonial Golf and Country Club is one in which the Peabody and Sharpners Pond rocks are transitional in terms of mineral composition, and not simply physically mixed. Traversing this zone from east to west over a distance of about 200 yards, one passes from clean hornblende granite into a somewhat more mafic plagioclase bearing rock that possesses a texture typical of the Peabody Granite, yet slightly finer-grained. The transition from granite to mafic hybrid rock is almost imperceptible; one is made aware of the change only by the presence here and there of small dikes of the more leucocratic granite. Toward the western end of the roadcut the rock is more typically dioritic with noticeably fewer dikelets of granite or pegmatite. The contact between diorite and granite is arbitrarily placed in the middle of this transition zone. Clapp (1921, p. 113-114) has reported igneous "shatter-breccias" in the mixed and hybrid zones, but true breccias are poorly developed in the contact zones exposed in the Reading quadrangle.

Petrographic studies of the hybrid zone south of the Colonial Golf and Country Club were not made in the course of the present investigation. Clapp (1921, p. 112-120), on the other hand, has examined the hybrid rocks in considerable detail and his petrographic observations accord with what may be deduced from field studies. Unfortunately, however, Clapp's descriptions are generalized over a broad area and it is not everywhere clear to what extent these generalizations apply locally. Clapp (1921, p. 116-118) found sodic plagioclase to be the chief feldspar of the hybrid rocks, locally complemented by the development of irregular patches of potassium feldspar or even microperthite. Where relatively calcic plagioclase remains, it generally is altered and surrounded by growths of unaltered alkali feldspar (op. cit., p. 116). A comparison of the chemical compositions of the hybrid rock near the Colonial Golf and Country Club, the Salem Gabbro-Diorite, and the Peabody Granite shows that, except for its relatively low $K_2O$ content, the composition of the hybrid rock is truly intermediate between diorite and granite.

The mixed and hybrid rocks exposed south of Bear Hill are developed on a considerably smaller scale than those near the Colonial Golf and Country Club. In this area a number of small granitic to syenitic and pegmatitic dikes cut the hornblende diorite facies of the Sharpners Pond Tonalite. Off-shoots of the granitic or pegmatitic dikes commonly are transitional with melanocratic alkali porphyries (see plate 50). The porphyries in turn are both sharply intrusive into and transitional with the diorite, and it is not uncommon to see these hybrid off-shoots with a sharp contact on one side and a transitional contact on the other (plate 50). Where sharp contacts occur between

Plate 50

Intrusion of hybrid "granite" dike in Sharpners Pond Tonalite exposed in large roadcut south of Bear Hill, Reading. Note gradational, "diffusive" contact between granitic material and diorite on right side of photograph.

the diorite and intruding dikes, phenocrysts of pink alkali feldspar commonly are developed near the contact, but within the diorite. None of the dikes were found to have chilled margins at their contacts with the diorite.

## Origin

The origin of the Peabody Granite and associated rocks has been discussed in detail by several writers (Clapp, 1921, p. 71-85, 107-109; Toulmin, 1960). Accordingly the petrogenesis of these rocks is discussed here only briefly, and the reader is referred to the above writings for a more comprehensive treatment.

The general uniformity of the Peabody suggests crystallization from an homogeneous magma under relatively stable P-T conditions. The prevalence of microperthite rather than two discrete alkali feldspar phases, points to primary crystallization under relatively low $P_{H_2O}$ (or $a_{H_2O}$) at temperatures above 660°C. (Tuttle and Bowen, 1958, p. 74-75). $P_{H_2O}$ certainly must have been below 4000 kg/cm$^2$, and Toulmin (1960, p. 283) has concluded that it "must have been considerably below 2000 atm and was probably about 1000 atm"; the basis for this latter conclusion, however, is unclear to the writer. There is, of course, no way to extrapolate from a suggested condition of low $P_{H_2O}$ to one of low $P_{total}$. In fact, the Peabody Granite may have crystallized under considerable pressure. The generally coarse-grained texture of the granite and the thorough hybridization of some of the contact rocks are both compatible with slow cooling (if low concentrations of fugitive components may be presumed), which in turn suggests the presence of a substantial insulating cover.

Crystallization probably began in the alkali feldspar field. The quartz field may have been intersected shortly thereafter with continued crystallization along the alkali feldspar - quartz cotectic (see figure 14A). Extraperthitic plagioclase apparently began its precipitation relatively late in the crystallization history, judging from its interstitial and limited occurrence in the granite. Whether or not this may be attributed to the development of a progressively more calcic (and less potassic) magma is moot; it might relate as well to the approach and intersection of the solidus and solvus feldspar boundaries in response to increasing $P_{H_2O}$. There are no reliable criteria to indicate when the ferrohornblende may have begun and ended its crystallization. In all probability hornblende, an alkali feldspar, and quartz were precipitated simultaneously through much of the magmatic history of the Peabody Granite.

## Correlation

The Peabody Granite, in a broad sense at least, is correlative with the other "alkalic" granites of Essex County. Moreover, "petrographic similarities between the ("alkalic") granites of Essex County and the Quincy Granite are much more striking than their differences, and the general correlation of the two groups seems justified" (Toulmin, 1961, written communication).

There seem to be no field or petrographic characteristics that distinguish the "alkalic" granites of Essex County from those of the White Mountains plutonic series of New Hampshire (Toulmin, 1961, p. 778). On the other hand, field evidence and radiometric ages indicate that the Quincy Granite is Carboniferous or older, whereas the White Mountains series may be as young as Triassic (*op. cit.*, p. 776-777). Nevertheless, there are a number of subtleties involved, and it is not yet certain that two distinct magmatic series are represented. For example, Toulmin (*op. cit.* p. 778) has pointed out that "there is no clear cut geographic break in the distribution of the 'alkalic' rocks," and there conceivably may be "a complete gradation in age among all the 'alkalic' rocks of New England." Contrarily, the writer's studies in this area suggest the presence of a major structural discontinuity along the northern edge of the "alkalic" rocks of Essex County (see section on structural geology, this report). Accordingly, the writer for the present is inclined to doubt a temporal equivalence or common magmatic source for the "alkalic" rocks of the White Mountains plutonic series and those of Essex County.

Bell (1948, p. 97) has defined a granitic unit cropping out along the northern edge of the Boston North quadrangle as the "Stoneham red granite." According to Bell (*op. cit.*, p. 98), this rock has a cataclastic texture, is composed principally of microcline and microperthite, and is characterized by alteration of all the original mafic minerals to chlorite and epidote. Owing chiefly to the degree and nature of its alteration, Bell considered the Stoneham red granite a variant of the Dedham Granodiorite. However, the description of the Stoneham is compatible with that of the sheared granite that occurs at the southern end of the Reading rock. For this reason and because of its apparent continuity with the Peabody Granite of the Reading stock, the writer prefers to view the Stoneham red granite as a sheared and altered facies of the Peabody.

### Trachyte south of Middleton center

A single exposure of sodic trachyte or keratophyre occurs south of River Street in Middleton, near the eastern border of the Reading quadrangle. It is the only example of a non-oversaturated alkalic rock discovered in this area, and because of its unique composition it has been delineated separately on the geologic map. Although the writer has no real knowledge of the shape or extent of the trachyte body, it is assumed to be relatively narrow and roughly conformable with the regional strike.

The trachyte is very light gray with flecks of black on fresh surfaces and weathers to a deep-brown color. It is apparently massive, and in this particular exposure it is highly fractured. The rock is generally fine grained, hypidiomorphic, and essentially equigranular, but it ranges toward a poikilitic and porphyritic texture. The groundmass is composed of an interlacing network of albite laths, not unlike that of the so-called "bostonite."

The rock is composed chiefly (up to 70 percent) of albite that occurs mainly in the groundmass. Potassium(?) feldspar phenocrysts make up about 10 percent of the rock. Aegirine-augite composes up to 10 percent of the trachyte and occurs as concentrations of small grains that are in part remnants of larger phenocrysts, since altered to chlorite, albite(?), sericite, and epidote(?). Flourite and optically positive riebekite or barkevikite are present in small amounts.

The origin of the trachyte is unknown. Its genesis may be related to that of nearby syenites whose origin has been attributed by Toulmin (1960, p. 284-285) to feldspar showers developed in response to volcanic dehydration of a granitic magma.

## Age of the "alkalic" intrusive series

The age of the "alkalic" series is important to an understanding of the geologic history of northeastern Massachusetts, if for no other reason than that it puts a minimum age on the mélange of rocks that it intrudes. Assuming a temporal equivalence among the "alkalic" rocks of eastern Massachusetts, field evidence alone permits the establishment of a minimum age for the series and is believed to provide a maximum age as well. Radiometric dates tend to corroborate the field estimates and imply that the "alkalic" series probably belongs at the younger end of the age range suggested by areal studies.

The Peabody Granite intrudes the subalkaline series of this area, which in turn is believed to intrude the Upper Silurian Newbury Formation. "In the Quincy and Blue Hills area the Quincy granite and associated rocks are intruded into and include masses of the Cambrian Braintree slate, and the granite is possibly also intruded into the (Devonian?) Dedham granodiorite. The Quincy granite...is in fault contact with the presumably younger (Carboniferous) Roxbury conglomerate of the Boston Basin, in which, however, no certainly identified pebbles of the granite have been found. On the south the Blue Hills granite porphyry, which is associated with the Quincy granite, is overlain by and has furnished material to the Carboniferous Pondville conglomerate" (Emerson, 1917, p. 188). The Pondville in turn is conformably overlain by the Wamsutta Formation that since has been dated paleontologically as lower Allegheny (lower Pennsylvanian) (Knox, 1944, p. 137-138). Considered in their entirety, the field relationships seemingly bracket the "alkalic" series between uppermost Silurian and lowermost Pennsylvanian.

A number of radioactive age measurements have been made on the "alkalic" granites in recent years. Webber *et al*. (1956, p. 580) obtained lead-alpha ages ranging from 235 to 290 million years for the Peabody and Cape Ann granites. Quinn *et al*. (1957, p. 556, 558) have reported lead-alpha ages of 273 and 275 million years for the Peabody Granite and have concluded that the average age for the Rhode Island and Massachusetts "alkalic" granites is 270±7 million years. Hurley *et al*. (1960, p. 253) obtained a K-Ar whole-rock age of 280±15 million years for the Quincy Granite, but they noted that owing to argon leakage from feldspar, this is a minimum age only. The most recently determined radiometric age known to the writer is a K-Ar hornblende date of 345±15 million years obtained from the Cape Ann Granite cropping out near Rockport, Massachusetts (Anonymous, 1960, p. 289).

In spite of the apparent concordance between the K-Ar whole-rock age for the Quincy Granite and lead-alpha ages obtained throughout the "alkalic" series, a figure of 270-280 million years is considered too low to be compatible with the observed field relationships. As the Quincy Granite K-Ar date is probably an extreme minimum, the writer is inclined to accept the Cape Ann K-Ar hornblende date of 345±15 million years as a more realistic figure. Thus, in accordance with Emerson's (1917, p. 187) deduction of half a century ago, the rocks of the "alkalic" intrusive series are assigned here to the lower Carboniferous.

## Rocks of Mesozoic(?) age

### Triassic(?) igneous rocks

Diabasic or doleritic dikes, presumably unrelated to other mafic intrusives in the area, occur in the Lawrence, Reading, and Wilmington quadrangles. The diabase in the Lawrence quadrangle is very fine grained, whereas that in the Reading and Wilmington quadrangles is somewhat coarser grained and commonly porphyritic.

The age of the dikes is inferred chiefly from their apparent correspondence with the Triassic diabase of the Connecticut Valley. The two groups are lithologically similar, and both are demonstrably post-orogenic and comprise the youngest igneous rocks in their respective areas.

#### Basic dike in the Lawrence quadrangle

A single diabase dike has been mapped in the Lawrence quadrangle, where it occurs as an essentially vertical sheet, 20 to 30 feet thick (the width has been slightly exaggerated on the accompanying geologic map). It trends at a small angle to the regional foliation and contains numerous xenoliths of the host granite-gneiss.

The diabase is dark greenish gray to black on fresh surfaces and weathers rusty gray to reddish brown. It is massive throughout and shows no apparent foliation or lineation. If a chilled border is present along its contacts, it is not discernible to the naked eye. The rock is generally very fine grained and hypidiomorphic; matted laths of plagioclase are intergrown with pyroxene (now altered largely to chlorite) to form a poorly defined ophitic texture.

The diabase is composed chiefly of plagioclase, chlorite, and pyroxene. Sericitized plagioclase composes up to 40 percent of the rock and ranges from calcic andesine to sodic labradorite. The pyroxene is identified tentatively as magnesian augite and initially composed up to 50 percent of the rock. It occurs chiefly as small interstitial grains between plagioclase laths. Chlorite occurs with both finely disseminated magnetite pseudomorphously after pyroxene phenocrysts, and scattered throughout the groundmass.

### Basic dikes in the Reading and Wilmington quadrangles

A number of locally porphyritic diabase dikes or necks crop out in the southern Wilmington and Reading quadrangles and are well exposed around the cloverleaf intersection of Routes 28 and 128. The diabase is greenish black, fine to medium grained and massive. The porphyritic facies contain tabular plagioclase phenocrysts that measure up to 1 inch in diameter. Except for the dike intruding the Peabody stock, there is generally little evidence of chilling along the diabase margins.

The diabase in the Reading and Wilmington quadrangles is composed chiefly of plagioclase and pyroxene. The plagioclase is labradoritic in composition and accounts for about 55 to 60 percent of the rock. It occurs mainly as lath-shaped, poorly zoned, and moderately sericitized crystals. Pyroxene composes up to 30 percent of the diabase and was identified as pigeonite by the writer on the basis of its very low 2V. Toulmin (1960, written communication), however, has identified as augite the pyroxene in the diabase cutting the Peabody stock and has suggested theoretical reasons for doubting the writer's pigeonite identification. The pyroxene is partly uralitized to hornblende and locally altered to chlorite. Magnetite composes up to 5 percent of the diabase and is locally intergrown with chlorite with which it is pseudomorphous after pyroxene.

The non-porphyritic diabase is similar in hand specimen to melanocratic rocks from the Sharpners Pond Tonalite. Accordingly it may have been overlooked locally, and many of the rocks mapped with the hornblende diorite may actually be diabase. The converse is unlikely.

## Structural geology

Many or most of the rocks in this area have been intensely folded or otherwise deformed; there is a suggestion that the older rocks have been subjected to at least two major deformations. The resulting structures are extremely complex and the structural complexity has been further obscured by the extensive intrusion.

The dominant structural characteristic is the generally northeastward trend of both the foliation and the belts of metasedimentary rocks; divergence from this pattern is best displayed by the Boxford Formation, the Fish Brook Gneiss, and the Marlboro Formation and Brimfield-type schist cropping out in the Concord quadrangle. The rocks of the Merrimack Group lie on the southeast limb of a postulated major anticlinorium (Billings, 1956, p. 113-114); the Nashoba Formation crops out along the eastward extension of a supposedly synclinorial belt mapped to the southwest (Hansen, 1956, p. 51). Formations exposed southeast of the Merrimack Group and Nashoba Formation have not been associated previously with any particular structural feature.

Because of the many obscure structural relationships, discussion of structural features has been divided arbitrarily into sections on (1) minor, observable structures and (2) major, inferred structural elements that cannot be observed directly.

## Minor structures

### Foliation

Foliation in its various forms is the most conspicuous of the small scale structures observed in the area. It is also the only structural element that has proved particularly useful in elucidating the overall geologic relationships. Definition of foliation in both intrusive and metamorphic rocks ranges from excellent to poor. It is most easily measured in the Boxford, Marlboro, and Kittery.

### Bedding

Bedding attitudes have been mapped chiefly in the Kittery Quartzite. The bedding in the Kittery is defined by alternating layers of quartzite and quartz-mica schist and possesses a consistent northeasterly strike and northwesterly dip. Bedding also has been mapped by the writer in the Westboro-type quartzite and by Cuppels (1962, written communication) in the Marlboro Formation, Brimfield-type schist, and Nashoba Formation cropping out in the Concord quadrangle. It is doubtful, however, that structures mapped by Cuppels as bedding east of the Lincoln-Lexington town line in the Concord quadrangle are actually bedding; the rocks in this area are on strike with a major shear zone known to exist in the Wilmington quadrangle.

## Cleavage

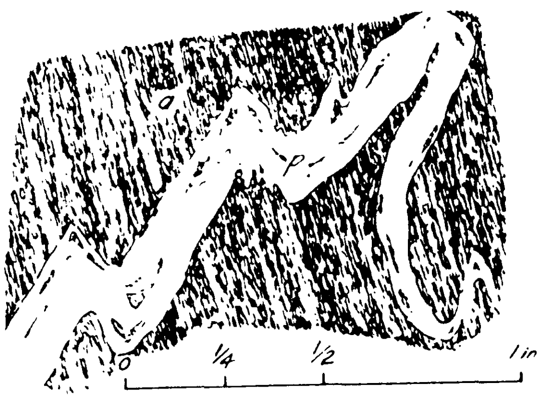
The Kittery Quartzite is the only formation east of 71°15' in which cleavage has been mapped, for it is the only unit in which it occurs at a distinct angle with identifiable bedding and thus is not mimetic. The cleavage attitudes in the Kittery are similar to those of the bedding in that they strike to the northeast and dip to the northwest. The dip of the cleavage, however, is more uniform than that of the bedding over the limited area in which both have been mapped. Cleavage also has been mapped within the Brimfield-type schist where it crops out in the Concord quadrangle (Cuppels, 1962, written communication). Its attitude here is almost at right angles with what has been mapped by Cuppels as bedding.

## Undifferentiated foliation

Most of the planar structures in this area are mapped simply as undifferentiated foliations (*s*-surfaces). Much of the undifferentiated foliation, particularly in the Boxford Formation, doubtlessly is coincident with or parallel to bedding, but the presumed mimetic relationship generally cannot be proved. In places the writer has observed a pronounced divergence in attitude between the dominant foliation and lithologic layers within the rocks (see figure 21); this relationship is perhaps a common one, but it

Figure 21

Folded prehnite (p) layer contained within amphibolite (a) of the Marlboro Formation exposed 3800 feet south of Chestnut St.-Lowell St. intersection, Lynnfield.



p
0
1/4
1/2
1 in

is usually detectable only where a strong lithologic contrast exists between layers. Many of the planar features, particularly in the Marlboro Formation, are identifiable shear surfaces paralleling lithologically distinct layers. Locally, however, the shear surfaces occur at small angles with these layers; as one structure or the other generally is dominant, the presence of the second planar feature commonly may be detected only with the aid of the microscope.

Foliation in the plutonic rocks is the result of (1) primary flow, (2) recrystallization of tabular or linear minerals in a preferred orientation, or (3) shearing (see plate 24A). The presence of primary foliation is difficult to demonstrate in the plutonic rocks, for many of the intrusive bodies are broadly concordant and their contact zones commonly are poorly exposed. What is thought to be primary foliation occurs mainly in the binary granite facies of the Andover Granite. Recrystallization in a preferred orientation has not been demonstrated in any of the plutons cropping out locally. Foliation attributable to the pervasive shearing of plutonic rocks is particularly common in this area, especially in the granite-gneiss facies of the Andover.

## Minor folds

Minor folds have been mapped locally in the Marlboro, Boxford, and Nashoba Formations. Apparently they are conspicuous in the Nashoba Formation exposed in the Hudson and Maynard quadrangles (Hansen, 1956, p. 52), but they are completely absent over large parts of the map area. Detailed mapping does suggest (see plate 1), however, that there may be many small folds with wave lengths just above those detectable through direct observation.

Structures mapped as minor folds range in size from a few inches across to those with wave lengths of 2 or 3 yards. They range in style from open forms to tight, isoclinal features and are more generally evident in the gneissic rocks. Owing chiefly to limited exposure and in part to the effects of shearing, there are no more than three or four places east of 71°15' where these minor folds may be interpreted as drag folds. Hansen (1956, p. 52) and Cuppels (1962, written communication), however, have recorded what appear to be drag folds in the Nashoba Formation. Although many of the minor folds are probably of the parallel slip type, some of those in the Marlboro Formation in particular seem to have arisen in part through a process of shear folding (see figure 21).

The plunges of the minor fold axes range from almost vertical through almost horizontal. The few fold axes mapped in the Marlboro Formation east of 71°15' plunge generally northeast at relatively shallow angles; those cropping out in the Marlboro Formation exposed in the Maynard quadrangle are characterized by a somewhat erratic orientation pattern, but they plunge generally north at relatively steep angles. The fold axes mapped in the Boxford Formation near Hoveys Pond plunge generally northwest at angles ranging from 40° to almost vertical. Mappable fold axes in the Nashoba Formation occur entirely west of 71°15'; most plunge gently west-southwest and their declivities in general increase toward the east.

Only the axes of the minor folds have been mapped in most places; axial planes have been mapped locally, chiefly in the Boxford Formation.

## Undifferentiated linear elements

Structures mapped simply as linear elements are distributed over much of the map area, but their density is nowhere particularly high. Linear elements mapped east of 71°15' consist chiefly of tiny crenulations (in effect, minor folds of extremely short wave length); the axial lines of a few minor warps or undulations in the Boxford Formation also have been included in this group. Undifferentiated lineations mapped elsewhere in the area include mineral streakings and roddings as well as crenulations or wrinklings (Hansen, 1956, p. 56; Cuppels, 1962, written communication). Attitudes range widely among the linear elements, but they commonly approach those of any minor folds that may be exposed nearby.

The intersection of cleavage with bedding ideally defines a line paralleling the axis of the including fold. The plunges of bedding-cleavage intersections in the Kittery Quartzite, however, are commonly steep and generally fail to agree with the shallower plunges suggested by the orientation of other linear elements and geometric analysis of the foliation. Bedding-cleavage lines have not been mapped separately inasmuch as they may be deduced from the individually recorded attitudes of bedding and cleavage.

## Jointing

Jointing is developed in every formation in the area; sheeting that is commonly indistinguishable from "tectonic" jointing is developed locally. However, joints have not been mapped nor have they been systematically studied in any way during the course of the present investigation.

## Major structures

Inferred major structures in this area are shown on the generalized geologic map in figure 22. The hypothetical distribution and configuration of major faults in the Lawrence, Wilmington, South Groveland, and Reading quadrangles are represented in figure 23 as they might have obtained had there been no major intrusion in this area. The positions, and in some cases even the existence, of these major structural elements commonly are little more than considered guesses. Although most of the structures shown in figure 22 probably had been developed to some extent prior to intrusion, there is much evidence that intrusion was at least in part synkinematic and prekinematic. Delineation of the inferred major structures has been based chiefly on stratigraphic considerations, orientation of minor structures, and petrographic evidences of deformation.

Minor structures other than planar features have been of limited value in defining the locally developed major structures. Although locally consistent, orientations of small fold axes and other lineations commonly range widely over short distances. Crenulations are prominent, for example, in the unnamed gneiss in the Reading quadrangle, but the attitudes of their axes vary considerably over the width of a single exposure.

## Folds

The presence of relatively large folds in this area is suggested in only a few places owing chiefly to poor stratigraphic control. The general configuration and attitudes of most of the hypothesized folds is based on the map patterns of local marker units coupled with interpretation of the available structural data. The terms "anticline" and "syncline" are employed here in their geometric of spatial context only; folds generally concave downward are regarded as anticlines, whereas those concave upward are considered synclinal. Relative positions of units within folds do not necessarily position the considered units stratigraphically.

In an effort to define the geometry of the folds more precisely, $\pi$ diagrams (plots of poles to s-surfaces on stereographic or equal area nets) have been constructed for several formations or groups cropping out east of 71°15'. The extent to which the individual $\pi$-poles are coincident with the great circle they crudely define is a measure of the approach to cylindroidal folding in the rocks; thus the pole to the great circle defined by the $\pi$-poles roughly parallels the major fold axis in the considered area. Although specifically constructed for a particular formation or group, each diagram is representative of a moderately well defined map area as well owing to the general restriction of individual formations to limited parts of the area.

Measurements were selected for plotting by laying a grid over the map area and taking the most northwesterly dip and strike from each grid unit (many grid units, of course, were devoid of any sort of structural data owing to the local absence of outcrop). In this way errors resulting from overweighting structural data in areas of good exposure tend to be minimized. The only conscious departures from this semi-statistical approach consisted of (1) obtaining as wide a range of dips as possible in order to better define the individual circles and (2) selecting additional measurements from each grid unit in an attempt to represent separately the smaller folds in the Boxford

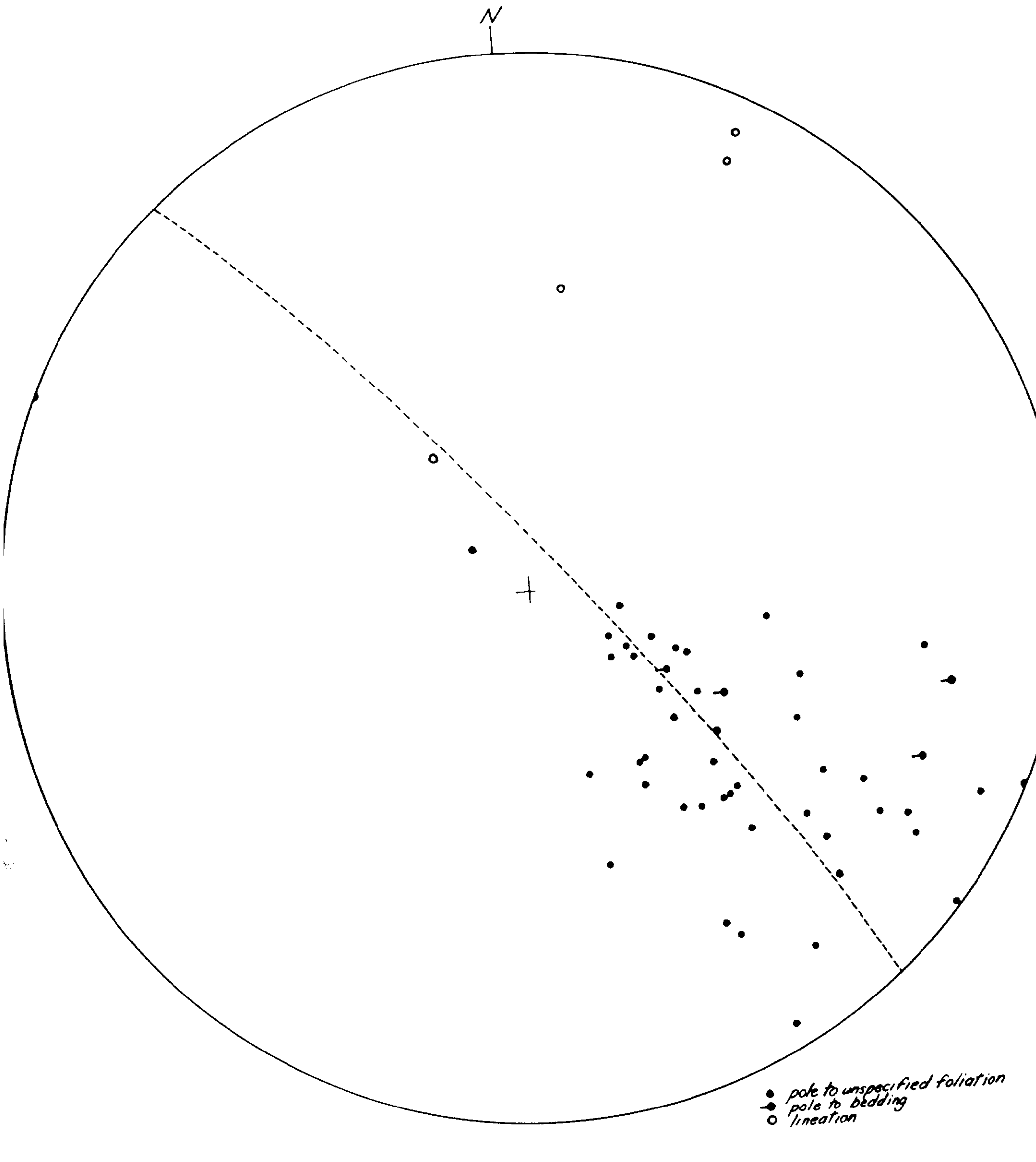
Formation. Minor fold axes and undifferentiated lineations have been superimposed on the $\pi$-diagrams for comparison.

The $\pi$-diagrams locally are subject to ambiguous interpretation. For example, in the event of multiple deformation the orientations of the plotted s-surfaces may not be representative of the major fold. Whether or not this is the case commonly may be deduced from the style of folding or configuration of s-surfaces in outcrop; it is doubtful that subsequent deformation in the units considered here has modified the orientations of s-surfaces sufficiently to obscure the $\pi$-pole pattern of the major folds. Still another condition leading to ambiguous interpretation is moderate departure from cylindroidal folding; this is probably the case in at least one of the units investigated.

It was noted in the introductory remarks that the locally exposed Merrimack Group is thought to lie along the southeast limb of a major anticlinorium; the bunching of $\pi$-poles in the southeast quadrant of the plot in figure 24 indicates that this limb is generally overturned to the southeast. The fold axis obtained through construction of a $\pi$-diagram based on unspecified or undifferentiated foliations (s-surfaces) plunges very gently to the southwest; the fold axis that might be obtained by employing bedding attitudes only would plunge gently to the north-northeast. Folding in this unit thus is either non-cylindroidal or the attitudes of the actual axial elements are substantially

Figure 24

Lower hemisphere Schmidt net plot of poles to s-surfaces ($\pi$ diagram) and lineations in the Merrimack Group. Statistically defined fold axis is normal to the great circle represented by dashed line.


N
pole to unspecified foliation
pole to bedding
lineation

different over the considered area. Perhaps significantly, the attitudes of the plotted lineations more nearly accord with the deduced north-northeast trend of folding. The presumed presence of the two northwesternmost folds shown within the Kittery Quartzite in figure 22 is based on the occurrence of the acinolitic quartzite facies along their supposed axes; the assumptions are made that this facies characteristically developed in the lower parts of the section and that the Kittery actually does occur along an anticlinorial limb. The existence of these particular folds, however, is open to great doubt if only because the definition of the actinolitic quartzite facies itself is very poor. The other two northeast-trending folds within the Kittery Quartzite in figure 22 are defined entirely on the basis of bedding-cleavage relationships; the assumption is made that the measured cleavage attitudes parallel the axial planes of the major folds. The magnitudes of these folds is highly speculative; consistency and spacing of structural observations suggest that the anticline has a width or wave length of at least one-half to three-quarters of a mile. The presence of the syncline is suggested on the basis of a single observation and its eastward extent is unknown. In accord with the notion of general overturn to the southeast, the southeast limb of the anticline (northwest limb of the syncline) apparently is overturned.

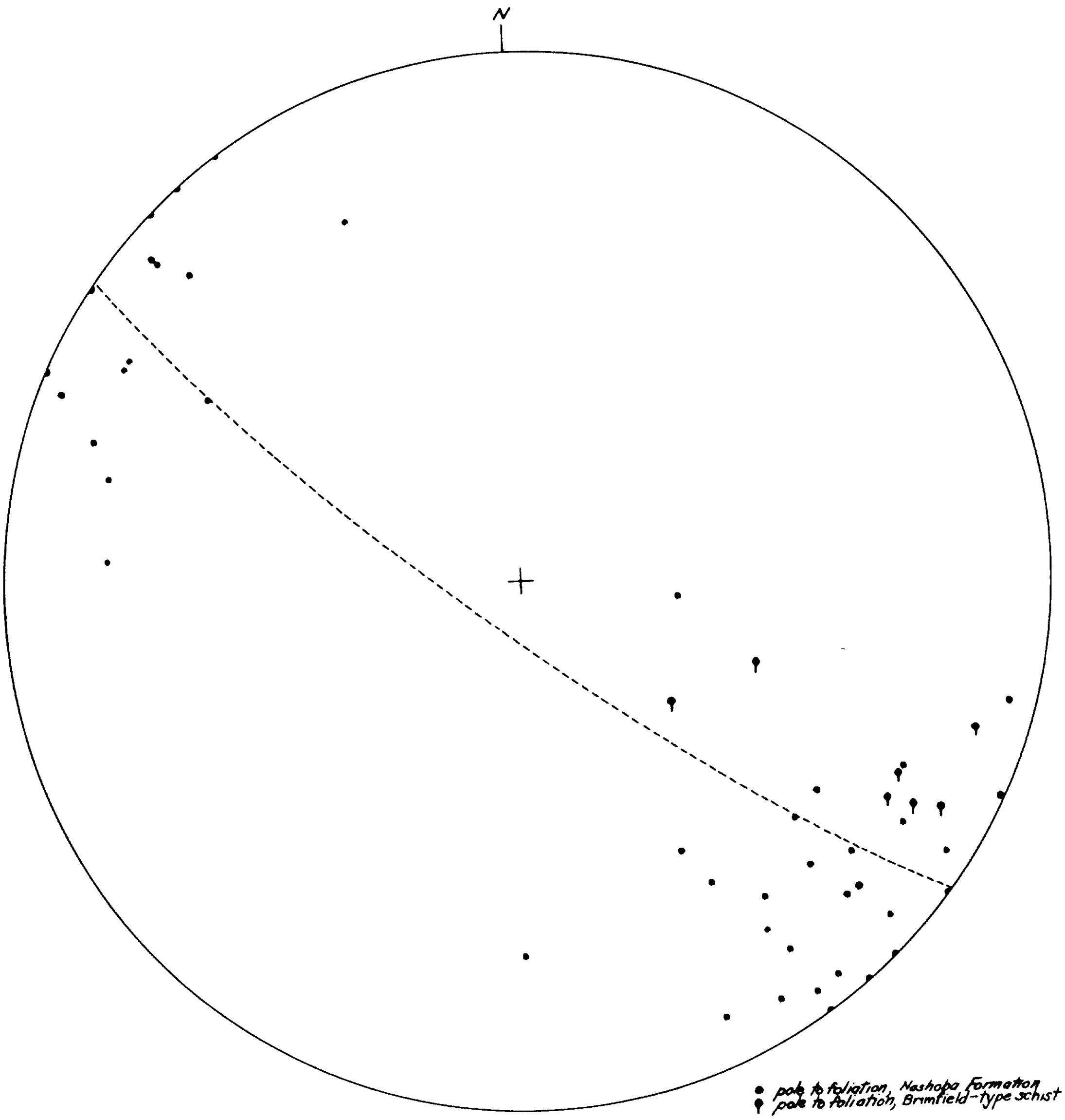
The syncline shown within the northern belt of the

Nashoba Formation in figure 22 is an extension of one thought to exist in the Hudson quadrangle (Hansen, 1956, p. 51, pl. 1); its presence in this area is largely speculative. The map pattern of the Nashoba Formation and Brimfield-type schist suggests only that these two apparently conformable units pinch out to the northeast, and it is likely that this pinchout is in part the reflection of a plunging fold. The recorded minor fold axes along the eastern reaches of the Nashoba Formation (see plate 1, this report; Hansen, 1956, pl. 1) plunge generally southwest, suggesting that major folding in this unit is more likely synclinal than anticlinal. There is, however, no structural evidence east of 71°15' tending to corroborate this generalization; the statistically determined regional fold axis for the Nashoba Formation and Brimfield-type schist cropping out in this area, if anything, plunges very gently to the northeast (see figure 25). Regardless of the form of any particular major fold in the Nashoba Formation, the $\pi$ diagram in figure 25 indicates that folding in this area is generally isoclinal; the degree of overturn, moreover, apparently is significantly less than that suggested for the Merrimack Group cropping out in the Lawrence and South Groveland quadrangles.

Folds shown in the Boxford Formation (figure 22) have been defined chiefly through detailed mapping of lithologies and minor structures; the most anomalous folding discovered

Figure 25

Lower hemisphere Schmidt net plot of poles to s-sur-
es ($\pi$ diagram) in the Brimfield-type schist and Nashoba
mation cropping out in the Lawrence and Wilmington quad-
gles. Statistically defined fold axis is normal to the
at circle represented by dashed line.


N
pole to foliation, Nashoba Formation
pole to foliation, Brimfield-type schist

in the course of this mapping is reflected by the sharp curve in the axial trace of the major anticline in the northeast corner of the South Groveland quadrangle. Although represented as simple forms in figure 22, the folds within the Boxford are believed to be extremely complex in detail (see geologic-sections, plate 1).

$\pi$ diagrams have been constructed for the area over which the Boxford Formation crops out; $\pi$-poles plotted for the entire outcrop area show an extremely weak preferred orientation and the diagram in figure 26 is geometrically useless. However, the degree of spread is reduced greatly if separate $\pi$ diagrams are prepared for each sub-area in which a major structural feature is believed to occur. Plunges in the different parts of the great anticline thus are seen to be very close to horizontal, but generally westward (see figures 27 and 28). Lineations plotted in figures 27 and 28 seem generally unrelated to the regional fold axes defined by the $\pi$ diagrams; they may have evolved in a subsequent period of deformation, perhaps concomitantly with the large bend in the major anticline. The plunge of the statistically defined fold axis for the small syncline in the north-central South Groveland quadrangle (figure 29) is very steep relative to that obtaining in both segments of the great anticline; the probably steep plunge is corroborated, moreover, by the plunges of the small fold axes shown in the same figure.

Figure 26

**Lower** hemisphere Schmidt net plot of poles to *s*-surfaces ($\pi$ diagram), small fold axes, and other lineations n the **Boxford** Formation.

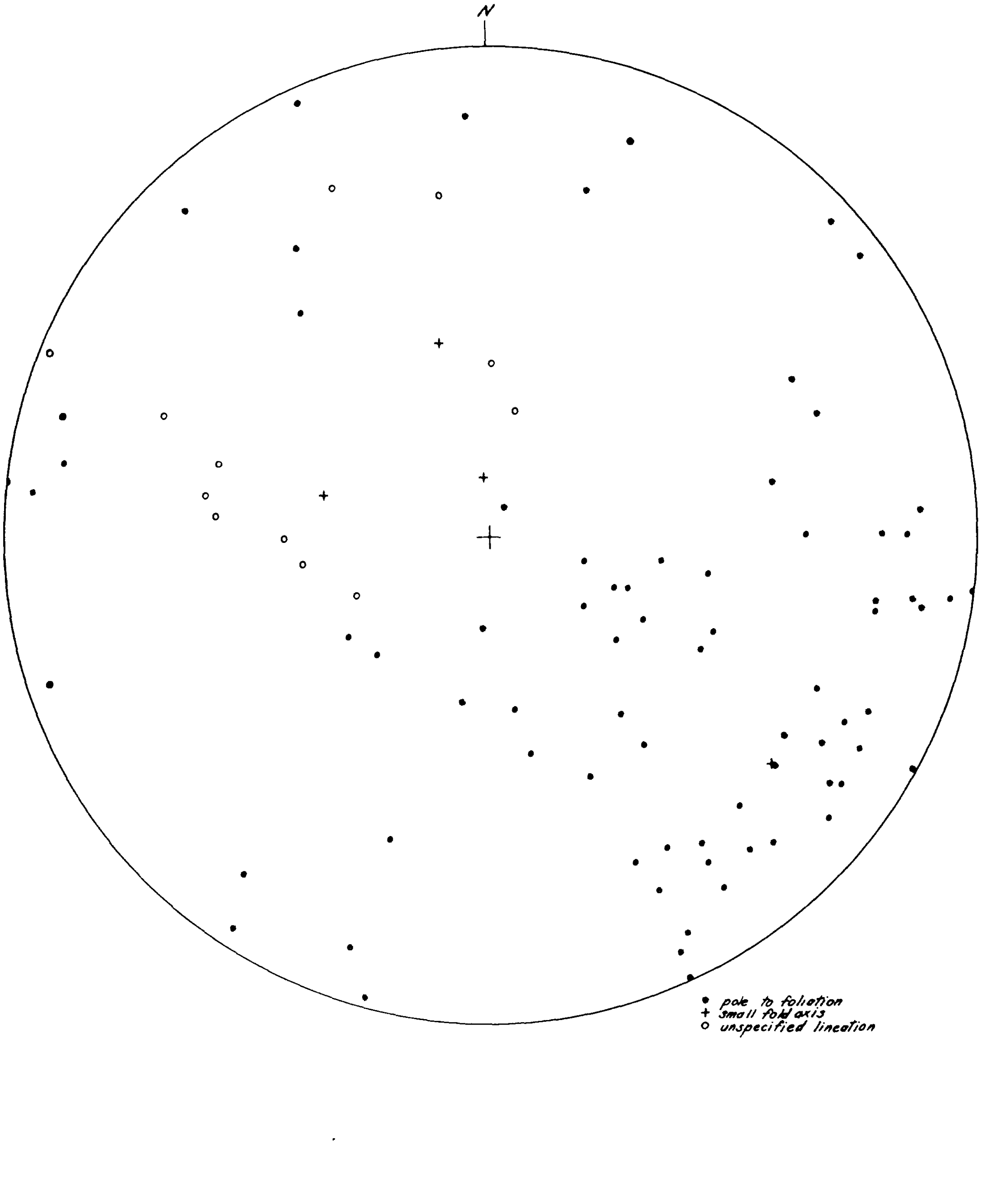

N
pole to foliation
small fold axis
unspecified lineation

Figure 27

Lower hemisphere Schmidt net plot of poles to s-surfaces ($\pi$ diagram) and lineations in that part of the Boxford Formation cropping out along the major northeast trending anticline. Excludes data from that area in which the apparent trend of the fold is to the northwest. Statistically defined fold axis is normal to the great circle represented by dashed line.

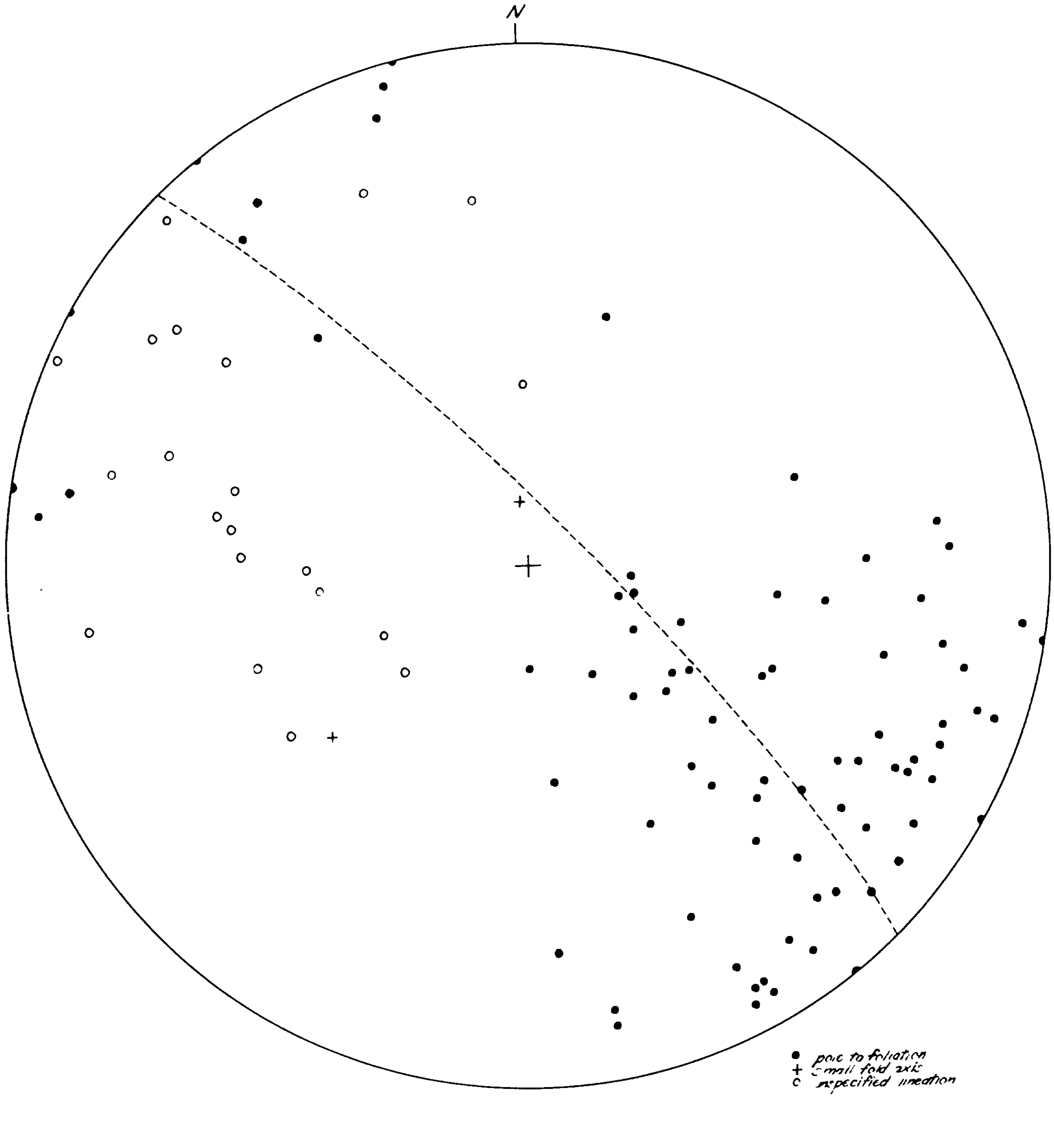

N
pole to foliation
small fold axis
unspecified lineation

Figure 28

Lower hemisphere Schmidt net plot of poles to s-sur-ces ($\pi$ diagram) and lineations in that part of the Boxford mation extending approximately 1.5 miles west of eastern der of area. This stereogram encompasses that part of Boxford Formation in which the major anticline apparent-curves to the southeast. Statistically defined fold s is normal to the great circle represented by dashed e.

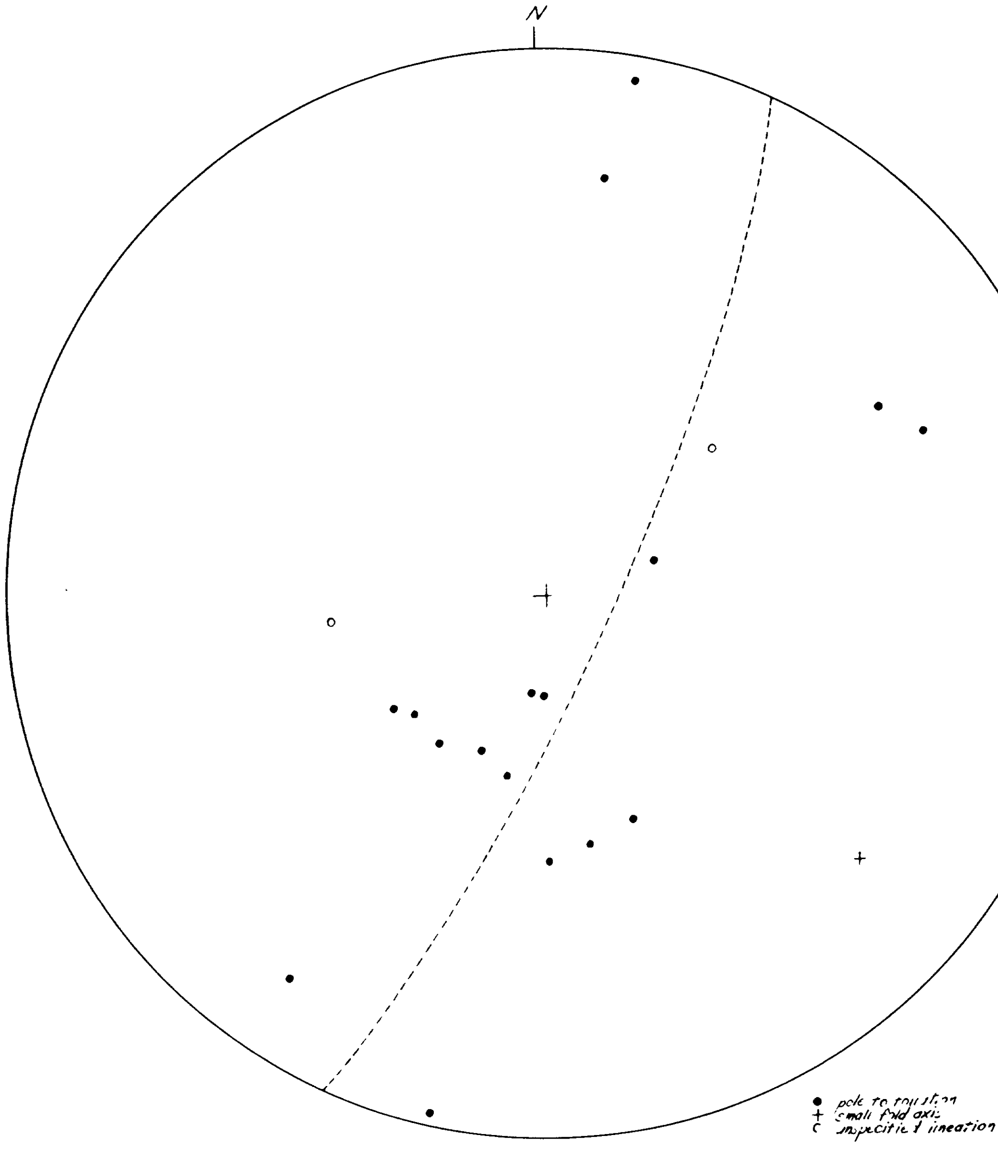
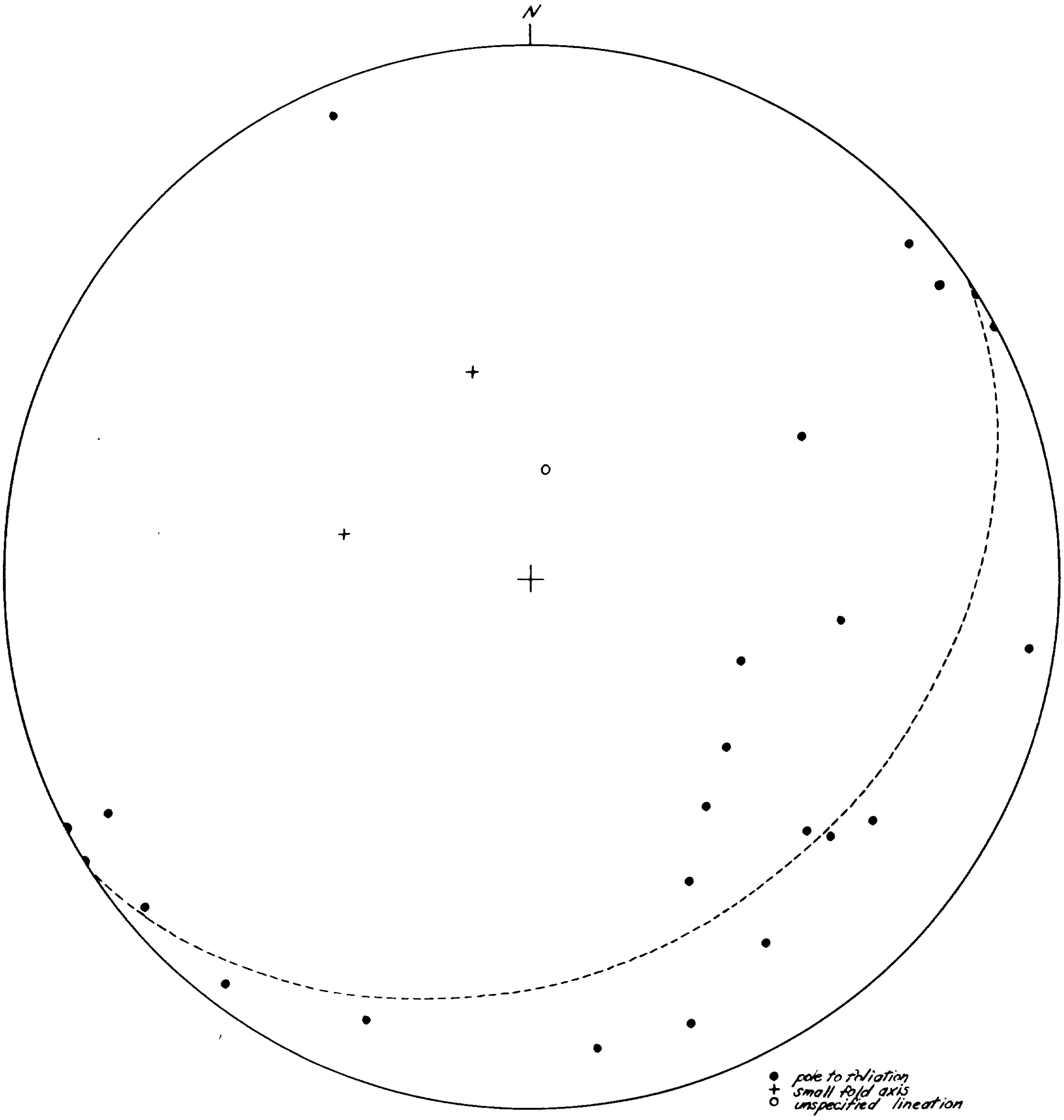

N
pole to
small fold axis
lineation

Figure 29

Lower hemisphere Schmidt net plot of poles to s-sur- ( $\pi$ diagram) and lineations in that part of the Boxford tion involved in the syncline shown in the north-central of the South Groveland quadrangle. Statistically ed fold axis is normal to the great circle represented shed line.

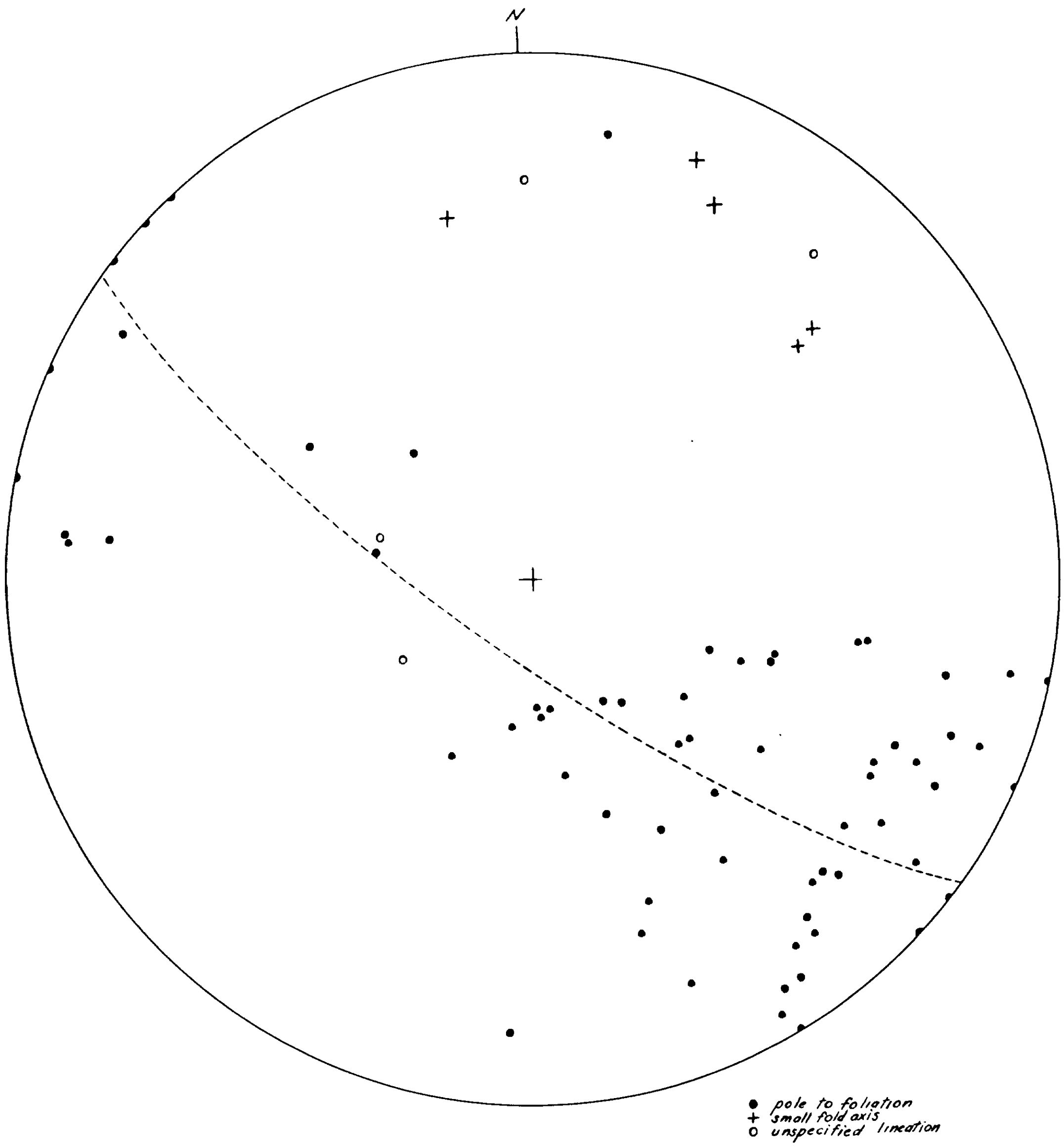

N
pole to foliation
small fold axis
unspecified lineation

The presence of a major fold in the southeastern section of the Wilmington quadrangle is suggested by the general correspondence in lithologies from one side of the Marlboro belt to the other. Its plunging nature is inferred from the convergence of foliations toward the northeast and the presence of a crudely defined, but mappable nose north of Reading center. Geologic mapping in itself has not disclosed directly whether the postulated fold is synclinal or anticlinal, but a $\pi$ diagram prepared for the Marlboro Formation cropping out in the Wilmington and Reading quadrangles (see figure 30) indicates that the statistically defined regional fold axis plunges gently northeast. Moreover, the orientations of small fold axes within the Marlboro are in general accord with the fold axis suggested by the $\pi$ diagram, and it is accordingly highly probable that the hypothesized fold is anticlinal.

Stratigraphic considerations outlined in the section on correlation and age of the Westboro-type quartzite and Marlboro Formation suggest that the Westboro may underlie the Marlboro beyond the area of plate 1. This interpretation is supported locally by the apparent dip of the Westboro-type quartzite beneath the Marlboro Formation. Thus the postulated anticlinal nature of the major fold in the Marlboro Formation seemingly is refuted by the presence of the Westboro-type quartzite along its southern flank. However, in the writer's view the locally based structural

Figure 30

Lower hemisphere Schmidt net plot of poles to s-surfaces ($\pi$ diagram), small fold axes, and other lineations in the Marlboro Formation cropping out in the Wilmington and Reading quadrangles. Statistically defined fold axis is normal to the great circle represented by dashed line.


N
pole to foliation
small fold axis
unspecified lineation

interpretation is of a higher order of reliability than any interpretation dependent on a series of rather nebulous stratigraphic correlations; the fact that the Westboro lies structurally beneath the Marlboro is less significant than its apparent position in the independently established anticline. The problem is perhaps academic for it is not unlikely that the Westboro-type quartzite cropping out locally is faulted against the southern limb of the postulated fold and its stratigraphic position with respect to the Marlboro consequently may be indeterminate.

## Faults and movement zones

A "fault" ideally and generally is treated as a two-dimensional feature; in point of fact, however, faults range from clean, sharp breaks to broad, vaguely defined movement or shear zones up to a mile or more in width. The faults occurring in this area commonly are more in the nature of diffuse movement zones; their very definition locally is dependent solely on the recognition of the sheared zones themselves rather than other evidences of offset. Accordingly, no attempt has been made here to distinguish conceptually between "movement zones" and "faults." However, those faults that have been located or inferred at least in part through criteria other than the sheared nature of the rocks themselves, are represented simply as "faults" in figure 22.

The major fault trending east-northeast across the Lawrence and South Groveland quadrangles is the most unambiguously defined fault in the entire area, particularly along its eastern extent. Several lines of evidence point to the existence of this break. (1) The juxtaposition of the younger (Eliot) rocks of the Merrimack Group against the Boxford Formation (currently thought to be correlative with the Rye Formation) almost demands the presence of a fault between these two units. (2) Considerable movement along the proposed fault line is suggested by the commonly highly sheared rocks cropping out along this line, especially in the area between Johnsons Pond and the southwestern corner of Lawrence (see plates 24A, 25A, and 48). (3) The existence of the very sharp break in metamorphic grade and pattern of intrusion between the Merrimack Group and the rocks to the south requires the presence of either a fault or an unconformity; an unconformity should be incompatible with points 1 and 2 and there is reason to question the petrologic soundness of such an explanation for the break in metamorphic grade. (4) Major structural features within both the Merrimack Group and Boxford Formation locally strike directly into the hypothesized fault line at relatively high angles; this spatial relationship is most reasonably explained by a fault contact between the Merrimack and Boxford. Extension of the proposed fault west of Lawrence currently is conjectural. Its presence between the Brimfield-type schist and Merrimack Group in the Lowell quadrangle (see plate 2) is not incompatible with the probable stratigraphic and spatial relationships between these two rock units. Moreover, the possibility of movement along a line more or less coincident with the Brimfield-Merrimack contact is supported by the local occurrence of intensely sheared rocks within the Dracut Diorite (see plate 19B). According to Jahns (1962, written communication), however, the Andover Granite cropping out in the Lowell quadrangle locally is strongly foliated, which suggests that the postulated fault may follow a more southerly trend than that shown in figure 22 and 23.

The essentially pre-intrusive occurrence of the two faults trending diagonally north-northeast across the area of figure 23 is highly conjectural. The possible existence of the western diagonal fault is inferred chiefly from the distribution and attitudes of the foliated rocks of the fine-grained granite-gneiss facies of the Andover Granite. It once may have passed through the area now occupied by the main tongue of the Andover Granite cropping out in the Billerica quadrangle, and ultimately joined up with one of the movement zones shown west of the central part of the Concord quadrangle in figure 22. The latter possibility is supported in the Billerica quadrangle by the abrupt westward termination (against the hypothesized fault line) of both the Brimfield-type schist and the main amphibolite belt within the Nashoba Formation (see figure 22 and plate 1).

The possibility of a second diagonal fault once having passed through the central part of the area represented in figure 23 is based on several very tenuous bits of evidence. (1) Several zones of sheared igneous rocks crop out along the line of the proposed fault (see figure 22); it is inferred that these sheared rocks may reflect "residual" movement along what previously may have been a well defined fault. (2) The map distribution of the Boxford Formation indicates a substantial loss of section within the upper member of the Boxford as it is traced southwest toward the center of the area shown in figure 23; the apparent loss in section is reasonably attributable to faulting, but it might be explained equally as well, of course, by the presence of a local unconformity between the Boxford and Nashoba. The almost solid intrusion along the entire length of the proposed fault probably precludes the possibility of ever establishing directly the existence of this fault.

The possible or probable presence of the north to north-northeast trending movement zone in the western part of the Concord quadrangle derives chiefly from evidence of intense deformation in the Marlboro Formation cropping out to the south (Cuppels, 1962, written communication) and the apparent offset or flexure of the mappable units extending through this zone. It is currently uncertain whether this postulated movement zone is an actual fault or, as shown here, more in the nature of a sharp flexure. The sharp bend (or break) in the pluton itself suggests that any north-south dislocation along this line must have occurred relatively late in the deformational and intrusive history. This conclusion is supported by two observations: (1) the present attitudes of protoclastic or post-intrusion shear planes in the Andover Granite in this area are more or less conformable with the foliation in the surrounding rocks, yet both trend at high angles to the general trend of the movement zone; (2) mappable offsets of intrusive contacts of the Assabet Quartz-Diorite immediately north-northwest of the flexure zone show the same sense of movement (Cuppels, 1962, written communication) as is thought to exist along the postulated movement zone. The inferred distribution of movement zones elsewhere along the western salient of the subalkaline pluton is based solely on petrographic evidence (see plate 28). It is almost certain that these zones of sheared rock are far more extensive than represented in figure 22; the limited information available to the writer simply precludes broadening the zones at the present time.

The series of faults trending east-northeast across the southern Wilmington and Reading quadrangles (see figures 22 and 23) are thought to be involved with a giant structural discontinuity cutting across southeastern New England. These faults are represented in figure 23 as surfaces, but the movement zone delineated in figure 22 indicates that they should be thought of at least in part as very broad shear zones, locally extending several thousand feet to either side of the pictured surfaces. Actually, the great size of the parent structure tends to obscure its existence; the narrow belt of non-plutonic rocks involved in this zone has been sheared so thoroughly that recognizable stratigraphic breaks are generally absent, and the rocks now appear as a somewhat irregular and deformed, but structurally conformable series.

The hypothesized fault shown in figure 23 as a folded, generally anticlinal thrust(?) surface plunging gently to the northeast through the southern Wilmington and Reading quadrangles, owes its recognition almost entirely to the sheared nature of the rocks within this zone. There is scarcely an outcrop in the area embraced by this folded fault in which the rocks show no evidence of shearing (see plates 4-16). Much of the movement within this fault zone roughly paralleled boundaries between lithic units; were this not the case the writer should have been unable to recognize the presumably folded configuration of this fault. On the other hand, recognition of the extensive shearing along and within the mapped rock units demonstrates why only limited stratigraphic significance at best should be attached to relative positions of units within this zone.

The most southeasterly fault represented in figure 23 is thought to have dipped gently to the northwest. Although the belt with which it is believed to have been coincident is now occupied almost exclusively by igneous rocks, several points suggest its former existence along this line; (1) the southern end of the hypothesized fault passes through the only part of the Peabody Granite in this area known to be sheared (it must be admitted, however, that the attitudes of these shears have been measured only in the Boston North quadrangle, where they seem to be at a high angle to the proposed fault); (2) the only non-igneous rocks along its postulated northeastern extension may be highly sheared (see plate 6A); (3) a projection of the postulated fault to the south coincides with rocks mapped as Woburn Formation and Waltham Gneiss by LaForge (1932, pl. 1); if these rocks are petrographically similar to those LaForge has mapped as Woburn and Waltham along the northern edge of the Lexington quadrangle, they almost certainly lie within an intensely sheared zone. It is along its eastern extension that the position of this fault becomes most doubtful, and its representation in figure 23 is problematical.

The somewhat steeper fault that is inferred to lie between the folded thrust and the gently dipping southeasterly fault (see figure 23), is not clearly separable from the two flanking faults. Nevertheless, there is some evidence pointing to its occurrence as a discrete structural feature. The limited available data indicate that the Marlboro Formation and Westboro-type quartzite cropping out north of Reading center are *not* structurally conformable. If the presence of this fault is denied, moreover, it is difficult to escape the conclusion that the Westboro-type quartzite locally *overlies* the Marlboro Formation, for it occurs along the outer flank of the major anticline involving the Marlboro Formation. The possible eastward extension of the fault is inferred from the presence of a highly sheared zone of the Marlboro and the fact that the map pattern of the Newbury Formation in the adjacent Salem quadrangle indicates that the Newbury is cut off along the northern boundary of its southwestern extension (Toulmin, 1961, written communication).

The folded "thrust" and most southeasterly fault of figure 23 at one time may have been continuous. However, the folded fault thrusts supposedly younger rocks (A member of the Marlboro) over older rocks (B member of the Marlboro; Waltham Gneiss equivalent), whereas the southeasterly fault thrusts presumably older rocks (Westboro-type quartzite and Waltham Gneiss) over the younger(?) rocks of the Marlboro Formation (see LaForge, 1932, pl. 1). Stratigraphic relationships are understood so imperfectly that it is doubtful that their equivalence could ever be proved or disproved conclusively.

A number of distinct "faults" doubtlessly occur in association with the major structural discontinuity through the southern Wilmington and Reading quadrangles, but it would be hopeless to attempt to specify their distribution in detail. For example, many of the igneous rocks north of Cedar Swamp are extensively sheared and much of the movement during and immediately following intrusion may have been taken up along a zone lying generally north of the major movement zone; the precise location of this younger movement zone would be difficult to establish. Nevertheless, it is of interest here that a southwestward projection of a line along the northern boundary of the major movement zone would coincide more or less with a major fault in the Concord quadrangle described by Cuppels (1961, p. D46-D47).

If the major discontinuity through the southern Reading and Wilmington quadrangles is as profound as the writer presently is inclined to believe, it must extend for a considerable distance beyond the map area of figure 22. Its general trend is such that J. L. Rosenfeld (1962, oral communication) has suggested that it might be continuous with the Honey Hill Fault of Connecticut. It is equally possible that near the Connecticut border, it joins with both the east-northeast trending fault through the Lawrence and South Groveland quadrangles and the Honey Hill. Recent speculation by J. T. Wilson (1963) is of interest in connection with a possible northeastern extension of the major discontinuity. Wilson (op. cit., p. 88, 90) has strung together as the "Cabot Fault" a group of "well-known"

faults extending from northern Newfoundland to Boston; the
southwestern terminus of the Cabot Fault is shown by Wilson
to be essentially coincident with the major movement zone
postulated by the writer. It is conceivable, then, that
the described discontinuity in the Reading and Wilmington
quadrangles may form a segment within a fault system over
000 miles in length.

Rocks clearly associated in age with the White Moun-
tains plutonic series all lie well north of the major struc-
tural break through the Wilmington and Reading quadrangles,
whereas none of the distinctly older rocks of the "alkalic"
intrusive series of Massachusetts and Rhode Island are
known to lie north of this line. The existence of this
major fault system may offer an explanation for the apparent-
ly sharp division of these petrologically similar series
into temporally distinct provinces. It would be helpful
in this regard to obtain radiometric dates on the alkalic
rocks from Cashes Ledge in the Gulf of Maine (Toulmin, 1961,
p. 775-776) and Mt. Agamenticus in southeastern Maine.
Granting the possible significance of the major discontin-
uity, the Mt. Agamenticus group should be identifiable with
the White Mountains series for it lies northwest of the
northeastward projection of this fault; Cashes Ledge, on the
other hand, lies southeast of its projection and the alkalic
rocks from this area should be more or less correlative
with the eastern Massachusetts "alkalic" series.

## Structural evolution

The number of major orogenic events and the kinematics involved in the formation of the major structures described above remain poorly known.

The Ordovician(?) and older(?) rocks may have been subjected to at least two distinct periods of orogenic activity. This is suggested in several ways. Axial plane attitudes in the small folds in the Boxford Formation cropping out in West Boxford differ markedly from foliation attitudes within the Boxford, yet they roughly parallel the mappable planar features and inferred axial planes in the rocks of the nearby Merrimack Group. It is reasonable, therefore, to suppose that the deformation that induced folding in the Merrimack Group may have been responsible for superimposing the small folds on the previously deformed Boxford. Still another piece of evidence suggesting two distinct strain patterns is the folding of the great anticline in the northeast section of the South Groveland quadrangle. Cuppels (1960, written communication) and Page have shown that the anticline is cut off by a major north-south trending fault a mile or two east of the map area; they have suggested that transcurrent movement along this fault produced the bend in the great anticline (and may have induced as well the minor folding around a steeply plunging axis).

Most of the local intrusion and much of the faulting and folding were associated with a period of intense deformation of great duration that is believed to have been more or less coincident with Acadian orogeny. If the locally exposed Ordovician(?) and older(?) rocks were deformed chiefly during a pre-Acadian orogenic period, faulting at least must have been reinstituted along the major discontinuity through the Reading and Wilmington quadrangles, for the subalkaline intrusive series here is locally sheared. Plutonism may have post-dated much of the presumably Acadian deformation, but faulting continued well into and perhaps beyond the period of major intrusion in this area. In fact, movement along the east-northeast fault through the Lawrence and South Groveland quadrangles may have been chiefly post-intrusive.

Shearing of the "alkalic" rocks may reflect a still later (third?) orogenic pulse of somewhat less intensity than the main Acadian orogeny. Presently available information, however, does not provide a basis for distinguishing between this deformation and any preceding Acadian orogeny of which this may have been simply a dying gasp.

Sense of movement through the several postulated periods of deformation in this area may have been extremely complex. If both measured and inferred fold axes are regarded as b-lineations, it would seem that movement associated with Acadian or pre-Acadian orogeny was in a generally northwest-southeast direction. If the folding of the major thrust in the southern Wilmington quadrangle simply reflects late-stage movement along this shear zone, it is probable that the sense of shear motion along this zone (whether Acadian or earlier) was also in a northwest-southeast direction. However, the deformation that produced the major shearing in this zone may have been associated with an earlier orogenic period, and the pre-folding fault movement may have been in an entirely different direction. A fabric analysis of the rocks across this fold might help to define the pre-folding kinematics.

Movement along other major faults in the area may have been more transcurrent in nature. This is suggested locally by the steep plunges of many of the small folds superimposed on the generally gently plunging larger folds represented in figure 22. However, the probability of strike-slip motion along the postulated east-northeast trending fault through the South Groveland quadrangle seems to be contradicted by the very shallow northeasterly plunge of the single measured lineation in the Eliot Formation cropping out near this fault.

## Economic geology

Deposits of economic interest in this area (exclusive of surficial materials) may be broadly categorized as water, metalliferous deposits, and nonmetalliferous deposits. Water occurs to some extent in the fractures and other voids in the bedrock, but its occurrence here is minor compared to that in the porous, permeable, glaciofluvial deposits. Water, therefore, is considered a negligible bedrock mineral commodity. Metalliferous deposits are of somewhat greater significance, and nonmetalliferous deposits are of greatest importance.

## Metalliferous deposits

Metallic sulfides and oxides are scattered randomly through much of the bedrock of this area, but they are most conspicuously developed in the relatively basic igneous rocks. The most prominent sulfide is pyrite and the commonest oxide is magnetite. Crystals of chalcopyrite, pyrrhotite, and specular hematite also have been seen, particularly in the Marlboro Formation and associated rocks. Metallic minerals, however, generally do not occur in sufficient concentration to be of economic interest.

The nickel deposit at Nickel Mine Hill is the only significant metalliferous deposit in the area. The geology and history of the deposit have been described in detail by Dennen (1943, p. 25-55). According to Dennen (op. cit., p. 28) the deposit may have been exploited for gold, silver, or other minerals as early as 1726. Serious attempts to recover the nickel, however, were not made until 1876 and exploitation ceased in 1883 (op. cit., p. 28).

The main sulfide of the ore body "is pyrrhotite with which is associated minor amounts of chalcopyrite, pentlandite and magnetite. Pyrrhotite and pentlandite were the first sulfides to form and were closely followed by chalcopyrite" (Dennen, 1943, p. 52). Pentlandite consistently composes about one percent of the ore, but nickel also occurs in significant quantities in the pyrrhotite (op. cit., p. 47). There has been much alteration of both silicates and metallic minerals throughout the Dracut stock, but it is especially prominent in the ore zone. The ore body itself is an apparently irregular mass in which the writer was unable to detect any structural control. Dennen (op. cit., p. 52), however, has noted some localization of sulfides along fractures. Resistivity studies in the area of Nickel Mine Hill have failed to reveal any extension of the ore body or the presence of other large sulfide masses (K. Vozoff, 1955, oral communication).

Evidence pertaining to the genesis of the deposit is somewhat contradictory. The presence of an irregular pocket of sulfides in the basic Dracut stock suggests a process of magmatic segregation, but the effects of hydrothermal activity are conspicuous and equally suggestive. Dennen (op. cit., p. 53) has concluded that the initial magma differentiated, leaving a residual magma rich in "precious and base metals." Metallic components of the residual magma then were introduced along fractures with the aid of gaseous mineralizers; this stage supposedly was followed by deposition of metallic constituents from hydrothermal solutions.

The entire process has been termed "pneumotectic" by Dennen (op. cit., p. 54).

## Nonmetalliferous deposits

### Crushed stone

A highly fractured facies of the Marlboro Formation (see plate 6A) currently is being quarried for crushed stone in the east-central section of the Reading quadrangle. The Marlboro Formation here is composed of highly contorted, ultra-fine-grained, impure chloritic, quartzose rocks. Similar rocks occur within the Marlboro Formation exposed southeast of Wilmington center and along Franklin Street in Reading. Diabasic trap rock is desirable as a source of crushed stone, but deposits of trap rock in this area are too small to be worth developing.

### Building stone

Granite has been quarried extensively as a dimension stone from both the muscovite-granite gneiss of the Andover Granite and the Peabody stock of the Peabody Granite. Other units probably quarried as a source of building stone include the Kittery Quartzite and the binary and pegmatitic granite facies of the Andover. There are no building-stone quarries operating in this area today, as the demand for dimension stone has abated. In addition, transportation and handling are no longer the acute problems they were when most of the quarries in this area were producing, and the net effect has been to limit the quarrying of dimension stone to a few select areas of New England.

The muscovite-granite gneiss has several features that make it desirable as a building stone. It possesses a single good foliation (rift) such that it can be split into almost any desired thickness, and it is essentially unaltered and apparently unshattered. The jointing, however, is somewhat irregular, and it could hardly be described as an aesthetically pleasing stone. It has been used extensively as a foundation stone in the older houses in the area and may have been used in dam construction.

Peabody Granite from the Peabody stock, particularly when polished, is a very clean and attractive stone. It is sparsely jointed and apparently suitable for the production of relatively large blocks. Unfortunately, it is commonly stained along joints and sheeting surfaces. Dale (1923, p. 287-290) has described in detail the commercial granites from the Peabody stock.

## Mica deposits

Books of muscovite up to 6 inches in diameter occur in some of the pegmatites associated with the Andover Granite. However, the muscovite crystals are characteristically much smaller and generally unconcentrated to any significant degree. According to Jahns (1960, written communication), warping, ruling, and locally abundant inclusions are as significant as size in making the Andover mica generally unsuitable for commercial purposes. Natives of Andover have told the writer that the pegmatites were locally hand picked for muscovite during World War II.

## Geologic history

Recorded geologic history in this area may have begun in Precambrian time with the deposition (or intrusion) and subsequent deformation, metamorphism, and erosion of the Fish Brook Gneiss and unnamed gneiss in the Reading quadrangle. However, the only evidence suggesting a Precambrian history for these rocks is the possibly unconformable relationship of the Fish Brook Gneiss beneath the Ordovician(?) Boxford Formation. Moreover, if (as LaForge suspected) the B member of the Marlboro Formation should prove to be stratigraphically distinct from the remainder of the formation, it too may have been deposited and perhaps deformed during Precambrian time.

The Westboro-type quartzite may be the oldest of the Paleozoic rocks in the area. It probably was deposited during Cambrian or Ordovician time under relatively stable crustal conditions; its compositional uniformity is the chief reason for assuming that its deposition was further removed (in time) from a major orogenic event than was that of the adjacent Marlboro Formation.

The intimate association of the Westboro-type quartzite and Marlboro Formation in this area and elsewhere indicates that the deposition of the Westboro was closely followed by (or followed closely) that of the Marlboro. The depositional history of the Marlboro is characterized by the semi-rhythmic alternation of several lithologies. Quartzo-feldspathic rocks seem to be more characteristic of the geometrically lower parts of the unit, whereas quartzites and calc-silicate rocks become increasingly prominent higher in the section; this sequence is suggestive of transgression by the sea or reduction in the land mass with advancing time, but the intensely deformed nature of these rocks precludes any rigorous appraisal of this possibility. The abundant amphibolites of the A member of the Marlboro probably reflect the increasing volcanic activity during the deposition of the A member.

If the Marlboro and Boxford Formations are correlative to any significant extent, the history of deposition within the Boxford must have paralleled roughly that of the Marlboro. Fortunately, the historical record of the Boxford is much better preserved than that of the Marlboro, owing chiefly to the less deformed nature of the former. The lower member of the Boxford is characterized by the presence of metamorphosed argillaceous to arenaceous sediments probably deposited in an offshore environment. With advancing time the sedimentation probably became more arenaceous, and the transition between upper and lower members of the Boxford is marked by the presence of the highly sodic quartzo-feldspathic gneiss that may reflect a period of either relatively arenaceous sedimentation or felsic volcanic activity. The diversity of lithologies within the upper member of the Boxford suggests a constantly changing depositional environment during upper Boxford time; the widespread occurrence of amphibolite indicates that this may have been a period of considerable volcanic activity as well.

The Brimfield-type schist and Nashoba Formation currently are thought to form a transitional sequence with at least the Marlboro and perhaps the Boxford. If this is actually the case, the inception of their deposition, probably during later Ordovician time, was marked primarily by a return to argillaceous sedimentation, coupled in part with continuing vulcanism. As sedimentation continued, the deposits of the Nashoba may have become more and more arenaceous, perhaps in response to a gradually shallowing environment. With the end of deposition of the Nashoba Formation, sedimentation in this area may have ended for a long period. Whether or not the Ordovician(?) and older rocks were then subjected to deformation is still not known for certain. It is likely that they were. The abundant vulcanism and rapidly changing conditions of sedimentation reflected in the Ordovician(?) rocks together with the local intrusion of sepentinite, are all suggestive of Taconic orogeny.

The presumably uplifted and deformed Ordovician(?) and older(?) rocks may have contributed sediment to the evolving Merrimack Group during the Silurian. With the initiation of deposition of the Merrimack there began a long, apparently uninterrupted period of basinal deposition. Judging from its great thickness and its impure, generally arenaceous and locally shaly nature, it is probable that deposition of the Merrimack Group progressed under shallow water conditions in a steadily sinking basin. As deposition proceeded the arenaceous materials of the Kittery Quartzite became more highly contaminated with argillaceous debris, reflecting the probable transgression of the sea and/or reduction of the adjacent land mass. By the time deposition of the Eliot Formation began the shore line may have migrated a considerable distance toward the source area; the location(s) of the sediment source cannot be determined presently owing to the meager data available.

Volcanic activity associated with the deposition of the Newbury Formation probably closely followed but may have paralleled in part the deposition of the Merrimack Group. There is, however, no suggestion of vulcanism within the Merrimack Group itself.

Toward the end of the deposition of the Eliot Formation, or perhaps after deposition had ceased, upwarp of the Merrimack Group took place. Erosion ensued and was followed by the Early Devonian(?) deposition of the Harvard(?) Conglomerate Lentil of the Worcester(?) Phyllite. That a hiatus exists between parts of the Merrimack and the Worcester is certain, but deposition of the Worcester locally may have been continuous with that of the Merrimack Group.

Subsequent to the deposition of the Worcester(?) Phyllite, intense deformation of the entire area began. It currently is thought that this deformation was associated with Acadian orogeny developed during Devonian time. Intrusion of the subalkaline series began sometime before the deformation ceased, and faulting at least apparently continued beyond this period of Acadian plutonism.

The stocks of the Peabody Granite were emplaced toward the close of or shortly following the Acadian deformation. If intrusion of the "alkalic" series actually followed Acadian orogeny, a period of orogenic activity toward the close of the Paleozoic may be indicated, for the Peabody Granite locally is sheared. Intrusion of the scattered diabase dikes almost certainly was associated with Triassic vulcanism that occurred elsewhere in New England; this brought to a close the local history of bedrock formation.

Uplift and denudation probably began long before major deformation ceased in this area. It continued for an indeterminate period into the Mesozoic and eventually reduced the entire area to a peneplain. Re-elevation took place from time to time with the consequent dissection of the peneplain and the production of an essentially subsequent drainage system. Whether or not Mesozoic or Tertiary sediments ever were deposited over this area is conjectural. It is not improbable that they were, for Cretaceous, Miocene, and Pliocene deposits have been reported from Martha's Vineyard, and Cretaceous deposits also occur in Scituate (Emerson, 1917, p. 132-133). There is today, however, no record of Mesozoic or Tertiary sedimentation in or near the area described in this report.

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