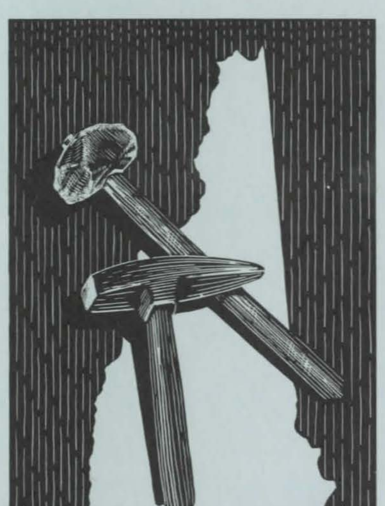
The Geology of the

MANCHESTER QUADRANGLE

NEW HAMPSHIRE

BULLETIN NO. 2

By Aluru Sriramadas



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Upper part of the Eliot formation on Interstate 93, Alan B. Shepard, Jr. Highway, 1 mile south of N.H. State Route 102 interchange to Derry and Londonderry.

(N. H. Dept. of Public Works and Highways, Photo by Bill Finney)

GEOLOGY of the MANCHESTER QUADRANGLE NEW HAMPSHIRE BULLETIN NO. 2

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ABSTRACT

The Manchester quadrangle, covering 218.5 square miles in southeastern New Hampshire, is in a region of rolling hills that rise a few hundred feet above sea level.

The Quaternary surficial unconsolidated deposits, consisting of till, sand, gravel, and silt, are mostly of glacial origin. This report is not concerned with them.

The bedrock consists chiefly of schists, granulites, and gneisses of probable Silurian and Devonian age, granitic rocks and pegmatites of probable Devonian age, and diabase dikes that may be as young as Triassic.

Except for 40 square miles in the northwest corner of the quadrangle, most of the bedrock belongs to the Silurian (?) Merrimack Group. This group consists chiefly of fine-grained pinkish-brown biotite granulite or schist that is composed of quartz, oligoclase, biotite and in places contains small amounts of microcline, muscovite, and garnet. Less common are lime-silicate granulites composed of quartz, andesine, actinolite, and biotite. The original rocks, prior to metamorphism, were siltstones, locally dolomitic or calcareous. The Merrimack Group in this area has been assigned to two formations, each of which has been subdivided into two members. The lower member of the Eliot Formation contains only 10% of the lime-silicate granulites, whereas the upper member contains 25%. The lower member of the Berwick Formation has only 5% of the lime-silicate granulites, whereas the upper member has about 15%. The thickness of the Merrimack Group can not be determined with precision, but is estimated to be about 17,500 feet.

The Devonian Littleton Formation, found in two small areas in the west-central and south-central parts of the quadrangle, consists chiefly of mica schist with such minerals as garnet and sillimanite in places. The small part of the formation exposed in this quadrangle is estimated to be 800 to 1500 feet thick.

Forty square miles in the northwest corner of the quadrangle are underlain almost exclusively by Massabesic gneiss. This is chiefly a coarse pink biotite-microcline gneiss. Much less common is a gray biotite-oligoclase gneiss. Amphibolite is relatively rare. The gray gneiss has formed from the granulites and schists of the Berwick Formation by partial melting. The pink gneiss is a hybrid rock, formed by the intricate mixing of pink microcline granite and granulites of the Berwick Formation. These transformations probably took place in the Middle Devonian.

The plutonic rocks are of four general types. The Ayer granodiorite forms several bodies, the largest of which is 5 miles long, in the southeast part of the quadrangle. It is chiefly a gray foliated granodiorite composed of oligoclase, quartz, biotite, and microcline. Some varieties have pheno-

crysts of microcline one-half to one inch long. The binary (two-mica) granite forms elongate bodies, the largest of which is eleven miles long. In most instances this rock is medium grained, foliated, and composed of microcline, quartz, albite, biotite, and muscovite. In a few small bodies in the northwest corner of the quadrangle the binary granite is massive, that is, not foliated. Pink microcline granite, which is so intimately entangled in the Massabesic gneiss, locally forms bodies large enough to map. Small bodies of pegmatite are common. Twenty diabase dikes are present, the smallest a few inches wide, the largest about 100 feet wide.

The rocks of the Manchester quadrangle strike northeast and dip very steeply. A major synclinal axis, in which the Devonian Littleton Formation is preserved, trends northeast, from the west-central to the north-central edges of the area. The southeasterly 80% of the quadrangle is on the southeast limb of this syncline. The northwesterly 20% is on the northwest limb, but the Berwick Formation has here been converted to the Massabesic gneiss. Countless minor folds are superimposed on this major syncline. Folds with a wave-length of a few inches or a few feet can be seen in individual outcrops. Folds with a wave-length of hundreds or thousands of feet are deduced from variations in the dip of the strata. The granitic bodies are mostly long sheet-like masses. The few silicified zones trend northeast.

The rocks have been regionally metamorphosed. The southeastern half of the quadrangle is in the chlorite and biotite zone, the northwestern half is in the garnet and sillimanite zones.

The known geological history of this quadrangle begins in the Silurian. Here, in the eastern part of the Appalachian geosyncline, many thousands of feet of silt, some of it slightly calcareous or dolomitic, were deposited. The source was the landmass of Appalachia which lay to the southeast. In early Devonian time more aluminous muds and sands were deposited. During the Acadian Revolution, in the Middle Devonian, the strata were folded, metamorphosed, injected by granitic material, and parts of the Berwick Formation converted into Massabesic gneiss. The formation of silicified zones and intrusion of diabase completed the development of the bedrock. Most of the subsequent history, occupying 200,000,000 years, is veiled in mystery. Certainly much erosion took place. During the Pleistocene glaciation till, sand, and gravel were deposited.

CHAPTER I
INTRODUCTION

Location

The Manchester quadrangle, with an area of 218.5 square miles, is located in Rockingham and Hillsboro Counties of southeastern New Hampshire. The quadrangle lies between north latitudes 42°45' and 43°00' and west longitudes 71°30' and 71°45' (Figure 1).

Purpose

The stratigraphy and structure of southeastern New Hampshire has not been well understood. The only modern work in this part of the state, by Freedman (1950) in the nearby Mt. Pawtuckaway quadrangle, demonstrated that previous concepts of the stratigraphy, structure and age of the rocks had to be extensively revised. Despite the excellent work by Freedman, much remained to be done in clarifying the details of the bedrock geology, especially in the Manchester quadrangle, which had not been mapped since the 1870's. Moreover, it was hoped that the structure, and consequently the stratigraphy, could be worked out in greater detail than in the Mt. Pawtuckaway quadrangle, where the structural interpretation was based in large part on 36 drag folds.

The Manchester quadrangle, where reconnaissance work had shown that the grade of metamorphism ranges from the chlorite to the sillimanite zones, seemed to offer an unusually good opportunity to study progressive metamorphism. Moreover, it seemed desirable to pay more attention to the mineralogical details, especially with the help of the x-ray spectrometer, than has been done in adjacent regions.

Numerous problems on the origin of the plutonic rocks were apparent. Freedman (1950) believed the rocks in the Fitchburg pluton were emplaced by stoping, whereas Larsen and Morris (1933) concluded that the Fitchburg granite in Massachusetts was the result of granitization. Moreover, Larsen and Morris state that "only locally did granite magma move as an ordinary intrusive granite." This later process may be similar to the rheomorphism of Goodspeed (1939, p. 399). Currier (1952, p. 105) has concluded that the Chelmsford granite, which lies a few miles southwest of the Manchester quadrangle, is a granitized sediment. The area thus affords a testing ground for various theories on the formation of plutonic rocks.

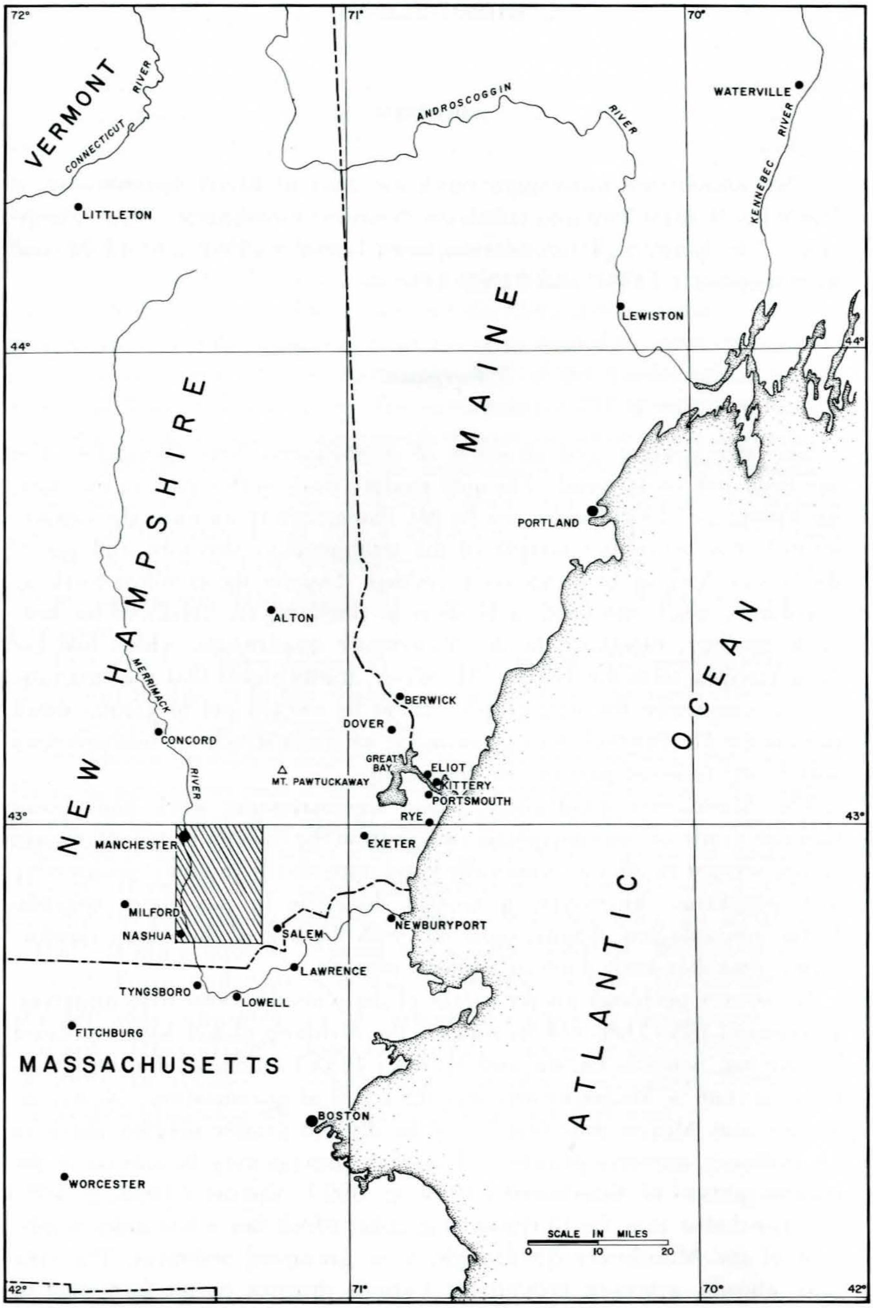

Figure 1. Index map. Manchester quadrangle is ruled.

Methods of Investigation

Approximately six months were spent in the field, evenly divided between the summers of 1953 and 1954.

A topographical map of the Manchester quadrangle, surveyed in 1903 and published on a scale of 1:62,500, was available for field work during the summer of 1953. Although reasonably satisfactory, much of the culture, especially the highways, was out of date. Fortunately, a manuscript topographic map, prepared in 1953 on a scale of 1:8,000, became available for the field work in the summer of 1954. It was a pleasure to work with such a superb topographic base. All the contacts traced in 1953 were remapped on the new base during the summer of 1954. Aerial photographs on a scale of 1:20,000 were also available during the summer of 1954. Not much use was made of these, however, because of the existence of a topographic map on a much larger scale.

Laboratory study was carried on at Harvard University after each of the field seasons. In 1953-54 the laboratory work was done in conjunction with course work, whereas in 1954-55 all of the author's time was devoted to the laboratory investigations and the preparation of this report. The methods employed and the results obtained are given in Table 1.

Previous Work

The geology of the Manchester quadrangle and surrounding areas has been described by C. T. Jackson (1844), C. H. Hitchcock (1877), F. J. Katz (1917), and B. K. Emerson (1917). One of the two most pertinent papers is that by Freedman (1950), describing the stratigraphy and structure of the Mt. Pawtuckaway quadrangle, which lies directly northeast of the Manchester quadrangle. The second significant work is that by Jahns (1952) in the Lowell and Tyngsboro quadrangles to the south. Field notes by Professor Marland P. Billings, made during the summer of 1951 in a reconnaissance survey of southeastern New Hampshire by himself and Milton T. Heald, were kindly made available to the author. Billings *et al* (1952) prepared an up-to-date map of southern New Hampshire, with a text, for the field trips held in conjunction with the meetings of the Geological Society of America held in Boston in the fall of 1952.

Table 1

LABORATORY METHODS OF STUDY

Objective	Method
1. Mineral separation	Screening, heavy liquids, isodynamic separator
2. Specific gravity	Berman balance
3. Identification of minerals	Petrographic microscope
4. Estimation of modes	Petrographic microscope
5. Refractive index	Immersion liquids, double variation procedure
6. Optic axial angles	Universal stage
7. Extinction angles	Universal stage
8. Identification of fine-grained minerals	X-ray spectrometer
9. Symmetry of feldspars	X-ray spectrometer
10. High-low feldspars	X-ray spectrometer
11. Composition of feldspars	X-ray spectrometer
12. Unit cell edge of garnets	X-ray spectrometer

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To Professor Marland P. Billings the writer is deeply indebted for suggesting the problem, inspiring interest in the field work, spending several days with the writer in the field, discussing the problems at every stage, and critically reading the manuscript, rephrasing the first chapter and parts of other chapters.

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Baker of Windham, New Hampshire were exceedingly kind and provided a home during the two summers of field work. George Robinson and Mrs. Althof prepared the thin sections. My thanks are due to the Government of India and Andhra University for the overseas scholarship and the Faculty of the Division of Geological Sciences for the Fellowship during the field seasons 1953 and 1954.

Geography

Topography and Drainage. The Manchester quadrangle lies in the Seaboard Lowland section of the New England Province, one of the subdivisions of the Appalachian Highlands (Fenneman, 1938). The quadrangle is characterized by low, rolling hills that rise 100 to 200 feet above the valleys. No pronounced topographic grain is apparent, although in the southeastern part of the area there is locally a northeasterly trend, and in the central part there is a vague northwesterly trend. The lowest point, 90 feet above sea level, is along the Merrimack River at Nashua. The highest point, Warner Hill in the east-central part of the quadrangle, is 605 feet above sea level.

The area lies entirely within the drainage basin of the Merrimack River, which flows southerly in the western part of the quadrangle. Beaver Brook, which flows southerly through the central part of the quadrangle and is a tributary of the Merrimack River, drains approximately half of the area. Lakes of various sizes are present. The largest is Massabesic Lake in the north-central part of the quadrangle. Among the ponds and lakes of intermediate size are Cobbetts Pond and Canobie Lake in the south-central part of the quadrangle.

Accessibility and Culture. The Manchester quadrangle is reached from Boston by U. S. Route 3 or N. H. Route 28, both of which pass through the quadrangle, and also by the Boston & Maine Railroad which passes through Nashua and Manchester, the two largest cities in the quadrangle. All parts of the area are readily reached by paved roads. The culture is typical of that characteristic of small urban communities and their surroundings. Many of the people who work in the cities live in the country. Agriculture is not extensively developed except for small gardens for home consumption. A few large poultry farms have been developed to supply the Boston market. Most of the area is consequently covered by second-growth timber, except in the cities and in the small fields surrounding habitations.*

* Interstate Route 93 has been completed since this report was written.

Rock Exposures

Rock exposures are relatively good despite the low relief. Enormous and, in some places, continuous outcrops are available along railroad cuts. The Manchester-Lawrence Branch of the Boston and Maine Railroad at Windham provides a section for 4 miles across the strike, with some of the individual cuts as much as 3,000 feet long and 5 to 50 feet high. Unfortunately, inasmuch as the railroad was built long ago, the outcrops are now covered by dirt and grime. A fairly continuous section, nearly across the strike of the formations, is provided by numerous highway cuts along the Londonderry Turnpike between Canobie Lake and the northern border of the quadrangle. Very fresh, new exposures, as much as 30 feet high, are available along the new Concord Turnpike between Nashua and Manchester. Steep ledges give excellent exposures at Rock Rimmon, Rattlesnake Hill, Mine Hill, Deer Ledge, and the hill north of Pennichuck Brook in Merrimack. A number of abandoned quarries also afford excellent exposures.

Glacial Geology

The trend of glacial striae observed in the quadrangle are shown on Figure 2. It is apparent that the ice was moving south-southeast.

Glacial till is present throughout the quadrangle. The depth ranges from a few inches to perhaps as much as 200 feet. Glacial outwash deposits are extensively exposed. Some of the deposits of sand exposed along the banks of the Merrimack River are as much as 200 feet high. Glacial gravel is obtained from many pits for use in highway construction. Some of these pits (Figure 2) although as much as 70 feet deep, do not expose the bedrock. Glacial erratics are also present. One, Butterfield rock in Windham, is composed of pegmatite with small fragments of schist.

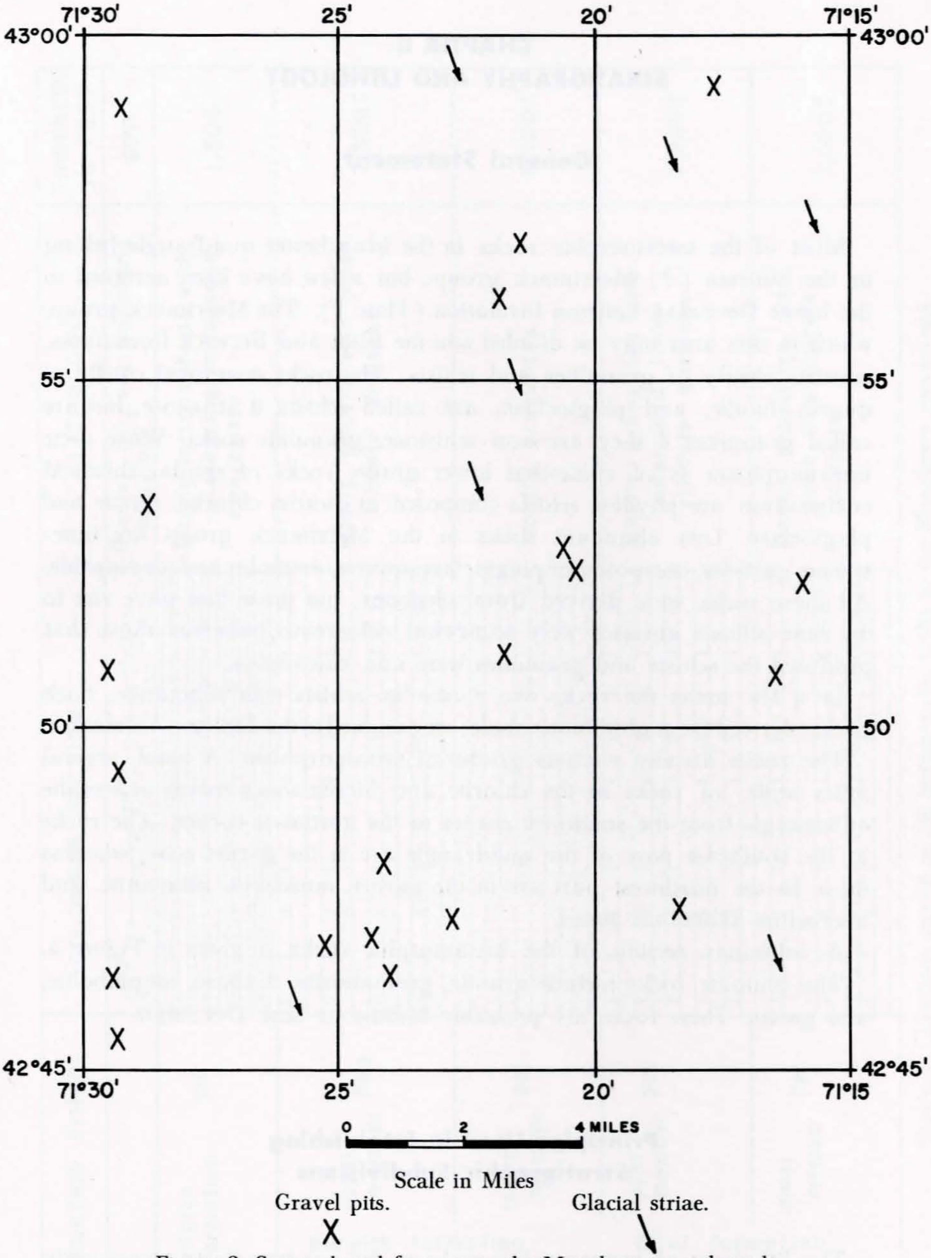


Figure 2. Some glacial features in the Manchester quadrangle.

CHAPTER II
STRATIGRAPHY AND LITHOLOGY

General Statement

Most of the metamorphic rocks in the Manchester quadrangle belong to the Silurian (?) Merrimack group, but a few have been assigned to the lower Devonian Littleton formation (Plate I). The Merrimack group, which in this area may be divided into the Eliot and Berwick formations, consists chiefly of granulites and schists. The rocks composed chiefly of quartz, biotite, and plagioclase, are called schists if schistose, but are called granulites if they are non-schistose, granulitic rocks. When their metamorphism is of somewhat lower grade, rocks of similar chemical composition are phyllitic schists composed of quartz, chlorite, sercite and plagioclase. Less abundant rocks in the Merrimack group are lime-silicate gneisses, composed of plagioclase, quartz, actinolite and/or diopside. All these rocks were derived from siltstones, but those that gave rise to the lime-silicate gneisses were somewhat calcareous, whereas those that produced the schists and granulites were non-calcareous.

In a few areas the rocks are muscovite schists with sillimanite. Such rocks, derived from aluminous shale, are assigned to the Littleton formation.

The rocks display various grades of metamorphism. A band, several miles wide, of rocks in the chlorite and biotite zones trends across the quadrangle from the southwest corner to the northeast corner. The rocks in the southeast part of the quadrangle are in the garnet zone, whereas those in the northwest part are in the garnet, muscovite-sillimanite, and microcline-sillimanite zones.

A columnar section of the metamorphic rocks is given in Figure 3.

The plutonic rocks include granite, granodiorite, diabase, amphibolite, and gneiss. These rocks are probably Middle or Late Devonian.

Principles Used in Establishing Stratigraphic Subdivisions

The lithology of metamorphic rocks in the quadrangle is surprisingly monotonous. Although several varieties of rocks are present, especially phyllitic schists, schists, and granulites, they are constantly repeated; consequently, at first it seems impossible to divide these rocks into any significant stratigraphic sequence.

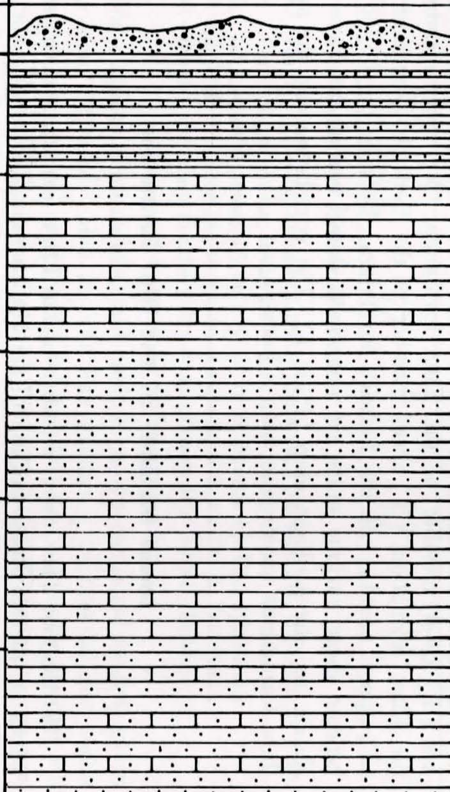
AGE	FORMATION	SYMBOL	COLUMNAR SECTION	LITHOLOGY	THICKNESS IN FEET
				Glacial till, out wash and alluvium	200
Lower Devonian	Littleton formation	Dl		Mostly mica schists with alternating micaceous quartzites	1,500
Silurian (?)	Merrimack group, Berwick formation, upper member	Sbu		Mostly schists with lime-silicate gneisses	7,500±
	Merrimack group, Berwick formation, lower member	Sbl		Mostly granulites	6,500±
	Merrimack group, Eliot formation, upper member	Seu		Mostly granulites and pinstriped lime-silicate gneisses	2,500±
	Merrimack group, Eliot formation, lower member	Sel		Mostly granulites with some lime-silicate gneisses	1,000±

Figure 3. Columnar section of the metamorphic rocks in the Manchester quadrangle.

But the sillimanite-bearing mica schists at Mine Hill and at the junction of the Souhegan River and Merrimack River are unlike rocks elsewhere in the area. Originally aluminous shales, these rocks are considered to belong to the Lower Devonian Littleton formation, so extensively developed in central and western New Hampshire.

Although the Merrimack group at first appears to be indivisible, more careful study shows that some parts contain more of the lime-silicate gneisses than other parts. A band almost a mile wide that extends from Nashua through Hudson, Londonderry, and Derry to Chester, approximately following Route 102, is relatively low in lime. Both to the northwest and to the southeast the strata become somewhat richer in lime, evidenced by the increase in the amount of lime-silicate gneiss in the rocks. Still farther southeast, in the southeast corner of the quadrangle, the amount of lime is less. It is thus possible to divide the Merrimack group into four subdivisions, which from southeast to northwest are: (1) lime-poor; (2) more calcareous; (3) lime-poor; and (4) more calcareous. These four units are assigned to four stratigraphic units, which are: (1) lower member of the Eliot formation; (2) upper member of the Eliot formation; (3) lower member of the Berwick formation; and (4) upper member of the Berwick formation. Because the boundaries between these various units are not sharp, dotted boundaries have been shown on the geologic map (Plate I). The correlation and the age of these formations are discussed on a later page.

Lower Member of the Eliot Formation

Distribution. The lower member of the Eliot formation occupies two areas in the southeast portion of the Manchester quadrangle. The main area occupies most of Windham and parts of Salem, Pelham, Hudson, and Derry; the minor area is in Derry.

The best exposures are in the cuts along the Manchester-Lawrence branch of the Boston and Maine railroad in Windham and along Route 28 also in Windham.

Lithology. The lower member of the Eliot formation is composed primarily (about 90%) of fine-grained pinkish-brown granulite, with lesser amounts (about 10%) of fine-grained gray lime-silicate gneisses. The lime-silicate gneisses are in lenses about an inch or less wide in the pinkish-brown granulite.

The fine-grained pinkish-brown granulite, in which the individual grains range from 0.1 to 0.5 mm. in diameter, is composed chiefly of quartz,

Table 2

ESTIMATED MODES OF THE LOWER MEMBER OF THE ELIOT FORMATION

Sample No.	1130	362	97	354	1125	1125.1
Quartz	45	35	15	15	35	20
Oligoclase	18		30	21	10	
Andesine		20				70
Microcline			15	15	8	3
Epidote	2			2		
Biotite	30	25	35	40	25	5
Chlorite					2	1
Muscovite	5		4			
Actinolite		15		5	20	
Garnet		2	1			
Sphene		1				
Apatite		1		2		1
Zircon		1				
Grain size in mm.	0.1-0.3	0.5-2.0	0.5-3.0	0.5-5.0	0.1-0.5	1.0-2.0

No. Description and location of samples

97. Pinkish-brown granulite (slightly gneissose) 0.6 mile SW. of North Pelham.
354. Lime silicate gneiss, Route 28, 1 mile S. of Seavey Pond, Windham.
362. Lime silicate gneiss, 0.5 mile N. W. of St. Matthew's Ch., Windham.
1125 and 1125.1. Lime silicate gneiss, 1 mile E. of Rock Pond, Windham.
1130. Pinkish-brown granulite, 0.1 mile E. of Gage Hill School, Pelham.

biotite, oligoclase, muscovite, and epidote. A representative mode is given in column 1130 of Table 2. The fine-grained gray lime-silicate gneiss in which the grains range from 0.5 to 2.0 mm. (actinolite needles 5.0 mm. long), is composed of quartz, biotite, andesine, actinolite, garnet, sphene, apatite, and zircon. A representative mode is given in column 362 of Table 2. Less common varieties contain microcline; representative modes are given in columns 97, 354 and 1125 of Table 2.

Although the texture of these rocks is dominantly granoblastic, some are schistose and other are gneissose. Even rocks with as much as 30% biotite are granoblastic, because the biotite wraps around quartz. Myrmekite, although of minor importance, is striking in some rocks. The myrmekite, composed of quartz and albite, is intergrown with microcline.

Thickness. Since the lower member of the Eliot formation extends southeast beyond the limits of the Manchester quadrangle, the total thickness is not known. But the portion that is exposed in the Manchester quadrangle is about 1,000 feet thick (Plate I).

Upper Member of the Eliot Formation

Distribution. The upper member of the Eliot formation extends from Nashua through Hudson, Windham, Londonderry, Derry, to Chester. No exposure of the northwest contact of the upper member of the Eliot formation with the Berwick formation is available, because it is occupied by the foliated binary granite in the southwest, and drift and alluvium along Beaver Brook in the northeast.

The best exposures are: (1) along Route 28 in Derry; (2) the Manchester-Lawrence branch of the Boston and Maine railroad in Derry; (3) Route 111 in Hudson; and (4) the abandoned Worcester-Nashua-Portland branch of the Boston and Maine railroad in Hudson.

Lithology. This member is composed chiefly of pinkish-brown granulite (about 75%), with local thin beds of lime-silicate gneiss (about 25%). This member contains more lime-silicate than the lower member of Eliot formation. Moreover, bedding is more prominent than in the lower member because of the presence of the lime-silicate beds.

The pinkish-brown granulite, a fine-grained rock in which the grains are 0.1 to 0.5 mm. in diameter, is composed of quartz, biotite, oligoclase and minor calcite. A representative mode is given in column 310.1 of Table 3. The texture is granoblastic in spite of the fact that biotite constitutes 35% of the rock.

The pinstriped lime-silicate gneiss occurs in beds 0.2 inch to a few inches thick in the pinkish-brown granulite. The designation "pinstripe" is applied because of the exceedingly thin layers of light-colored and dark minerals. This unusual rock, confined to the upper member of the Eliot formation, is absent from many outcrops. The pinstriped gneiss is composed chiefly of epidote, actinolite, oligoclase, quartz, and biotite, with minor amounts of calcite, diopside, garnet, sphene, apatite, and muscovite. A representative mode is given in column 287 of Table 3. Additional approximate modes are also given in Table 3.

Thickness. Outcrops of the upper member of the Eliot formation are not as closely spaced as in the lower member. Nevertheless, from the structure sections (Plate I) the thickness may be measured as about 2,500 feet.

Lower Member of the Berwick Formation

Distribution. The lower member of the Berwick formation occurs in a northeast-southwest belt extending through Chester, Derry, Londonderry, Litchfield, Hudson, and Nashua. It has a width of about one and one half to two miles and occurs on either side of Route 102. The contacts with the upper member of the Eliot formation and the upper member of

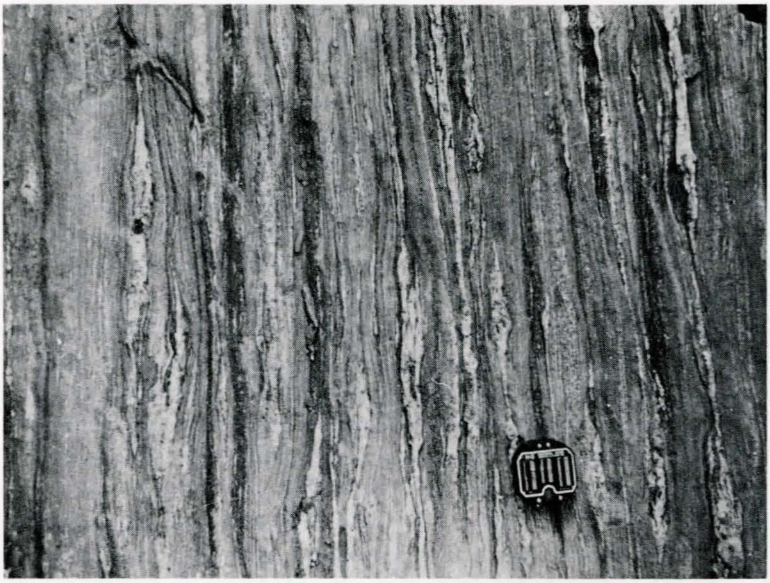


Plate II. Pinstriped lime-silicate gneiss, showing the bedding in the upper member of the Eliot formation.

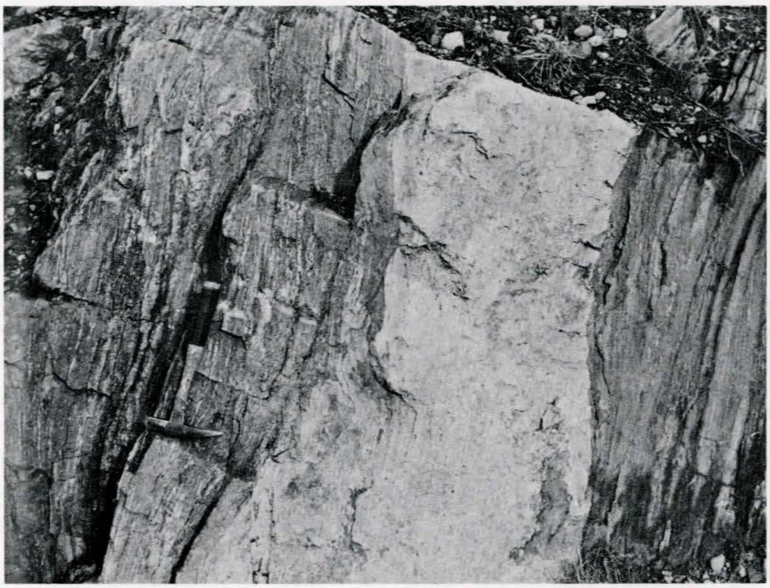


Plate III. Pinstriped lime-silicate gneiss in contact with foliated binary granite.

Table 3

ESTIMATED MODES OF THE UPPER MEMBER OF THE ELIOT FORMATION

Sample No.	310.1	50	287	341	340.1	60	52	44	256	205
Quartz	35	25	15	15	25	20	30	20	15	20
Oligoclase	25	35	20	20	30	10	25	30	25	30
Epidote			10	25		25	5	15	30	15
Biotite	35	37	10	3	20	5	15	5	5	
Muscovite		2	2							
Calcite	5		5	4		10	1			5
Actinolite			20	15	17	16	15	24	20	17
Diopside			5	12		10	5	5	5	5
Garnet			5		2					
Magnetite		1	4	2				1		3
Sphene			2	4	3	4	3			2
Apatite			2		3					
Zircon							1			3
Grain size in mm.	0.1-0.5	0.1-1.0	0.1-1.0	0.1-11.0	0.1-1.5	0.1-0.5	0.1-0.8	0.1-0.5	0.1-0.5	0.1-1.0

No. Description and location of samples listed in Table 3.

44. Pinstriped lime-silicate gneiss, 1 mile W. of West Windham.
50. Pinkish-brown granulite, 1.5 miles SW. of West Windham.
52. Pinstriped lime-silicate gneiss, 1.8 miles W. of West Windham.
60. Pinstriped lime-silicate gneiss, 0.6 mile NE. of Hudson Center.
205. Pinstriped lime-silicate gneiss, 0.3 mile N. of North Pelham.
256. Pinstriped lime-silicate gneiss, 1 mile NNW. of West Windham.
287. Pinstriped lime-silicate gneiss, 0.9 mile NW. of Windham.
310.1. Pinkish-brown granulite, Route 28, 0.7 mile SE. of Derry.
340.1. Pinstriped lime-silicate gneiss, 0.2 mile N. of Ezekial Pond, Derry.
341. Pinstriped lime-silicate gneiss, Route 28, 0.8 mile SE. of Derry.

the Berwick formation are gradational.

The best exposures of the lower member of the Berwick formation are along Route 102.

Lithology. This member consists chiefly of pinkish-brown granulite. Greenish phyllitic schist and lime-silicate, occurring as bands and lenses, are less common. The lime-silicate amounts to about 5%. The pinkish-brown granulite is characterized by punky weathering; that is, the rock is stained brown and is somewhat porous because of the solution of the dolomite. The lithology is so distinct that Professor J. B. Thompson, Jr., on his visit to the area in 1953, pointed out its similarity to the Oakdale formation in Massachusetts. The writer, on a field trip to Bolton, Massachusetts, with Professor Thompson also recognized this similarity. On a field trip with Professor M. P. Billings in 1954 to Dover quadrangle to the northeast, the writer also recognized this same lithology.

Joints diagonal to the bedding are common. Moreover, small concentric fractures, a few inches in diameter, are filled with muscovite and quartz. Some of these joints are easily mistaken for fossils.

Inasmuch as the pinkish-brown granulites are very fine-grained (0.01 to 0.1 mm.), the microscopic identification of the minerals has been confirmed by the X-ray spectrometer patterns. In the biotite zone the principal minerals are quartz, albite, biotite, chlorite, and muscovite (sericite) with small amounts of magnetite. A representative mode is given in column 23.1 in Table 6. In the chlorite zone the principal ferro-magnesian minerals are chlorite and green biotite. Some of the pinkish-brown granulite in the chlorite zone contains dolomite. The more metamorphosed equivalents in the biotite zone are lime-silicate gneisses that contain actinolite and epidote, as shown in columns 254 and 313 of Table 6.

Beds of green phyllitic schist, as much as three feet thick are interbedded with the pinkish-brown granulite in the chlorite zone. Slip cleavage, also called false cleavage or strain-slip cleavage (Harker, 1939, p. 157-158) is a striking characteristic of the phyllitic schist. Bedding schistosity and drag folds are also present. The principal minerals (grain size 0.01 to 0.1 mm.) in the chlorite zone are quartz, green biotite, chlorite, muscovite, and magnetite, with lesser amounts of albite and dolomite. Representative modes are given in Table 6, columns 28 and 23.1. In the biotite zone the phyllitic schist becomes purplish-brown schist, for which a representative mode is given in column 270 of Table 6.

Two typical measured sections of parts of the lower member of the Berwick formation are given in Tables 4 and 5.

Thickness. Reasonably connected data are available in certain zones along the strike in the lower member of the Berwick formation, but the data are not so continuous across the strike. Within this limitation, the thickness from the structure sections (Plate I) is about 6,500 feet.

Table 4

MEASURED SECTION OF PART OF THE LOWER MEMBER OF THE BERWICK FORMATION

(Five-eighths of a mile southwest of Londonderry-Hudson Town line on Route 102.)

Lithology	Thickness in feet
Pinkish-brown granulite	30.0
Slightly schistose pinkish-brown granulite	4.0
Phyllitic-schist inter-banded (bands about a foot) with pinkish-brown granulite	10.0
Pinkish-brown granulite	4.0
Highly plicated phyllitic schist	1.0
Pinkish-brown granulite	30.0

Table 5

MEASURED SECTION OF PART OF THE LOWER MEMBER OF THE BERWICK FORMATION IN THE BIOTITE ZONE.

(About one mile southwest of junction Routes 102 and 128 on Route 102.)

Lithology	Thickness in feet
Lime-silicate gneiss	1.0
Pinkish-brown granulite	1.0
Lime-silicate gneiss	1.0
Schistose pinkish-brown granulite	2.5
Pinkish-brown granulite	2.5
Lime-silicate gneiss	1.0
Pinkish-brown granulite	3.0
Schistose pinkish-brown granulite	3.0
Pinkish-brown granulite	28.0
Schistose pinkish-brown granulite	2.0
Pinkish-brown granulite	4.0

Table 6

ESTIMATED MODES OF THE LOWER MEMBER OF THE BERWICK FORMATION

Sample No.	28	28*	17*	23	23.1	270	254	79	313
Quartz	20	x	x	20	45	30	25	30	20
Albite	5	x	x	3	3		20		
Oligoclase						16		22	15
Epidote			x				5	5	10
Brown biotite					20	45	26	10	
Green biotite	22	x		35					
Chlorite	22	x	x	24	10		5	5	15
Muscovite	22	x	x	15	20	9	4	10	
Dolomite	5	x							
Calcite								6	15
Actinolite							15	10	5
Diopside									5
Magnetite	4			3	2				2
Sphene								2	2
Apatite									11
Grain size in mm.	0.01-0.1			0.01-0.1	0.01-0.1	0.1-1.0	0.1-0.4	0.1-1.0	0.5-0.5

* "x" under columns 28 and 17 indicates identification by x-ray powder pattern.

No. Description and location of samples listed in Table 6.

17. Gray phyllitic schist, 1.4 miles SW. of Londonderry.
23. Gray phyllitic schist, Route 102, 0.2 mile SW. of Hudson-Londonderry town line.
23.1. Pinkish-brown granulite, Route 102, 0.2 mile SW. of Hudson-Londonderry town line.
28. Gray phyllitic schists, Route 102, 0.3 mile SW. of Litchfield-Hudson town line.
79. Lime-silicate gneiss, 1 mile NW. of Robinson Pond.
254. Lime-silicate gneiss, 1.1 miles NE. of Breakneck Hill, Londonderry.
270. Purplish-brown schist, 0.1 mile NW. of Beaver Lake, Derry.
313. Lime-silicate gneiss, 0.6 mile NW. of Beaver Lake, Derry.

Upper Member of the Berwick Formation

Distribution. The upper member of the Berwick formation occurs in Auburn, Derry, Londonderry, Litchfield, and Merrimack. It extends in a northeast-southwest belt about three to five miles wide, with the lower member of the Berwick formation to the southeast and the Massabesic gneiss to the northwest. A few inclusions of the upper member of the Berwick formation also occur in Manchester, surrounded by Massabesic gneiss.

The best outcrops are: (1) along Route 121 in Auburn and Chester; (2) half a mile east of the point where the Auburn, Londonderry, and Derry town lines join; and (3) on a hill north of Pennichuck Brook in Merrimack.

Lithology. The upper member of the Berwick formation consists principally of metamorphosed siltstones (about 85%), with small amounts of metamorphosed calcareous siltstones (about 15%). Inasmuch as the grade of metamorphism ranges from the chlorite to the sillimanite zone, the texture and mineralogy of the rocks differ considerably.

The most common rock is the gray phyllitic schist in the chlorite zone, purplish-brown schist in the biotite zone, and gray schist in the garnet and sillimanite zones. The lime-silicate rocks, although not abundant, are conspicuous, especially in the garnet zone. They occur as beds as much as ten feet thick and lenses one foot thick. They include such variations as green granulite, spotted gneiss, gray gneiss, and a fasciculated gneiss in which the actinolite forms rosettes. White quartzite occurs as inclusions in the Massabesic gneiss.

The gray phyllitic schist, typical of the chlorite zone, is a very fine-grained fissile rock in which the grains are 0.005 to 0.01 mm. in diameter. The principal minerals are quartz, chlorite, muscovite (sericite), and biotite, with small amounts of albite, magnetite, and dolomite (Table 7, column 241). The purplish-brown schist, characteristic of the biotite zone, is composed of grains 0.1 to 0.2 mm. in diameter; the principal minerals are quartz, biotite, and oligoclase, with small amounts of chlorite, muscovite, and apatite (Table 7, column 396). The gray schist in the garnet and sillimanite zones is a coarse-grained rock in which the grains are 0.2 to 1.0 mm. in diameter. The principal minerals are quartz, oligoclase and biotite, with minor muscovite and zircon (Table 7, columns 242, 235, 419, and 471).

The less common rocks in the upper member of the Berwick formation contain lime-bearing minerals. These rocks are especially abundant in that part of the formation lying in the garnet zone, because these strata had the appropriate chemical composition. A fine-grained green granulite in which the grains are 0.05 to 0.1 mm. in diameter, is composed chiefly

Table 7

ESTIMATED MODES OF THE UPPER MEMBER OF THE BERWICK FORMATION

Sample No.	241	396	417	1098	419 235 242	471	388	417.1	422	1050.1	1087	1081
Quartz	45	45	35	20	35	35	30	20	20	25	26	25
Albite	5											
Oligoclase		17	15	25	34	35			20			
Andesine							25	20		15	25	
Labradorite												25
Epidote								10	25	5		
Biotite	10	25	15	30	29	25	25			15	27	
Chlorite	20	3	25	24			5	5	30			
Muscovite	15	6	10			5	10	5				
Dolomite	1											
Calcite								2	5			
Actinolite								26		25	20	
Hornblende												43
Diopside								1		15		
Garnet							1	10				
Magnetite	4											
Sphene											2	4
Apatite		4		1			4					3
Zircon					2			1				
Grain size in mm.	0.005-0.01	0.1-0.2	0.1-0.3	0.1-0.4	0.1-1.0	0.2-0.5	0.1-0.2	0.1-2.0	0.005-0.1	0.4-5.0	0.5-1.5	0.5-3.0

No.	Description and location of samples listed in Table 7.
235.	Gray schist, 0.4 mile WNW. of Horseshoe Pond, Merrimack.
241.	Gray phyllitic schist; hill W. of Daniel Webster Airfield, Merrimack.
242.	Gray schist, 0.2 mile NW. of Last Rest Cemetery, Merrimack.
388.	Gray schist, 0.6 mile NE. of Upper Shields Pond.
396.	Purplish-brown schist, 0.6 mile SE. of Wilson.
417.	Gray schist, 3 miles NW. of Derry, Londonderry Turnpike.
417.1.	Spotted gneiss, 3 miles NW. of Derry, Londonderry Turnpike.
419.	Gray schist, Londonderry Turnpike, E. of Rattlesnake Hill, Auburn.
422.	Green granulite, 0.1 mile N. of Wilson.
471.	Gray schist, 0.2 mile SSE. of Mine Hill, Auburn.
1050.1	Fasciculate schist, 1.7 miles SE. of Rattlesnake Hill, Auburn.
1081.	Gray-black gneiss, Candia Road, 1-1/4 mile N. of Route 121, Chester.
1087.	Spotted gneiss, near summit of Rattlesnake Hill, Auburn.
1098.	Gray schist, abandoned road to Musquash Swamp, 0.7 mile E. of Litchfield town line.

of chlorite, epidote, quartz, and oligoclase with a little calcite (Table 7, column 422). A medium-grained spotted gneiss, in which the grains are 0.1 to 2.0 mm., is composed chiefly of actinolite, quartz, andesine, epidote, almandite-grossularite, with lesser amounts of chlorite, muscovite, calcite, diopside, and apatite (Table 7, column 417.1). A coarse-grained fasciculate schist is composed of actinolite, quartz, andesine, biotite, diopside, and small amounts of epidote, and sphene (Table 7, column 1050.1). The actinolite needles, 0.5 to 5.0 mm. long, form star-shaped aggregates lying in the plane of schistosity. A coarse-grained gray-black gneiss in which the grains are 0.5 to 3.0 mm. in diameter, is composed chiefly of hornblende, quartz, labradorite, with small amounts of sphene and apatite. The hornblende tends to be randomly oriented (Table 7, column 1081).

Thickness. The data from the individual outcrops in the upper member of the Berwick formation that help the interpretation of the major structure are good. But the outcrops are not sufficient for a complete determination of structure. Moreover, an attempt to trace the characteristic lime-silicate gneisses along the strike is not successful, partly because of the probable pinching out of these beds, and partly because of the limited outcrops. The thickness of this member of the formation, based on these structure sections, is about 7,500 feet.

Littleton Formation

Distribution. The Littleton formation occurs in two localities, one at Mine Hill in Auburn, and the other near Souhegan River in Merrimack and Litchfield. In both places the contact between the Littleton and Berwick formations is not exposed, but outcrops of both formations are within about two hundred feet of each other.

Very good exposures may be seen both on Mine Hill and in the bed of the Souhegan River under the bridges for Route 3 and the Concord turnpike. The best outcrop in which to see the structure is about 100 feet southwest of Route 121 at Mine Hill.

Lithology. The Littleton formation is chiefly crinkled gray schist, in which rusty weathering is common. Less abundant is a coarse gneiss occurring as beds or lenses. Sills of foliated binary granite and microcline-albite pegmatite range in thickness from 1 to 8 feet. A measured outcrop is given in Table 8.

The coarse-grained (0.3 to 2.0 mm.) crinkled gray schist is composed of biotite, quartz, sillimanite, muscovite, almandite, with a minor amount

Table 8

MEASURED OUTCROP OF THE LITTLETON FORMATION

(In Souhegan River under the bridge for Route 3 in Merrimack.)

Lithology	Thickness in feet
	Sillimanite Zone
Pegmatite	2.0
Biotite-muscovite-quartz schist	1.0
Pegmatite	1.0
Biotite-muscovite schist	1.0
Pegmatite	0.5
Quartz-muscovite-biotite schist	8.0
Pegmatite	4.0
Quartz-muscovite biotite schist	5.0
Garnet-mica schist	12.0
Pegmatite	6.0
Foliated binary granite	3.0
Pegmatite	6.0
Garnet-mica schist	5.0

Table 9

ESTIMATED MODES OF THE LITTLETON FORMATION

Sample No.	1070	234	234.1	233*
Quartz	25	20	35	x
Oligoclase	?	5		
Biotite	25	30	25	x
Muscovite	25	20	15	x
Sillimanite	20	15	15	x
Cordierite	?			
Almandite	5	8	10	x
Zircon		2		
Grain size in mm.	0.3-2.0	0.2-1.5	0.2-1.5	

* "x" under No. 233 indicates that the minerals are identified by x-ray.

No.	Description and location of samples
233.	Gray gneiss, Daniel Webster Highway, Merrimack Village.
234.	Crinkled gray schist, Route 3 at Souhegan River.
234.1.	Crinkled gray schist, Route 3 at Souhegan River.
1070.	Crinkled gray schist, 0.3 mile SSW. of Mine Hill, Auburn.

of what is probably oligoclase. Another variety of the schist has more almandite and some undoubted oligoclase. The coarse-grained gneiss is composed of quartz, biotite, muscovite, sillimanite, and almandite. The modes are given in Table 9. Sillimanite occurs as fasciculate aggregates, in cracks in quartz, and also as intergrowths with quartz. Some muscovite is also in cracks in quartz or oligoclase.

Thickness. Since only a small portion of the Littleton formation is present in the Manchester quadrangle, the true thickness is not obtainable. The thickness as represented in the structure sections (Plate I) is 800 to 1,500 feet. Because of minor folds the thickness may be less.

CHAPTER III
PLUTONIC ROCKS

General. The plutonic rocks of the Manchester quadrangle, comprising about 20% of the area, range in composition from granite to gabbro, and in size from lenses a few inches long to bodies 11 miles long. They are in general elongated parallel to the regional trends.

Based on composition, size, structure, texture, and convenience of description, the plutonic rocks are classified as follows: (1) Ayer granodiorite, (2) foliated binary (two-mica) granite, (3) microcline-albite pegmatite, (4) microcline granite, (5) microcline pegmatite, (6) massive binary (two-mica) granite, and (7) diabase. Their relative ages are discussed after the presentation of the descriptive data.

Ayer Granodiorite

Nomenclature. Emerson (1917, pp. 223-228) said that the Ayer granite, named from Ayer, Massachusetts, is, typically, a biotite-muscovite granite of moderately coarse grain that in many places contains feldspar phenocrysts 1 to 3 inches long. But he says most of the rock is non-porphyritic. Jahns (1952, p. 112) says that the average composition is granodiorite, and has called this rock Ayer granodiorite(Jahns, personal communication to Professor Marland P. Billings).

Distribution. The Ayer granodiorite occurs in three bodies in the southeast corner of the quadrangle. The largest, three-fourths of a mile wide, extends south-southwest from south of Canobie Lake for five miles and continues into the Lowell quadrangle. A second body, one mile long and about half a mile wide, lies one mile north of Canobie Lake. The third body is a lens one-fourth mile across, about two miles north of Canobie Lake.

The best outcrops are north of Flat Rock Brook on Route 28, east and south of Rock Pond, at and near Deer Ledge in Windham, and one mile southwest of Rock Pond, on either side of Derry Road in Pelham.

Lithology. Much of the Ayer granodiorite is a coarse-grained, foliated, gray granodiorite with variations such as, massive granodiorite, compositionally banded granodiorite, and granodiorite with phenocrysts of twinned microcline. Minor varieties are: (1) coarse-grained to medium-grained massive pink garnetiferous granodiorite, (2) medium-grained foliated green-gray quartz diorite, and (3) coarse-grained massive to foliated perthite pegmatite.

The most common rock, the coarse foliated to massive, gray granodiorite, is composed of grains 0.3 to 7.0 mm. in diameter. The foliation strikes N. 40°E. and dips 60°NW. The principal minerals are oligoclase, microcline, biotite, and quartz, with small amounts of hornblende, zircon, sphene, apatite, muscovite, and magnetite. The porphyritic granodiorite, less extensive compared to the non-porphyritic granodiorite, contains microcline phenocrysts one-half inch to 1 inch long. The phenocrysts are arranged parallel to the foliation. The microcline phenocrysts of the granodiorite that grade into the perthite pegmatite are 1 to 3 inches long. The phenocrysts of microcline in the pegmatite are twinned, apparently on the Carlsbad law. The compositionally banded type, less extensive compared to the non-banded type, shows biotite-rich and biotite-poor bands. The banded and non-banded types contain the same minerals. The porphyritic, the non-porphyritic, and the banded granodiorites show micrographic intergrowth of quartz and microcline, microperthitic intergrowth of microcline and plagioclase, and myrmekitic intergrowth of plagioclase and quartz. The approximate modes are given in columns 1119a, 1112, and 318 of Table 10.

The garnetiferous granodiorite, especially well developed in the body two miles north of Canobie Lake, is a gray foliated to massive rock in which the grains are 0.2 to 1.5 mm. in diameter. Some garnets are up to 10 mm. in diameter, although having cores of other minerals. The principal minerals are oligoclase, biotite, almandite, quartz, microcline, hornblende, epidote, and apatite. The modes are given in Table 10, columns 370, 353 and 355.

The medium-grained, foliated, green-gray quartz diorite occurs along the southeast contact of the main body of the Ayer granodiorite, one mile southwest of Rock Pond. This is the only exposure of the quartz diorite. The mineral grains, 0.2 to 2.0 mm. in diameter, are chiefly oligoclase, hornblende, biotite, with lesser amounts of quartz, chlorite, sphene and zircon. All the grains of sphene show lamellar twinning. The mode is given in column 1111 of Table 10.

The perthite pegmatite occurs as lenses in the granodiorite. The rock at the contact of the pegmatite and the granodiorite resembles porphyritic granodiorite with microcline phenocrysts. The pegmatite is composed of microcline, quartz, biotite and almandite. The microcline is 1 to 4 inches long, whereas the almandite is up to one-half inch in diameter. The microcline shows, besides cross-hatched twinning, probable Carlsbad twinning. Microscopic study shows that plagioclase occurs as veins as well as lamellae in the microperthite.

Relations with the Eliot formation. The contact of the Ayer granodiorite

Table 10

ESTIMATED MODES OF AYER GRANODIORITE

Sample No.	1119A	1112	318	355	353	370	1111
Quartz	15	10	15	25	25	15	5
Oligoclase	30	35	40	25	25	25	42
Microcline	20	15	23	20	10	15	
Epidote						1	
Biotite	20	25	20	25	20	25	15
Chlorite							5
Muscovite			2		5		
Hornblende	6	10				3	25
Almandite				2	9	15	
Magnetite	1	1			3		2
Sphene	2						5
Apatite	3	2		1	3	1	
Zircon	3	2		2			1
Grain size in mm.	0.3-5.0	0.5-7.0	0.5-2.0	0.2-0.5	0.3-1.0	0.2-1.5	0.2-2.0

No. Description and location of samples

318. Granodiorite, SW. edge of Deer Ledge, Windham.
353. Garnetiferous granodiorite, 0.9 mile NE. of St. Matthew Church, Windham.
355. Garnetiferous granodiorite, 0.4 mile N. of St. Matthew Church, Windham.
370. Garnetiferous granodiorite, Route 28, 0.2 mile NW. of Seavey Pond.
1111. Quartz diorite, road E. side of Beaver Brook at map edge, Pelham.
1112. Granodiorite, beneath power line, 0.3 mile NW. of map edge, Pelham.
1119A. Granodiorite, Marblehead Road, 0.3 mile E. of Deer Ledge, Windham.

with the Eliot formation is a zone about 300 feet wide. This zone is well exposed in the outcrops southwest of Rock Pond. Towards the Eliot side of the contact the granodiorite forms lenses, whereas towards the granodiorite side of the contact the Eliot is present as inclusions. The contact of the granodiorite with the Eliot is conformable on a large scale, but is locally discordant on a small scale.

Foliated Binary (two-mica) Granite

Distribution. The foliated binary (two-mica) granite occurs in two main bodies and numerous other small bodies. One body, 10 miles long and about a mile wide, is in Londonderry, Derry, Auburn, and Chester, and extends into the Hampstead quadrangle. A second body, about 11 miles long and a mile wide, is in Londonderry, Hudson and Nashua, and extends beyond the southwest corner of the quadrangle.

In the northeasterly body the best outcrops are along Routes 121, 28, and 28 bypass. The best outcrops in the southwesterly body are in the quarry at the end of Ledge Road in Nashua, in the quarries one mile northwest of Otternic Pond in Hudson, and along the high pressure gas line, one mile southwest of the village of Londonderry.

Lithology. The foliated binary granite is a medium-grained white-gray rock that locally contains garnet. The foliation strikes northeast and dips between 65° southeast and vertical. In places, muscovite and biotite crystals, larger than the groundmass, cut across the foliation. The quartz veins in the quarry near Otternic Pond cut across the granite; tourmaline crystals in the veins are aligned parallel to the foliation of the granite.

The foliated binary granite is composed of microcline, albite, and muscovite phenocrysts, where porphyritic, in a groundmass composed of microcline, quartz, albite, muscovite, biotite, apatite, zircon, and, in some specimens, almandite (Table 11). Some grains with a refractive index near that of microcline, but not showing twinning in the plane of the section, are considered to be microcline. The phenocrysts range in size between 1.0 and 4.0 mm., whereas the groundmass minerals are 0.1 to 0.5 mm. in diameter. Some granite lenses, 2 to 3 feet thick, are coarse-grained (1.0 to 12.0). Other small granite lenses contain amphibole. The texture of the foliated binary granite is hypidiomorphic to cataclastic. Special textural features are: (1) intergrowth of biotite and almandite, (2) sericitization of feldspar, and (3) deformed plagioclase and almandite. (Slide No. 1001).

The albite grains show multiple twinning. About half the lamellae in an albite grain are straight whereas the other half are bent. Starting from one end of the albite the following can be observed: (1) straight lamellae of albite, with quartz grains in contact; (2) slightly bent albite lamellae at the center of the grain, the bending increasing towards the other end; (3) a depression, due to the bending of the albite grain, with an almandite fitting into the bend; and (4) quartz grains next to the almandite grain.

Relations with the Eliot and Berwick formations. The southwestern body of foliated binary granite occurs at the contact of the Eliot and Berwick formations. The smaller granite bodies are very common in the Eliot formation and the upper member of the Berwick formation, whereas they are rare in the lower member of the Berwick formation.

The contact between the granite and the metasediments is a zone 10 feet to 100 feet wide. As the contact is approached from adjacent formations towards the granite, the following sequence is observed: (1) the granite appears as lenses in the metasediments; (2) the metasediments and granite are in equal proportions; (3) the metasediments appear as inclusions in the granite; and (4) finally the granite contains no metasediments.

Generally, the strike and dip of the foliation in the granite at the contact is the same as the strike and dip of the metasediments. This contact is interrupted locally by a disconformable contact. A silicified zone at the contact of the granite and the metasediments northwest of Robinson Pond may also point to a disconformable relation.

Microcline-albite Pegmatite

Distribution. Microcline-albite pegmatites are distributed throughout the Manchester quadrangle. In Auburn and Chester, northwest of the binary foliated granite, the pegmatites are larger and more numerous than in other areas. Many of the hilltops are occupied by the pegmatites, such as Rock Rimmon in Manchester and Moore Hill in Derry.

The pegmatites are lenses elongated parallel to the regional trend. The size ranges from lenses a few inches thick to bodies nearly half a mile across. The bigger bodies contain inclusions of schists, consequently the bodies represented on the geological map (Plate I) are not entirely pegmatite.

Lithology. The pegmatite is composed of microcline-perthite, albite, quartz, muscovite, and biotite. The pegmatite is white due to the dominance of white feldspar. Muscovite plates from 2 to 6 inches in diameter constitute 25% of the pegmatite in the abandoned quarry in Auburn; elsewhere muscovite is negligible.

Relations with the adjacent formations. The pegmatite occurs as lenses in all formations, but is very sparse in the lower member of the Berwick formation. The lenses, generally concordant, are locally discordant. The concordant and discordant relations are seen in an outcrop 20 feet southeast of the intersection of the Manchester-Lawrence branch of the Boston and Maine railroad with Derry Road at Windham Depot.

Microcline Granite

Distribution. The southeast knob of Rattlesnake Hill in Auburn is made up of microcline granite. An outcrop 20 feet north of the intersection of the Manchester-Lawrence branch of the Boston and Maine railroad with Route 28 in North Londonderry shows microcline granite. The microcline

Table 11

ESTIMATED MODES OF FOLIATED BINARY GRANITE

Sample No.	1001	35	54	254	258	464	398	279	327	52*	349*	360*	340*	97*	1130*	31*
Quartz	30	20	25	20	30	25	35	25	20	20	20	20	10	25	15	15
Albite	20	20	20	25	20	5	15	10	18	25	25	15	15	20	25	25
Microcline	25	30	35	30	30	40	27	35	40	30	45	45	65	50	40	40
Biotite	4	5	3	5	8	5	5	2	5	10	5	8	5	1	10	10
Chlorite			2					5	1							
Muscovite	20	20	15	15	12	20	15	20	10	15	5	3	5	2	10	5
Hornblende														2		5
Almandite	1	3		5		3	3		6		5	8				
Magnetite								3								
Apatite		1				1						1				
Zircon		1				1										
Phenocrysts size in mm.	1.0-2.0	1.0-3.0	2.0-3.0	1.0-2.0	1.0-2.0		1.0-2.0		1.0-4.0							
Groundmass size in mm.	0.1-0.3	0.1-0.5	0.1-0.3	0.1-0.5	0.1-0.5	0.1-0.5	0.1-0.3	0.1-1.0	0.4-1.0							
Grain size in mm.										0.5-1.0	0.5-1.0	0.5-1.0	1.0-12.0	0.5-20.0	1.0-3.0	0.3 3.0

* These foliated binary granites occur as small lenses in the Eliot and Berwick formations.

No.	Description and location of samples listed in Table 11
35.	Garnetiferous foliated binary granite, 0.3 mile ENE. of St. Patrick's Cemetery, Hudson.
54.	Foliated binary granite, W. of power line, 0.9 mile N. of Robinson Pond, Hudson.
254.	Garnetiferous foliated binary granite, 0.2 mile W. of Mammoth Road, 1.8 miles NW. of W. Windham.
258.	Foliated binary granite, 0.1 mile W. of Kendall Pond, Londonderry.
279.	Foliated binary granite, 0.7 mile NNE. of North Pond, Chester.
327.	Garnetiferous foliated binary granite, Featherbed Road, 0.2 mile NNE. of Route 28, Derry.
398.	Garnetiferous foliated binary granite, 1.2 miles SE. of Wilson, Route 28, Londonderry.
464.	Garnetiferous foliated binary granite, 0.2 mile ESE. of Hillcrest Cemetery, Litchfield.
1001.	Garnetiferous foliated binary granite, 0.6 mile ENE. of SW. map corner, Nashua.
31.	0.9 mile SSE. of Sunnyside Cemetery, Hudson.
52.	0.3 mile N. of Robinson Pond, Hudson.
97.	Route 111A, 0.6 mile W. of N. Pelham.
340.	0.2 mile N. of Ezekiel Pond, Route 28, Derry.
349.	Morrison Road, 0.2 mile SW. of Mitchell Pond, Windham.
360.	B. & M. R. R., 0.7 mile SE. of Mitchell Pond, Windham.
1130.	0.1 mile E. of Gage Hill School, Pelham (Lowell quadrangle).

granite is in lenses elongated parallel to the regional trend.

Lithology. The pink, coarse-grained microcline granite is massive near the center of the body. Towards the contacts, however, it is characterized by foliation that strikes northeast and dips 50°SE. The principal minerals are microcline, quartz and biotite. The microcline is partly sericitized. A mode is given in Table 14, column 1097.

Relations with the Berwick and Massabesic formations. Proceeding from the upper member of the Berwick formation towards the northwest, the following rocks are noted: (1) schists of the upper member of the Berwick formation; (2) microcline granite with schist inclusions; (3) main microcline granite body; (4) microcline granite with schist inclusions; and (5) Massabesic gneiss with alternating layers of biotite-poor and biotite-rich bands. The contact zone between the microcline granite and the Massabesic gneiss is about 200 feet wide on Rattlesnake Hill.

Microcline Pegmatite

Distribution. Microcline pegmatite occurs only in the northwest portion of the quadrangle, in the Massabesic gneiss. A good exposure of the microcline pegmatite is seen 200 feet west of the junction of Routes 28A and 101 in Manchester. Very big exposures are found along Route 121, one and one-half miles northwest of Mine Hill. The microcline pegmatite occurs mainly as small pods 20 feet across. In the Suncook quadrangle to the north they are larger.

Lithology. The microcline pegmatite is pink because of the characteristic pink color of the microcline. The pegmatite is composed of microcline, quartz, biotite and minor muscovite. The microcline pegmatite does not contain sodic plagioclase and differs in this respect from the microcline-albite pegmatite. The microcline and biotite in the microcline-pegmatite are up to about 12 inches by 6 inches in size. The composition of microcline perthite is given under Chapter V, Mineralogy.

Relations with the Massabesic gneiss. The microcline pegmatite cuts across the Massabesic gneiss with a sharp contact.

Massive Binary (two-mica) Granite

Distribution. Massive binary (two-mica) granite occurs as small bodies in the northwestern part of the Manchester quadrangle. A good exposure is in the roadcut of the Concord Turnpike, a mile north of Sebbins Pond

Table 12

ESTIMATED MODES OF MASSIVE BINARY GRANITE

Sample No.	1128	1027
Quartz	25	35
Microcline	33	26
Oligoclase	25	22
Biotite	10	10
Chlorite	2	2
Muscovite	5	5
Magnetite	trace	trace
Grain size in mm.	0.5-1.0	0.5-2.5

No. Location of samples

1027. Route 101, Bedford, 0.4 mile SW. of Manchester quadrangle margin.
1128. Route U. S. 3 – Everett Turnpike intersection, Bedford.

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in Bedford. The granite occurs as bigger bodies in the Suncook and Milford quadrangles. A quarry near Derryfield Park in Manchester is actually in the Suncook quadrangle 500 feet north of the northern boundary of the Manchester quadrangle.

Lithology. The massive binary granite is a fine-grained to medium-grained white-gray rock composed chiefly of microcline, quartz, oligoclase, biotite, and muscovite, with some chlorite and magnetite. Some grains of microcline do not show twinning in the plane of the microsection. Replacement of feldspar by sericite, and of biotite by chlorite with the release of magnetite, are noticed. The modes are given in columns 1128 and 1027 of Table 12.

Relations with the Massabesic gneiss and the microcline-albite pegmatite. The massive binary granite clearly cuts across the Massabesic gneiss and also the microcline-albite pegmatite. The crosscutting relation of massive binary granite with the microcline pegmatite is noticed in the quarry north of Derryfield Park.

According to Professor Marland P. Billings the massive binary granite resembles the granite in the quarries of Milford quadrangle, which are thought to be "Concord granite."

Diabase Dikes

Distribution. About twenty diabase dikes were observed in the Manchester quadrangle. They are more densely distributed in the southeast portion of the quadrangle (Figure 4). The width of the dikes ranges from a few inches to about a hundred feet. All the dikes, where the strike is known, show a northeast trend. Despite the coincidence of the trend with the trend of the schists, they are not conformable, because they cut across the dip of the schists. The diabase dikes also cut across the microcline-albite pegmatite. The dikes are massive. Some show two sets of jointing, one parallel to and the other across their trend.

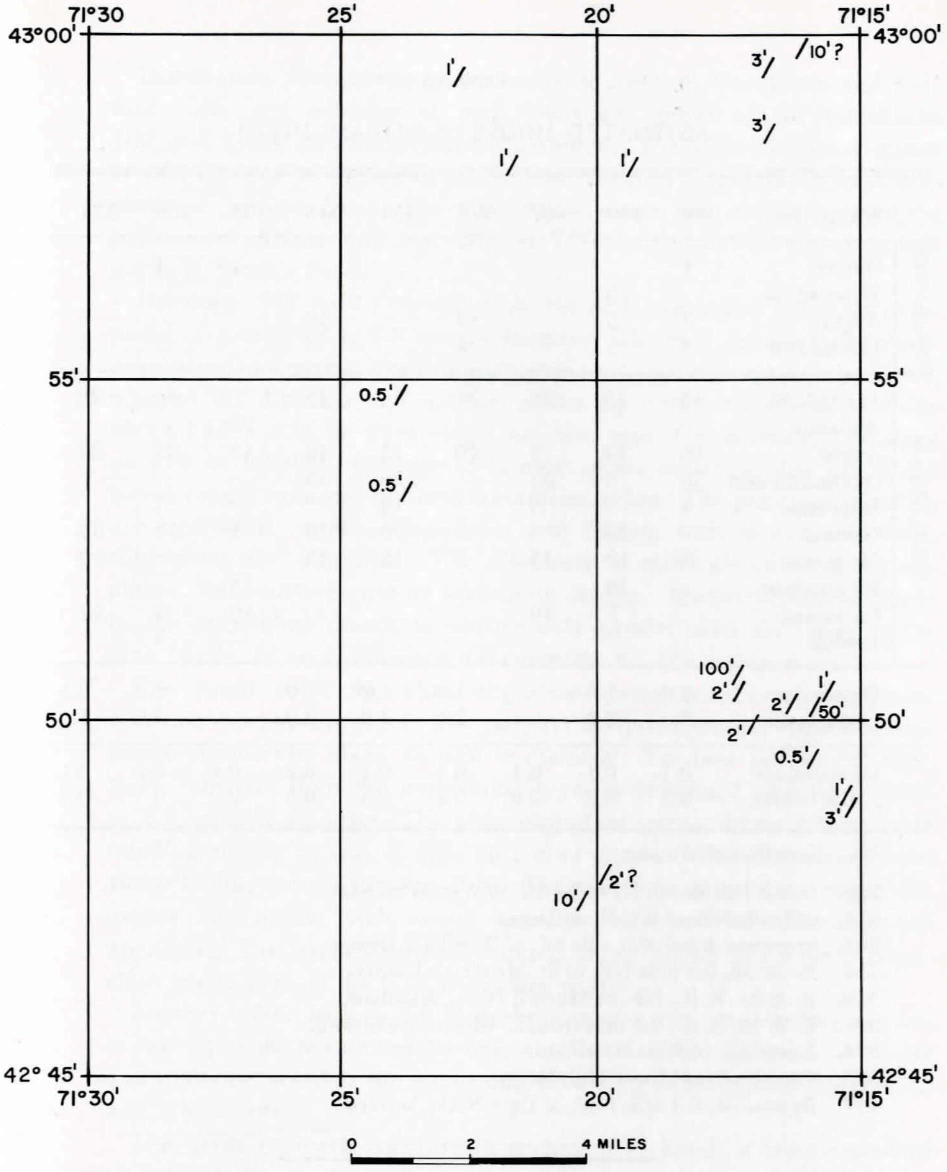
Lithology. The greenish-black diabase is composed of olivine, labradorite, and augite phenocrysts set in a groundmass composed of oxyhornblende, labradorite, augite, serpentine, and magnetite. In addition, non-pleochroic hypersthene occurs as phenocrysts, and andesine, carbonate, and epidote occur in the groundmass. Replacement textures of olivine by serpentine, plagioclase by epidote and carbonate, and augite by chlorite are observed in the dikes. The modes are given in Table 13.

Massabesic Gneiss

General Statement. The northwest portion of the Manchester quadrangle contains schists, granites, pegmatites, and gneiss. Emerson (1917, pp. 232-233) mapped similar rocks in Massachusetts with the Fitchburg granite. Billings (1952, p. 29) included these rocks in the Fitchburg pluton. However, Emerson, to some extent, and Billings (1952, p. 29) fully recognized the complexity of the rocks. So under the advice of Professor Marland P. Billings different rock units are mapped, and where big enough, are described separately.

The schists of the upper member of the Berwick formation, the microcline-albite pegmatite, microcline granite, microcline pegmatite, and the massive binary granite in this northwest portion of the quadrangle, have been separately mapped and are described above. The remaining rocks, the gneisses consisting of the biotite-rich and biotite-poor bands, make up the bulk of the northwest portion of the quadrangle. They are very well exposed around Lake Massabesic. Hence they are termed Massabesic gneiss.

The Massabesic gneiss consists of pink microcline gneiss and white oligoclase gneiss. The two can be distinguished by the presence or absence of the characteristic pink microcline. The Massabesic gneiss represented



Scale in Miles

Figure 4. Distribution of diabase dikes in the Manchester quadrangle. (Length of dike given in feet.)

Table 13

ESTIMATED MODES OF DIABASE DIKES

	Sample No.	361	359	467	377	354	348	333	230	374
Phenocrysts	Olivine	4							5	
	Hypersthene		5			5				
	Augite	3	5		12		10			5
	Labradorite	4	5		8		5		5	3
Groundmass	Labradorite	15	15	25	30	15	15		40	20
	Andesine							25		
	Augite	15	20	5	40	15	10	45	35	20
	Oxyhornblende	50	5	40		20	35			
	Serpentine	4		5		10			3	
	Chlorite		20		5	20	10	5	12	30
	Magnetite	5	10	15	5	15	15			10
	Hypersthene		10					15		
	Carbonate		5	10				10	5	12
	Epidote								5	
	Phenocrysts size in mm.	2.0-3.0	1.0-2.0		1.0-2.0	1.0-3.0	1.0-2.0		2.0-3.0	0.5-1.0
	Groundmass size in mm.	0.1-0.5	0.1-0.2	0.1-2.0	0.1-0.2	0.1-0.5	0.2-0.5	0.5-2.0	0.2-0.5	0.1-0.5

No. Location of samples

230. Castle Hill Road, 1.1 miles SE. of West Windham.
333. 0.2 mile NE. of Windham Depot.
348. Morrison Road, 0.9 mile SE. of Windham Depot
354. Route 28, 0.5 mile NE. of St. Matthew's Church.
359. B. & M. R. R., NE. of Mitchell Pond, Windham.
361. B. & M. R. R., 0.3 mile from E. edge of quadrangle.
374. 1 mile SE. of West Windham.
377. 0.6 mile E. of Moore Hill, Derry.
467. Bypass 28, 0.3 mile NW. of Deer Neck, Auburn.

on the map also includes a little amphibolite. The pink microcline gneiss comprises the major portion of the Massabesic gneiss, whereas the oligoclase gneiss and the amphibolite are of minor importance. The approximate percentages by area are pink microcline gneiss 70%, white oligoclase gneiss 25%, and amphibolite 5%. These percentages are merely estimates, and not based on any statistical data. The two gneisses and the amphibolites are not mapped separately, but they are described separately.

Distribution. Massabesic gneiss occurs in Auburn, Manchester and Bedford. The best outcrops of pink microcline gneiss are on Rattlesnake Hill and Route 28 around Lake Massabesic. The white oligoclase gneiss is well exposed in a roadcut on the new Concord Turnpike about a mile north of Sebbins Pond. The amphibolite crops out 200 feet west of the junction of Routes 101 and 28A at Wilson Hill and on top of the hill north of Stevens Pond.

Lithology. The most common rock, the pink microcline gneiss, is composed of grains 0.4 to 8.0 mm. in diameter. The pink color is very characteristic of this gneiss. The foliation strikes northeast with minor variations, whereas the direction and amount of the dip varies considerably. Folds about half a foot in wave length are also seen. Compositional banding as well as foliation, is observed in most of the outcrops. The size of the bands ranges from one-half inch to about six inches. The principal minerals are microcline, quartz, oligoclase, and biotite, with minor muscovite, sillimanite, and magnetite. The sillimanite is more abundant along slip planes. Sillimanite occurs as fasciculate needles. The proportion of biotite in the gray-black bands is considerably greater than the biotite in the pink bands. In some outcrops the magnetite is very conspicuous.

The minor rock, the white oligoclase gneiss, consists of porphyritic and non-porphyritic types. The porphyritic type contains oligoclase and biotite phenocrysts about an inch in diameter. The non-porphyritic type, more extensive than the porphyritic type, is composed of grains of 0.2 to 8.0 mm. in diameter. The white oligoclase gneiss shows foliation and banding similar to that of pink microcline gneiss. White oligoclase gneiss shows folding in hand specimens also. The principal minerals are oligoclase, quartz and biotite, with minor amounts of muscovite, sillimanite and almandite. The biotite content is comparatively higher in the white oligoclase gneiss than in the pink microcline gneiss.

Another minor rock in the Massabesic gneiss, the amphibolite, consists of two types; the more extensive one, which occurs as bands, has actinolite and andesine, whereas the minor one, occurring as lenses, has hornblende and labradorite.

The green to black amphibolite occurring as bands is coarse-grained with the grains ranging from 1.0 to 4.0 mm. in diameter. The foliation is generally parallel to the foliation of the Massabesic gneiss. But unlike the gneiss, it has no distinct banding. The principal minerals are actinolite, diopside, quartz, and andesine with minor biotite, microcline, and sphene. The actinolite needles are black and about 2 to 8 mm. long. The diopside is green and in sugary grains.

The minor amphibolite that occurs as lenses is fine-grained, the grains ranging in size from about 0.2 to 0.5 mm. in diameter. It is black and distinctly gneissose. The principal minerals are hornblende, labradorite

Plate IV. Foliation and compositional banding in Massabesic gneiss.

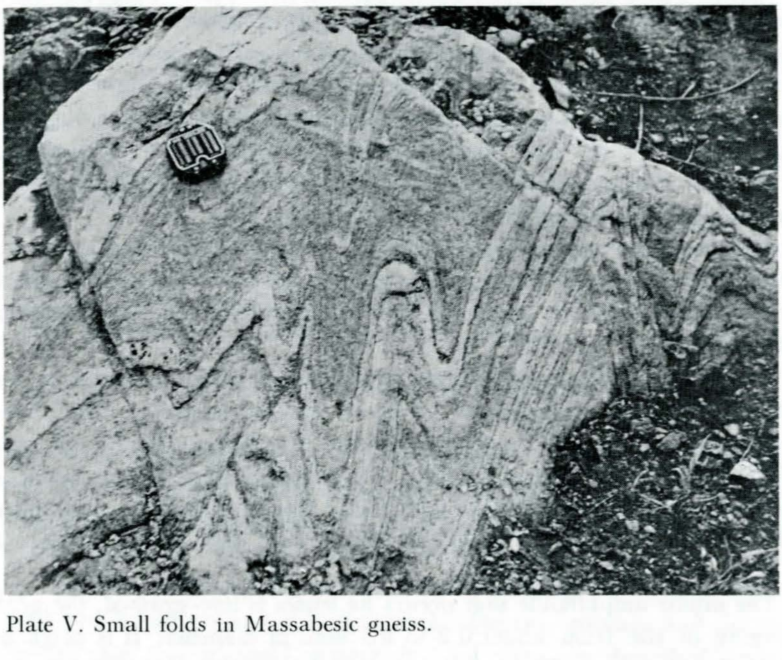


Plate V. Small folds in Massabesic gneiss.

Table 14

ESTIMATED MODES OF MICROCLINE GRANITE AND MASSABESIC GNEISS

Sample No.	1097	466	1021	468	1028	1128	1043	468.1
Quartz	40	25	20	40	30	20	25	15
Microcline	48	44	25				5	
Oligoclase		10	10	20	40	35		
Andesine							23	
Labradorite								17
Biotite	10	15	30	20	25	35	5	2
Chlorite								
Muscovite	2	1	5	10				
Sillimanite			10	10				
Almandite					5	10		
Hornblende								65
Actinolite							25	
Diopside							15	
Calcite								1
Magnetite		5						
Sphene							2	
Grain size in mm.	0.4-3.0	1.0-8.0	1.0-3.0	0.5-8.0	0.5-2.0	0.2-5.0	1.0-4.0	0.2-0.5

No. Description and location of samples

466. Pink microcline gneiss of Massabesic gneiss, Route 28 bypass, W. flank of Mount Misery, Auburn.

468. White oligoclase gneiss of Massabesic gneiss, Route 28 bypass, 0.4 mile N. of Deer Neck, Auburn.

468.1. Amphibolite of Massabesic gneiss, Route 28 bypass, 0.4 mile N. of Deer Neck, Auburn.

1021. Pink microcline gneiss of Massabesic gneiss, B. & M. R.R., 0.8 mile N. of Pine Island Park, Manchester.

1028. White oligoclase gneiss of Massabesic gneiss, 0.1 mile N. of St. Joseph Cemetery.

1043. Amphibolite of Massabesic gneiss, 0.3 mile NE. of Stevens Pond, Manchester.

1097. Microcline granite, E. of Route 28, North Londonderry.

1128. White oligoclase gneiss of Massabesic gneiss, Route U. S. 3 – Everett Turnpike intersection, Bedford.

and quartz, with minor biotite and calcite.

Relations with other rocks. The relations of pink microcline gneiss with the microcline granite and its relation with microcline pegmatite have already been described. The relationship between the white oligoclase gneiss and the massive binary granite has also been given. A roadcut on the Concord Turnpike a mile north of Reeds Ferry shows the contact between the schist of the upper member of the Berwick formation and the white oligoclase gneiss. From southeast to northwest the rocks are as follows: (1) coarse biotite-feldspar-quartz schist; (2) coarse biotite-feldspar-quartz schist with 2 inch phenocrysts of oligoclase and biotite; and (3) white oligoclase gneiss with biotite-rich and biotite-poor bands. The amphibolite occurs mostly as bands and less commonly as lenses in Massabesic gneiss.

Quartz Veins and Silicified Zones

Distribution. Quartz veins occur in both metamorphic and plutonic formations throughout the Manchester quadrangle. Silicified zones are limited in number. The biggest one extends northeast from Wilson, on Route 28 to Route 28 bypass in Auburn. Another is one and a half miles northeast of Litchfield village east of the cemetery. Two minor silicified zones are found; one is 20 feet northwest of the hill north of Pennichuck Brook, and the other half a mile north of Robinson Pond. The best exposures are 10 feet northeast and 200 feet southwest of Route 28 bypass in Auburn.

Size. The quartz veins are a fraction of an inch to a few inches in width, whereas the silicified zones are from four feet wide (north of Robinson Pond) to about 100 feet wide (in Auburn southwest of Route 28 bypass). This latter silicified zone extends more than 200 feet and rises 35 feet above the adjacent plains.

Structure. The trend of the quartz veins is generally northeast-southwest, parallel to the regional structure. However, some of them strike at different angles from this general trend and cut across the schists and plutonic rocks. Some other quartz veins show an anastomosing habit in the schist. Crystals of quartz are seen in the vugs of the quartz veins. Folded quartz veins are associated with folded schists, but the quartz veins may or may not be parallel to the bedding. In some outcrops folded quartz veins cut across the bedding of schists that appear not to be folded.

The strike of the silicified zones is northeast-southwest, and the dip is 50°SE. The dip of many silicified zones, however, is not clear. A general alignment in strike may be seen between the silicified zones in Auburn, Wilson and Litchfield.

CHAPTER IV
STRUCTURE

Metamorphic Rocks

Bedding. Beds and lenses of lime-silicate gneiss show the bedding in the Merrimack group, but such rocks are not abundant. Moreover, variations in the ratio of biotite and quartz in the granulite indicate bedding. Alternate schists and micaceous quartzites show the bedding in Littleton formation.

The strike of the bedding is usually N.10°E. to N.45°E. Locally, a particular zone in the formation may strike northwest, as for example, on the hill two miles southeast of Otternic Pond in the upper member of the Eliot formation, on the hill 200 feet north of Pennichuck Brook in the upper member of the Berwick formation, and on Mine Hill in the Littleton formation.

Contacts. The contacts between the metamorphic formations may be either relatively sharp or gradational (Plate I). The contact between the Merrimack group and the Littleton formation is relatively sharp and is easily located where the outcrops are good. The contact between the Eliot and Berwick formations of the Merrimack group is gradational, whereas those between the upper and lower member of the Eliot and Berwick formations are very gradational. Inasmuch as many of the contacts are gradational, their map pattern in many cases is not helpful in deducing the structure.

Schistosity and cleavage. Schistosity is common in both Merrimack group and the Littleton formation. Wherever compositional banding is present, it is parallel to the schistosity. This relationship indicates that the schistosity is bedding schistosity. Hence in those outcrops lacking compositional banding it has been assumed that the schistosity is bedding schistosity.

Slip cleavage (Billings, 1954, p. 339) is apparent in the Berwick formation. The small displacements and drags can be observed on the hill north of Pennichuck Brook. This slip cleavage is also clear in thin section. The slip cleavage is not used in interpreting the regional structure, as it occurs locally and in many instances with no consistency.

Axial plane cleavage diagonal to the bedding and more or less parallel to the axial planes of the folds, has been observed in the upper member of the Berwick formation. The axial plane cleavage strikes northeast and in many outcrops dips at a lower angle than the bedding. This relationship of the axial plane cleavage to the bedding is one of the factors that led to the recognition of the overturned folds in the upper member of the Berwick formation.

Lineation. In the metamorphic rocks the lineation is expressed by: (1) the crests of drag folds; (2) the crests of crinkles; (3) recrystallized minerals; and (4) boudinage.

The lineation on the crests of drag folds in the Merrimack group strikes northeast. The plunge is generally northeast in the northeast part and southwest in the southwest portion of the quadrangle. The plunges are usually gentle. In the upper member of the Berwick formation, occurring as inclusions in the Massabesic gneiss, a few drag folds are doubly plunging. The lineation in the drag folds of the Massabesic gneiss is generally not consistent in strike. Hence this lineation, unlike that in the Merrimack group, is not used to interpret the plunge of the folds. The lineation expressed by the crests of crinkles is very well seen in the Littleton formation on Mine Hill. The plunge of the lineation in this area is consistently northeast showing that the syncline of the area is plunging towards the northeast.

In some beds the actinolite crystals show lineation in the plane of the bedding schistosity. In the same bed a few inches away they do not show any preferred orientation, but are in fasciculate aggregates.

The small granite and pegmatite lenses suggest by their shape that they have been drawn out. These boudins have been folded after being drawn out. Some outcrops in the Littleton formation suggest that the micaceous quartzites are drawn out and formed boudins in the schist. Of course, there is the other possibility that this pinching out of the original sandstone beds is a primary feature inherited from the time of their deposition.

Minor folds. The structure sections (Plate I) show the folded metamorphic rocks in the Manchester quadrangle. The following is the description of certain outcrops (in many cases minor folds) in each formation that contributed to the construction of these structure sections. In the lower member of the Eliot formation the data on the direction and the amount of dip, obtained from railroad and roadcuts in Windham, show that the beds form broad open folds. The data come from fairly continuous outcrops and so the interpretation is reasonable. An outcrop 100 feet west of the junction of Routes 28 and 28 bypass, in the lower member of the Eliot formation around Derry, shows a minor fold. The beds are very nearly horizontal, with an indication that they are on the nose of an anticline that is plunging to the southwest. In West Run Brook, about 1,000 feet northeast, another outcrop also shows a broad anticline also plunging towards the southwest. This outcrop is on the same strike as the first.

In the upper member of the Eliot formation, a hill 2 miles southeast of Otternic Pond shows a minor fold. The beds on the northeast side of the hill strike northwest and dip southwest. This change of strike, from a general northeast to a northwest direction, coincides with a steep ledge. Although the northwest and southeast flanks of the hill are covered, the structure may be interpreted as due to a minor syncline plunging southwest.

In general the minor folds in the upper member of the Eliot formation show that the beds are right-side-up. However, in two outcrops the drag folds indicate overturning.

The lower member of the Berwick formation shows beds nearly vertical or dipping about 70° northwest, in most of the outcrops. A few drag folds show the tops to the northwest. In the upper member of the Berwick formation the hill 200 feet north of Pennichuck Brook shows a minor fold (Figure 5). As the hill is bare, providing continuous outcrops, the structure is very clear. On the southeast side of the hill the beds are vertical, with a northeast strike. The beds strike northwest and dip 45°S.W. on the northeast side of the hill. The beds strike northeast, again, with a dip 50°S.E., on the northwest side. This gives an asymmetrical syncline plunging southwest. Northwest of this hill, although the data are not as continuous, an asymmetrical anticline plunging towards the southwest is seen (Figure 5).

The Littleton formation at Mine Hill in Auburn forms a minor fold. On the northwest part of the hill the beds strike northeast and dip 70°S.E. In a line with the center of the hill, southeast of Route 121, the beds strike northwest and dip towards the northeast. The plunge measured on the crests of the crinkles is 20°N.E. The beds on the southeast part of the hill again strike northeast with vertical dip. This gives a syncline plunging northeast.

The drag folds in the Massabesic gneiss, unlike those of the Merrimack group, show minor irregularities. But close and detailed study reveals that the tops are towards the northwest.

Major folds. The data from minor folds, from the relation of axial plane cleavage to bedding and from stratigraphic relations, together with the regional considerations, shows that the metamorphic rocks in the Manchester quadrangle are on a northwest limb of a major anticlinorium, with minor anticlines and synclines. From the southeast towards the northwest, from the lower member of the Eliot formation, younger beds are encountered, with local exceptions, through the upper member of the Eliot formation, the lower and upper members of the Berwick formation, to the Littleton formation. The Littleton formation at Mine Hill and at the Souhegan River represents the youngest formation in a syncline axis that plunges northeast at the northeast portion and plunges southwest at the southwest portion

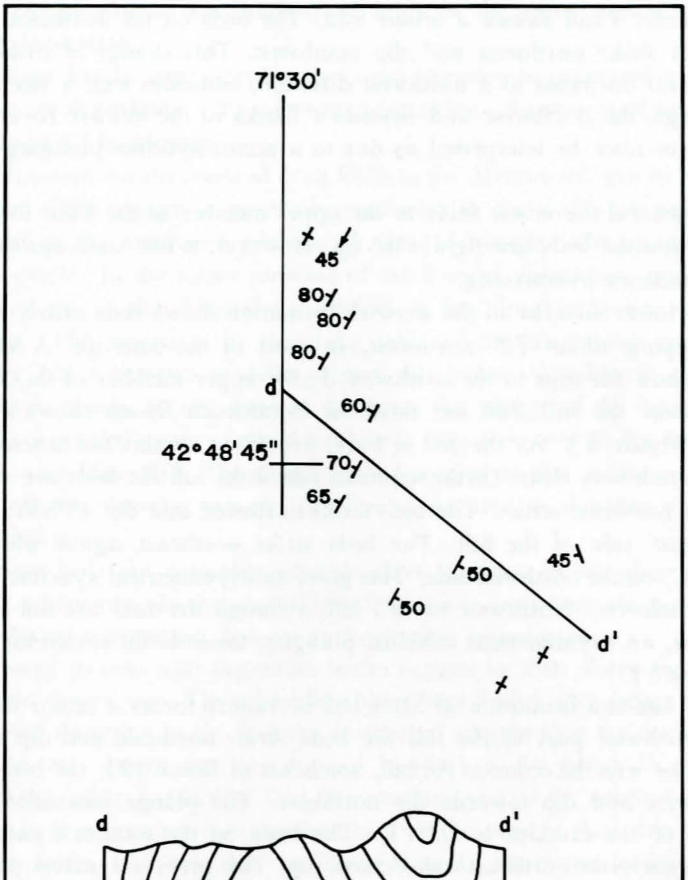


Figure 5. Structure section showing the minor folds in the upper member of the Berwick formation on hill north of Pennichuck Brook. See geologic map, Plate I, for explanation of symbols.

of the quadrangle. The upper member of the Berwick formation reappears northwest of this synclinal axis.

Faulting. Some silicified zones are mapped in the Manchester quadrangle. Billings (1937, p. 526) considered silicified zones as one of the criteria indicating faulting. However, other criteria that indicate faulting, such as repetition or omission of strata, and breccia are not observed. The facts connected with silicified zones in the Manchester quadrangle, some of which may indirectly show faulting are: (1) anastomosing quartz veins in schist adjacent to the silicified zone; (2) presence of vugs in the quartz veins; (3) a smooth surface bounding the silicified zone at Wilson; (4) the alignment of the silicified zones along the strike in Auburn, Londonderry, and Litchfield; (5) slippage in the beds on either side of the silicified zones; (6) presence of silicified zones at the contact of the foliated binary granite and the schists; and (7) the close coincidence of the 50°S.E. dip of the silicified zone with that of the axial plane of the overturned tight folds of the upper member of the Berwick formation.

The presence of vugs in the quartz veins shows that the quartz veins are formed at least in part by open-space filling, although there may have been replacement of the rock as well. The presence of a smooth surface coinciding with the dip of the silicified zone is indicative of faulting. Since this plane does not show any slickensides, there is some doubt about this inferred faulting. The alignment in strike of silicified zones in Auburn, Londonderry, and Litchfield indicates at least a weakness plane in that direction, if not faulting. The contact of foliated binary granite with the schist is a weakness plane, even though the presence of faulting is doubtful. The occurrence of a silicified zone at the contact of granite and schist also indicates that the silicified zones are indirectly connected with the plane of weakness.

The slippage in beds on either side of the silicified zone indicates that there was some sort of movement. The dip of the silicified zones coincides with the dip of the axial planes of the tight overturned folds. Mechanical interpretation of the tight overturned folds indicates the action of a couple. The parallelism of the dip of the silicified zone and the dip of the axial planes of the tight overturned folds may signify that the same couple produced the faulting.

Plutonic Rocks

Concordant plutons. The Ayer granodiorite is generally concordant with the lower member of the Eliot formation. Discordant contacts are local. In some places the contact is a zone as much as 100 feet wide, composed of alternating concordant bands of Ayer granodiorite and the schists.

The microcline granite is generally concordant with the schists of the upper member of the Berwick formation, but is locally discordant. Also the microcline granite is flanked by an extensive banded gneiss. These two contacts, in the opinion of the writer, are of the permissive type as opposed to the forceful type. The permissive type of contact is that between schist conditioned to receive the plutonic rock and the plutonic fluid ready to move in.

The contact between the foliated binary granite and the schist is mainly concordant but is locally discordant. Unlike the Ayer granodiorite and the microcline granite, the foliated binary granite shows a rather sharp contact. This is true even in the case of small lenses of foliated binary granite. The writer interprets this to mean that the foliated binary granite is not the result of permissive injection.

A factor that is to be mentioned here is that of composition. The Ayer granodiorite is similar in mineralogy to the schists of the lower member of the Eliot formation. The microcline granite is similar in mineralogy to that of the pink biotite-poor bands of the Massabesic gneiss. But the foliated binary granite is distinctly different in composition from the schist with which it comes into contact. The origin of these rocks is discussed in a later section.

The foliated binary granite and the Ayer granodiorite are more than 10 times longer than wide, parallel and mainly concordant with the adjacent schists, so they may be classified as large sills. The tapering and disappearance of the foliated binary granite and the Ayer granodiorite also suggests that they are sills.

Discordant plutons. The contact of the microcline pegmatite with Massabesic gneiss is clearly discordant. Similarly, the contact between the massive binary granite and the Massabesic gneiss, and the contact between the massive binary granite and the microcline-albite pegmatite are discordant.

Even though the northeast-southwest strike of the diabase dikes coincides with the strike of the metamorphic rocks, the difference in the dips makes the contacts discordant. Moreover, in a few outcrops, the diabase dikes change in strike, cut across the schist, and then resume the former strike parallel to the bedding.

Foliation and banding. The Ayer granodiorite and the foliated binary granite show foliation parallel to the schistosity of the metamorphic rocks. In addition to the foliation caused by the parallel arrangement of the platy minerals in the groundmass, the foliated binary granite shows muscovite phenocrysts which give minor foliation at an angle to the general foliation. Locally the minor foliation at an angle to the general foliation is due to the parallel arrangement of the biotite phenocrysts. Compositional banding as distinct from foliation is shown by the biotite-rich and biotite-poor bands. The compositional banding is observed in Ayer granodiorite and microcline granite.

Sheeting. Sheeting is observed in all the granite quarries. The quarries include both foliated and massive binary granites. The sheeting is parallel to the surface of the hill. The sheeting is intersected by a set of steeply dipping joints. Quarrying of the granite is carried out by taking advantage of these two sets of fractures.

CHAPTER V
MINERALOGY

Introduction. Mineralogical investigations were carried out in order to determine the composition of the minerals without chemical analysis and to get an idea of the physico-chemical environment of their formation. The major rock-forming minerals, namely, alkali-feldspars, plagioclases, pyroxenes, amphiboles, micas, and garnets that occur in the formations of the Manchester quadrangle were selected for study. It was not possible and in some cases was not necessary to determine all the physical characters. Those physical characters that were determined in the various mineral groups are given in Table 15.

Alkali-feldspars

Occurrence. The alkali-feldspars studied are from the following rocks: (Locations in Table 16) (1) 1036: microcline pegmatite in Massabesic gneiss; (2) 1051: microcline-albite pegmatite in upper member of the Berwick formation; and (3) 1119: microcline pegmatite in Ayer granodiorite.

Procedure. The alkali-feldspar was examined under the microscope to see whether it was homogeneous. All the alkali-feldspars examined are perthites. This is also seen from the X-ray powder pattern, where plagioclase lines are present. The alkali-feldspars were then homogenized, by keeping the grains (size 0.1 to 0.05 inches) at 1,000°C. for about 24 hours. Part of the grains were powdered and their X-ray powder pattern was obtained. If the duration of the heating was not enough and the alkali-feldspar was not homogenized, as shown by the presence of the strong (020,004) albite line on the X-ray pattern, the grains were heated again for an additional period of time.

The refractive indices of the homogenized grains were measured; moreover, the optic axial angle and the extinction angle of the natural alkali-feldspar were determined.

The content of potash feldspar in the alkali-feldspar is obtained from the (201) '<u>d</u>' spacing of the X-ray powder pattern (Bowen and Tuttle, 1950, p. 493). The type of symmetry is obtained from the separation or coincidence of the (131) and ($1\bar{3}1$) reflections of the X-ray pattern (Mackenzie, 1954, pp. 355-356; Goldsmith and Laves, 1954, pp. 3, 5). The amount of departure from monoclinic symmetry is obtained from

Table 15

MINERAL GROUPS AND THE PHYSICAL CHARACTERS DETERMINED

Mineral Group	Physical characters
Alkali-feldspars	Refractive indices, optic axial angle and extinction angle on (010) Interplanar d spacing of (1$\bar{3}$1) and (131) and after homogenization (20$\bar{1}$)
Plagioclases	Refractive indices Interplanar d spacings
Pyroxenes, amphiboles and micas	Refractive indices
Garnets	Refractive index, specific gravity, and unit cell edge

the angular separation of the reflections of the (1$\bar{3}$1) and ($\bar{1}$31) planes, and the separation is not affected by the homogenization process.

Having determined the composition by an X-ray method, the optical characters are used to assign the sample to one of the series of alkali-feldspars proposed by Tuttle (1952). The fact that the extinction angle was not zero, denotes that the alkali-feldspars belong to the microcline cryptoperthite series.

Discussion. The study of the alkali-feldspars shows that they all originally contained between 84 and 88 percent potash feldspar; that they are now triclinic in symmetry; and that they belong to the microcline-cryptoperthite series. This series is thought to be more stable at lower temperatures than other alkali-feldspar series (Tuttle, 1952).

The laboratory study shows that the microcline from the microcline-albite pegmatite contains nearly the same amount of albite as the microcline from the microcline pegmatite. But the field study shows that the microcline-albite pegmatite contains the two separate feldspars; therefore, the bulk composition of the albite-microcline pegmatite must be richer in albite. The results are used in discussing the origin of the pegmatites.

Table 16

COMPOSITION AND DEGREE OF TRICLINICITY OF ALKALI-FELDSPARS

Number	'd' ($20\bar{1}$) Å spacing	Potash Feldspar component, Wt. %	Symmetry degree of triclinicity
1036	4.2055	86.5%	0.86
1051	4.2009	84.5%	0.98
1119	4.2065	87.5%	0.98

No. Location of samples

1036. 0.4 mile E. of Wilson Hill, Manchester.
1051. 0.5 mile SSE. of 340 feet benchmark, Pingray Hill Road, Auburn.
1119. Marblehead Road, 0.3 mile N. of Rock Pond, Windham.

Plagioclase Feldspar

Occurrence. Plagioclase occurs in most of the formations in the Manchester quadrangle. The plagioclase selected for study is from: (1) 1128: massive binary granite; (2) 466.1: Massabesic gneiss; (3) 1051: microcline-albite pegmatite; (4) 1128.1: phenocrysts in oligoclase gneiss of Massabesic gneiss; and (5) 1081: lime-silicate rock in the upper member of the Berwick formation.

Procedure. The plagioclase of the microcline-albite pegmatite is available in separate crystals an inch or two in size, whereas the plagioclase from other rocks has to be separated by physical methods. The 'd' spacings of the plagioclase were obtained from the X-ray spectrometer patterns. The refractive indices were determined by the double variation method. The values of the refractive indices were not as accurate as is expected from the double variation method, since no orientation device (Universal Stage) is attached to it. Still the indices are good enough to confirm the results from the X-ray study.

The composition of the plagioclase is obtained (Goodyear and Duffin, 1954, p. 319 and 324) from the angular separation of the pairs ($2\bar{2}0$) or (220) and ($1\bar{3}1$); ($\bar{1}32$) and ($24\bar{1}$); and ($\bar{1}32$) and ($\bar{2}41$). Whether the feldspar is high or low temperature plagioclase was determined from the 3.01 Å (29.65° 2θ for Cu $K\alpha$) d spacing (Tuttle and Bowen, 1950, p. 574), as well as from the use of angular separation data in the pairs; the first to approximate the composition and the second to check whether consistency verifies the high or low assumptions.

Table 17

COMPOSITION AND STRUCTURAL MODIFICATION OF PLAGIOCLASES

Number*	Formation	Composition (Anorthite component in weight percent)	"High" or "Low" temperature modification
1128.1	Phenocrysts in Massabesic gneiss	26.5	Low
1051	Microcline-albite pegmatite	3.0	Low
466.1	Massabesic gneiss	20.0	Low
1128	Massive binary granite	24.5	Low
1081	Lime-silicate gneiss in the upper member of Berwick formation	57.0	Low

* The location of each of these specimens has been given in preceding tables arranged by formation.

The composition obtained from the different sets of angular separations in the same plagioclase sample was not as consistent as expected. The inconsistency, however, is not more than 2% in the samples, even though it is higher in the plagioclases from the lime-silicate gneisses. The compositions are shown below (Table 17).

Discussion. The plagioclase in the microcline-albite pegmatite shows 3% anorthite component. Since the pegmatite is a two feldspar pegmatite associated with granite, the 3% anorthite is in order. The Massabesic gneiss in the sillimanite zone has plagioclase with 20.0% to 26.5% anorthite, whereas the lime-silicate gneiss in the garnet zone has plagioclase with 57% anorthite. There is considerably less anorthite component in the rocks of higher grades. This is because of the higher calcium content of the lime-silicate gneisses in the garnet zone. Thus the original composition of the rock, from which the plagioclase formed, may have more effect on the anorthite component than the grade of metamorphism.

All the plagioclases are low temperature forms, which confirms the result obtained from the alkali-feldspar study. This is also expected from the other observations.

Pyroxene

Occurrence. Pyroxene occurs in the lime-silicate gneisses of the Eliot formation and the upper member of the Berwick formation. It also occurs in the amphibolite of the Massabesic gneiss. It is also present in the diabase dikes.

The pyroxene in the lime-silicate gneiss is diopside. The refractive indices of pyroxene in the amphibolite of the Massabesic gneiss are $\alpha = 1.674$, $\beta = 1.694$ and $\gamma = 1.699 \pm 0.002$. These values give diopside with 5% hedenbergite (Hess, 1949). In the diabase dikes common augite and non-pleochroic hypersthene are present.

Amphibole

Occurrence and composition. Amphibole is present in the lime-silicate gneisses, amphibolite, Ayer granodiorite, and diabase. The refractive indices of the amphiboles were determined. As the amphiboles contain many components and as only refractive indices were determined, it is not possible to get the true composition. However, the composition in terms of Mg number is obtained (Foslie, 1945, p. 78) using the mean refractive index. The nature of the amphiboles (either tremolite-actinolite or hornblende) known from the microscopic study helped to select the proper curve.

Discussion. In view of the smaller number of grains studied, the discussion has to be limited in its scope. The amphiboles from the lime-silicate gneisses, occurring in the garnet zone, show noticeable variation in the Mg number. As there is some variation in the mineral assemblages, expecially in the percentages of the minerals, there might have been some variation in the original composition of the lime-silicate gneisses. This variation in the original composition might be the reason for the variation in the Mg number of the amphiboles. That the original composition of the rocks caused the variation in the composition of the amphiboles is also illustrated by the amphiboles from the amphibolites. The amphiboles from numbers 1036 and 1043 are separated by about two miles. But inasmuch as they come from rocks on the same strike, the rocks were probably of the same original composition. Both are from the microcline-sillimanite zone. Belonging to the tremolite-actinolite series, they show nearly the same Mg number (73.5 and 76.5). The amphibole from number 468 is

Table 18

COMPOSITION AND THE ENVIRONMENT OF AMPHIBOLES

Number **	Rock and Formation	Metamorphic Zone	Mean Refractive Index	Composition in Mg Number* Tremolite-actinolite	Hornblende
1111	Quartz diorite in Ayer granodiorite	---	1.688		23.0
468	Amphibolite in Massabesic gneiss	Sillimanite	1.669		50.5
1036	Amphibolite in Massabesic gneiss	Sillimanite	1.638	73.5	
1043	Amphibolite in Massabesic gneiss	Sillimanite	1.636	76.5	
1081	Lime-silicate gneiss in upper member of the Berwick formation	Garnet	1.649	59.5	
1050	Lime-silicate gneiss in upper member of the Berwick formation	Garnet	1.640	71.5	
417	Lime-silicate gneiss in upper member of the Berwick formation	Garnet	1.658	44.0	
205	Lime-silicate gneiss in upper member of the Eliot formation		1.653	52.5	

$$* \ \underline{Mg}: \frac{MgO}{2Fe_2O_3 + FeO + MnO + MgO}$$ (Foslie, 1945, p.78)

** The location of each of these specimens has been given in preceding tables arranged by formation.

also separated from the above two by about the same distance. But this comes from a different horizon, which was probably of different original composition. Although this also comes from the microcline-sillimanite zone, the Mg number is 50.5 and the amphibole is hornblende.

Biotite

Occurrence, composition, and discussion. Occurring in metamorphic and plutonic rocks, biotite is the most ubiquitous mineral, except for quartz and feldspar, in the Manchester quadrangle. The $\beta = \gamma$ indices of refraction were determined and are given in Table 19.

The $\beta = \gamma$ refractive index of the biotites in the formations of the Manchester quadrangle ranges from 1.621 to 1.655. The biotites are about half way between annite-siderophyllite and phlogopite-eastonite (Winchell, 1951). Biotite from the lime-silicate gneiss (number 205), has a higher index than the biotite from granulite (number 1130). Both are from the Eliot formation in the garnet zone. Number 1130 is associated with quartz-biotite-calcite gneiss. One would expect the biotite in the lime-silicate gneiss to have a higher ratio of Mg to Fe, and thus a lower index of refraction than the biotite in the granulite. However, the index of the biotite from specimen 205, in the lime-silicate gneiss, is actually higher than the biotite in the granulite.

Table 19

INDEX OF REFRACTION OF BIOTITE

Number *	Formation	Index (Na)
1128	Massive binary granite	1.645 ± 0.003
1112	Ayer granodiorite	1.647 0.003
1128.1	Massabesic gneiss	1.652 0.003
1028	Massabesic gneiss	1.648 0.003
1070	Littleton formation	1.646 0.003
396	Upper member of the Berwick formation	1.637 0.003
1130	Lower member of the Eliot formation	1.621 0.003
97	Lower member of the Eliot formation	1.645 0.003
205	Upper member of the Eliot formation	1.655 0.003

* The location of each of these specimens has been given in preceding tables arranged by formation.

Garnet

Occurrence. Garnet occurs in metamorphic and plutonic rocks throughout the quadrangle, except in a small strip in the center trending northeast-southwest. The garnets vary in size from microscopic dimension to about an inch in diameter.

Procedure. The specific gravity of small garnets crystals (about 25 mg. weight) was determined by using the Berman balance (Berman, 1939). The refractive index was determined using immersion liquids. The unit cell edge was determined from the X-ray spectrometer patterns.

Results. The specific gravity of garnet from the Ayer granodiorite (Number 1119) is 4.18 ± 0.01 and its unit cell edge 11.56 Å ± 0.01. The refractive index of this garnet and others are given in Table 20.

Composition. Triangular diagrams for determining the composition of garnets were constructed by the writer using recent data on the refractive index and the unit cell edge. These diagrams are published in the *American Mineralogist* (Sriramadas, 1957).

The composition of the garnet from the Ayer granodiorite, using the triangular diagrams, is 79% almandite, 10% pyrope, and 11% grossularite. The triangular diagrams of Kennedy (1947) were used to confirm this

Table 20

REFRACTIVE INDICES OF GARNETS

Number[a]	Formation	Refractive index (Na)
1119	Ayer granodiorite	1.808 ± 0.003
1131	Ayer granodiorite in contact zone	1.800 0.003
370	Ayer granodiorite	1.798 0.003
349	Foliated binary granite	1.813 0.003
360	Foliated binary granite	1.808 0.003
1128	Massabesic gneiss	1.798 0.003
234	Schist from Littleton formation	1.813 0.003
417	Lime-silicate gneiss of the upper member of the Berwick formation	1.778 0.003

[a] The location of each of these specimens has been given in preceding tables arranged by formation, with one exception. The location of No. 1131 is not known.

composition. The composition according to the latter diagrams is almandite 82%, pyrope 12%, and grossularite 6%.

Since the refractive index of the rest of the garnets, except No. 417, is nearly the same, their composition may also be nearly the same. But the refractive index of No. 417 is considerably less than others. Since this garnet comes from a lime-silicate gneiss, it may be that it contains more grossularite component in which case the refractive index would be expected to be lower.

CHAPTER VI
METAMORPHISM

Original Composition

As the minerals produced by the grade of metamorphism depend in part on the original composition of the rocks, it is necessary to consider the formation in terms of their original composition first. Rocks such as shales or siliceous dolomites are very suitable for study. The Littleton formation is composed of schists that were probably originally shales, and hence suitable for the study of metamorphic effects. But this formation is very limited in areal extent. The Merrimack group, consisting of schists, lime-silicates, gneisses, and granulites, probably represents calcareous silt-stones (graywackes) and this group occupies much of the quadrangle. The group as a whole is not useful in analysing the metamorphic effects. However, some units of the group were argillaceous and siliceous dolomites, and so the argillaceous portions and siliceous dolomitic portions that form minor units in the Merrimack group are used, along with the argillaceous rocks of the Littleton formation.

Metamorphic Index Minerals

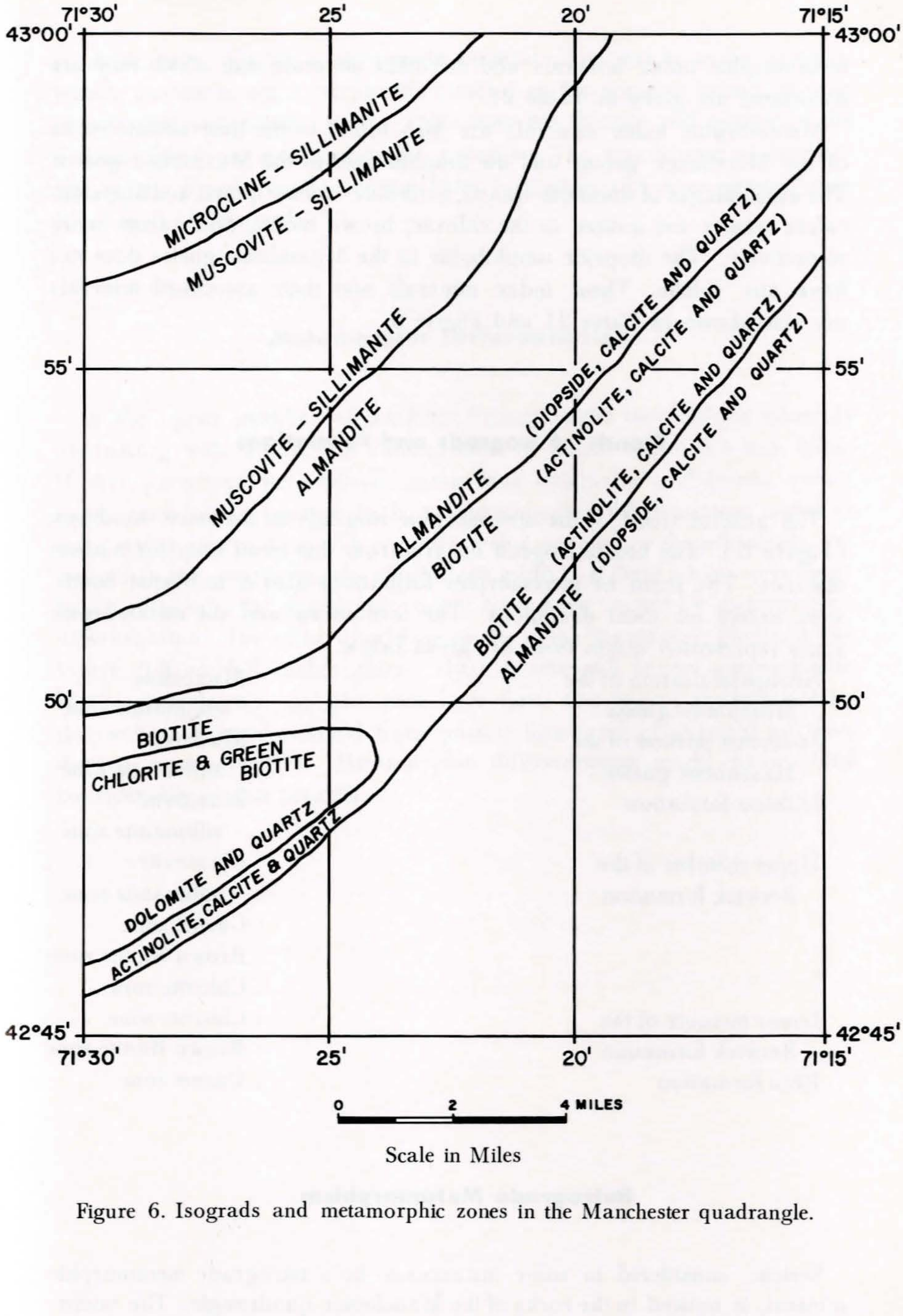
The argillaceous portions of the Merrimack group, the Littleton schist, and the argillaceous portion of the Massabesic gneiss contain metamorphic index minerals. The southwest portion of the Berwick formation contains chlorite along with green biotite and sericite. A strip about three miles wide trending northeast-southwest contains brown biotite. The upper member of the Berwick formation and the Eliot formation contain garnet. The Littleton formation and portions of the Massabesic gneiss contain sillimanite. The northwest portion of Massabesic gneiss contains microcline and sillimanite.

Metamorphic index minerals and isograds. All the metamorphic index minerals found after microscopic study have been plotted on the map. The isograds are drawn at the first appearance of these index minerals. Thus there are the brown biotite, garnet, muscovite-sillimanite, and microcline-sillimanite isograds giving chlorite, brown biotite, garnet, muscovite-sillimanite and microcline-sillimanite zones (Plate I and Figure 6). The

Table 21

METAMORPHIC INDEX MINERALS OF THE MANCHESTER QUADRANGLE

Zone	Associated minerals (in argillaceous rocks)	Minerals (in lime-silicate rocks and amphibolites)
Chlorite	Quartz, green biotite, chlorite, sericite, and albite (No. 23)	Quartz, chlorite, green biotite, sericite, albite and dolomite (No. 28)
Brown biotite	Quartz, brown biotite, oligoclase, and muscovite (No. 270)	Quartz, oligoclase, actinolite, biotite, muscovite, epidote, chlorite and calcite (No. 79)
Garnet	Quartz, biotite, andesine, muscovite, chlorite and almandite (No. 388)	Actinolite, quartz, andesine, epidote, grossularitic garnet, chlorite, muscovite, calcite, and diopside (No. 417)
Muscovite-sillimanite	Quartz, sillimanite, muscovite, biotite, almandite (No. 1070)	Hornblende, labradorite, quartz, biotite, and calcite (No. 468.1)
Microcline-sillimanite	Biotite, microcline, quartz, sillimanite, oligoclase and muscovite (No. 1021)	Actinolite, quartz, andesine, diopside, and biotite (No. 1043)



Scale in Miles

Figure 6. Isograds and metamorphic zones in the Manchester quadrangle.

metamorphic index minerals and the other minerals with which they are associated are given in Table 21.

Metamorphic index minerals are also found in the lime-silicate rocks of the Merrimack group and the amphibolites of the Massabesic gneiss. The assemblages of dolomite-quartz, actinolite-calcite-quartz and diopside-calcite-quartz are noticed in the chlorite, brown biotite, and garnet zones respectively. The diopside amphibolite in the Massabesic gneiss does not have any calcite. These index minerals and their associated minerals are also shown in Table 21 and Figure 6.

Trends of Isograds and Formations

The general trend of the metamorphic isograds is northeast-southwest (Figure 6). The biotite isograd departs from this trend only for a short distance. The trend of metamorphic formations also is northeast-southwest, except for local deviations. The formations and the metamorphic zones represented within them are given below.

Northwest portion of the Massabesic gneiss	: Microcline-sillimanite zone
Southeast portion of the Massabesic gneiss	: Muscovite-sillimanite zone
Littleton formation	: Muscovite-sillimanite zone
Upper member of the Berwick formation	: Muscovite-sillimanite zone
	: Garnet zone
	: Brown Biotite zone
	: Chlorite zone
Lower member of the Berwick formation	: Chlorite zone
	: Brown Biotite zone
Eliot formation	: Garnet zone

Retrograde Metamorphism

Sericite, considered in some instances to be a retrograde metamorphic mineral, is noticed in the rocks of the Manchester quadrangle. The microcline in foliated binary granite and Ayer granodiorite are syntectonic. Whether these are metamorphosed or not is not apparent; so the sericite in these may not be a retrograde mineral. The sericite in the massive binary granite is not a retrograde mineral as the massive binary granite is not metamorphosed. In the same way the chlorite and epidote of the diabase dikes are not retrograde minerals. The significance of myrmekite in the lower member of the Eliot formation and Ayer granodiorite is not well understood.

Metamorphic Differentiation

In the upper member of the Eliot formation the lime-silicate minerals alternating with quartz are concentrated in bands about 0.4 inch thick. If this pinstriped lime-silicate gneiss was originally a dolomite-quartz sand, then some process such as metamorphic differentiation aided in the present segregation. Thin quartz veins parallel to the schistosity are noticed in the quartz-biotite-plagioclase schists. If these schists were originally siltstones, the segregation might have been caused by metamorphic differentiation. The white oligoclase gneiss of the Massabesic gneiss shows layers 0.2 to 5.0 inches thick, where biotite-rich layers alternate with biotite-poor layers. As discussed later these two layers are believed by the writer to have resulted from partial fusion of the original mixture, during metamorphism. Metamorphic differentiation might have aided considerably in this process.

CHAPTER VII
DISCUSSION

Lithology

Environment of deposition of metasediments. Any analysis of sediments concerning their environment of deposition involves knowledge of their primary structures (current bedding, ripple marks, graded bedding, etc.), color (red beds, black shales, etc.), textures (size, shape, rounding), and finally the chemical and mineralogical composition.

In the Manchester quadrangle the knowledge of metasediments is limited to their textures and composition. Even these two characters are inferred from their metamorphic equivalents. Primary sedimentary structures, except bedding, are not seen either because they were not present originally or have not been preserved. Hence the following discussion is to be taken in this perspective.

The inferred original composition of the metasediments in the Manchester quadrangle is, from northwest to southeast:

(a) Shale with some alternating sandstone (Littleton formation);

(b) Mostly shaly siltstone with dolomitic lenses (upper member of the Berwick formation);

(c) Mostly siltstone (lower member of the Berwick formation);

(d) Mostly dolomitic siltstone with laminated shaly siltstone (upper member of the Eliot formation);

(e) Mostly shaly siltstone with some lenses of dolomitic siltstone (lower member of the Eliot formation).

To fix the environment for this inferred composition the following quotation from Pettijohn (1949) will be helpful.

> " The geosynclinal facies is marked by its great thickness. Deposition most nearly was continuous and with least interruption. The arenaceous and argillaceous materials are intimately mingled . . . the proportions of sand to clay supplied to the geosyncline are about 1 to 8 . . . . Carbonate rocks are absent or occur only as nodules. " (Pettijohn, 1949, pp. 444 - 445)

> " The foreland or platform facies is a product of accumulation in shallow seas . . . . The materials are well sorted. The argillaceous material is clearly separated from the arenaceous debris. The sandstones belong to the ortho-quartzite clan. Calcareous matter is abundant as shells and shell debris. " (Pettijohn, 1949, pp. 451 - 452).

According to this scheme the metasediments of the Manchester quadrangle are near to the geosynclinal facies. But the carbonate content is a little more than mere nodules; so the geosynclinal facies is mixed with some foreland facies.

Source. The inferred metasediments of both the Merrimack group and the Littleton formation show that they are nonvolcanic. However, there is a thin belt of amphibolite not more than 50 feet wide in the Massabesic gneiss. Since this amphibolite is in the sillimanite zone of metamorphism, it is not possible to say definitely whether it is of volcanic or sedimentary origin. The Merrimack group represents a thickness of about 17,500 feet. So even if the amphibolites are volcanic, they are very minor in bulk compared to the nonvolcanics, and the 17,500 feet of nonvolcanics are too much for the source to have been volcanic islands (Kay, 1951, pp. 90-92). The source must have been rather large and contained few, if any, volcanoes (Schuchert, 1923).

It is not possible to infer the direction of the source since diagnostic sedimentary structures are absent. However, the regional studies involving the Appalachians show that the source of the sediments in the Manchester quadrangle lay to the southeast.

Stratigraphy: Correlation and Age of Metamorphic Rocks

Introduction. The following points are borne in mind in attempting to correlate and get the age of the formations in the Manchester quadrangle:

(1) no fossils are found in situ;

(2) no key horizons are present to trace into the fossiliferous beds to the northeast or northwest;

(3) the formations are intensely deformed, resulting in complicated structure;

(4) the metamorphism reaches sillimanite grade in some formations; and

(5) plutonism in some parts obscured the structure of the metamorphic formations.

Correlations of Merrimack group. The lithology of the Merrimack group in the Manchester quadrangle is very similar to the lithology of the Eliot and Berwick formations in the Mt. Pawtuckaway quadrangle. The rocks in both areas are also along the same strike. However, the lower part of what Freedman called the Littleton formation has been assigned to the upper member of the Berwick formation in the Manchester quadrangle. One distinction between the Merrimack and Littleton formations is that no lime-silicate rock is found in the Littleton. Lime-silicate rocks are present in the lower part of Freedman's Littleton formation, which makes it desireable for this formation to be included in the Merrimack group. Billings et al., (1952) recognized this when they included the lower part of what Freedman called Littleton in the Merrimack group.

This correlation may be extended to the Dover quadrangle and beyond by tracing the lower member of the Berwick formation, as noticed by the writer during the field trip to Dover quadrangle in the fall of 1954.

The description of the Merrimack quartzite (Jahns, 1952, p. 111) in the Ayer-Lowell region to the south indicates that it is lithologically similar to the Merrimack group in the Manchester quadrangle. Professor J. B. Thompson and the writer have noticed the similarity of the Oakdale quartzite to the south in Massachusetts to the lower member of the Berwick formation in the Manchester quadrangle. Hence, the Merrimack group in Manchester quadrangle may be correlated with the Merrimack quartzite and with the Oakdale quartzite to the south and the southwest.

The above discussion indicates that the Merrimack group in the Manchester quadrangle may be correlated with the Eliot and Berwick formations of New Hampshire and Maine to the northeast, and with the Merrimack quartzite and Oakdale quartzite of Massachusetts to the southwest.

Correlation of Littleton formation. The characteristics of the Littleton formation in the Manchester quadrangle, considered in connection with correlation are:

(1) Mineralogy: biotite-sillimanite-quartz-muscovite-almandite schist and biotite-quartz gneiss;
(2) Inferred original lithology: shale with some sandstone;
(3) Structural position: overlying Merrimack group; and
(4) Weathering: generally rusty.

The descriptions of the Littleton formation in the northwest part of the Mt. Pawtuckaway quadrangle are similar to this. Also they are on the same strike as the Littleton of the Manchester quadrangle. Hence these may be correlated.

The correlation to the southwest depends on the descriptions and the geological map of Emerson (1917). He describes the Brimfield schist west of the Worcester phyllite as follows:

> " . . . it is a coarse deep-brown biotite-muscovite schist in which the red-brown shade of the biotite is characteristic. A fine amber fibrolite is very common. Crystals of clear pink garnet are abundant, and their easy decomposition gives the rock its rusty color in part, but there is commonly much pyrite, which causes the rock to slake and cover the surface with an efflorescence of salts of iron and aluminum and deep streaks of rust. " (Emerson, 1917, p. 69).

> " The rock is thrown into great north-south synclines, which are folded into the Paxton quartz schist . . . " (Emerson, 1917, p. 70).

These descriptions by Emerson show that the Brimfield schist in Massachusetts is similar in lithology, structural position and weathering to the Littleton formation in the Manchester quadrangle. Moreover, the formations along the Souhegan River are on the same strike.

Thus the Littleton formation in Mine Hill and Souhegan River may be correlated with the Littleton formation of the Mt. Pawtuckaway quadrangle. The Brimfield schist, with similar lithology and occupying the same syncline, may be correlated with the Littleton of the Manchester quadrangle.

Age of the Merrimack group. There is no direct evidence on the age of the Merrimack group in the Manchester quadrangle. But it is older than the Littleton formation of Lower Devonian age, as discussed later.

The Merrimack group in the Manchester quadrangle is correlated with the Eliot and Berwick formations of the Mt. Pawtuckaway quadrangle. Freedman (1950, p. 488) assigned a Silurian age to the Berwick formation by a "tenuous correlation" with the Waterville slates (Fisher, 1941) of Maine. According to this the Merrimack group of the Manchester quadrangle is also considered Silurian.

Jahns (1952, p. 108) considers the Merrimack quartzite to be older than the Harvard conglomerate and Brimfield schist. According to Jahns, the Harvard conglomerate, basal to the Brimfield schist, contains pebbles that appear to be derived from the Merrimack quartzite and other older formations. The Merrimack quartzite is, thus, older than the Brimfield schist. The Brimfield schist is correlated with the Littleton formation of lower Devonian age. Hence, the Merrimack quartzite in Massachusetts and the Merrimack group in the Manchester quadrangle are older than lower Devonian and are probably Silurian in age. Even if the Brimfield schist is considered equivalent to the Worcester phyllite of Carboniferous age, this will not come into conflict with the Silurian age of the Merrimack quartzite, which is older.

Hence, the evidence from the quadrangle, that from the northeast, and that from the southwest shows that the Merrimack group of Manchester quadrangle may be of Silurian age.

Age of the Littleton formation of Manchester quadrangle. The Littleton of Mine Hill in the Manchester quadrangle is correlated with the Littleton of the Mt. Pawtuckaway quadrangle. Freedman (1950, pp. 487-488) correlated the latter with the Littleton formation of the type locality (Billings, 1937). Since the Littleton of the type locality belongs to the Lower Devonian, the Littleton of Manchester may also be Lower Devonian.

The Brimfield formation, correlated with the Littleton of the Manchester quadrangle, may also belong to the Lower Devonian. Although Emerson considered the Brimfield schist and the Worcester phyllite to be equivalent, he was not definite in this regard. Hence, the Lower Devonian age assigned to the Brimfield schist may not affect the age of the Worcester phyllite.

Origin of Plutonic Rocks

Ayer granodiorite. The following points about the Ayer granodiorite of the Manchester quadrangle are pertinent to the discussion of its origin:

(1) A comparison of the modes of the Ayer granodiorite (Table 10) and the lower member of the Eliot formation (Table 2), which surrounds the Ayer granodiorite, shows that the mineralogy is similar in both. The variations in the Ayer granodiorite have corresponding variations in the lower member of the Eliot formation. This similarity is very striking about one mile east of Jenny Hill in Windham. At the junction of the Ayer granodiorite and the schist, it is hard to decide to which formation some outcrops belong;

(2) There is, in general, a textural difference between the schists and the Ayer granodiorite;

(3) Locally there is some compositional banding;

(4) Structurally, the Ayer granodiorite is generally concordant, but with local discordance; and

(5) The temperature of formation of the Ayer granodiorite appears to have been low, as shown by the study of microcline crystals.

Discussion. Jahns (1942, pp. 341 - 342) considers that at least large portions of the granodiorite were formed from mechanically injected molten material. He considers the apparent transition zones as clear - cut lit - par - lit injections in which the granodiorite appears within the country rocks as long sharply defined septa. Currier (1952, pp. 113 - 115) explains the origin of Chelmsford granite to the south by granitizing solutions and believes "that direct infusion of magma, whether from deep seated sources or by more local remelting, was not necessary."

The mineralogy and the composition of the Ayer granodiorite and the lower member of the Eliot formation surrounding the Ayer granodiorite show that there is no necessity of granitizing solutions to convert the schists of the lower member of the Eliotformation to the Ayer granodiorite. Hence, the granitization theory, in so far as it calls for the introduction of the material, is ruled out. The Ayer granodiorite could have formed by the recrystallization of the schists of the lower member of the Eliot formation. But it is not clear, for this mode of origin, what special conditions favored the recrystallization in special places. In the opinion of the author the Ayer granodiorite crystallized from a magma that came from below. This magma might have originated from partial fusion of the sediments of the composition of the Eliot formation at depth or it might have come from some other source.

Foliated binary granite. The important points regarding the foliated binary granite that concern its origin are:

(1) The foliated binary granite contains two feldspars, microcline and albite. The mineralogy of the foliated binary granite differs from that of the surrounding schist, even where the granite occurs as small lenses in the schist;

(2) There is no gradation between the texture of the granite and the surrounding schist;

(3) The contact is mainly concordant, with local discordances; the contact zone is narrow;

(4) No compositional banding is seen at the contact zone;

(5) Fine-grained (0.01 to 0.4 mm.) granulite is seen right at the contact of the granite. This fine-grained granulite is also common in other parts of the formation; and

(6) Foliation of the granite is parallel to the regional structures.

Discussion. Jahns (1952, p. 110) considers the binary granite in Pelham to the south as an intrusive body. The mineralogy of this granite is the same as the foliated binary granite in the Manchester quadrangle, but there is some textural difference, so the two bodies may be different.

The contacts of the foliated binary granite indicate that it may be an intrusive sill. The presence at the contact of granulite that does not differ from other parts of the formation indicates that there is no metasomatism due to the granite. The mineralogy of the foliated binary granite, which contains microcline and albite, indicates a composition close to the minimum melting point in the system nepheline-kaliophilite-silica (Schairer, 1950).

Flow in a magma containing biotite crystals would result in primary foliation. In this case the foliation should be more or less parallel to the contacts. But the foliated binary granite does not show this parallelism. Instead, the foliation is parallel to the regional trends, which may indicate that the foliation may be secondary. The foliated binary granite also shows cataclastic structure, which may be as a result of granulation during tectonism, and which resulted in the foliation. There may be some amount of recrystallization, especially of the micas. Hence the foliation, in the opinion of the writer, may be secondary.

Microcline-albite pegmatite. Genetically significant characteristics of the microcline-albite pegmatite are:

(1) The pegmatite is composed of microcline, albite, quartz and micas, with microcline and albite in almost equal amounts;

(2) Generally concordant, but locally discordant contacts with the schists;

(3) Close association in space with the foliated binary granite; and

(4) A relatively low temperature of formation indicated by its mineralogy. The mineralogy corresponds compositionally to a low-melting mixture in the system nepheline-kaliophilite-silica (Schairer, 1950), like the foliated binary granite. The pegmatite magma, presumably with higher water content, may have resulted from the fractional crystallization of the foliated binary granite (Cameron et al., 1949).

Microcline granite. The important factors to be taken into consideration in connection with the origin of the microcline granite are:

(1) Composed of microcline, quartz, and biotite;

(2) Massive, foliated and compositionally banded structural phases;

(3) Low temperature of formation as shown by the mineralogy;

(4) Although some of the bodies of microcline granite are large enough to show on the geological map, most of these are thin sheets forming part of the Massabesic gneiss; and

(5) High grade of metamorphism of the associated schist and the gneiss.

Discussion. Freedman (1950) favors piecemeal stoping and locally permissive intrusion for the origin of the microcline granite of the New Hampshire magma series in Mt. Pawtuckaway quadrangle. In the Manchester quadrangle, the contact between the microcline granite and the upper member of the Berwick formation on Rattlesnake Hill, is a transition zone composed of Massabesic gneiss. This shows that the microcline granite is intrusive. Here the composition of the Massabesic gneiss is a mixture of microcline granite and schists of the upper member of the Berwick formation. This portion of the Massabesic gneiss is a migmatite resulting from the intrusion of the microcline granite (Sederholm, 1913). No structures indicative of forceful injection are seen, so the intrusion may be permissive type. The permissive type of intrusion is characterized by schists in the semiplastic state where much force from the magma is not needed for intrusion. This state may have been obtained by the schist due to the high grade of metamorphism.

Microcline pegmatite. The microcline pegmatite is composed of microcline, quartz and micas. Mineralogical study indicates a comparatively low temperature of formation. Found only in the sillimanite zone it cuts sharply across the Massabesic gneiss.

A comparison of the mineralogy of the microcline pegmatite and the microcline granite shows that the two are similar, hence the origin may be similar. Some additional factors, possibly abundance of water, favored the continued crystallization of the microcline pegmatite magma, resulting in the coarse texture.

Massabesic gneiss. Some of the characteristics of the pink microcline banded gneiss of the Massabesic gneiss have already been referred to in considering the origin of the microcline granite. There the pink microcline banded gneiss is thought to have been formed by the permissive intrusion of the microcline granite into the schist, so that the pink microcline banded gneiss of the Massabesic gneiss would be genetically a migmatite (Sederholm, 1913).

The white oligoclase gneiss in the Massabesic gneiss differs from the pink microcline gneiss. A mode of the white oligoclase gneiss, including both the light colored and dark colored bands, is similar to the average mode of the schists of the upper member of the Berwick formation. No addition of material, such as microcline granite in the case of pink microcline banded gneiss, is involved. The other characteristics of white oligoclase gneiss are as follows:

(1) The biotite content of the biotitic bands of the white oligoclase gneiss is distinctly higher than the biotite content of the schists of the upper member of the Berwick formation;

(2) The white oligoclase gneiss is coarse-grained. The schists of the upper member of the Berwick formation are fine-grained away from the contact and the grain size increases towards the contact;

(3) The width of the bands in the white oligoclase banded gneiss varies; and

(4) The white oligoclase gneiss is in an area of high grade metamorphism.

All the characteristics of the white oligoclase banded gneiss favor the idea of partial fusion to explain its origin. If a schist from the upper member of the Berwick formation were heated, the first liquid obtained would probably approximate granite in composition, leaving biotite-rich material behind. These two portions correspond to the coarse-grained granitic bands (fused) and the fine-grained biotite-rich bands (merely recrystallized) seen in the white oligoclase banded gneiss. This would correspond to the "palingenesis" of Sederholm (1923).

The mineralory of the amphibolite in the Massabesic gneiss and its interbanding with the gneiss suggest that it was interbanded either as a calcareous sediment or as andesitic volcanic material. Since the amphibolite is in the sillimanite grade of metamorphism no original textures or structures are preserved. Consequently the composition gives no clue concerning its sedimentary or volcanic origin.

Optical study of the amphibole has shown that it is actinolite with about 75% Mg number. F. R. Boyd of the Geophysical Laboratory in Washington has taken a specimen of the amphibolite for possible chemical analysis of the amphibole. Further study is necessary to say anything more about the origin of the amphibolite.

Massive binary granite. The facts that are to be considered in connection with the origin are:

(1) Mineralogy consisting of microcline, oligoclase, quartz, and micas;

(2) Massive nature; and

(3) Contacts cut across the Massabesic gneiss and the microcline-albite pegmatite.

The mineralogy indicates that it is a low-temperature granite. The structure and the contacts show that it is an intrusive of magmatic origin.

Silicified zones: Origin. The characteristics of the silicified zones, that should be restated in connection with a discussion of its origin are:

(1) silicified zones, about 300 feet long and 100 feet wide, in places involving a huge quantity of silica;

(2) quartz occurring as open fillings in vugs;

(3) anastomosing quartz veins in adjacent schist;

(4) association with probable siltstones with very fine-grained quartz;

(5) association with a number of granites; and

(6) association with probable slippage of beds.

The problem of the source of silica is important since the quantity involved is huge. This quantity is available in fine-grained form in the associated siltstones and might be transported by solutions, or the silica may have come from the residual solutions from the associated granites (Goranson, 1932). The silica thus available in solution was deposited by replacement or by open space filling or preferably by both. The movement of the silica-bearing solutions is facilitated by the slippage of the beds.

Structure

Relation of tight folding and the intrusion. The upper member of the Eliot formation consists of open folds in the northeast and tight folds to the southwest. The stratigraphic position and the lithology of the formation is the same along the strike; so the factor that caused the difference in the type of the folds may be something else. One of the two bodies of foliated binary granite occurs at the northwest contact of the upper member of the Eliot formation. The body of foliated binary granite ends where the folds in the upper member of the Eliot formation change from tight folds to open folds. Hence the tight folding may be the result of the injection of the foliated binary granite. However, since the foliated binary granite is syntectonic, as discussed later, probably the granite was already present at the time of folding and served to localize folding by acting as a buttress or knots in the structure, as suggested by Professor H. E. McKinstry (personal communication).

Nearly vertical beds in the lower member of the Berwick formation. Whereas the Eliot formation, the upper member of the Berwick formation, and the Littleton formation have undergone intense folding, the lower member of the Berwick formation, although essentially vertical, shows relatively few minor folds. One striking lithological difference is that the lower member of the Berwick formation is less calcareous than the other units in the Merrimack group. The lower member of the Berwick formation contains more joints than the rest of the Merrimack group. Hence the writer believes it possible that the lower member of the Berwick formation was more competent than the other strata.

Two stages of deformation. Some of the data indicating two stages of deformation are as follows:

(1) The folding in the Massabesic gneiss is similar in its larger features, but more irregular in detail, compared to the folding in the upper member of the Berwick formation. One interpretation of this could be two stages of deformation in the Massabesic gneiss. The first stage of deformation could produce folding similar to that in the upper member of the Berwick formation. The second stage could produce the minor irregularities. The other alternative is to attribute the irregularity in the folds to the greater plasticity because of higher temperature;

(2) The muscovite porphyroblasts in the lower member of the Berwick formation are aligned at an angle to the bedding schistosity. One interpretation of this would be two stages of deformation;

(3) The foliated binary granite contains muscovite phenocrysts oriented at an angle to the foliation shown by the muscovite and other minerals in the groundmass. Two stages of deformation might have oriented the two kinds of muscovite. However, this is open to doubt.

(4) Boudins of foliated binary granite are seen in the metamorphic rocks. One such boudin in West Derry has been refolded.

Metamorphism

Chlorite-green biotite isograd. The rocks of the chlorite zone show green pleochroic biotite when examined under the microscope. However, this biotite can be identified only with practice under the microscope, inasmuch as it is fine-grained and resembles chlorite. As a matter of fact, the presence of biotite is demonstrated only after verification by X-ray study. In the field this green biotite is not identifiable. Hence the biotite isograd is drawn to separate the chlorite zone from the brown biotite zone.

Chlorite in the garnet zone. Lime-silicate gneiss in an outcrop near Wilson (No. 422) shows about 30% chlorite. The absence of biotite is verified by X-ray. About two miles to the northeast the lime-silicate gneiss contains almandite, with abnormally low refractive index, possibly due to the grossularite in solid solution; lime-silicate minerals are also present (No. 417). Apparently both these rocks are in the garnet zone. The association suggests a magnesian chlorite. Elsewhere, magnesian chlorites have been observed in rocks of the garnet zone and higher, in many places together with garnet (Lecture notes, Professor J. B. Thompson).

Absence of kyanite and staurolite zones. Neither kyanite nor staurolite is found between the almandite and sillimanite zones of Manchester quadrangle. As pointed out earlier, only the Littleton formation has the aluminous shales necessary to produce these minerals. But the Littleton formation is in the sillimanite zone of metamorphism. The Merrimack group contains some intercalations of argillaceous matter, but the alumina content in them is apparently insufficient. Hence the reason for the absence of kyanite and staurolite is the lack of rocks with suitable original composition in the places where these minerals might otherwise appear.

Microcline-sillimanite isograd. Sillimanite occurs in the Littleton formation and the Massabesic gneiss. In the Littleton formation and the Massabesic gneiss in a band 4 miles wide immediately northwest of the sillimanite isograd, sillimanite and muscovite are present with no microcline. However, further northwest in the Massabesic gneiss, microcline and sillimanite are seen together. Microcline and sillimanite appear to form at the expense of muscovite. The formation of microcline and sillimanite at the expense of muscovite marks a higher grade of metamorphism (Heald, 1950). Hence the microcline-sillimanite isograd is drawn at the first appearance of microcline and sillimanite together. The sillimanite zone can thus be subdivided into muscovite-sillimanite subzone and microcline-sillimanite subzone.

Metamorphism of foliated binary granite and Ayer granodiorite. The foliated binary granite contains almandite in some places. One of the two bodies at Nashua and Hudson is northwest of the upper member of the Eliot formation. The Eliot formation is in the garnet zone. The second body of the foliated binary granite is southeast of the garnet zone of the upper member of the Berwick formation. The Ayer granodiorite also contains almandite in some places. The Ayer granodiorite is surrounded by the lower member of the Eliot formation.

Almandite occurs in igneous as well as metamorphic rocks. No higher grade metamorphic index minerals characteristic of only metamorphic rocks, such as kyanite, are noticed, because the composition of both the foliated binary granite and the Ayer granodiorite is not appropriate. Hence, whether or not the foliated binary granite and the Ayer granodiorite have undergone metamorphism, is not possible to say from mineralogy alone.

Metamorphism and Plutonism

In analysing the relationships between metamorphism and plutonism, the following facts must be borne in mind:

(1) The grade of metamorphism in the Manchester quadrangle increases from the center (chlorite and brown biotite zones) outward towards the northwest (garnet and sillimanite zones) and towards the southeast (garnet zone);

(2) The rocks in the lower member of the Berwick formation directly northwest of the foliated binary granite in Nashua and Hudson are in the biotite and chlorite zones, and further northeast the same formation is in the brown biotite zone;

(3) The Berwick formation in the chlorite and brown biotite zones contains only a few small lenses of plutonic rocks;

(4) The rocks in the garnet and sillimanite zones are invaded by numerous bodies of plutonic rocks;

(5) The foliation in the plutonic rocks is parallel to the regional trends;

(6) Folding of the foliated binary granite along with the metamorphic rocks;

(7) Cataclastic texture in foliated binary granite;

(8) Bending of the twin lamellae of albite plagioclase against almandite in the foliated binary granite;

(9) Lamellar twinning of sphene in the Ayer granodiorite; and

(10) Myrmekite in the Ayer granodiorite.

The general distribution of metamorphism shows that all the sedimentary rocks in the Manchester quadrangle are metamorphosed, some of them to lower grades (chlorite - green biotite and brown biotite zones) and others to higher grades (garnet, muscovite - sillimanite and microcline - sillimanite zones). In the lower grades the rocks immediately northwest of the foliated binary granite in Nashua and Hudson are in the chlorite and biotite zones, whereas further northeast the same formation is in the biotite zone. The granite does not appear to have caused this metamorphism. That the lower grades of metamorphism are not directly connected with the plutonism, is also shown by the fact that the rocks in the lower grades are invaded by very few lenses of plutonic rocks. Hence it seems likely that some factor other than plutonism caused this low - grade metamorphism. On the other hand, the rocks in the higher grades are invaded by numerous plutonic lenses and bodies, suggesting that plutonism might have caused this high - grade metamorphism (Billings, 1937, pp. 557 - 559). The myrmekitic texture, according to Tyrell (1941, p. 94), is due to thermal metamorphism under uniform pressure. Myrmekite has been observed in the Eliot formation and the Ayer granodiorite.

That deformation took place after plutonism is shown by the following:

(1) The foliated binary granite lenses have been folded along with the metamorphic rocks;

(2) The foliation of the plutonic rocks is parallel to the regional trends, which indicates deformation after consolidation;

(3) The cataclastic structure in the foliated binary granite indicates deformation after consolidation;

(4) Bent twin lamellae of albite against almandite, according to the customary interpretation indicates that the deformation is later than the consolidation of the foliated binary granite; and

(5) Winchell (1951, p. 525) refers to the production of lamellar twinning in sphene artificially at 3,000 atmospheres and attributes lamellar twinning in natural sphenes to shearing stress. Hence this may also point out that the deformation is in part at least later than plutonism.

Age of Plutonic Rocks

Age of plutonic rocks relative to each other. The main factor used in determining the age of the plutonic rocks relative to each other is the nature of their mutual contacts. The mutual contacts observed are:

(1) Microcline pegmatite cuts across the pink microcline gneiss;

(2) Massive binary granite cuts across the Massabesic gneiss;

(3) Massive binary granite also cuts across the microcline-albite pegmatite; and

(4) The diabase dikes cut across the microcline-albite pegmatite. The rock that cuts across is younger. An indirect factor that may be considered is the lithologic similarity and association of the foliated binary granite to that of microcline-albite pegmatite and of microcline granite to that of granitic portion of the Massabesic gneiss. This indicates that the binary foliated granite and microcline-albite pegmatite are contemporaneous and if the microcline-albite pegmatite is formed by the fractional crystallization of foliated binary granite, the microcline-albite pegmatite is later. The second factor indicates — because the microcline gneiss is formed by the permissive injection of microcline granite — the microcline granite is contemporaneous. The Ayer granodiorite is older than the foliated binary granite (Jahns, 1952, p. 112). Thus the plutonic rocks, in their probable order of decreasing age, are: Ayer granodiorite, binary foliated granite, microcline-albite pegmatite, microcline granite, Massabesic gneiss, microcline pegmatite, massive binary granite, and the diabase dikes.

Age of plutonic rocks relative to tectonism and metamorphism. Some of the structures and textures showing that the tectonism and metamorphism are later than the plutonism have already been discussed. The massive binary granite and the microcline pegmatites may show that these are later than the tectonism. This suggests that the plutonic rocks are contemporaneous with the metamorphism and tectonism, hence they are syntectonic, like the other plutons of the New Hampshire magma series in other parts of the state.

Age of plutonic rocks relative to the metasediments. The metasedimentary rocks are Silurian(?) and lower Devonian. The plutonic rocks are intrusive into these; so the plutonic rocks are later than lower Devonian.

The intrusive nature of these rocks with the metasedimentary rocks of lower Devonian age, and their syntectonic nature, suggest that the plutonic rocks belong to the New Hampshire magma series. Since the New Hampshire magma series is believed to be late Devonian in age (Shaub, 1937) most of the plutonic rocks of the Manchester quadrangle may also be late Devonian age. The diabase dikes are later and may even be Triassic.

GEOLOGICAL HISTORY

The first known event in the Manchester quadrangle was the deposition of the Merrimack group, probably during the Silurian. In the Manchester quadrangle, a small part of the Appalachian geosyncline, about 17,500 feet of sediments were deposited at this time. These sediments were mostly siltstones, but contained lenses of calcareous silt. The source was to the southeast and, judging from the thickness of the sediments, it must have been extensive.

In the lower Devonian, because of a change in environment, the Littleton formation was deposited, at that time consisting of aluminous clays and sand. This change in the environment might be because of three reasons. There might have been an alternation in the nature of the source that supplied the sediment. There might have been a periodic change in the velocity of, and also in the nature of, the sediment carried by the transporting agent. Or there might have been sorting at the site of deposition.

The sedimentary strata were deformed during the middle or late Devonian, developing folding, bedding, schistosity, slip cleavage and lineation. The recrystallization of the sediments took place under low-grade metamorphic conditions. At this time the Ayer granodiorite and the foliated binary granite, early phases of the New Hampshire magma series, were intruded, coinciding with or followed by more intense deformation. This later phase of intense deformation probably produced the foliation in the intrusive rocks, axial-plane cleavage in the metamorphic rocks, slipping parallel to the bedding, and probably thrusting in the folded beds. The folds of the Manchester quadrangle were on the northwest limb of an anticlinorium. The metamorphism reached the sillimanite grade in the northwest part of the quadrangle, simultaneously with the intrusion of microcline granite and the production of Massabesic gneiss. The microcline pegmatite intruded slightly later. Near the end of the deformation, or shortly thereafter, the massive binary granite was intruded.

Still later, silicified zones formed. These silicified zones probably followed faults, presumably younger than the foliated binary granite.

Diabase dikes were intruded subsequent to the folding, metamorphism, and the microcline-albite pegmatite, possibly during Triassic. The chronological relationship between the silicified zones and the diabase dikes is uncertain.

During the Mesozoic and Tertiary the region was subjected to subaerial erosion, during which thousands of feet of rocks were removed. Continental glaciation during the Pleistocene carried away the soils, striated the rocks and deposited the till and outwash (Goldthwait, 1951).

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