The Bedrock Geology of the HAVERHILL 15' QUADRANGLE NEW HAMPSHIRE

Bulletin No. 5

By Daniel Alvin Sundeen

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DEPARTMENT OF RESOURCES AND ECONOMIC DEVELOPMENT

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NEW HAMPSHIRE
DEPARTMENT of RESOURCES and ECONOMIC DEVELOPMENT

GEORGE GILMAN, Commissioner

GLENN W. STEWART, State Geologist

B.

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Abstract

Geologic investigations in southeastern New Hampshire have now been in progress for about 50 years. With the present work, regional mapping is essentially complete.

The oldest rocks in the quadrangle are schists and calc-silicate rocks of the Merrimack group (Silurian (?) age). This group is divided into two formations: the calcareous Eliot formation which crops out in $>90\%$ of the quadrangle, and the younger, conformable, and essentially argillaceous Berwick formation which crops out in the northwestern corner of the quadrangle.

Range of metamorphism in the quadrangle is limited to the garnet and biotite zones. The area of the garnet zone coincides roughly with the area most intensely intruded by a series of granites and quartz monzonites of Late Devonian to Early Pennsylvanian age, known collectively as the Hillsboro plutonic series.

The major structure in the quadrangle is the Rockingham anticlinorium. The axis of this structure extends from the northeastern to the southwestern corner of the quadrangle. On a smaller scale, three planar structural elements have been defined: S_1, compositional banding which may be the same as bedding; S_2, foliation by mineral orientation parallel to S_1 (believed caused by regional or load metamorphism); S_3, foliation by mineral orientation parallel to the axial planes of mesoscopic folds and not necessarily parallel to S_1 or S_2. S_3 is considered a product of a later stage of tectonism occurring primarily in the northwestern portion of both the quadrangle and the southeastern New Hampshire region. S_3 foliation may have formed synchronously with the earlier stages of the Hillsboro plutonic series.

The Hillsboro plutonic series is fully represented in the quadrangle. The chronologic sequence of intrusion is: granite, quartz monzonite, quartz diorite, diorite, norite and pegmatite. Studies of major and trace element (Rb/Sr, K/Rb, and rare earths) made by the writer suggest that these rocks were derived from a common source. The distribution of the rock bodies in the region is delineated by a series of concentrically oriented zones of similar rock types. Granite and quartz monzonite compose the outermost zone; diorite, norite and gabbro compose the innermost zone. Continuous fractionation and/or partial

melting, synchronous with tectonism in their earlier stages of emplacement, are suggested as models to account for the petrogenesis of this plutonic series.

The White Mountain plutonic-volcanic series intruded the Merrimac group and the Hillsboro plutonic series during Late Triassic and Early Jurassic. The camptonite, diabase and riebeckite granite occur as hypabyssal intrusives in the Haverhill quadrangle. A significant amount of erosion must have occurred during the Late Paleozoic and Early Mesozoic eras to account for the juxtaposition of hypabyssal and plutonic rocks.

No rock or mineral deposits have been developed in the Haverhill quadrangle. Potential sites of economic interest are the pegmatite bodies in Kingston and Danville townships and the sulfide veins associated with the Sweepstake diorite in the city of Salem.

CHAPTER I INTRODUCTION

Previous work

The geology of southeastern New Hampshire has been described by Jackson (1844), Hitchcock (1877), Katz (1917), and Emerson (1917). More recently, Meyers (Dover quadrangle, 1940), Freedman (Mt. Pawtuckaway quadrangle, 1950), Novotny (Exeter and Dover quadrangles, 1963, 1969) and Sriramadas (Manchester quadrangle, 1966) have worked in quadrangles adjacent to the Haverhill 15' quadrangle. The regional stratigraphy, structure and petrology in southeastern New Hampshire have been briefly described by Billings (1955 map, 1956). No detailed studies have been made on any phase of the bedrock geology of the Haverhill 15' quadrangle.

Location and geologic setting

The Haverhill 15' quadrangle is located in southeastern New Hampshire in the Seaboard Lowland province (Fenneman, 1938). The topography consists of heavily wooded, gently rolling hills that are surrounded by numerous ponds, brooks and swamps (fig. 1). The maximum elevation just exceeds 500 feet on a few hills in Chester and Derry townships along the western edge of the quadrangle. The minimum elevation is less than 80 feet in Exeter in the northeastern corner of the quadrangle. The northeasterly flowing Exeter River and several small tributaries to it drain the northern portion of the quadrangle into Great Bay. The Powwow River and numerous other streams are tributaries providing drainage of the southern portion of the quadrangle into the Merrimack River to the south and southeast.

The area of study is limited to the New Hampshire portion of the Haverhill 15' quadrangle and it covers approximately 170 square miles (fig. 3). Most of the hills in this region are composed of or are capped by glacial material (fig. 2). Those hills that are composed primarily of bedrock invariably consist of granite and pegmatite. The metamorphic rocks in the Haverhill 15' quadrangle erode readily and provide little or no topographic relief. Consequently, extensive outcrops of metamorphic rocks are lacking, a fact that has seriously reduced the amount of structural information available.

Metamorphic rocks of the Merrimack group make up approximately 75% of the bedrock in the Haverhill quadrangle. The formation

Figure 1. View southwest of the Haverhill quadrangle from the fire tower on Rock Rimmon Hill, one of several large pegmatite bodies, on the Kingston-Danville townline. The north end of Long Pond can be seen just beyond the immediate foreground. Smith Mountain in Hampstead is on the horizon.

Figure 2. Glacial erratic in the Haverhill 15' quadrangle.

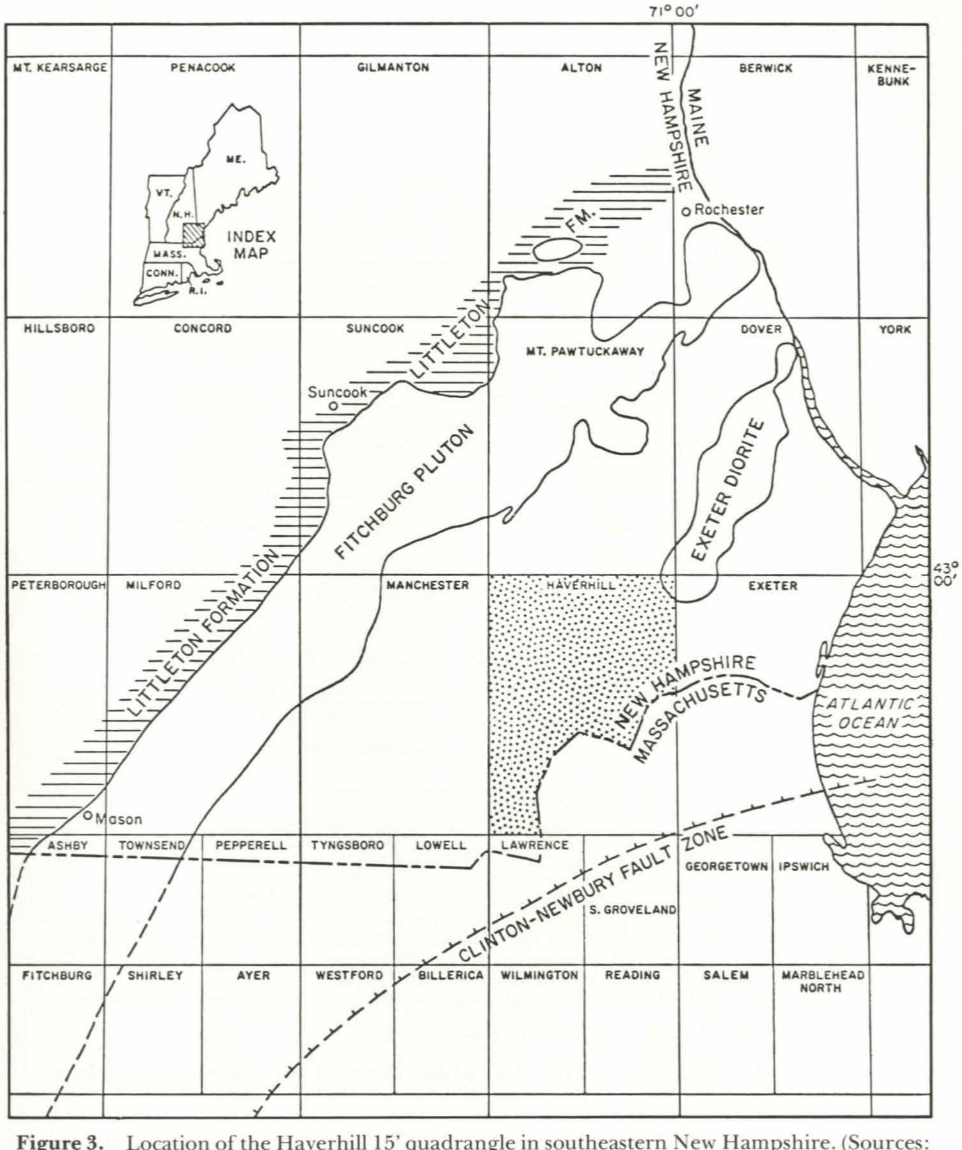

Figure 3. Location of the Haverhill 15' quadrangle in southeastern New Hampshire. (Sources: Billings, 1955, Skehan, 1968).

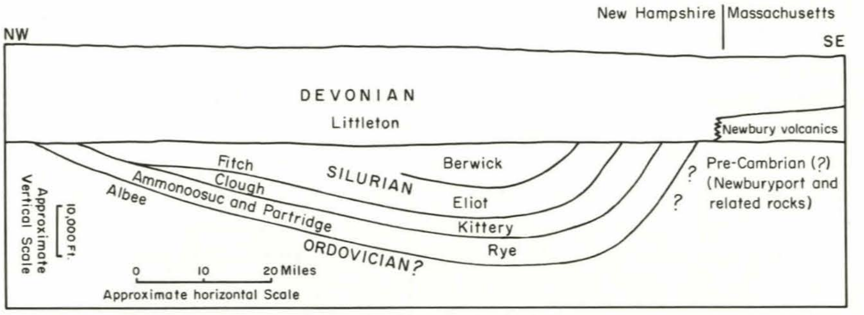

Figure 4. Stratigraphic sequence just prior to Acadian orogeny. (Billings, 1956, p. 150).

names (Berwick and Eliot) are unique to the southeastern New Hampshire area although equivalent rocks are thought to exist in western New Hampshire (fig. 4) In the Haverhill quadrangle, these formations correlate lithologically with the Eliot and Berwick type sections in southeastern Maine and are tentatively considered to be Silurian (Billings, 1956, p. 41-42).

Most of the igneous rocks belong to the Hillsboro plutonic series. Although this series is confined to the southeastern New Hampshire region, it is considered to be time-equivalent with the New Hampshire plutonic series. The White Mountain plutonic-volcanic series forms only a small portion of the igneous rocks in the Haverhill quadrangle.

Purpose

The purpose of this project is:

1. to map and study the petrography and petrogenesis of the Haverhill fifteen minute quadrangle, the last relatively uninvestigated portion of southeastern New Hampshire
2. to propose a model accounting for the surface distribution of the rocks of the Hillsboro plutonic series based on data from the Haverhill quadrangle and on previously published studies from adjacent quadrangles
3. to delineate by the use of isograds areas of similar metamorphic rank
4. to confirm the relocation of the contact between the Eliot and Berwick formations in the southern part of the Mt. Pawtuckaway quadrangle
5. to present evidence for two sets of planar surfaces (foliation) and to explain their significance in the interpretation of the geological history of the area.

The Haverhill 15' quadrangle is centrally located among six quadrangles that have already been mapped and described.[1] Within the quadrangle are two metasedimentary formations of the Merrimack group and all of the rock types in the Hillsboro plutonic series. The information from the Haverhill 15' quadrangle provides the basis for reasonable hypotheses regarding problems in igneous and metamorphic petrology and in stratigraphy and structural geology as well as the opportunity to synthesize work done in the southeastern New Hampshire area by a number of geologists during the last half century.

Method of study

Field relationships were recorded on topographic base maps at scales of 1:31,250 and 1:12,000. Normal geologic mapping techniques were used in the field. The numerous roads, railroads and powerlines provided a grid for traversing the area. From these other traverses were made across less accessible areas in the quadrangle.

Laboratory studies included examination of over five hundred thin sections with the petrographic microscope and determination of the rare earth abundances of seventeen selected rock samples with the X-ray emission spectrometer. Fifteen selected samples were analyzed for trace elements. Estimated modes for all the major rock types have been tabulated.

Acknowledgments

This study was conducted under the supervision of Dr. Charles J. Vitaliano, Dr. David G. Towell, Dr. Thomas E. Hendrix, and Dr. Carl W. Beck of the Department of Geology, Indiana University. Their encouragement, criticisms and suggestions are sincerely appreciated. Drs. Vitaliano and Hendrix spent several days with the author in the field and offered valuable comments concerning petrologic and structural relationships. The results presented in this bulletin represent a part of the work done for the Ph. D. thesis at Indiana University, Bloomington, Indiana.

Glenn W. Stewart, State Geologist and Professor of Geology at the University of New Hampshire, encouraged the author to undertake this study, accompanied the author in the field on several occasions, and was instrumental in securing financial assistance for field expenses through the New Hampshire Department of Resources and Economic Development. This is gratefully acknowledged.

Thanks are extended to the members of the staff of the Indiana

[1]These are: Mt. Pawtuckaway (Freedman, 1950), Dover and Exeter (Novotny, 1969), Manchester (Sriramadas, 1966), Lawrence (Castle, 1965) South Groveland (Castle, 1965).

Geological Survey Geochemistry Section for performing the chemical analyses. Maynard E. Coller and Richard K. Leininger gave a great deal of time, patience and advice to the author during the development of a method for the determination of the rare-earth concentrations in rock samples. This is sincerely appreciated.

The Department of Geology of Indiana University provided assistance in the preparation of thin sections. The Drafting Section of the Indiana Geological Survey aided the author in the preparation of field maps and final plates. This assistance is gratefully acknowledged.

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Special thanks go to my wife, Lillian, for her help as a field assistant during the summers of 1967 and 1968, and for her assistance in typing and performing other tedious chores involved in the preparation of this dissertation.

CHAPTER 2 STRATIGRAPHY AND PETROGRAPHY

General statement

The metamorphic rocks in the Haverhill 15' quadrangle are part of the Merrimack group of Silurian (?) age which has been divided into the Eliot and Berwick formations. The Eliot formation crops out over much of the quadrangle. The Berwick formation, considered to be the youngest in the Merrimack group, is assumed to lie conformably on the Eliot formation and crops out in the northwestern part of the quadrangle.

The rocks in these formations are predominantly schists, with lesser quantities of granulites, phyllites, and calc-silicate rocks. The schists are commonly composed of quartz, biotite, actinolite, and plagioclase. The granulites are similar to the schists in composition but lack the schistose texture. Phyllites are composed primarily of muscovite with some quartz and chlorite. The calc-silicate rocks may be either massive or foliated and are composed primarily of quartz, actinolite, diopside, and calcite.

The range in metamorphic rank is small. The garnet zone (equivalent to the lower amphibolite facies) occupies the western two-thirds of the quadrangle. The biotite zone (equivalent to the greenschist-amphibolite transition facies) occupies the remainder of the quadrangle.

Fossil data is not present in the Haverhill quadrangle nor in any of the adjacent quadrangles in southeastern New Hampshire. Correlations with formations outside of the Haverhill quadrangle were made on the basis of petrography. The formational boundaries were extended from the Manchester quadrangle to the west, from the Mt. Pawtuckaway quadrangle to the north and from the Exeter quadrangle to the east. The petrography is in good agreement with that of the workers in the above quadrangles.

The stratigraphic thicknesses of formations present in the Haverhill quadrangle were not determined because of insufficient data. Estimates given by Sriramadas (1966) in the Manchester quadrangle and by Freedman (1950) in the Mt. Pawtuckaway quadrangle are given in Table 1.

In Table 1, it will be noticed that the thicknesses of the Berwick and Littleton formations are combined in the Mt. Pawtuckaway quad-

Table 1

ESTIMATED THICKNESS OF THE BERWICK AND ELIOT FORMATIONS IN THE MANCHESTER AND MT. PAWTUCKAWAY QUADRANGLES

FORMATION	THICKNESS		QUADRANGLE
Littleton	7,750' ±		
		14,750' ±	Mt. Pawtuckaway
Berwick	7,000' ±		(Freedman, 1950, pp. 463, 469)
Eliot	6,500' ±	6,500' ±	Mt. Pawtuckaway
			(Freedman, 1950, p. 456)
Total		21,250' ±	
Berwick	7,500' ±		
(upper member)		14,000' ±	Manchester
			(Sriramadas, p. 9)
Berwick	6,500' ±		
(lower member)			
Eliot	2,500' ±		
(upper member)		3,500' ±	Manchester
			(Sriramadas, p. 9)
Eliot	1,000' ±		
(lower member)			
Total		17,500' ±	

rangle. The Littleton formation is not as extensive in the Mt. Pawtuckaway quadrangle as originally believed by Freedman (1950). The state geologic map (Billings, 1955) does not show the Littleton formation in the area of the Mt. Pawtuckaway quadrangle. The northwestern corner of the Haverhill quadrangle is located on strike between the Littleton in the Mt. Pawtuckaway quadrangle (Freedman, 1950) and the Berwick in the Manchester quadrangle (Sriramadas, 1966) fig. 5-A). The presence of calc-silicate rocks in the metasediments in this part of the Haverhill quadrangle requires that these rocks be assigned to the Berwick formation. Calc-silicates are characteristically absent in the Littleton formation and present in varying amounts in the Merrimack group (10-25% in the Eliot fm., 5-15% in the Berwick fm.) This is in agreement with the findings of Sriramadas (1966) who subdivided the Eliot and Berwick formations, in the Manchester quadrangle, into upper and lower members on the basis of the percentage of calc-silicate gneisses. The upper members in both formations contain 10-15% more calc-silicate. The writer was unable to distinguish the upper and lower members of the Eliot formation due to the scarcity of extensive outcrops. This difference of calc-silicate content between the two formations is dectectable only along the projected

Berwick-Eliot formational contact from the Manchester quadrangle. The Berwick formation is composed almost entirely of quartz, biotite, plagioclase, lesser amounts of epidote, and some garnet, whereas the Eliot formation contains significant amounts of actinolite, calcite and diopside in addition to quartz and biotite.

On the basis of the consistent lithology it was determined that the Eliot formation crops out throughout most of the Haverhill quadrangle. The Eliot formation, therefore, would abut both the Berwick and Eliot formations along the boundary between the Haverhill and Mt. Pawtuckaway quadrangles (fig. 5-A). The writer concludes the Eliot-Berwick contact in the southern part of the Mt. Pawtuckaway quadrangle should be relocated to coincide with the contact location in the Haverhill quadrangle. The new location of the Berwick formation corresponds with the former location of the Littleton formation. (Compare the positions of Merrimack group rocks shown on sketch maps in figures 5-A and 5-B.)

Correlation of the formations of the Merrimack group within southeastern New Hampshire is reasonably well understood and accepted. Correlations of the Merrimack group with formations in Maine and Massachusetts, on the other hand, are still not satisfactory. The problem is primarily one of dating the formations. In Massachusetts, for example, rocks thought to be a continuation of the Merrimack group, have been assigned a Carboniferous age by some workers (Jahns, 1952) and (Currier, 1952). In western New Hampshire the Littleton formation is accepted as Early Devonian in age. In southeastern New Hampshire, the Littleton formation has been identified and is present to a limited extent and overlies the Berwick formation. The Merrimack group, therefore, cannot be younger than the Early Devonian of the Littleton formation[1]. Although more work has been done on the correlation problem in recent years, the writer is unaware of any new conclusions. For more detailed discussion of the problem see Freedman (1950, pp. 487-489), Billings (1956, pp. 99-105), Novotny (1963, pp. 163-168), and Sriramadas (1966, pp. 61-64).

Eliot formation

General statement

The Eliot formation, the oldest metasedimentary unit in the Haverhill 15' quadrangle, underlies more than 90 per cent of the area. It also crops out in the adjacent Manchester quadrangle. There it has been studied by Sriramadas (1966, pp. 10, 12) who subdivided it into upper and lower members on the basis of difference in calc-

[1]There is no observed physical continuity between the Littleton formation in western and southeastern New Hampshire. This fact significantly weakens the argument for the youngest rock in southeastern New Hampshire being limited to a Devonian age.

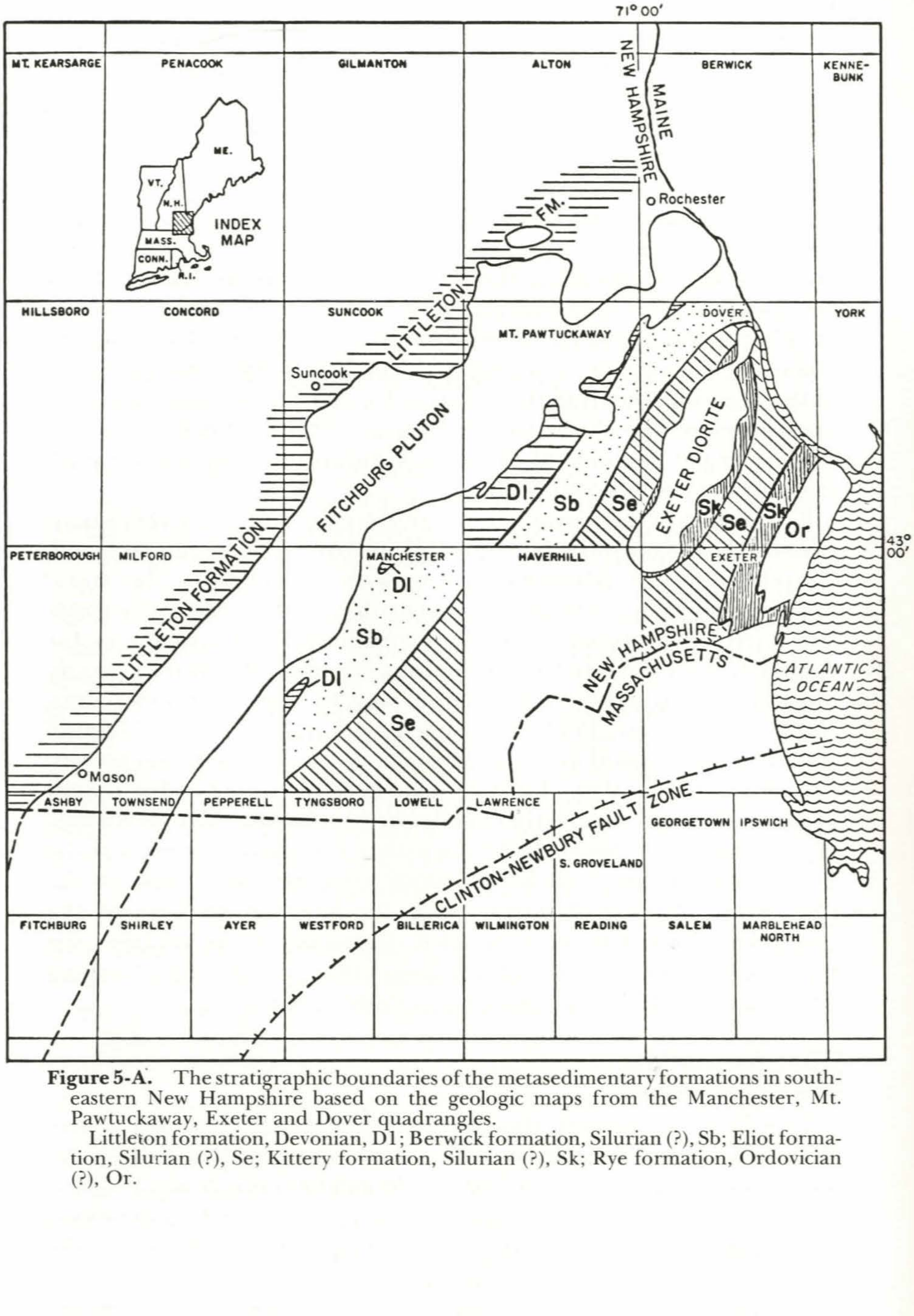

Figure 5-A. The stratigraphic boundaries of the metasedimentary formations in southeastern New Hampshire based on the geologic maps from the Manchester, Mt. Pawtuckaway, Exeter and Dover quadrangles.

Littleton formation, Devonian, Dl; Berwick formation, Silurian (?), Sb; Eliot formation, Silurian (?), Se; Kittery formation, Silurian (?), Sk; Rye formation, Ordovician (?), Or.

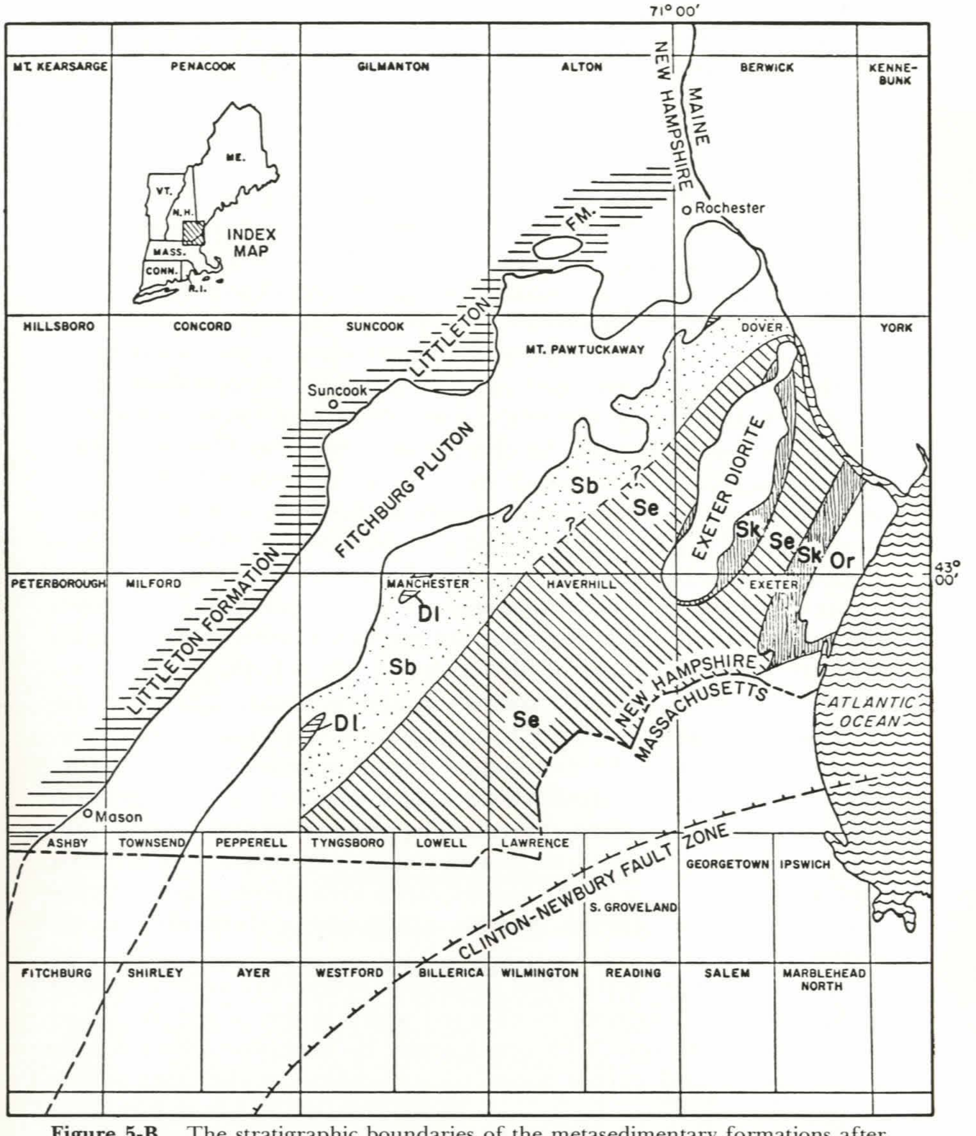

Figure 5-B. The stratigraphic boundaries of the metasedimentary formations after modification by Sriramadas (1966), Billings (1955) and information from the Haverhill 15' quadrangle.

Littleton formation, Devonian, Dl; Berwick formation, Silurian (?), Sb; Eliot formation, Silurian (?), Se; Kittery formation, Silurian (?), Sk; Rye formation, Ordovician, Or.

silicate rock content; the lower member containing about 10 per cent calc-silicate, the upper about 25 per cent. Limited size of outcrops prevented the writer from subdividing the Eliot formation in the Haverhill 15' quadrangle.

Billings (1955) has assigned the metasedimentary units in this portion of the quadrangle to the Merrimack group. Data from this investigation, along with that of Sriramadas and Novotny, suggest that the major stratigraphic unit in the quadrangle is the Eliot formation.

Structurally, the Eliot formation is on the crest of the Rockingham anticlinorium in the Haverhill 15' quadrangle. The dip of the foliation is steep (>45) in the northwest and relatively shallow (>45) in the southeast. The character and appearance of the deformation of the Eliot formation changes from the northwestern and west central area to the southeastern area. In the former area, the Eliot formation appears to have responded to stress as an incompetent rock. Manifestations of this are sinuous texture in foliation and the manner in which the foliation "flows" around the abruptly terminated boudins (fig. 6-A, 6-B). In the latter area (southeastern), the Eliot formation appears to have responded to stress as a competent rock and exhibits the properties of brittle fracture. Manifestations of this are complex fracture zones and zones of ultramylonite (fig. 44, 45, p. 134).

Deformation of the Eliot formation appears more intense in the northwestern and west-central areas than in the southeastern area. In the former area, the dominant foliation appears to be primarily a tectonically imposed planar element. In the latter area (southeastern) the foliation appears to be controlled by some relict form of bedding.

The change in texture and type of foliation from the northwestern and west-central area to the southeastern area corresponds roughly with a decrease in plutonic igneous activity of the Hillsboro plutonic series.

The mineralogy of the Eliot formation remains consistent, within certain limits, throughout its exposed width in the New Hampshire portion of the Haverhill 15' quadrangle. Its metamorphic rank falls in the biotite and garnet zones corresponding to the greenschist-amphibolite transition facies and the amphibolite facies respectively.

The Eliot formation is composed of three major lithologies: schists, calc-silicate rocks, and phyllites, in that order of abundance.

Schists

The schists are fine to medium grained and well foliated. Most can be assigned to two mineral assemblages: quartz-biotite-plagioclase schist ("biotite schist") and the quartz-actinolite-biotite-plagioclase schist ("actinolite schist"), both of which commonly occur in the same outcrop. The "biotite schist" has a medium to dark, distinctly purplish-brown color on a fresh surface. As the actinolite content increases,

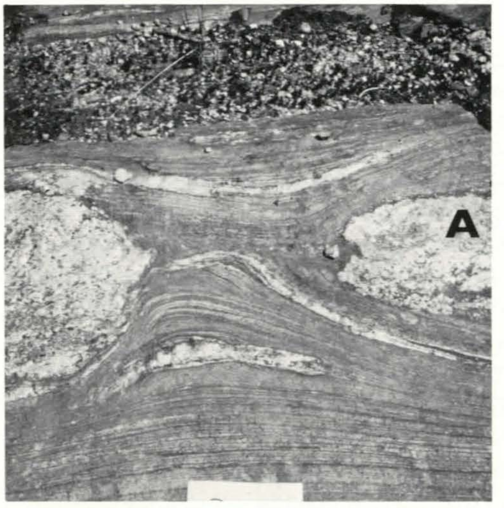

Figure 6. Plastic flow texture in the Eliot formation. The surfaces are horizontal and the strike of the foliation is approximately NE-SW in both photographs.

A. The foliation fills in between the edges of abruptly terminated pegmatite boudins. The outcrop is located on the west edge of the Haverhill 15' quadrangle on Kilrea Road, Derry, N. H. (Scale: ID card is 5 inches or 12.7 centimeters long.)

B. The sinuous texture is indicative of an incompetent rock. Note the well developed, closely spaced joints parallel to the hammer handle. The outcrop is located on East Road, Hampstead, N. H.

the color becomes a lighter purplish-brown on fresh surfaces. Both assemblages weather medium gray to medium brownish-gray. The foliation is due to the parallel and planar alignment of the biotite flakes and the actinolite needles.

In hand specimen brown biotite flakes, dark green actinolite needles, and vitreous gray quartz can be identified. The size of the minerals rarely exceeds 2 mm and is more commonly slightly less than 1 mm. Throughout the Eliot formation actinolite is found in thin white bands and in ellipsoidal bodies up to 8 cm across (fig. 7) associated with quartz and calcite.[2] The white bands are oriented both subparallel and oblique to the dominant foliation. They are usually less than 5 mm thick (fig. 7) and probably represent fracture fillings that subsequently were metamorphosed. The grain size of the actinolite in the bands is usually larger than it is in the host rock.

The schists of the Eliot formation are well foliated. Examination of thin sections with the microscope reveals a porphyroblastic texture because of the occasional occurrence of biotite or actinolite crystalloblasts. Quartz, biotite and actinolite are the commonest minerals. Plagioclase, microcline and diopside are present in smaller quantities. Quartz, the abundant mineral, occurs primarily as a matrix mineral. It also constitutes the major component of thin white stringers associated with fracture fillings or with granulation and recrystallization along cleavage surfaces. Quartz grains in the matrix are angular to subangular. The larger grains exhibit wavy extinction.

Biotite occurs most commonly as a primary mineral but is also present as an alteration product of actinolite. It is pleochroic in pale yellowish-brown to medium orange-brown or dark reddish-brown. The grain size varies within a range from 0.1 mm to 2 mm, but is usually consistently one size in any specific outcrop. Sphene inclusions are present and produce pleochroic halos. Biotite alters to pale green chlorite.

Actinolite is most commonly seen as a matrix mineral. It is pleochroic in pale green to medium bluish-green. It occurs as euhedral crystals randomly distributed throughout the rock. It poikiloblastically includes small quartz grains, has an extinction angle of 15^0 to 20^0, and alters to biotite. Actinolite exhibits a porphyroblastic texture in samples from several locations. The metacrysts have essentially the same optical and physical characteristics as the matrix actinolite except that twinning is more common.

Plagioclase though common is not abundant. In thin section it is usually observed in various stages of alteration. Twinning is often

[2]The term "calcite" is used in this work to designate an occurrence of a carbonate mineral which has the physical and optical properties of minerals in the calcite-dolomite series.

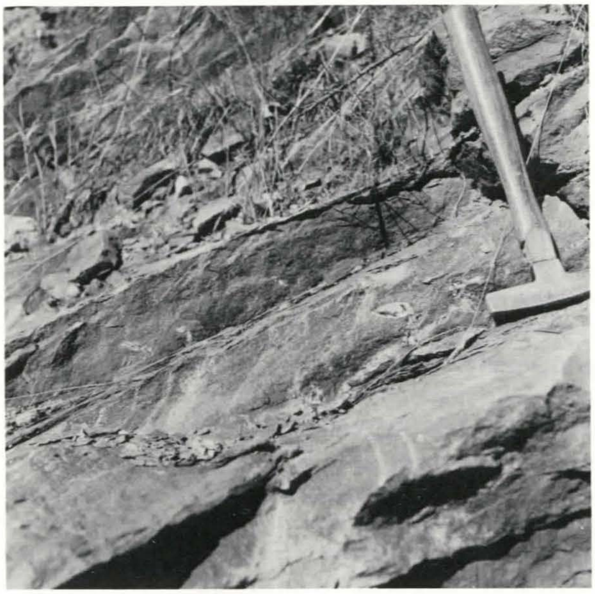

Figure 7. Quartz-calcite-actinolite assemblages in Eliot formation. These outcrops are located just north of the Brentwood-Kingston townline on Route 125.

White calc-silicate bands dip steeply to the left. The foliation in the purplish-brown schist dips about 25° to the left (west). Note the ellipsoidial "concretion" located about 8 cm to the left of the hammerhead.

obscured by the alteration products, sericite, clay minerals, and clinozoisite, making the anorthite content difficult to determine. In the "biotite schists", the plagioclase composition averages An(29-32). In the biotite-actinolite schists it averages somewhat higher at An(36-43).

Microcline is observed occasionally, usually as a matrix mineral. It occurs interstitially with quartz, exhibits good microcline twinning and normally is fresh and unaltered. Microcline is also seen with quartz in small intrusive stringers.

Diopside occurs as ragged anhedral metacrysts. It is colorless, poikiloblastically includes small round quartz grains, and is commonly accompanied by actinolite, biotite and chlorite as alteration products.

The accessory minerals in the schists of the Eliot formation are chlorite, epidote-clinozoisite, sericite, calcite, sphene, tourmaline, magnetite, pyrite and apatite. The chlorite, epidote-clinozoisite and sericite are all alteration products of primary minerals such as diopside, actinolite and plagioclase. Chlorite is pleochroic from colorless and pale green to light to medium green. The deep blue interference color indicates that it is of the variety penninite. Epidote-clinozoisite is usually seen replacing actinolite. Small, wispy flakes of sericite are most commonly seen replacing plagioclase. Calcite and sphene are particularly abundant in those assemblages containing actinolite. They are apparently independent mineral phases that do not occur consistently with another mineral as an alteration product. The calcite usually is seen occurring interstitially with quartz and exhibits the characteristic multiple twinning pattern of the carbonate group. Calcite is commonly present in fracture fillings and concretions. Sphene is present as ragged anhedral clots, subhedral elongated prisms and diamond-shaped forms. It is slightly pleochroic in light to medium brown. Tourmaline is generally too small to be seen in the hand specimen. From the several specimens which have large tourmaline crystals present, it is assumed that all the tourmaline is of the black variety schorl. It is strongly pleochroic in shades of olive green. Some rare samples exhibit a colorless and pale blue to deep blue pleochroism. The tourmaline invariably is associated with thin, pegmatitic stringers. Magnetite is an ubiquitous mineral. It appears as slightly elongated anhedral clots oriented parallel to the foliation. Pyrite is not common and is usually seen associated with minerals in fractures or stringers. Apatite is present in trace amounts and appears either as tiny euhedral inclusions in quartz or as small rounded grains in the matrix.

Approximate modal analyses of the schists in the Eliot formation are given in Table 2 (p. 23).

Calc-silicate rock

Calc-silicate rocks are present in small amounts in almost every outcrop in the Eliot formation. They appear in thin beds or lenses and form a gradational contact with the biotite and biotite-actinolite schists. They are fine to medium grained, and massive as well as strongly lineated varieties are present. The rocks are a light grayish-green and weather to a dull medium gray.

In hand specimen, the only minerals that are identifiable are dark green actinolite and white to gray vitreous quartz.

In thin section, the calc-silicate rocks have a granoblastic to lepidoblastic texture. They are composed of quartz, actinolite, plagioclase and diopside. Quartz or actinolite may be the most abundant mineral. Quartz occurs in the matrix as angular to subangular grains. Actinolite occurs as euhedral laths. It may also occur as metacrysts 4-5 mm in length which give the rock a porphyroblastic texture. Actinolite is pleochroic in pale green to medium bluish-green and in the calc-silicate rocks appears to have a more intense pleochroism than in the biotite-actinolite schists. It is poikiloblastic and includes rounded quartz grains, calcite, and crystals of sphene that form the core of pleochroic halos. Plagioclase occurs as partially altered, subangular grains, generally of andesine, twinned according to the albite law. The anorthite content in the samples studied ranges from 30 to 68 per cent. Most of the samples, however, have a composition in the range of An(38-44).

Diopside occurs in calc-silicate rocks throughout the garnet zone in the Eliot formation. It is most commonly seen as a ragged relict associated with actinolite as an alteration product. Numerous small rounded quartz grains are poikiloblastically included and give the diopside a diablastic or sieve texture.

Accessory minerals include sphene, magnetite, apatite, chlorite, biotite, sericite, epidote, clinozoisite and calcite. The first three are primary minerals; the remainder are alteration products after actinolite or plagioclase or both. The chlorite is faintly pleochroic in pale green and exhibits a dark brown and dark blue interference color. It is probably of the variety penninite. Biotite is pleochroic in pale to medium orange-brown, occurs as minute euhedral flakes, and it is not abundant in the calc-silicate rocks. Epidote-clinozoisite is seen primarily as the alteration product of plagioclase, exhibits inclined extinction and has a deep blue interference color. Tiny grains of epidote exhibit a high birefringence and are alteration products of actinolite. Small shreds of sericite are seen as inclusions in plagioclase. Calcite, in addition to being an alteration product, is a primary independent mineral phase in the calc-silicate rock. It is more abundant in the surface-samples of calc-silicate rocks than in the schists, commonly occurs in amounts ranging from 5-10 per cent and has been seen to comprise over 30 per cent of the total rock. Sphene is ubiquitious in the calc-silicate rock and occurs in amounts ranging from trace quantitites to 5 per cent. Magnetite is sporadic in occurrence and apatite occurs in trace amounts as small rounded grains in the matrix or as tiny euhedral inclusions in quartz.

The modal analyses of the calc-silicate rocks are given in Table 2.

Phyllite

The phyllite member of the Eliot formation is restricted to the central and eastern portions of the Haverhill quadrangle. It crops out in a large area in East Kingston and Newton. The phyllite has been described by Billings (1956, pp. 42, 43, 44, 102, 112) who has extended it into the Exeter quadrangle.

A similar phyllite unit in the Mt. Pawtuckaway quadrangle described by Freedman (1950, p. 456) and referred to by Billings (1956, p.

41) is called the Calef member of the Eliot formation. By finding new outcrops in the Mt. Pawtuckaway quadrangle, the writer was able to extend the Calef member to within one mile of the Haverhill quadrangle. New road cuts provide exposures of the Calef at the intersection of the new Route 101 and the Boston and Maine railroad crossing in Epping and also along the road between Route 125 and Lyford Crossing in Brentwood. The extension of the Calef runs roughly parallel to and within 1/4 mile west of Route 125.

In addition to the large phyllite body in East Kingston and Newton, the writer found outcrops of phyllite in the Haverhill 15' quadrangle in the following locations:

1. large phyllite boulders approximately 3/4 mile south of Fremont Station in the Exeter River, Fremont
2. 1/2 mile east of French Hill, just west of the Sandown-Danville townline, Sandown
3. along the southwest shoreline of Cub Pond, Sandown
4. along Hawkwood Road, 1/4 mile west of the Sandown-Danville townline, Sandown
5. along Route 121-A in southeastern Sandown and East Hampstead
6. along Route 125, on and just south of the Plaistow-Kingston line, Plaistow.

The outcrops listed above, those of the Calef member, and those of the large phyllite outcrops in East Kingston and Newton are similar in mineralogy and manner of deformation. Evidence, admittedly somewhat insufficient, suggests, that the phyllite is (or was) a continuous unit forming a marker bed in the Eliot and describing a major anticlinal fold plunging to the southwest. The chemical compositions of samples from the Calef and the large phyllite in East Kingston and Newton are given in Table 15 (pl. 5).

The deformation previously referred to is two sets of small folds or crenulations ranging from 1-3 mm in amplitude and 5-10 mm in wave length which intersect each other at an oblique angle. These folds are common to all of the phyllites in the Haverhill 15' quadrangle. In thin section, the crenulations are similar in form to kink bands (fig. 8).

A phyllite crops out along Interstate Route 495 near the Duston School in Haverhill, Massachusetts. It differs in appearance from that in the New Hampshire portion of the Haverhill 15' quadrangle because the mineral grains are coarser, the rock does not have characteristic sheen, and there are no intersecting crenulations.

The phyllite is lead gray in color and has a sub-metallic luster on fresh surfaces. It weathers to a dull, mottled greenish-gray and reddish-brown. A sulphurous odor is often detectable.

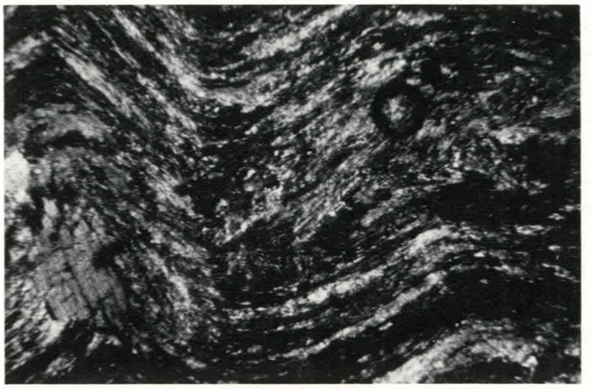

Figure 8. Photomicrograph of crinkled texture of phyllite in the Eliot formation. Sample taken from outcrop on Route 121-A on the Sandown-East Hampstead townline.

In hand specimen, pyrite cubes and quartz in small attenuated stringers have been identified. These minerals are not consistently present.

In thin section, the phyllites are foliated and intensely folded. Porphyroblastic texture is common (fig. 8). The essential minerals are muscovite, quartz, biotite and chlorite. Muscovite comprises from 50 to 85 per cent of the rock, and angular to subangular quartz grains comprise as much as 50 per cent, biotite is present in minor amounts and is pleochroic in light brown to medium greenish or orange-brown. It usually occurs as porphyroblasts and is commonly altered to chlorite. Phyllites in Sandown and East Hampstead contain as much as 80 per cent chlorite and are heavily stained with reddish-brown limonite.

Ghost outlines of former porphyroblasts of garnet and staurolite are completely altered to sericite and chlorite. These occurrences are extremely rare.

Accessory minerals include pyrite, limonite, tourmaline and calcite. Pyrite occurs as euhedral and anhedral porphyroblasts and alters to limonite. Tourmaline is present in broken but essentially euhedral forms and is pleochroic in light brown to dark orange-brown. Calcite is common in trace amounts and occurs interstitially to the micas.

An estimated modal analysis of a phyllite is given in Table 2 (p. 23).

Well cuttings

Studies of well cuttings from artesian wells drilled into the Eliot formation in the eastern half of the quadrangle (depths up to 500 feet) showed the presence of:

1. metamorphic rocks including phyllites, biotite, biotite-chlorite, and biotite-actinolite schists, and calc-silicate rock
2. igneous rocks including pegmatite (?), quartz monzonite, and camptonite
3. calcite as a major constituent (5-25 per cent) of the lithologies examined at all horizons. Rock consisting of 90 per cent calcite was found in several thin sections and may represent large fracture fillings.

Berwick formation

General statement

In the Haverhill quadrangle, the Berwick formation consists of fine-grained schists and calc-silicate rock. It is the youngest formation in the Merrimack group in southeastern New Hampshire and crops out sparsely over approximately six square miles in Raymond and Chester townships in the northwestern corner of the Haverhill quadrangle (pl. 1, 2). The outcrops are badly weathered. The formation is in contact with an intensely foliated two-mica granite and inclusions of the schistose Berwick formation are common in the granite.

The contact between the Eliot and the Berwick formations was extended along the strike from the Manchester quadrangle where, according to Sriramadas (1966, p. 15), it is gradational. The exact contact in the Haverhill quadrangle could not be determined. It is assumed, however, that the formations are conformable. Although calc-silicate indicator minerals are found throughout the quadrangle, the indicator mineral garnet is found only in that part of the quadrangle occupied by the Berwick formation. This unique occurrence of garnet implies a change in composition from the Eliot to the Berwick formations. Although no chemical analyses were made of the Eliot and Berwick formations, the change in the average composition in the Berwick formation is probably a decrease in calcium and an increase in iron and magnesium compared with the average composition of the Eliot formation.

Schists

The schists in the Berwick formation are generally fine to medium grained and well foliated. Most can be assigned to three assemblages: quartz-plagioclase-biotite schists, quartz-biotite-muscovite-garnet schists, and quartz-chlorite-epidote schists. The first two are medium to dark brownish-gray and weather light to medium gray; the third (found adjacent to the foliated two-mica granite) is medium to dark greenish-gray and weathers light to medium gray. In the latter,

Table 2

ESTIMATED MODAL ANALYSIS OF ROCKS FROM THE ELIOT FORMATION

SAMPLE NO.	85*	128*	44	66*	302	522	267
Quartz	4	40	35	35	30	10	25
Plagioclase	--	--	20	15	9	--	5
% Anorthite	(--)	(--)	(25-33)	(25-30)	(37-43)	(--)	(--)
Biotite	5	9	45	40	10	30	--
Microcline	--	--	--	--	1	25	--
Muscovite	85	tr	--	--	--	--	--
Sericite	tr	tr	tr	tr	--	--	--
Chlorite	tr	49	--	tr	--	--	--
Actinolite	--	--	--	10	25	5	tr
Diopside	--	--	--	tr	--	--	15
Calcite	--	tr	--	--	5	tr	33
Epidote	--	2	--	--	15	tr	20
Magnetite	--	--	--	tr	tr	5	--
Limonite	3	--	--	--	tr	tr	--
Sphene	--	--	tr	tr	5	tr	2
Apatite	--	--	tr	tr	tr	--	--
Tourmaline	--	tr	--	tr	tr	--	--
PORPHYROBLASTS							
Biotite	3	--	--	--	--	--	--
Actinolite	--	--	--	--	--	25	--
SIZE in mm							
Matrix	0.1-0.5	0.05-0.2	0.1-0.4	0.05-0.2	0.15-1.5	0.2-0.4	0.1-2
Porphyroblasts	1.0-1.3	--	--	--	--	2.0-2.5	--

TYPE AND FIELD LOCATION OF ROCKS LISTED IN TABLE 2

SAMPLE NO.	ROCK TYPE	LOCATION
85	phyllite	Route 108, East Kingston, 600' north of Newton townline.
128	chlorite-biotite schist	North of Sweet Hill on Plaistow-Newton townline.
44	biotite schist	600' south of Fremont Center.
66	biotite-actinolite schist	Exeter River and Route 125, Brentwood.
302	actinolite-biotite schist	South of Lily Pond on Phillips Road, Sandown.
522	porphyroblastic actinolite-biotite schist	Artesian well, 90' deep, southeast corner of Route 125 and Newton Road, South Kingston.
267	calc-silicate rock	1/2 mile north of junction between old and new Route 111, east of Island Pond.

* Chemical analysis in Table 15 (pl.5); rare earth analysis in Table 20 (pl.7).

chlorite is the dominant micaceous mineral.

The foliation of the schist is due to the parallel, planar orientation of the biotite, muscovite and chlorite. The planar aspect of the foliation is dominant in the Haverhill 15' quadrangle although there are outcrops that exhibit some minor open folds. The schists have a homogeneous texture and contain broad, stratified compositional units up to several meters thick. Attenuated stringers of white quartz, usually less than 10 mm thick, are common. Lenticular clusters of black biotite, 2-5 mm thick, are also present but are not too common.

Minerals which are identifiable in the hand specimen are biotite, muscovite, chlorite and quartz.

Microscopically, the schists exhibit strong foliation and, to a lesser degree, porphyroblastic texture.

Quartz and biotite are the predominant minerals in the schists. Plagioclase, muscovite, chlorite and actinolite are common but occur in lesser quantities. Quartz occurs primarily as a matrix mineral but commonly is the major component of small stringers. The grains are angular to subangular, and some of the larger grains exhibit wavy extinction.

Biotite is usually present as matrix grains and occasionally as metacrysts. It is pleochroic from light yellowish-brown to medium orange-brown. It also occurs as an alteration product of garnet and in turn, it alters to chlorite. The cleavage planes of the flakes are oriented parallel to each other. The metacrysts are essentially elliptical clusters of randomly oriented biotite flakes which are larger than the grains in the matrix.

Muscovite is common but it differs slightly from quartz and biotite in its mode of origin because it is primarily a product of dynamic metamorphism. It occurs as bands of coarse to fine grained flakes oriented parallel to a cleavage plane along which granulation has occurred. It is associated with attenuated quartz stringers and microfolds. The occurrence of muscovite is most common in the vicinity of the intensely foliated two-mica granite.

Chlorite is common and its mode of occurrence suggests clearly that it is an alteration product and should not be used as an indicator mineral for the greenschist facies on a regional scale. Chlorite occurs as: (1) contact zone around the foliated two-mica granite, the width of this zone varies from several cm to as much as two meters; (2) alteration product of biotite; (3) alteration product of garnet. Chlorite is pleochroic from colorless or pale green to medium bluish-green. The dark blue interference color is indicative of the variety penninite.

Plagioclase may be more common than indicated by using the crossed-nichols of the petrographic microscope because the albite twinning is poorly developed. The usual range of composition is about

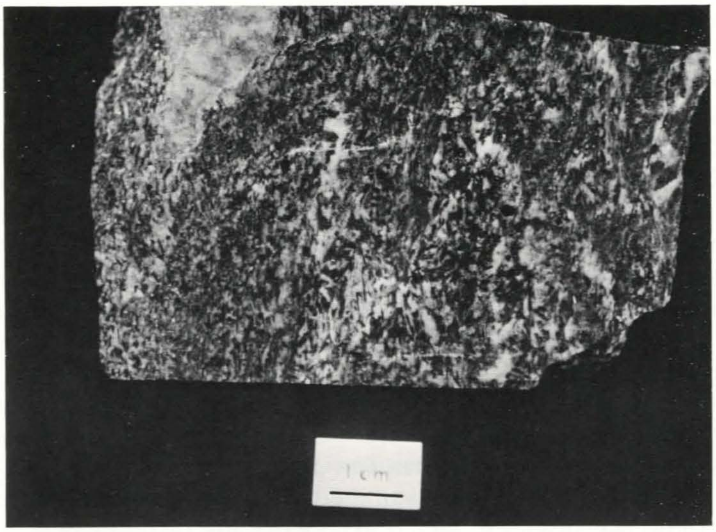

Figure 9. Calc-silicate gneiss, Berwick formation. The face of the rock is nearly parallel to the plunge of the lineation of the fasicular actinolite. Sample location is 2,500 feet south of Lane Road on Ledge Road, Chester, N.H.

An(28-35) but values from An= 20 to An= 50 have been recorded.

Actinolite occurs only in trace amounts. It is euhedral to subhedral in form and is pleochroic from very pale green to pale green.

Accessory minerals are tourmaline, magnetite, sphene, epidote-clinozoisite, and garnet. The tourmaline is presumed to be the black variety, schorl. It is euhedral in form, pleochroic from light yellowish-green to dark olive green, and is usually associated with quartz stringers. Magnetite is the only opaque mineral observed. It is always present and in some thin sections comprises as much as 3 per cent of the minerals in the sample. It occurs as angular grains and is usually oriented in a direction parallel to the foliation. Sphene, occuring as well-rounded blebs, is common but is not always present. Epidote-clinozoisite is not common but does occur in trace amounts. The garnet is sparse and probably almandine-rich because it is slightly pink in color and has magnetite inclusions. As is the case with tourmaline and muscovite, garnet is most commonly found along granulated cleavage planes in the schists of the Berwick formation.

The estimated modal analysis of rocks from the Berwick schist is given in Table 3 (p. 27).

Calc-silicate rock

Calc-silicate rocks are not common in the Berwick formation. The best outcrops are found on Ledge Road along the northwesternmost edge of the quadrangle. The several beds or lenses of calc-silicate rock observed by the writer ranged in thickness from about 2 cm to 60 cm. The rock appears medium to coarse grained, is white and light grayish/green, and weathers to a dull medium gray.

In hand specimen, the only readily identifiable mineral is the profusely abundant, dark green actinolite (fig. 9). It occurs as fine needles in bundles up to 5 mm long. With the possible exception of diopside, the other minerals are so small that they cannot be identified without the use of a microscope. The trend of the actinolite needles is oriented parallel to the regional structural trend. Diopside appears as stubby, dark green to black crystals. The white mineral is probably a mixture of quartz and sericite.

Microscopically, the calc-silicate rocks are granoblastic in texture but contain from 20 to 55 per cent lineated actinolite porphyroblasts. The matrix also contains quartz and plagioclase.

The actinolite is euhedral to subhedral, is pleochroic in pale green to medium bluish-green, and poikiloblastically includes quartz and sphene. Simple twinning along the (100) direction is common.

Quartz, the most abundant matrix mineral, ranges in size from 0.03 mm to 0.1 mm. The smaller sizes are usually observed along cleavage planes in zones of granulation and have a subangular to subrounded shape. Isolated relicts of quartz stringers contain quartz grains up to 0.7 mm across. Quartz is also present as inclusions in actinolite. Only the larger quartz grains exhibit wavy extinction.

Plagioclase is almost entirely altered to sericite, calcite, and epidote. Relict plagioclase has a composition of An(50-58). Sericite is the most abundant of the alteration products. It also is present along cleavage planes in zones of granulation.

Accessory minerals consist of magnetite, sphene, leucoxene, and apatite. Magnetite is usually present in trace amounts and is slightly altered to limonite and leucoxene. Sphene is an abundant and common accessory mineral; it is slightly pleochroic in light brown, occurs in lozenge-shaped and subhedral-prismatic forms and is poikiloblastically included in actinolite where it produces pleochroic halos. Apatite was observed in several thin sections as small anhedral grains.

The estimated modal analysis of the Berwick calc-silicate rocks is given in Table 3 (p. 27).

Table 3

ESTIMATED MODAL ANALYSIS OF ROCKS FROM THE BERWICK FORMATION

SAMPLE NO.	4	22-C	33	6-A	12-C
Quartz	45	40	20	30	45
Plagioclase	7	25	5	2	30
% Anorthite	(?)	(25-40)	(36)	(50-55)	(50-58)
Biotite	35	tr	40	--	--
Muscovite	--	--	10	--	--
Sericite	--	tr	10	8	2
Chlorite	--	34	tr	tr	tr
Actinolite	--	--	--	25	20
Diopside	--	--	--	tr	3
Garnet	--	1	3	--	--
Magnetite	3	--	tr	--	tr
Leucoxene	tr	--	--	--	tr
Tourmaline	--	--	1	--	--
Sphene	tr	--	tr	5	tr
Apatite	--	--	--	--	tr
Epidote	--	tr	2	tr	tr
Calcite	--	--	--	tr	tr
Clay	--	tr	tr	tr	tr
PORPHYROBLASTS					
Biotite	5	--	--	--	--
Actinolite	--	--	--	30	--
Quartz	--	--	9	--	--
SIZE in mm					
Matrix	0.05-0.7	0.05-0.6	0.2-1.5	0.03-0.25	0.1-0.2
Porphyroblasts	3-4	--	3-8	0.5-5	--

TYPE AND FIELD LOCATION OF ROCKS LISTED IN TABLE 3

SAMPLE NO.	ROCK TYPE	LOCATION
4	quartz-biotite schist	1,000 feet north of Lane Road on extension of Ledge Road, Raymond, N. H.
22-C	quartz-chlorite-epidote schist	Contact zone, north end of foliated two-mica granite, Raymond, N. H.
33	quartz-muscovite-biotite-garnet schist	West of Route 102 and Fremont Road junction, Chester, N. H.
6-A	calc-silicate rock	2,500 feet south of Lane Road on Ledge Road, Chester, N. H.
12-C	calc-silicate rock	700 feet north of Lane Road in large Berwick inclusion, Chester, N. H.

Chapter 3 Metamorphism

The rocks of the Eliot and Berwick formations have been subjected to regional metamorphism. According to Billings (1956, p. 140):

> The regional metamorphism in New Hampshire appears to have taken place at essentially one time in geological history. The independence of the grade of metamorphism from stratigraphic position is one indication of this. The relatively simple pattern shown by the isograds is a second indication. Finally, there is nothing in the paragenesis to suggest two or more widely spaced periods of regional metamorphism. Of course, the metamorphic evolution was complex and lasted for a long time. Although much of the metamorphism accompanied the deformation, some rocks underwent final crystallization after the deformation ceased.

The commonest mineral assemblages in the rocks of the major portion of the Haverhill 15' quadrangle in southeastern New Hampshire belong to the almandine-amphibolite facies.[1] The highest index mineral in the calcareous Eliot formation is diopside. Garnet was not observed in hand specimens or thin sections or metasedimentary rocks of the Eliot formation. Garnets were observed, however, in a series of limited exposures of metadiorites in Hampstead, Sandown, and Danville. The results of the analysis of such a garnet are listed under number 338 in Table 25, (p. 112). The composition is almandite (51%), grossularite (33%), and pyrope (16%).

Small garnets are common in the pelitic schists of the Berwick formation. Diopside is the common index mineral in the calc-silicate rocks.

In the extreme eastern portion of the quadrangle, however, key minerals in the assemblages are biotite and actinolite, which, along with quartz, epidote, chlorite and calcite are indicative of the greenschist facies. However, plagioclase in the eastern part of the Haverhill quadrangle is oligoclase An(20-25) rather than albite. Oligoclase is also characteristic of the mineral assemblages in the lower rank metamorphic rocks in southeastern New Hampshire (Freedman, 1950, p. 486) and (Sriramadas, 1966, p. 56) particularly in assemblages of the greenschist-amphibolite transition facies (Turner, 1968, pp. 303-307). Therefore, the metamorphic rocks in the eastern part of the Haverhill 15' quadrangle are classified as belonging to the

[1]Lower grade of the amphibolite facies which is equivalent to the almandine zone in the Barrovian Sequence.

Table 4

METAMORPHIC INDEX MINERALS OF THE HAVERHILL 15' QUADRANGLE

ZONE	FACIES[1]	MINERAL ASSEMBLAGES	
		argillaceous & pelitic metasediments	calc-silicate rocks
biotite	greenschist-amphibolite transitional	quartz-biotite-muscovite-oligoclase quartz-biotite-chlorite-oligoclase quartz-biotite-epidote	quartz-calcite quartz-oligoclase-actinolite-calcite quartz-actinolite-epidote quartz-actinolite-biotite-oligoclase chlorite
garnet	amphibolite	quartz-biotite-andesine-garnet quartz-biotite-epidote	quartz-andesine-actinolite-diopside (sphene, calcite) quartz-actinolite-biotite (sphene-calcite) quartz-diopside-calcite-epidote

[1]as designated by Turner, F. J. (1968, Chapter 7).

greenschist-amphibolite transition facies.

The mineral assemblages, zones and the equivalent facies are listed in Table 4 (p. 29).

The location of the isograds correlates well with the results of Novotny (1963) and Sriramadas (1966). In the Mt. Pawtuckaway quadrangle to the north, however, there is a discrepancy in the location of the garnet isograd. A scarcity of outcrops prevented maintaining good control on the location of this isograd near the northern boundary of the Haverhill 15' quadrangle. A compilation of the location of isograds in southeastern New Hampshire is shown in Figure 10.

The isograds in the Haverhill 15' quadrangle have little or no correlation with either stratigraphy or structure. Billings (1956, p. 141) has suggested that the grade of metamorphism may be influenced by the presence of volatile-rich granitic intrusions because the heat which they contain is readily transferred by solutions emanating from them. This appears to be the case in the Haverhill quadrangle also, because all of the major pegmatite, granite and quartz monzonite bodies (potential sources of heat and volatiles) are located in the garnet zone.

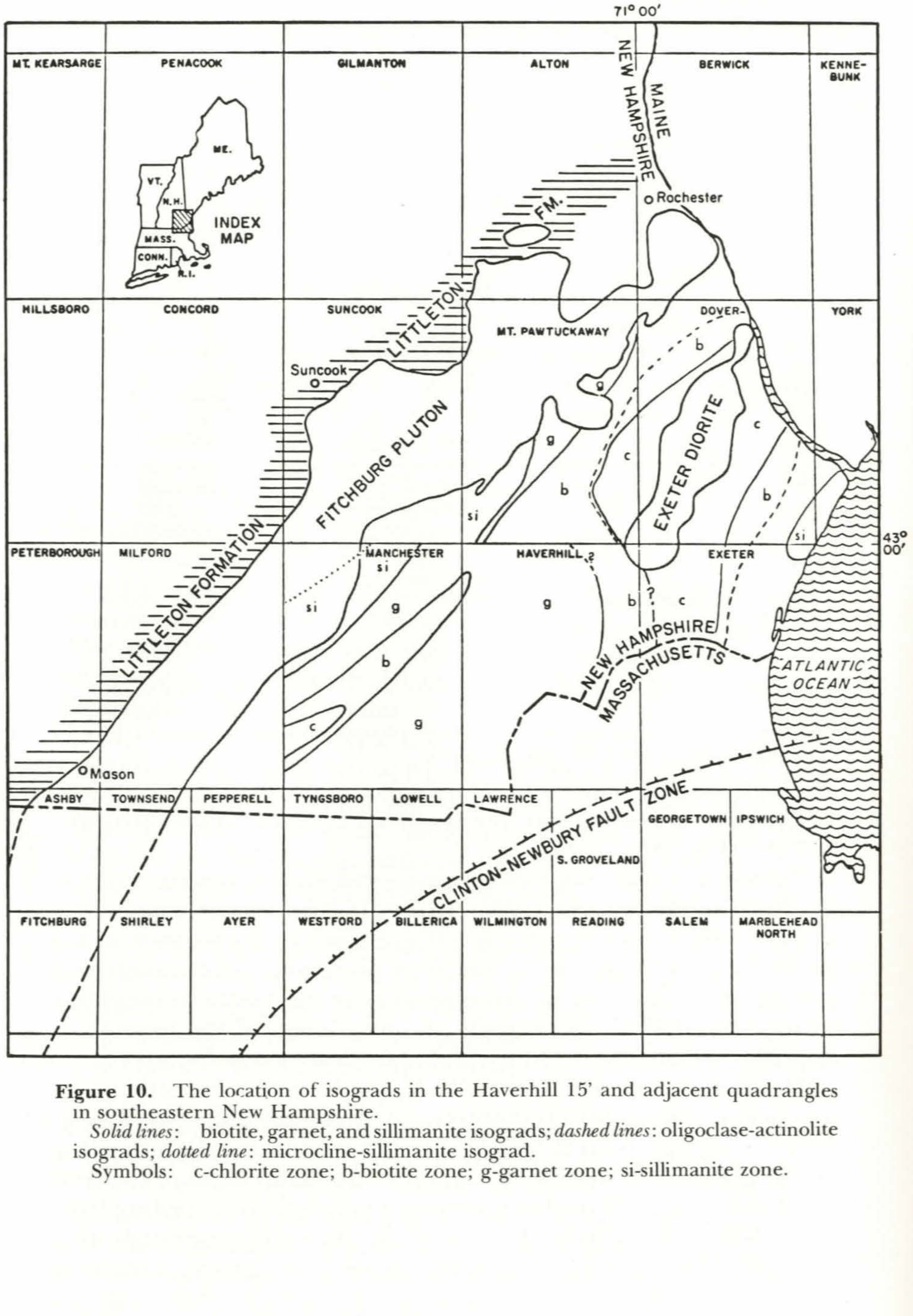

Figure 10. The location of isograds in the Haverhill 15' and adjacent quadrangles in southeastern New Hampshire.

Solid lines: biotite, garnet, and sillimanite isograds; *dashed lines*: oligoclase-actinolite isograds; *dotted line*: microcline-sillimanite isograd.

Symbols: c-chlorite zone; b-biotite zone; g-garnet zone; si-sillimanite zone.

Chapter 4 Intrusive Igneous Rocks

General statement

In the New Hampshire portion of the Haverhill quadrangle igneous rocks occur in a variety of forms ranging from large circular and elliptically shaped plutons to narrow dikes. The composition ranges from noritic gabbro to granite and pegmatite. All may be classified in two series which occur generally throughout southeastern New Hampshire. The Hillsboro plutonic series and the White Mountain plutonic-volcanic series. The Hillsboro plutonic series (Billings, 1956, p. 65-69) includes all the medium to coarse grained plutonic rocks of the area. Billings considered these to be of Late Devonian age, but isotope dating (Lyons et al., 1957, pp. 535-536) gives an age of 286-307 million years or Pennsylvanian (using the revised time scale, Eicher, 1968). The Ayer granodiorite, the Exeter diorite and related diorites, along with numerous small granitic intrusions in southeastern New Hampshire have been assigned by Billings (1956, pp. 65-69) to the Hillsboro plutonic series. The Sweepstake diorite and the Island Pond plutons (pl. 1, 3, 4) also belong to the Hillsboro plutonic series. Both names are new and assigned for the first time in this report.[1]

The White Mountain plutonic-volcanic series (Billings, 1956, p. 86) is a series of hypabyssal intrusive rocks thought originally to be of probable Mississippian age but now thought to be late Triassic to early Jurassic in age. Isotopic age determinations (Lyons, et al., 1957, p. 540; Hurley, et al., 1960, p. 254; Tilton, 1957, p. 369-371) give an age range of 170-212 million years. Diabase and lamprophyre dikes of the Haverhill 15' quadrangle belong to this series.

Hillsboro plutonic series

The Hillsboro plutonic series consists of a series of plutonic intrusives arranged in the following chronological order (oldest on the bottom), based on the intensity of foliation and their crosscutting relationships:

Sweepstake norite
Exeter diorite

[1]Sweepstakes diorite is used in place of Tombstone diorite (Sundeen, 1970) because that name has been used elsewhere.

Island Pond diorite
Sweepstake diorite
Quartz monzonite
Ayer granodiorite
Island Pond porphyritic quartz monzonite
Two-mica granite

The locations of the major intrusive bodies of the various rock types in the Hillsboro plutonic series are shown on a map of southeastern New Hampshire (fig. 11).

Pegmatites, as a group, were emplaced throughout the entire time span of the Hillsboro plutonic series. However, pegmatites associated with individual intrusives of the series probably can be considered as the latest events in the emplacement of these particular intrusives. Therefore, the pegmatite associated with the two-mica granite is considered earlier than the pegmatite associated with the Sweepstake diorite.

Two-mica granites and Quartz monzonite

Two-mica granitic rocks are located in the northwestern part of the Haverhill quadrangle and the quartz monzonites are located in the central section. Both are discussed under the same general heading because of their similarity in field appearance and mineral composition. Sriramadas (1966, p. 25-31) discusses the same rock types under the single headings of either foliated or massive binary granite. More than half of the rocks listed in the tables of estimated modal analysis for the binary granites in the Manchester quadrangle (Sriramadas, 1966, p. 28, 31) have the feldspar abundances characteristic of quartz monzonites. In the Mt. Pawtuckaway quadrangle to the north and in the Exeter and Dover quadrangles to the east and northeast, Freedman (1950, p. 466) and Novotny (1963, p. 89-99) respectively, have classified as granite only those rocks which have microcline and orthoclase abundances exceeding two-thirds of the total feldspar abundances. Other rocks, similar in composition except for an approximately equal percentage of both K-feldspar and plagioclase were classified as monzonites or quartz monzonites. The writer will follow the convention of Freedman and Novotny and distinguish between granites and quartz monzonite as observed in thin section. Distinction between the two types was impossible in the field.

Except for the intensely foliated granite in the extreme northwestern corner of the Haverhill 15' quadrangle, the shapes of the intrusive bodies and the range of the colors and textures are essentially the same for both granite and quartz monzonite. The intrusive bodies range in sized from thin seams and lenses to small elliptical shaped bodies elongated in the direction of the regional foliation. The color ranges from a light yellow to buff brown on weathered surfaces and

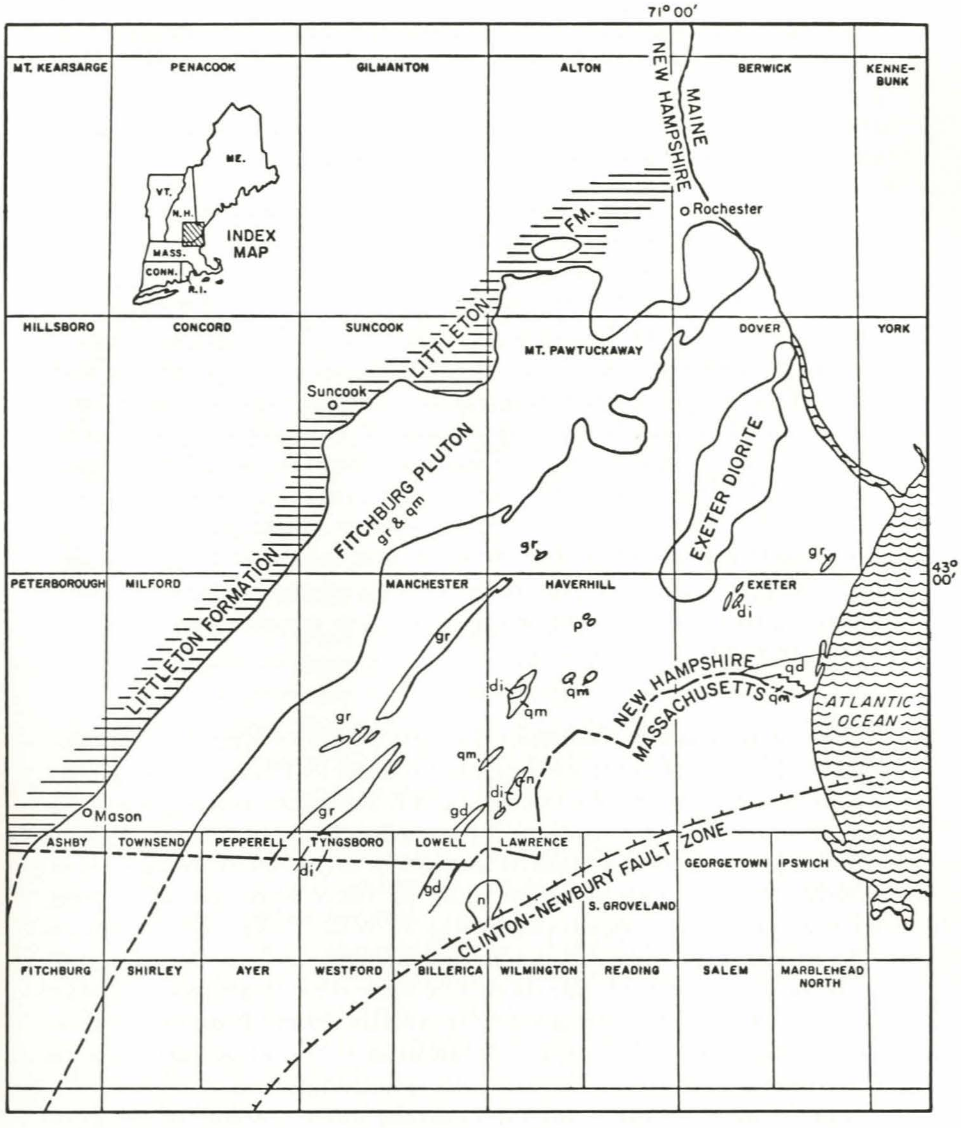

Figure 11. Location of the major intrusive bodies of the various rock types in the Hillsboro plutonic series, southeastern New Hampshire. (gr = granite; qm = quartz monzonite; gd = granodiorite; qd = quartz diorite; di = diorite; n = norite; p = pegmatite)

a white to grayish-white on fresh surfaces. The texture ranges from strongly lineated and foliated to massive; the grain size ranges from fine to medium grained (less than 2 mm) to very coarse (pegmatitic texture). Porphyritic texture and the more extreme examples of foliation and lineation are restricted to the granitic rocks.

The two-mica granite intrusive bodies are located in Raymond, Chester, Danville, Sandown, and Hampstead townships. The intrusive in the extreme northwestern corner of the quadrangle (pl. 1, 2; fig. 11) is about 2½ miles long and 1 mile wide and is the extension of a 10-mile long by 1-mile wide body from the Manchester quadrangle. It does not extend into the Mt. Pawtuckaway quadrangle at the surface. This is the most severely deformed of the two-mica granite intrusions. The rest of the mappable-sized intrusions are located to the southeast in the towns of Sandown, Danville, and Hampstead. The texture of the rock is generally massive to moderately well foliated. The less deformed bodies are relatively small, elliptical in shape, and range in size from 1,000 feet to 4,000 feet long and from 400 feet to 2,000 feet wide. Both the intensely foliated and massive two-mica granite intrusives are elongated in a direction parallel with the trend of the regional foliation.

Two-mica granite (foliated): The grain size of the intensely deformed granite ranges from medium to coarse (3-10 mm). A porphyritic texture is present but not abundant. Foliation, when present, is seen as the planar orientation of muscovite. However, in many cases what appears to be foliation is impossible to measure because it is poorly defined. This structure may be more appropriately called a lineation, at least megascopically (fig. 12-A 12-B). The most common type of structural element seen in this intrusive body in the Haverhill quadrangle is a mineral lineation. The same type of structural feature is observed in the Sweepstake diorite, and the Island Pond porphyritic quartz monzonite. This type of lineation is found in intrusives in the western part of the Haverhill 15' quadrangle.

The foliated granite is intruded into the lower member of the Berwick formation and inclusions of fine grained, quartz-biotite schist as much as one meter across are common. Contact with the host rock is sharp with hydrothermal alteration of the minerals extending only a few centimeters into the host rock.

Minerals readily observed in hand specimen are biotite (at some places altered to dark green chlorite), quartz and feldspar. The feldspars are difficult to differentiate where the grain size is small unless a cleavage surface exhibits the diagnostic polysynthetic twinning of the oligoclase. Phenocrysts, where present, are K-feldspar and

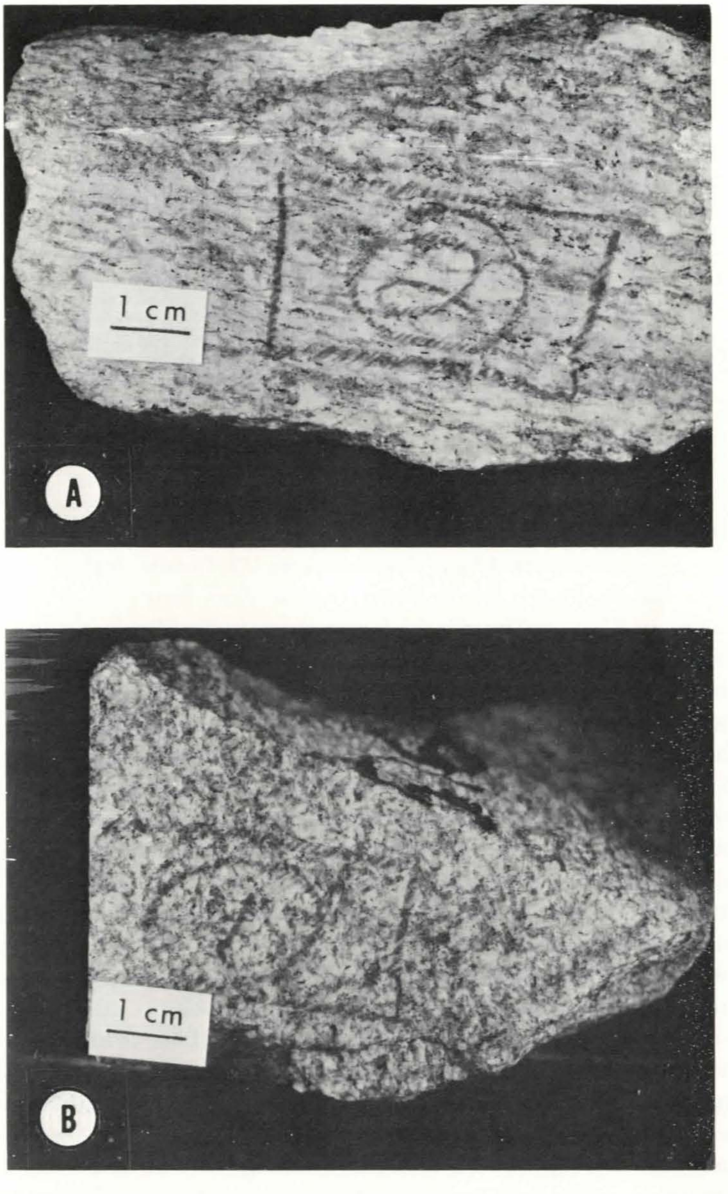

Figure 12. Lineation in deformed two-mica granite (full scale). Sample no. 516 was taken from a roadcut on the new Route 101, 3/4 mile east of the Lamprey River, Epping, N. H.

A. The section of a "foliated", slightly porphyritic, two-mica granite is cut parallel to the lineation.

B. This section of the same specimen is cut perpendicular to the lineation and appears as a "massive" texture.

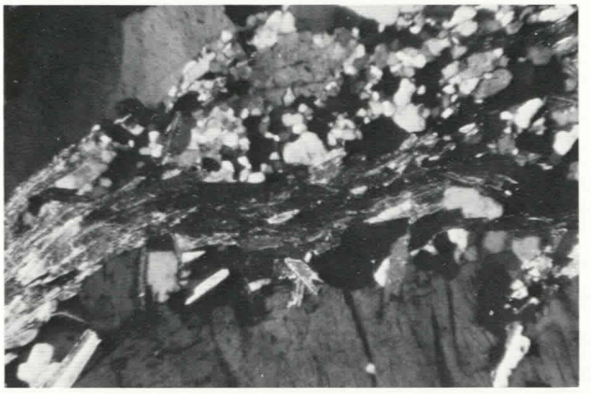

Figure 13. Zone of crushed minerals exhibiting mortar structure and secondary muscovite oriented parallel to plane of granulation.
Sample no. 32, from two-mica granite, 3,500 feet north of intersection of Lane Road and route 102, Chester, N.H.

Carlsbad twinning is usually observed. A common, but irregularly occurring mineral is the red almandine-rich garnet.

Thin section study shows granulation and elongation of minerals in the foliated granite. Fresh euhedral muscovite is most abundant in the areas of maximum granulation (fig. 13). The granulation and subsequent mineral growth suggests that the deformation in this granitic body is not a primary flow structure and is a result of shearing.

In thin section, the texture of two-mica granite is hypidiomorphic granular and many samples exhibit evidence of cataclastic deformation. A porphyritic texture with potassium feldspar phenocrysts is observed occasionally.

The essential minerals are microcline, oligoclase, quartz, biotite, and muscovite. Microcline exhibits its characteristic twinning best in those rocks that are least deformed. The writer concluded that the microcline apparently lost its characteristic gridiron twinning when the rock fabric and mineral structure had been strained and the internal order disrupted. To facilitate making a modal analysis, it was necessary to stain thin sections of the more deformed granites in order to distinguish between plagioclase and K-feldspar. The most common inclusions seen in microcline are quartz and oligoclase.

Oligoclase, An(19-23), is the plagioclase present. The anorthite content was measured as high as 30 per cent. It is usually highly altered to sericite and clay minerals. In the more intensely deformed rock, the oligoclase grains are broken and exhibit bent twin lamellae.

Quartz is present both as massive anhedral minerals and as bleb-like inclusions in microcline. Moderate to extreme wavy extinction is present in all of the thin sections studied.

Biotite, pleochroic from light brown to medium reddish- to orange brown, is present as ragged subhedral grains and is most abundant in and is parellel to zones of granulation. Only a small percentage of the muscovite in the more deformed granites can be considered a primary mineral. The accessory minerals are chlorite, sericite, apatite, sphene, rutile, magnetite, limonite, and garnet. Chlorite and sericite are alteration products of biotite and feldspar respectively. The chlorite is pleochroic from colorless to pale green and exhibits the Berlin blue interference color of penninite. Sericite is most abundant in oligoclase but is also seen as an alteration product of K-feldspar in the extremely deformed granites. Apatite and sphene are ubiquitous and are present in small subhedral forms. Rutile occurs occasionally as swarms of needles in quartz and oligoclase. Magnetite and limonite occur together as small anhedral clots associated with biotite. The red almandine garnet is locally present in small amounts. Quartz inclusions and biotite rims are often seen associated with the almandine. Except for almandine, all of the accessory minerals are microscopic in size (less than 0.1 mm). Almandine ranges in size from microscopic to 5 mm across.

Two-mica granite (massive to moderately foliated): The grain size of the granite ranges from fine to medium (0.5-4 mm). Foliation is most pronounced near contacts with the upper member of the Eliot formation. These rocks have been intruded into the upper member of the Eliot formation. Xenoliths are uncommon. Contact with the host rock is sharp.

Minerals readily observable in hand specimen are biotite, quartz, and feldspar. Again the feldspars are difficult to differentiate. Almandine occurs occasionally.

In thin section, the rock is hypidiomorphic granular in texture. The subparallel alignment of biotite and muscovite flakes brings out the texture in the slightly foliated variety.

The essential minerals are microcline, oligoclase, quartz, biotite and muscovite. The microcline consistently exhibits good gridiron twinning and some Carlsbad twinning. Quartz blebs, oligoclase and biotite are present as inclusions. Microcline is the dominant feldspar and usually is clear and unaltered.

The plagioclase constituent is oligoclase, An(22-28), although an anorthite composition as high as 32 per cent was detected. Albite twinning and albite-Carlsbad twinning are present though often masked by a moderate to intense alteration to sericite and a clay mineral.

Quartz occurs primarily as anhedral masses, but is also found as bleb-shaped inclusions in microcline and as myrmekitic intergrowths with oligoclase and microcline. Extinction is sharp in the smaller grains and slightly wavy in the larger masses of quartz.

Biotite is pleochroic in light brown to medium and dark reddish-brown. It occurs both in ragged subhedral and sharp euhedral forms; it alters to penninite. Pleochroic halos are common and probably due to inclusions of sphene. When garnet is present, biotite is usually seen as an inclusion or as an alteration product occurring on the rim of garnet.

Muscovite is consistently present but usually is less abundant than biotite.

The accessory minerals are chlorite, sericite, apatite, sphene, rutile, magnetite and garnet. Chlorite and sericite are alteration products of biotite and feldspars, respectively. The chlorite is pleochroic in colorless and pale green to pale and medium bluish-green. The interference color is the Berlin blue of the variety penninite. Sericite is most commonly observed as the alteration product of microcline. Apatite is ubiquitous and is seen as both anhedral and euhedral forms. Sphene is not abundant and occurs in a lozenge-shaped form. Rutile occurs occasionally in swarms of tiny needle-like inclusions in oligoclase and quartz. Magnetite, when present, is in the form of anhedral clots and is usually seen in association with biotite and chlorite. Except for almandine, all of the accessory minerals are microscopic in size (less than 0.1 mm). Almandine ranges in size from microscopic to 5 mm across and is usually the largest mineral in the rock sample.

The estimated modal analysis of samples representative of the foliated and massive two-mica granites are given in Table 5, (p. 40).

Quartz monzonite: Intrusive bodies of quartz monzonite crop out in Hampstead, Plaistow, and South Kingston townships. All are located due east of the Island Pond porphyritic quartz monzonite in Hampstead (fig. 11, p. 33). All occur in an east-west oriented band about one mile wide and over six miles long stretching from Island Pond to Misery Hill.

The intrusive bodies range in size from 1,200 feet to 6,500 feet long and from 600 feet to 3,000 feet wide. Good outcrops are present along new Route 111 in Hampstead and along Route 125, on Misery Hill in South Kingston.

The texture of quartz monzonite is massive to moderately foliated. In some instances, especially along contacts, intense foliation and/or lineation is encountered. This may be either a primary flow texture formed during the emplacement of the magma, or due to tectonic activity imposing structural elements on the non-viscous rock in the contact zone. The writer favors a tectonic origin for the lineation and foliation because (a) the shape of the intrusives is concordant to regional foliation and (b) granulation and a mortar structure are observed in thin section of rocks from the contact. This interpretation infers a late syntectonic time of emplacement.

In the hand specimen biotite, quartz, feldspar, and garnet have been identified. It is difficult to distinguish between plagioclase and microcline due to their similarity in color and small grain size. Occasionally, however, a grain of plagioclase will cleave so that the polysynthetic twinning can be seen with a hand lens. The grain size for all the major minerals most commonly ranges from 0.1 to 2 mm. Grain sizes over 3-4 mm are uncommon. Garnet (almandine) though a minor mineral constituent, often attains a size of 7 or 8 mm.

Microscopically the texture is hypidiomorphic granular, equidimensional and ranges from massive to moderately foliated. The essential minerals are microcline, oligoclase, quartz, biotite, and muscovite. The microcline is usually fresh and unaltered and exhibits excellent characteristic gridiron twinning. Sericite is seen occasionally as the alteration product of microcline. Quartz blebs, biotite and some plagioclase are occasionally seen as inclusions.

The plagioclase is oligoclase An(22-28). It is usually altered to sericite and a cloudy clay mineral. It generally shows albite twinning and, less commonly, albite-Carlsbad twinning. Continuous zoning is common and the difference in anorthite content from the core to the rim is approximately −4 per cent.

Quartz is present as massive anhedral forms. It also occurs to a much lesser extent as inclusions in microcline and interstitial to oligoclase and microcline. Wavy extinction is most pronounced in the moderately foliated rocks.

Biotite, the dominant dark mineral in the rock, is always present. It is pleochroic in light yellowish-brown to dark reddish- and orangish-brown. It contains sphene inclusions surrounded by pleochroic halos. Rutile needles were seen as inclusions in only one thin section. Biotite is commonly seen associated with the garnet (almandine) and is probably one of its alteration Products. Biotite also alters to chlorite, variety penninite.

Muscovite is commonly present but in amounts much less than biotite.

The accessory minerals include chlorite, sericite, apatite, sphene, rutile, magnetite, and almandine-rich garnet. Chlorite and sericite are commonly seen as alteration products of biotite and plagioclase, respectively. The chlorite exhibits the Berlin blue interference color characteristic of the variety penninite and is pleochroic in light to medium bluish-green. Apatite is ubiquitous, but is present only in

Table 5

ESTIMATED MODAL ANALYSIS OF TWO-MICA GRANITES AND QUARTZ MONZONITE

SAMPLE NO.	9*	342	348	138*	391	394*
Quartz	45	30	30	20	25	37
Plagioclase	5	10	15	25	25	23
% Anorthite	(12-18)	(24-26)	(22-26)	(25-29)	(23-27)	(22-30)
Microcline	25	45	30	30	30	27
Biotite	--	13	20	5	10	11
Muscovite	15	2	5	15	5	2
Chlorite	5	tr	tr	2	tr	tr
Sericite	5	tr	tr	3	tr	tr
Magnetite	--	tr	tr	tr	tr	--
Apatite	--	tr	--	tr	tr	--
Rutile	--	--	--	--	--	--
Sphene	tr	--	tr	--	--	tr
Calcite	tr	--	--	--	--	--
Garnet	--	tr	--	--	5	--
Myrmekite	--	--	--	--	tr	--
Grain Size (mm)	0.1-4	0.05-1.5	0.1-1.5	0.1-3	0.1-1.5	0.05-1

TYPE AND FIELD LOCATION OF ROCKS LISTED IN TABLE 5

SAMPLE NO.	ROCK TYPE (Map abbreviation)	LOCATION
9*	two-mica granite extremely foliated (bgf)	On Ledge Road, one mile south of Lane Road, Haverhill 15' quadrangle, west boundary.
342	two-mica granite foliated (bgf)	Baggett's Grove, south of Wash Pond (Sunset Lake), Hampstead, N. H.
348	two-mica granite massive (bgm)	Smith Mountain, 1/2 mile north of Wash Pond (Sunset Lake) Hampstead-Sandown townline.
138 *	quartz monzonite massive (qm)	Misery Hill, Route 125, South Kingston, N. H.
391	quartz monzonite moderately foliated (qm)	Intersection East Road and new Route 111, Hampstead, N. H.
394*	quartz monzonite massive (qm)	Intersection Route 121 and new Route 111, Hampstead, N. H.

* Chemical analyses in Table 11 (pl. 5); rare-earth analyses in Table 19 (pl. 7).

trace amounts. When it occurs as an independent phase it is seen as subhedral prismatic and basal sections. Apatite is euhedral when it occurs as minute inclusions in oligoclase and quartz. Sphene is lozenge-shaped and is usually associated with biotite when present. Magnetite occurs as anhedral clusters and is seen associated with almandine and biotite. The red garnet, almandine, is common but not ubiquitous. It is usually the largest mineral in the rock and occurs as broken, rounded subhedral crystals. It is usually slightly altered to biotite.

Estimated modal analysis of representative rocks is given in Table 5 (p. 40).

Ayer granodiorite

Two bodies of the Ayer "granodiorite" large enough to show on the geologic map are found in the Haverhill quadrangle. Both are located on the Windham-North Salem townline. One is an extension of a long lens-shaped pluton from the Manchester quadrangle, elongated northeast-southwest parallel to the strike of the regional structure. The other is a small elliptically-shaped body occurring primarily in the extreme northeastern corner of Windham township about one mile south of Goodhue Road. For several miles adjacent to these bodies, there are numerous small concordant lenses measuring no more than two meters across. Outcrops that resemble the small lens-shaped bodies in the Windham area are found along the north shore of Captain Pond in Salem and on the southwestern side of Providence Hill in Atkinson.

Quartz monzonite: These rocks are coarse grained, moderately to intensely foliated, porphyritic, light creamy-white to light bluish-white, and slightly peppered with biotite flakes. The minerals readily observed in hand specimen are microcline phenocrysts, quartz, biotite, and muscovite. The microcline phenocrysts are usually oriented with the long dimension in a direction subparallel to the foliation. They show twinning apparently on the Carlsbad law and usually range in size from 5 to 15 mm in their longest dimension on the surface of the rock specimen. Quartz grains are much smaller than the microcline phenocrysts, generally about 1 to 3 mm and rarely larger than 4 mm. Biotite is conspicuous as the only dark mineral present. Thin flakes of this mineral range in size from 0.5 to 2 mm. In many cases, the flakes occur in clusters about 2 to 4 mm across. Muscovite flakes are sparsely distributed but are easily seen because of the bright reflection from their cleavage surfaces.

Microscopically the Ayer granodiorite (a quartz monzonite in the Haverhill 15' quadrangle) is hypidiomorphic granular and weakly foliated. The essential minerals are microcline, plagioclase, quartz, biotite, and muscovite. Microcline is the most abundant mineral. Gridiron and Carlsbad twinning are prominent. Quartz and plagioclase are commonly present as inclusions in the microcline phenocrysts. Approximately 50 per cent of the microcline occurs as phenocrysts (5-15 mm); the remainder (1-5 mm) occurs in the matrix.

Plagioclase (0.1-2.5) is present in lesser quantities than the microcline. The composition is oligoclase-andesine (An20-30). It occurs as subhedral crystals that exhibit albite-Carlsbad twinning and some continuous zoning. It is moderately to well sausseritized. Sericite and epidote are the common alteration products.

Perthite (1-2 mm) with a patchy texture was observed in one thin section from an outcrop south of Goodhue Road in Windham.

Quartz (0.1-3 mm) occurs predominantly as anhedral matrix material, as bleb-shaped inclusions in microcline, and as a vermicular shaped constituent of the micrographic intergrowth of quartz and microcline.

Biotite (0.05-2 mm) is the only major ferromagnesian present in all of the thin sections analyzed from the Ayer "granodiorite". It is pleochroic in light greenish- or yellowish-brown to dark orange or reddish-brown. It is almost invariably associated with chlorite, an alteration product of biotite.

Muscovite (0.05-1 mm) is present but occurs sporadically.

Accessory minerals are apatite, chlorite, epidote, sericite, magnetite, rutile, sphene, zircon, and garnet. Apatite is the most abundant and persistent of the accessory minerals and occurs as subhedral prisms. Chlorite is an alteration product after biotite and is pleochroic in light yellowish- to bluish-green. The anomalous Berlin blue interference color suggests that it is the pennine variety. Epidote and sericite occur as alteration products of plagioclase. Magnetite, usually surrounded by limonite, occurs occasionally as randomly distributed anhedral clots. Rutile occurs as needle-shaped inclusions in microcline and quartz. It is well displayed in sample no. 211 taken from the small elliptically-shaped pluton in Windham. Sphene and zircon are the least abundant of the accessory minerals and occur in only two of the thin sections studied. Deep red garnets are found in several of the outcrops and, unlike the rest of the accessory minerals, are large enough (1-3 mm) to be recognized in hand specimen. The size of the accessory minerals ranges from microscopic to less than one millimeter.

The estimated modal analysis of several rocks representative of the Ayer "granodiorite" in the Haverhill quadrangle is given in Table 6 (p. 45).

The Ayer granodiorite as determined by Sriramadas (1966) occurs in three bodies in the southeastern corner of the Manchester quadrangle. The extension of one of these bodies is located in Windham and North Salem in the Haverhill quadrangle. It is a lens 1½ miles long and less than ½ mile wide (fig. 11, p. 33). Sriramadas (1966, p. 23) has chosen to call these rocks the Ayer granodiorite because of compositional and textural similarities to the Ayer granodiorite located nearby in Ayer, Massachusetts.

It is important to note that on the basis of the Moorhouse classification (1959, pp. 154-155) the estimated modal analysis of seven Ayer granodiorites in the Manchester quadrangle (Sriramadas, 1966, Table 10, p. 25), could be as follows: four are quartz monzonites, two are within three to five per cent of K-feldspar content of being classified as quartz monzonites, and one (No. 1111) is a diorite. Moorhouse suggests that in quartz monzonites the plagioclase present is greater than one-third but less than two-thirds of the total feldspars present, the mafic minerals constitute less than 40 per cent of all of the minerals, and quartz abundance is greater than 5 per cent.

In the Haverhill quadrangle, rocks which appear to be an extension of the Ayer granodiorite series from the Manchester quadrangle differ in composition and dominant texture from the non-porphyritic granodiorite in the type locality in Ayer, Massachusetts (Jahns, 1952, p. 112). They are dominantly porphyritic and their estimated modal analysis as determined by the writer (Table 6) are that of quartz monzonites.

Pegmatite: Pegmatite associated with the Ayer granodiorite occurs in relatively small lenses less than four or five feet long and one to two feet across. It is usually found with the Ayer intrusives and it appears to be a coarser phase of the associated rocks.

Megascopically, the pegmatite is massive, coarse grained, and creamy to bluish-white. The minerals which compose most of the rock are microcline (5-20 mm) and quartz (1-10 mm). Muscovite and biotite are also present in smaller amounts. Unfortunately, no hand specimen was taken of pegmatite from the Ayer rocks. A thin section was cut and studied from a finer grained rock occurring within several feet of a pegmatite lens. The microscopic description is the same as above for the Ayer "granodiorite" except for a greater percentage (5%) of the accessory mineral apatite.

Island Pond pluton

The Island Pond pluton is located in the west-central portion of the Haverhill quadrangle and crops out in the towns of Salem, Atkinson, Derry and Hampstead (pl. 3). The name of this pluton is derived from Island Pond, a lake near which many outcrops were found.

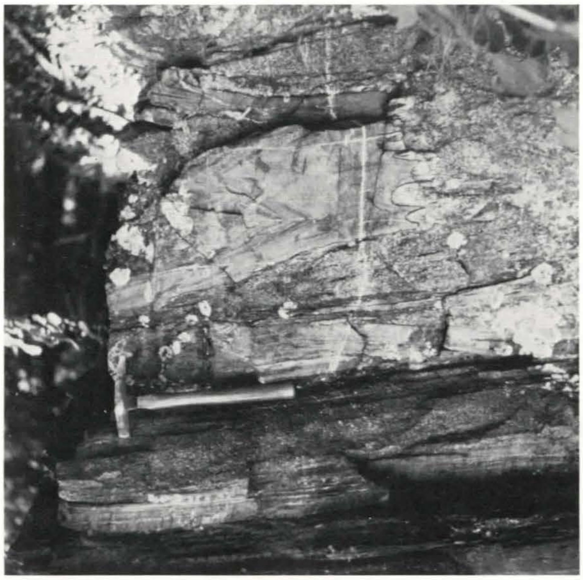

Figure 14. Outcrop of Island Pond porphyritic quartz monzonite-Eliot formation contact on the northeast shoreline of Island Pond. Notice the interfingering of the light-colored, foliated Eliot formation with the darker, coarse grained porphyritic quartz monzonite.

The Island Pond pluton is composed primarily of two rock types. About 75 per cent of the pluton is composed of a moderately to well foliated porphyritic quartz monzonite and about 25 per cent is composed of a massive diorite. A few small, unzoned, pink perthite-bearing pegmatite bodies are spotted throughout the pluton.

The intrusive is elliptically-shaped and is about three miles long by one mile wide. The direction of the long dimension is north-northeast. It is intruded into the Eliot formation. The contacts are not well exposed but where observed they are sharp (fig. 14, p. 44). The contact is a zone as much as 500 feet wide in which the metasedimentary host rock and porphyritic quartz monzonite are interfingered. In this contact zone, the intrusions appear dike-like, are only a few meters wide, and are concordant with the foliation of the Eliot formation.

Island Pond porphyritic quartz monzonite: Porphyritic quartz monzonite is the predominant rock type in the pluton. It makes up about 75 per cent of the igneous rocks present. Good outcrops are found at the southern tip of the body at Cowbell Corners in North

Table 6

ESTIMATED MODAL ANALYSIS OF AYER GRANODIORITE

SAMPLE NO.	192	210	211
Quartz	20	20	20
Plagioclase	15	15	5
% Anorthite	(22-25)	(28-30)	(37)
Microcline*	50	50	55
Perthite	--	5	--
Myrmekite	6	--	--
Granophyre	--	5	3
Epidote	tr	tr	tr
Biotite	5	5	15
Chlorite	tr	tr	tr
Muscovite	3	--	tr
Almandite	1	--	--
Magnetite	tr	--	--
Sphene	--	--	tr
Apatite	tr	tr	2
Zircon	--	tr	--
Rutile	--	--	tr
GRAIN SIZE in mm	0.05-5	0.01-7	0.1-10

* Approximately 50 per cent of the microcline occurs as phenocrysts.

TYPE AND FILED LOCATION OF ROCKS LISTED IN TABLE 6

SAMPLE NO.	ROCK TYPE (Map abbreviation)	LOCATION
192	quartz monzonite (agd)	Outcrop along roadway on the Salem-Windham townline, just north of Shadow Lake.
210	quartz monzonite (agd)	2,500 feet south of Goodhue Road, Windham, N. H., near Windham-Salem townline.
211	quartz monzonite (agd)	In the elliptically shaped intrusive 1.9 miles south of Goodhue Road, Windham, N. H.

Figure 15. Outcrop of the Island Pond Porphyritic quartz monzonite exhibiting intensely foliated bands of feldspar-rich facies (light area left of hammer) and biotite-rich facies (dark area under hammer).

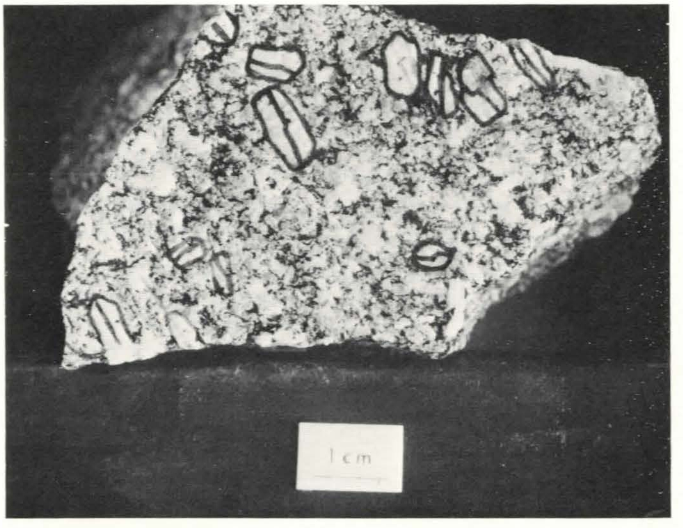

Figure 16. Cut section of the Island Pond porphyritic quartz monzonite with the microcline phenocryst faces and twin plane outlined in ink. Note the subparallel alignment of the twin plane traces from upper left to lower right hand corner of the photograph. The sample (204) is from Cowbell Corners in North Salem, N.H. at the southern edge of the intrusive.

Salem on Route 111 at the central part of the eastern edge of the body along the old Route 111 about 4,200 feet southwest of Hampstead Center (fig. 15) and along the northeastern shoreline of Island Pond.

Several inclusions of fine grained, quartz-biotite schist were noted in an outcrop about 300 feet from the shore at the southern end of the lake. These are the only xenoliths noted in the main body of the pluton. There is no indication of contact metamorphism megascopically, and unfortunately no samples were taken from the inclusions for detailed study of thin sections with the petrographic microscope. The trend of the foliation of the schistose xenoliths is approximately parallel to the strike of the regional foliation.

Megascopically, the Island Pond porphyritic quartz monzonite is a light to medium greenish-gray, porphyritic, moderately to well foliated, coarse grained igneous rock. Minerals readily identifiable are microcline, biotite, and quartz. The microcline (5-20 mm) occurs notably as creamy white to light bluish-gray phenocrysts. They are euhedral, twinned, and aligned in a direction generally parallel to the strike of the regional structural trend (fig. 16, p. 46). Microcline and plagioclase (0.1-5 mm) occur together as smaller minerals in the matrix, but they cannot be recognized separately in hand specimen. Biotite (0.1-5 mm) is the only mafic mineral present and the trace of the cleavage plane is also subparallel to the direction of the strike of regional structural trend. Quartz (0.05-4 mm) occurs as small, vitreous, light gray masses. The structural texture of the rock is predominantly linear rather than planar. The process of structural deformation must have been one of viscous flow or stretching rather than shearing. In sections cut perpendicular to the lineation, the mineral orientation appears quite random. This same structural pattern was observed in the Sweepstake diorite in Salem.

Microscopically, both foliated and non-foliated hypidiomorphic granular textures have been observed. This may be the result of the degree of deformation and/or the orientation of the thin section with respect to direction of the structural trend in the rock. Deformational features such as broken crystals, bent twin lamellae, and wavy extinction of quartz are present but not common. The occurrences of such features seem to be local and are random throughout the pluton.

The essential minerals are microcline, plagioclase, quartz and biotite. The microcline occurs as both phenocrysts and in the groundmass. The phenocrysts exhibit the typical grid pattern and also twinning after the Carlsbad law is usually present. Biotite and quartz-blebs are present as inclusions. Patchy perthite is present but it is not common. Microcline as the matrix mineral has the same properties as in the phenocrysts except that it is smaller and Carlsbad twinning is less common.

The plagioclase is oligoclase-andesine, An(20-30), with one sample containing as much as 37 per cent anorthite. Normal zoning is common but several thin sections studied showed plagioclase crystals with oscillatory zoning. The difference in anorthite content from the core to the rim ranged from -5 to -7 per cent. One thin section showed plagioclase with small microcline inclusions. Both albite-Carlsbad and pericline twinning are present.

Quartz occurs as an anhedral matrix mineral and to a much lesser degree as blebs in microcline and as myrmekite.

Biotite is present as an alteration product of amphibole and clinopyroxene as well as being a primary mineral. Ragged relicts of actinolite and augite have been observed in association with fresh euhedra of biotite. The biotite is usually pleochroic in light yellowish-brown to very dark reddish-brown. In one thin section, the pleochroism is from dark grayish-green to nearly black. Only a small percentage of the biotite is altered to penninite.

Accessory minerals are chlorite, saussurite, apatite, sphene, magnetite, ilmenite, and rutile. Chlorite and saussurite are alteration products of biotite and oligoclase-andesine, respectively. The chlorite, variety penninite, is faintly pleochroic in light bluish-green and has an intense Berlin blue interference color. Apatite is universally common in small (0.05-0.2 mm), stubby, subhedral crystals. Sphene, magnetite, and ilmenite are occasionally present in trace amounts and in sizes comparable to apatite. These three minerals are usually found associated with biotite. When present, rutile is seen as tiny needles in rutilated quartz and plagioclase.

The Island Pond porphyritic quartz monzonite is consistently foliated, either moderately or intensely (fig. 15, p. 46). The porphyritic texture is consistently present and the trace of the twin plane of the microcline phenocrysts is parallel to subparallel to the strike of the northeast-southwest regional foliation (S_3) in this part of the state (fig. 16, p. 46). The size of the phenocrysts ranges from 5 to 20 mm.

The composition and texture of the rock are relatively uniform within the area where it is exposed. Compositional variations usually reflect a change in the amount of biotite present, produce sharp differences in color, and form a thickly banded texture (fig. 15, p. 46). This type of banded texture, although present, is not common.

Although much of the description above can be applied to the rocks described under the Ayer granodiorite, it should be noted that there are three differences between the Ayer and Island Pond rocks. The composition of the Island Pond varies well within the limits of a quartz monzonite; the composition of the Ayer varies from a quartz monzonite to a diorite. Compositional banding is a rare occurrence in the Island Pond rocks and more common in the Ayer (Sriramadas, 1966, p. 24). The color index for the Island Pond rocks is as high as 35 to 40; that for the Ayer rocks in the Haverhill quadrangle is about 10 and never exceeds 15.

The estimated modal analysis of the Island Pond porphyritic quartz monzonite rocks is given in Table 7, (p. 52).

Diorite: The dioritic facies of the Island Pond complex consists of two small elliptically-shaped bodies located in the northern half of the main pluton (pl. 1, 3; fig. 11, p. 33). The smaller of the two bodies is about 2,000 feet across and is located on Governors Island in Hampstead and Derry. The larger body is about one mile across its longest dimension and comprises the entire hill just west of Hampstead Center.

Although there are numerous exposures of the Island Pond diorite, none could be found in which contact relationships between the massive diorite, the foliated porphyritic quartz monzonite, or even the Eliot formation into which it has been intruded were present. Thin sections from samples taken from the area between the two dioritic bodies were studied. These show essentially the same properties as the rest of the porphyritic quartz monzonite specimens except that some relicts of green hornblende are present and that the biotite is more intensely pleochroic. This suggests that the contact between the two rocks may be gradational.

Megascopically, the Island Pond diorite is a medium to dark greenish-gray, massive to slightly foliated, usually very coarse grained igneous rock. A generally finer grained texture is observed in outcrops on the western edge of Governors Island in the contact zone with the Eliot formation. Minerals readily identifiable in the hand specimen are amphibole, biotite, and plagioclase. The amphibole (0.1-5 mm) occurs as stubby, black subhedral crystals. The biotite occurs in clusters up to 8 mm across, is usually associated with amphibole, and ranges in color from black to brownish-black or a dark greenish-black. The plagioclase occurs in clusters of small white to grayish-white anhedral crystals.

Microscopically, the rocks consistently exhibit a non-foliated hypidiomorphic granular texture. The most felsic mineral is andesine with an average composition of An(41-48). Some of the plagioclase from the finer grained diorite on the western shore of Governors Island has a composition as high as An 55, whereas the coarser grained diorite on the east side of the hill on the mainland has a composition of An(28-35). The form ranges from subhedral to anhedral; albite-Carlsbad and pericline twinning are common; continuous zoning, where present, indicates an anorthite content difference from core to rim of about -5 to -7 per cent; and hornblende is sometimes poikiolitically included. Except for some slight saussuritization, the plagioclase appears fresh and unaltered.

Quartz is present in minor amounts and is seen as an interstitial phase or as bleb-like inclusions in the amphibole.

Amphibole is the predominant ferromagnesiam mineral in the Island Pond diorite. Both the intensely pleochroic hornblende and the slightly pleochroic pale green actinolite are present although rarely in the same specimen. The hornblende is euhedral to anhedral in form and is pleochroic in light yellowish-green and light yellowish-brown to a medium to dark bluish- and grayish-green in the prismatic section; the pleochroism is pale yellowish-brown to dark green in the basal section; $\gamma \wedge c$ ranges between 11° and 13° and the 2V is about 60° to 65°. Small plagioclase grains, bleb-like quartz, apatite and magnetite are common inclusions; simple twinning, parallel to the {100} is common. Thin opaque platelets, magnetite(?) - ilmenite(?), exsolved along the cleavage planes are common. Both hornblende and actinolite alter to biotite. Some of the hornblende is an alteration product of augite. Clear augite is seen occasionally as a ragged relict rimmed by fresh hornblende.

In the diorite on the west edge of Governors Island the amphibole mineral is actinolite. It is pleochroic in light grayish-green to medium grayish-green. The actionolite cleavages are filled with exsolved platelets of an opaque mineral, probably magnetite and/or ilmenite (fig. 17).

Biotite is present in all thin sections studied from the Island Pond diorite. Most of the biotite is associated with magnetite and represents the alteration product of amphibole. It is pleochroic in pale brown to medium dark green or orange-brown. Biotite is also an alteration product of actinolite. It is pleochroic from clear to light orange-brown, and alters to chlorite, variety penninite. Pleochroic halos from radioactive inclusions are rare.

Accessory minerals present are calcite, epidote, sericite, chlorite, apatite, rutile, magnetite, ilmenite, and pyrite. The calcite, epidote, and sericite occur as the alteration products of plagioclase (saussurite). Occasionally epidote is present with chlorite as the alteration product of biotite and some hornblende. Apatite is present in minor amounts in all of the thin sections studied. It occurs as clear, stubby euhedra exhibiting good basal and prismatic sections; it is found as part of the smaller constituents of the matrix and as inclusions in hornblende, biotite, and magnetite. Apatite crystals never exceed 1 mm in length along the prismatic section.

Rutile is locally present as swarms of needles in rutilated quartz and plagioclase. Magnetite and ilmenite occur as exsolved platelets in hornblende and actinolite and as possible alteration products of

Figure 17. Exsolved platelets of magnetite and/or ilmenite in cleavage planes of actinolite (act) from the Island Pond diorite.

the amphiboles along with biotite. Massive, anhedral clots of magnetite and/or ilmenite usually occur with biotite. Limonite is an alteration product of the iron minerals magnetite and pyrite and is probably the result of surface water reactions. Pyrite is present locally in amounts up to about 3 per cent. It is seen both as anhedral masses and as euhedral cubic sections.

The estimated modal analysis of representative samples from the Island Pond porphyritic quartz monzonite and the diorite is given in Table 7 (p. 52).

The massive to slightly foliated texture of the diorite implies that either the diorite was more resistant to the stress which deformed the porphyritic quartz monzonite or it was emplaced later after the stress had subsided. The writer favors the latter interpretation (i.e. that requiring two separate intrusive events which spanned the late- to post-tectonic periods) even though a possible gradational contact was inferred from field and laboratory investigations. The writer bases this opinion on the similar coexistence of massive and foliated textures in the Sweepstake diorite complex located five miles south of Island Pond. Here a sharp contact was found (fig. 18, p. 87) implying that there were two separate intrusive events spanning the time at the end of a period of tectonic activity.

The rocks in the Island Pond pluton are similar in many respects to rocks described as the Newburyport quartz diorite and porphyritic quartz monzonite located about 15 miles due east in the southeastern

Table 7

ESTIMATED MODAL ANALYSIS OF ROCKS FROM THE ISLAND POND COMPLEX

SAMPLE NO.	204	253	270-BR*	251**	478
Quartz	20	25	2	1	--
Plagioclase	25	22	15	35	40
% Anorthite	(22-38)	(24-28)	(22-27)	(38-40)	(50-55)
Microcline	30	30	40	--	--
Biotite	20	20	35	20	10
Chlorite	tr	tr	tr	tr	tr
Sericite	tr	tr	tr	tr	tr
Actinolite	--	--	--	tr	40
Hornblende	--	--	--	30	--
Augite	--	--	--	5	--
Epidote	--	tr	tr	tr	tr
Magnetite (ilmenite)	tr	1	1	5	10
Pyrite	--	--	--	3	--
Apatite	tr	tr	1	1	tr
Zircon	--	tr	tr	--	--
Rutile	--	--	--	tr	tr
Sphene	1	1	1	--	--
Calcite	--	--	tr	--	--
Myrmekite	4	1	5	--	--
Grain size (mm)	0.05-5	0.1-2	0.1-3	0.1-8	0.5-2.5
Phenocrysts	10-12	8-10	4-12	--	--

TYPE AND FIELD LOCATION OF ROCKS LISTED IN TABLE 7

SAMPLE NO.	ROCK TYPE (Map abbreviation)	LOCATION
204	porphyritic quartz monzonite (ippqm)	Cowbell Corners, No. Salem at southern edge of intrusive
253	porphyritic quartz monzonite (ippqm)	Tel Noar Camp lawn, 3,500 feet north of Hampstead Center
270-BR*	biotite-rich band porphyritic monzonite (ippqm)	Old Route 111, 4,200 feet southwest of Hampstead Center
251**	diorite (ipdi)	750 feet east of bridge on road to Governors Island
478	diorite (ipdi)	Extreme west shore, Governors Island

* Chemical analysis, Table 11 (pl. 5); rare-earth analysis Table 19 (pl.7).

** Rare-earth analysis only, Table 19 (pl.7).

corner of the Exeter quadrangle (fig. 11, p. 33). The similarity of these rocks strengthens the claim by Novotny (1963, p. 108-114) that the Newburyport rocks are part of the Hillsboro plutonic series.

Sweepstake diorite

The Sweepstake diorite pluton is located entirely in the city of Salem, New Hampshire in the southwestern corner of the Haverhill 15' quadrangle. It occurs as one large elongate body about two and one half miles long by two-thirds of a mile wide at its widest point. Two much smaller satellitic bodies occur south of the large body. The pluton is elongate in a northeasterly direction parallel to the regional strike.

Massive and foliated diorite, norite, pegmatite, and sulfide veins are present. Although a diorite body is shown in the Salem area on the state geological map (Billings, 1955), no written references are available describing the rock. The only such rock in southeastern New Hampshire described to date is the Exeter diorite (Johnson, 1935 and Novotny, 1963).

The name Sweepstake diorite is proposed by the author for this rock because of it proximity to a colorful landmark.[2] The outcrop area that best exhibits rocks typically observed in the pluton is less than a mile away from Rockingham Park. This race track is a well known tourist attraction in southern New Hampshire and, for a while, had the unique distinction of being the only state-run sweepstake or lottery in the nation.

Both the large pluton and the satellitic bodies of diorite are exposed in the areas of highest relief. The main body extends from the hill at Foster Corners northeasterly to about 2,000 feet north of Pine Grove Cemetery (pl. 1, 4).

Diorite: The most abundant single rock type in the Sweepstake pluton is diorite that exhibits textures ranging from massive to strongly deformed and foliated. The most intense deformation is found along the western and northern edges of the intrusion; the more massive and less deformed rock is found along the southeastern edge of the body.

The rock is light to dark greenish or purplish-gray and is medium to coarse grained. Minerals which are visible in hand specimen are white to purplish-gray plagioclase, with some of the laths as much as 8 mm in length; medium to dark green tremolite-actinolite clusters as much as 4 mm across; dark brown biotite flakes up to 7 mm across; stubby black pyroxene grains up to 1 mm; and some dark green

2 The more obvious selection of the name Salem diorite was rejected because of the possible confusion with the Salem diorite of Salem, Massachusetts.

chlorite flakes associated with the mafic minerals.

Thin section analysis shows that plagioclase content ranges from andesine to labradorite An(34-55). The plagioclase is relatively clear and unaltered, even in those specimens showing extreme alteration of the mafic minerals. Alteration products include epidote-zoisite, some albite, and sericite. Most plagioclase crystals show complex twinning according to the albite-Carlsbad and albite twin laws. Pericline twinning is present but not common. Plagioclase phenocrysts give a slightly porphyritic texture to several samples which were studied in thin section. These phenocrysts show normal zoning with an anorthite composition difference of up to -15 per cent from core to rim. Quartz blebs are poikiolitically included in some of the plagioclase.

Orthoclase occurs in only one of the thin sections examined (sample 160). In this sample there was less than 5 per cent orthoclase present as stubby subhedral crystals less than 1 mm across. The potash feldspars were recognized on the basis of a thin section staining procedure by Chayes, F. (1952).

The presence of pyroxene was inferred from the form of the amphibole alteration product. A small portion of the original material which escaped alteration (e.g. sample 169), was identified as hypersthene on the basis of parallel extinction, negative sign of interference figure and faint yellow to gray pleochroism.

Amphiboles are present in two general forms in about equal proportions. One type appears as the alteration product of primary pyroxenes since it appears as a matted accumulation of small crystals forming within borders of the former pyroxene. A small fraction of the unaltered pyroxene occasionally survives admist the amphibole. The second type of amphibole occurs as single fresh appearing euhedra. The well defined prismatic and pinocoidal forms appear to have been part of the original mineral assemblage as they do not seem to have cannibalized pre-existing minerals. Both types are of the tremolite-actinolite variety and are pleochroic in colorless or very pale grayish-green to pale blue-green. The extinction angle to the prismatic axis is 13° to 16°, with some angles as high as 25° to 27°. Small blebs of quartz are commonly seen as inclusions. In some thin sections both common and lamellar twinning are exhibited in the euhedral type of amphibole.

Biotite is a major mineral in the more deformed and foliated rocks. It is pleochroic in pale yellowish-orange to deep orange-brown, and usually occurs with amphibole and pyroxene as an alteration product. Inclusions are magnetite-ilmenite and minerals which produce pleochroic halos in the mica minerals.

Quartz is present in all the rocks studied in thin section but never exceeds 5 per cent. It occurs as intersertal grains to plagioclase or as inclusions in amphibole and plagioclase.

Among the minor accessories are epidote-zoisite, chlorite, sericite, magnetite, ilmenite, pyrite, limonite, apatite, rutile, sphene, zircon, and tourmaline. Epidote-zoisite are essentially alteration products of plagioclase and to a minor extent the mafic materials. Sericite is found only as the alteration product of the feldspars. Chlorite, penninite variety, is the common alteration product of biotite, amphibole, and pyroxene. Magnetite is usually present but in varying quantities and the presence of the white, semi-opaque leucoxene indicates the presence of ilmenite. All of the opaque minerals are anhedral. Apatite prisms and needles are ubiquitous. Rutile is seen in one instance as a rim around a core of magneto-ilmenite and in turn is rimmed by biotite. Sphene is present as euhedral and anhedral grains distributed throughout the rock. Zircon is enclosed in most other minerals and produces pleochroic halos in biotite and chlorite. The tourmaline is anhedral with a brown rim and a deep blue core and may represent a relict component of an assimilated xenolith.

Quartz diorite: Quartz diorite is a relatively minor lithologic type in the Tombstone diorite intrusive body. Specimens were collected along the western edge of the body in an area located 2,000 to 3,000 feet south and southwest of the new Salem High School and at the junction of Geremonty Drive and the Veterans Memorial Parkway (pl. 4). The specimens were collected from the area of the foliated diorites. Small, local occurrences may have been due to assimiliation of the quartz-rich country rock. Megascopically it is essentially identical to the above described diorite in color, texture, and mineralogy with the exception of the abundance of quartz.

In the thin sections of the samples collected, the quartz content was 10 to 15 per cent and occurs as subhedral to anhedral grains and as blebby inclusions in the actinolite and biotite. Quartz near the center of the body generally extinguishes sharply, but the quartz in the rock near the western boundary (the area of greatest rock deformation) exhibits a moderate degree of wavy extinction.

The plagioclase is essentially andesine An(30-48). It has been altered to sericite and kaolinite, as well as some saussurite. Twin laws observed are the albite, albite-Carlsbad, and some pericline in association with the albite twinning. Normal zoning is common and the difference in anorthite content from core to rim is on the order of -5 per cent.

Orthoclase is the potassium feldspar present in this rock type. It occurs as small stubby, subhedral crystals, 0.1 to 0.5 mm in size, exhibits the characteristic Carlsbad twinning and represents less than 3 per cent of the rock in the samples studied.

Pyroxene is observed in only one of the specimens of quartz diorite. This was collected just southwest of the Pine Grove Cemetery, the location of a noritic gabbro facies. The presence of about 10 per cent quartz may have been the result of assimilation of either quartz rich country rock (Eliot formation) or of older quartz diorite by the noritic gabbro intrusion. The former seems to be the more likely case. Pyroxenes occur as ragged relicts of hypersthene and augite making up no more than 2 per cent of the rock. They are only faintly pleochroic in pale grayish-green.

Amphiboles, primarily actinolite, occur in the same manner as those in the diorites. They are generally only faintly pleochroic from colorless and grayish-green to light bluish-green, have an extinction angle ranging from 14^0 to 17^0, range in size from 0.1 to about 2.0 mm, and constitute from 10 to 55 per cent of the rock. Simple twinning is commonly exhibited, as well as quartz bleb inclusions and opaque minerals exsolved in the cleavage lamellae. Actinolite alters to brown biotite, to colorless epidote-zoisite, and to very pale green chlorite.

Biotite occurs as both the alteration product of amphibole and pyroxene as well as a primary mineral. The pleochroism varies slightly (from one sample location to another), generally a light yellowish-brown to either a medium orange-brown or a dark chocolate brown. Biotite generally constitutes from 25 to 50 per cent of the rock. The primary alteration product is a colorless to very pale green chlorite.

Among the minor accessories are apatite, magnetite, rutile, sphene, and tourmaline. Apatite needles and clots are present in amounts less than 2 per cent in all specimens. Magnetite, rutile and sphene do not consistently occur throughout this rock type and appear in anhedral form in trace quantities. Tourmaline occurs in a specimen collected from the outcrop in Salem at Geremonty Drive and Veterans Parkway near a pegmatite body. The tourmaline may be the result of metasomatism from the pegmatite or may be, as suggested before, a relict from assimilated country rock. The tourmaline is subhedral and broken into three or four pieces across the basal section of the prism. It is pleochroic in light brown to deep greenish-blue.

The estimated modal analysis of rocks from the Tombstone diorite pluton is given in Table 8 (p. 64).

Pegmatite and sulfide body: Because these two minor phases in the Sweepstake diorite pluton may have been emplaced at some time later than the Hillsboro plutonic series, they will be described under separate headings which include all of the pegmatites and sulfides throughout the Haverhill quadrangle (see Pegmatite, p. 66, and Economic Geology p. 110).

Norite: Exposures of norite in the Sweepstake diorite are found along the eastern edge of the intrusive body. Megascopically the norite is massive, mottled medium to dark greenish-gray, or dark purplish-gray to nearly black, equigranular, and coarse grained. Minerals readily observed in hand specimen are pyroxene and amphibole as much as 5 mm long, plagioclase as much as 7 mm long, and biotite and chlorite as much as 1 mm long.

Microscopically the norite is hypidiomorphic granular. The essential minerals are plagioclase, pyroxene, and uralitic amphibole.

The plagioclase is andesine-labradorite An(45-65), and in some specimens it has been altered deuterically to epiodote-zoisite, albite, and sericite. Plagioclase crystals are twinned according to the albite and the albite-Carlsbad laws, and some pericline twinning appears in association with the albite twinning. The plagioclase from the outcrop along Lawrence Road at Pine Grove Cemetery exhibits bent twin lamellae. Oscillatory zoning is common and the difference in anorthite content from core to rim is -8 to -10 per cent. Orthoclase and quartz are present only in minor quantities as granophyre.

The pyroxenes are represented by hypersthene and augite. The orthopyroxene is faintly pleochroic in pale yellowish-pink to gray, shows good parting, parallel extinction, and is commonly rimmed with uralitic amphibole. Some of the orthopyroxenes are biaxial positive and are probably enstatite. Augite is present but not as abundantly as the orthopyroxene. It is essentially colorless and extinction angles on the prismatic section range from 41^0 to 48^0. Some of the augite poikilitically includes plagioclase. Paired twins are common in augite. Both augite and the orthopyroxenes are commonly rimmed with uralitic amphibole.

Amphibole and biotite are the major alteration products in the norite. The uralitic amphibole occurs most commonly. However, in several thin sections, the entire pyroxene crystal has been replaced by a fibrous, patchy mat of colorless to pale yellowish-green tremolite-actinolite. The biotite is pleochroic in pale yellowish-orange to dark orange-brown and usually occurs with magnetite, although it occasionally occurs with amphibole. It is partly altered to colorless chlorite.

Accessory minerals of the norite include magnetite, pyrite, apatite, rutile, and sphene. The magnetite is generally anhedral and is found in all specimens. The apatite occurs as small, stubby prisms. Occasionally rutile is seen as a swarm of tiny needles (sample 494). Pyrite and sphene occur only occasionally.

Figure 18. Contact between the finer grained lineated earlier Phase I diorite (upper left) and the coarser grained, later Phase II diorite separated by a thin green amphibole-rich zone (along crack below hammer) in the Sweepstake diorite.

Discussion: The contact between the foliated and non-foliated diorites is sharp as is shown in the outcrop at the intersection of Geremonty Drive and the Veterans Memorial Parkway, in which the contact is delineated by a thin zone of actinolite-rich rock (fig. 18). The contact zone is about 3 cm. wide. Inclusions of this actinolite-rich contact rock are found in the undeformed phase of the diorite.

The Sweepstake diorite occurs in two distinct phases. Phase I crops out in the western and northern portion of the pluton, is coarse grained, exhibits a distinct foliation and lineations, and generally weathers to a dark greenish-gray. The foliation in this phase is defined by the subparallel orientation of the biotite flakes. In the other parts of the pluton where Phase I diorites are exposed, the texture is commonly lineated due to the parallel alignment of amphibole prisms, biotite flakes, and elongated mineral clusters. Foliation is not readily observable in hand specimens; lineation, however, is easily seen in outcrop when examined in a direction perpendicular to the lineation; otherwise, the rock has an equigranular texture. The same textural character is observed in the two-mica granite (fig. 12, p. 35).

The Phase I diorite occurs most commonly as a medium grained

Figure 19. Examples of both autoliths and xenoliths occurring in diorite. The two brownish-gray inclusions in the center of the picutre are schistose xenoliths; the greenish-gray inclusion at the upper right is a dioritic autolith (Pine Grove Cemetery, Salem, N.H.).

rock showing good lineation of the mafic minerals. Highly weathered outcrops are light to medium gray; fresh surfaces weather to a chalky white, and fresh unweathered surfaces are a light to medium purplish gray and green.

Phase II diorite occurs in several grain sizes and compositions and exhibits a massive texture. At the outcrop at Geremonty Drive and Veterans Memorial Parkway (fig. 18), the equigranular diorite is coarse to medium grained. Relatively fine grained diorite and norite crops out in a small quarry along Lawrence Road. Highly weathered surfaces of Phase II diorite are medium to dark gray. These surfaces are often deeply pitted as the plagioclase is readily destroyed and removed, and the pyriboles stand out in relief. Fresh surfaces weather to a chalky white and fresh unweathered surfaces are a light to medium purplish-gray and green.

Inclusions are common in the Sweepstake diorite. Large inclusions of schists from the Eliot formation are found on the northeastern side of the hill at Foster Corners and in an outcrop in the front lawn of the Salem High School on the west side of Geremonty Drive. Relicts of inclusions are found also in the strongly deformed rock which outcrops behind Elementary School No. 1. In this location is the only example of deformation of inclusions. These inclusions are deformed along with the diorite. It is not known for certain whether this inclusion was an autolith or a metamorphosed xenolith. The writer suspects the former.

Both autoliths and xenoliths occur in the Sweepstake diorite. Figure 19 shows two small mica schist inclusions and a dark, fine grained diorite inclusion found in a rock in a stone wall along the Pine Grove Cemetery boundary. The schists probably represent the host rock, the Eliot formation. Most inclusions exhibit schistosity which suggests that metamorphism had preceded, at least in part, the emplacement of the Sweepstake diorite.

A consistent direction of jointing is found in the Sweepstake diorite. Orientation of subsequent instrusions of pegmatite and sulfide bodies seem to be strongly controlled by this major joint set, which is steeply dipping and trends northwest-southeast, normal to the strike of the regional structure.

Exeter diorite

Outcrops of the Exeter diorite are located about 15 miles northeast of the Sweepstake diorite in Brentwood, New Hampshire. The Exeter diorite is the largest pluton of the Hillsboro plutonic series. It covers a surface area of almost 50 square miles and is exposed in the Exeter and Dover 15' quadranles (Novotny, 1962), the Pawtuckaway 15' quadrangle (Freedman, 1950), and in the Haverhill 15' quadrange.

The Exeter diorite was named by C. H. Hitchcock (1877) for exposures in Exeter, New Hampshire. Other studies of the pluton were made by Katz (1917), Johnson (1936). Billings summarized the findings (1956).

The mass of the main pluton trends northeast-southwestward and conforms regionally to the trend of the intruded metamorphic rocks. In addition, eight smaller satellitic bodies occur southeast of the main mass. These smaller bodies are also elongate in form and trend northeast-southwestward.

Novotny (1962) has studied the Exeter pluton and describes it as follows:

> The Exeter pluton shows a gradational change in composition from gabbro in the soutwest to diorite and quartz monzonite in the northeast, as determined from microscopic study. Diorite is the dominant rock type, however, and local deviations from the general trend of compositional change are also present. Many aplite dikes and a few granite dikes are also present in the diorite bodies and the Exeter pluton, none of which exceed one foot in thickness.
>
> Rocks of all the diorite bodies are massive with one exception. Those at Sawyers, one mile south of Dover, are strongly sheared parallel to the contact with the Kittery formation. The deformation may be either syntectonic or post-tectonic. Stresses due to regional deformation concomitant with emplacement of the diorite could have produced shear zones locally and marginally. Regional or local de-

formational stresses post-dating the emplacement of the diorite could also have been responsible for marginal shearing of the diorite.

About two square miles of the extreme southwestern end of the Exeter diorite pluton crops out in the northeastern corner of the Haverhill 15' quadrangle. Outcrops are few and generally limited in extent, especially near the suspected contact zone.

In the Haverhill 15' quadrangle the Exeter diorite is massive to slightly foliated, coarse grained, and light to medium-dark greenish-gray. Biotite flakes in a subparallel orientaton give the slightly foliated texture to the rocks. Occurrences of inclusions up to about 50 cm across were common in the outcrops visited by the writer. These inclusions were both autoliths of a darker, fine-grained phase as well as xenoliths of the metasedimentary host rock. A specimen of the host rock in the contact zone located about 350 feet south of Route 111-A in Brentwood is light brown and has a fine grained, homogeneous texture. Megascopically it strongly resembles a quartzite. Microscopic examination of a thin section of this rock showed a significant percentage of epidote and some calcite in a matrix essentially composed of quartz. The country rock at the contact is of albite-epidote-hornfels facies. The mineral assemblage is quartz-epidote-calcite. The extent of this contact metamorphism is about 10 to 15 cm from the contacts observed.

Diorite and quartz diorite: Diorite and quartz diorite (?) are the only rock types appearing in the Haverhill 15' quadrangle portion of the Exeter diorite pluton. The occurrence of the more silica rich rocks at this extreme end of the pluton may be, in part, a result of assimilation of quartz-rich country rock near and in the contact zone.

Minerals recognized in a hand specimen are black biotite up to 6 mm across, plagioclase as much as 7 mm long, appearing as either anhedral clusters or in euhedral laths, and dark greenish-gray clots of hornblende up to 4 mm across.

Microscopically, the rock is hypidiomorphic granular and exhibits varying degrees of hydrothermal alteration and moderate strain effects such as bent plagioclase and wavy extinction in quartz.

Thin section analysis shows that plagioclaseis the only feldspar present and it ranges in composition from oligoclase to andesine An(28-40). The cores of the larger crystals are saussuritized. The recognizable products are sericite, epidote, and calcite. Continuous normal zoning is common and the compositional difference between the core and rim is about -7 per cent. The plagioclase exhibits complex twinning according to the albite, albite-Carlsbad, and the pericline twin laws. Myrmekitic texture at the plagioclase-quartz boundary was recognized in one thin section. Bent twin lamellae are present but not common.

Quartz is present in small amounts, less than 3 per cent, in the thin sections examined, and occurs as anhedral interstitial grains with sharp extinction. It also occurs as small blebs enclosed in hornblende. Some of the interstitial quartz is heavily rutilated.

Pyroxene is present only as ragged relicts of augite which is almost totally altered to amphibole (hornblende).

Hornblende is a major femic component of the diorite. It exhibits a variety of pleochroic colors. Larger and more euhedral grains are strongly pleochroic from light green and brown to medium grayish- and bluish-green. The euhedral hornblende shows normal twinning, has an extinction angle of 16°, includes quartz and plagioclase as well as some biotite and calcite. Anhedral clusters of amphibole (actinolite?) appear to be alteration products of pyroxenes and are pleochroic from very pale green to light bluish-green. Biotite, epidote and chlorite are the alteration products of the hornblende.

Biotite occurs as an alteration product of hornblende and commonly is associated with magnetite. It is pleochroic from light brown to reddish- and chocolate brown. Chlorite, usually intergrown with the biotite, is pleochroic from colorless to light green and has anomalous interference colors of brown and Berlin blue. Apatite, quartz, and sphene are common inclusions in the biotite; apatite forms the core of the pleochroic halos in the biotite.

Accessory minerals include chlorite, magnetite, rutile, sphene, and apatite. Sericite, epidote, and calcite are alteration products of plagioclase. Chlorite, epidote, and some calcite occur as alteration products of the amphiboles and biotite. Small amounts of anhedral magnetite associated with some limonite is common but not consistently present in all specimens examined. Rutile is present as tiny needles in the interstitial quartz. Sphene occurs sporadically as clusters of lozenge-shaped grains exhibiting high relief. The apatite is ubiquitous.

The estimated modal analysis of the minerals in these rocks are given in Table 8 (p. 64).

Dracut diorite

The group of igneous rocks collectively known as the Dracut diorite is considered part of the Hillsboro plutonic series (Billings, 1956). Available evidence suggest that the Sweepstake, Island Pond, and Exeter diorites are related to it. It crops out primarily in the town of Dracut in northeastern Massachusetts and is composed of two small elongate igneous bodies that trend northeast-southwest parallel to the trend of the regional structure of the metasedimentary host rock. One of these bodies is intensely foliated, composed of diorite and quartz diorite, and extends northeasterly from Dracut into Pelham, New Hampshire. The other is a massive norite and is located immediately to the east of the diorite. Rocks belonging to the Dracut diorite crop out about four miles southwest of the Sweepstake pluton in Salem, New Hampshire.

Dennen (1943) described the Dracut diorite in detail. His description of the norite is presented here:

> Along the northeast border of the intrusive is a gradational zone where the acidity of the intrusive, as evidenced by lighter color and the presence of more leucocratic constituents, increases towards the quartzite. The inclusions grade from rock which is indistinguishable from the norite except by grain size in the hand specimen, through schistose inclusions, to quartzite which is in every respect similar to the surrounding Merrimack formation.
>
> The increase in acidity of the norite towards the contact with the quartzite is probably due to magmatic differentiation with the later and more granitic products emplacing themselves around the periphery of the stock. An alternate possibility is that the increase in acidity is due to assimilation of the quartzite. (p. 33).
>
> Extrene local variations in percentage of mineral constitutents, grain size, kind and amount of alteration and metamorphism are numerous. The texture of the average rock is holocrystalline with hypidiomorphic crystals. The original texture was essentially granitoid. Surface weathering apparently has not affected the rock to any great depth, for no difficulty was experienced in obtaining fresh specimens from outcrops. Many exposed surfaces of the rock are pitted. The pyribole stands out; the feldspar decomposes more rapidly. Weathering seems to lighten the rock considerably, and staining by iron oxide is noted almost everywhere. (p. 35).
>
> In general, the Dracut is composed of hypersthene, augite, common hornblende, and olivine, the chief melanocratic constituents; labradorite, the only important leucocratic mineral; and 5-10 per cent of metallic constituents. The main accessory mineral is apatite. The numerous alteration products include hornblende, uralite, tremolite, biotite, chlorite, talc, sericite, kaolin, and iron oxide.
>
> The norite varies considerably in texture, both in grain size and in orientation of the grains. Normally it has a granitoid texture, but in several places it has distinct lineation. Lineation ranges from a statistical orientation of stubby augite grains to the parallel orientation of lath-like feldspar and hornblende crystals. In some places the lineation flows around irregularities in the border between the lineated and randomly oriented areas; in others it ends abruptly against an area of granitoid texture. (p. 36).

An estimated modal analysis of a thin section of the Dracut norite is given in Table 8 (p. 64).

Table 8

ESTIMATED MODAL ANALYSIS OF ROCK TYPES

IN THE DIORITE MEMBERS OF THE HILLSBORO PLUTONIC SERIES

SAMPLE NO.	499-C	162**	160	169	505	503*	506-D*	459*	57	E-1*	11***
Quartz	--	--	4	2	--	20	10	--	3	10	12
Plagioclase	45	35	40	70	60	35	70	45	40	50	52
% Anorthite	60-65	48-60	48-55	34-57	48-64	30-40	40-48	45-55	28-38	28-35	31
Orthoclase	--	--	tr	--	--	tr	--	--	--	--	--
Microcline	--	--	--	--	--	--	--	--	--	4	17
Biotite	--	4	20	5	--	25	1	2	30	15	4
Chlorite	1	1	3	1	2	1	3	2	tr	tr	8
Sericite	tr	tr	1	1	--	1	1	--	tr	tr	3
Tremolite-Actinolite	1	10	30	15	35	10	15	1	tr	--	--
Hornblende	--	--	--	--	--	--	--	25	25	20	--
Uralite	1	1	--	--	--	--	--	--	--	--	--
Hypersthene	45	30	--	5	--	--	--	15	--	--	--
Augite	5	15	--	--	--	--	--	5	--	--	--
Epidote	tr	--	tr	1	1	1	--	tr	tr	tr	--
Magnetite	tr	4	1	tr	1	tr	tr	3	1	--	2
Pyrite	--	tr	tr	--	--	--	--	1	tr	--	--
Apatite	2	1	tr	--	1	1	1	1	tr	tr	--
Zircon	--	--	tr	--	--	--	--	--	--	tr	--
Calcite	--	--	--	--	--	tr	--	--	tr	--	1
Rutile	--	tr	tr	tr	1	tr	--	--	tr	--	--
Sphene	--	--	--	--	--	--	--	--	1	1	1
Tourmaline	--	--	--	--	--	1	--	--	--	--	--
GRAIN SIZE (mm)	0.5-2	0.3-4	0.1-3	1-4	1-4	0.1-2	0.1-5	0.5-3	0.2-7	0.1-3	0.12-4.2

* Rare-earth and chemical analyses, Tables 19 (pl. 7) and 11 (pl.5)
** Rare-earth analyses only, Table 19 (pl. 7)
*** Approximate modal analyses from Table 6 (Novotny, 1962)

TYPE AND FIELD LOCATION OF ROCKS LISTED IN TABLE 8

SAMPLE NO.	ROCK TYPE (Map abbreviation)	LOCATION
499-C	Norite (sn)	South end of a small quarry on west side of Lawrence Road, about 1/2 mile south of Salem, N. H.
162**	Norite (sn)	South entrance of Pine Grove Cemetery, Salem, N. H.
160	Diorite (sdi)	Northeast corner of School No. 1, Salem, N. H.
169	Diorite (sdi)	North side of hill at Foster Corners, Salem, N. H.
505	Diorite (sdi)	West side of hill at Foster Corners, Salem, N. H.
503*	Quartz diorite (sdi)	500 feet south of new Salem High School on east side of Geremonty Drive, Salem, N. H.
506-D*	Quartz diorite (sdi)	Junction of Geremonty Drive and Veteran's Memorial Parkway, Salem, N. H.
459*	Norite (Dracut)	George Brok, Inc. crushed stone quarry north of Route 110, Dracut, Mass.
57	Diorite (edi)	Route 111-A, west of Dudley Brook, Brentwood, N. H.
E-1*	Quartz diorite (edi)	South of Route 111-A, 1/2 mile east of Brentwood townline, Exeter, N. H.
11***	Quartz diorite (edi)	Exeter Quadrangle

(s-Sweepstake, e-Exeter)

Pegmatite

Microcline-albite pegmatites are distributed throughout the Haverhill quadrangle. They occur as dikes from a few centimeters thick, to as much as 15 feet across, and as large circular and elliptical shaped bodies up to three-quarters of a mile across. Pegmatite dikes intrude both igneous and metamorphic rocks. Smaller lenses and dikes in the metamorphic rocks generally are concordant with the foliation (fig. 20) although crosscutting relationships are common (fig. 21).

The larger pegmatites are restricted to the Eliot formation in the Haverhill quadrangle and have no apparent association with other igneous types. They are located in a zone about three miles wide which can be traced from the northeastern corner to the southwestern corner of the quadrangle and are especially abundant along the Danville-Kingston townline They are also found in Plaistow, Hampstead, and Atkinson. This zone of pegmatites continues to the south of the quadrangle along the Salem, Nea Hampshire - Methuen, Massachusetts townline (Castle, open file, USGS).

The pegmatites are grayish-white to buff and tend to take their color from the predominant feldspar mineral. Exceptions to these colors are noted in the small pegmatites associated with the Island Pond pluton. The microcline and the pegmatite are a light pinkish-brown and are found in both the porphyritic quartz monzonite and the diorite.

The pegmatites in the Haverhill quadrangle are composed of microcline, perthitic microcline, muscovite, biotite, albite, quartz (clear, cloudy, smokey, and rose), pyrite, chalcopyrite, tourmaline (schorl), almandine, apatite (bluish-green) ad beryl (aquamarine).

The pegmatites in the Haverhill quadrangle are transected by lamprophyre and diabase dikes of the Late Triassic-Early Jurassic White Mountain plutonic-volcanic series and in view of their close relationship to the Hillsboro plutonic series, they are considered by the wrier to be of Late Devonian-Early Pennsylvanian (?) (late syntectonic to post-tectonic, Acadian) age.

Despite the lack of good exposures which prevented a detailed description of the structure and mineralogy of the larger bodies in Kingston, Danville, Plaistow, and Atkinson townships, road construction did provide cross sections of some of the dikes and smaller veins, some of which often exhibited crude zoning. Minerals in the contact zone are coarse-grained and consist of quartz, albite, microcline and black toumaline. They are often aligned more or less perpendicular to the contact. The inner core zone is composed predominately of a fine-grained aplite and consists of microcline, albite, and quartz. The microcline in the aplite often occurs as phenocrysts which are

Figure 20. Pegmatite boudins. The pegmatite was intruded concordant with the foliation of the Eliot formation. Locaton is half a mile east of Hampstead center on old Route 111.

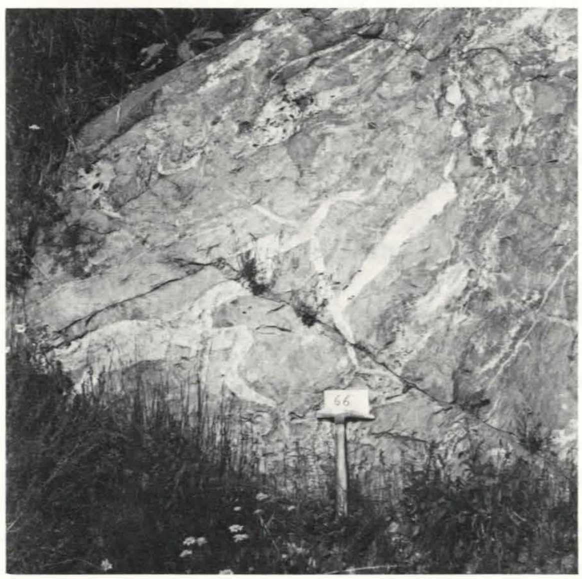

Figure 21. Crosscutting pegmatite veins. Pegmatite veins form discordant intrusives in Eliot formation (foliation trends from lower left to upper right). Location is south of Exeter River bridge, Route 125, Brentwood, N. H.

as much as 5 cm across and are twinned according to the Carlsbad law. Common accessory minerals are dark red almandine garnets, bluish-green apatite and black tourmaline.

At least four distict zones were determined in each of two pegmatite dikes exposed along the Veterans Memorial Parkway in Salem, New Hampshire. In addition to the minerals described above, the presence of muscovite and biotite were the criteria used for delineating the zones. In addition to zoning, some unusual mineral textures and structures associated with pegmatites were observed. They included graphic intergrowths of microcline and quartz, miarolitic cavities filled with tiny smoky quartz crystals, radially dispersed muscovite flakes, and an aplitic phase (sample no. 506-F) near the core zone. The aplite contains microcline, albite An(5-7), quartz, tourmaline (black in hand specimen, zoned and pleochroic in light blue to deep blue in thin section), almandine (red, see MINERALOGY, p. 111), apatite (bluish-green), and beryl (aquamarine), all homogeneously dispersed.[3]

Despite their abundance in the Haverhill quadrangle, commercial pegmatite deposits have not been worked to date.

Discussion of the Hillsboro plutonic series

Field data, variation diagrams based on chemical analyses (fig. 30, p. 96), the trace element distribution (fig. 31, p. 198; fig. 33, p. 109), indicate that the igneous rocks described above belong to a related magma series and were emplaced as late syntectonic and post-tectonic igneous events.

Two-mica granite: In southeastern New England the Hillsboro plutonic series is so complex that no single model appears adequate to account for its origin and evolution. Two-mica granites, for example, are found in relatively large plutons with similar physical and chemical properties. One, however, is extremely deformed and dynamically metamorphosed; the other plutons are massive. In the Haverhill quadrangle, the foliated granites occur in the northwestern half and are associated with intensely deformed metasedimentary country rock. The massive granites, on the other hand, crop out in areas to the southeast and are associated with less deformed metasedimentary rocks of a lower metamorphic rank. This relationship suggests that deformation may be due to either of the following: (a) all the granites in the Hillsboro plutonic series were emplaced at essentially the same time but, because of their geographi-

[3]The aplite occurrence may be a result of a "dry" period during the various stages of intrusion. No micaceous minerals are present except for some chlorite as an alteration product of almandine (Jahns, 1955, p. 1102).

cal position with respect to variations in the intensity of deformation during tectonism, they were not deformed to the same degree; or (b) the granites were emplaced at significantly different times and the earlier became foliated due to subsequent tectonism whereas the later granite was emplaced after tectonism ceased. The latter explanation does not appear to conform with the available evidence because the metamorphic rocks are likewise less deformed in the area of the essentially massive granites.

Sweepstake diorite pluton: The Sweepstake diorite pluton in Salem, New Hampshire is small and well enough exposed so that a model can be proposed to account for the foliated and massive textures of the rocks. Figure 22-A shows the original intrusion of biotite-rich[4] diorite (Phase I). Numerous xenoliths suggest that the roof of the instrusion was nearby. Emplacement occurred during tectonism which continued deforming both the diorite and host metasediments (fig. 22-B). Upon cessation of deformation, hornblende-rich diorite (Phase II) was emplaced (fig. 22-B) followed by a norite (fig. 22-C). Subsequently small pegmatite dikes and sulfide veins were emplaced (fig. 22-D). These latest intrusives are difficult to correlate with either the Hillsboro plutonic series or the White Mountain plutonic-volcanic series.

Metadiorite: Several outcrops of garnetiferous diorite occur in Hampstead and Danville townships. They were classified in the field as quartz-biotite-garnet schists, but thin section study revealed a typical diorite mineral assemblage which included zoned and twinned plagioclase. The results of both common and trace element analyses of these rocks are very close to results from the Island Pond and Exeter diorites. It seems, therefore, that they should be considered as diorites in the Hillsboro plutonic series that underwent a form of autometamorphism. They occur in small intrusive bodies and are not shown on the geologic map of the quadrangle.

Petrogenesis: Both fractional crystallization and partial melting were considered as models to explain the sequence of intrusion and the distribution of the rocks of the Hillsboro plutonic series in southeastern New Hampshire (fig. 11, p. 33). Fractional crystallization of a "parent magma" produces a continuous series of rocks such that the residual melt of the last rocks to be emplaced are granitic in composition. This sequence is contrary to the field evidence. The most deformed rocks are granites and the least deformed are diorites and norites. Also the more basic rocks intrude the acidic rocks in

[4]The biotite may be secondary, an alteration product of primary amphibole subjected to tectonic stresses in a relatively high P_{H_2O} environment.

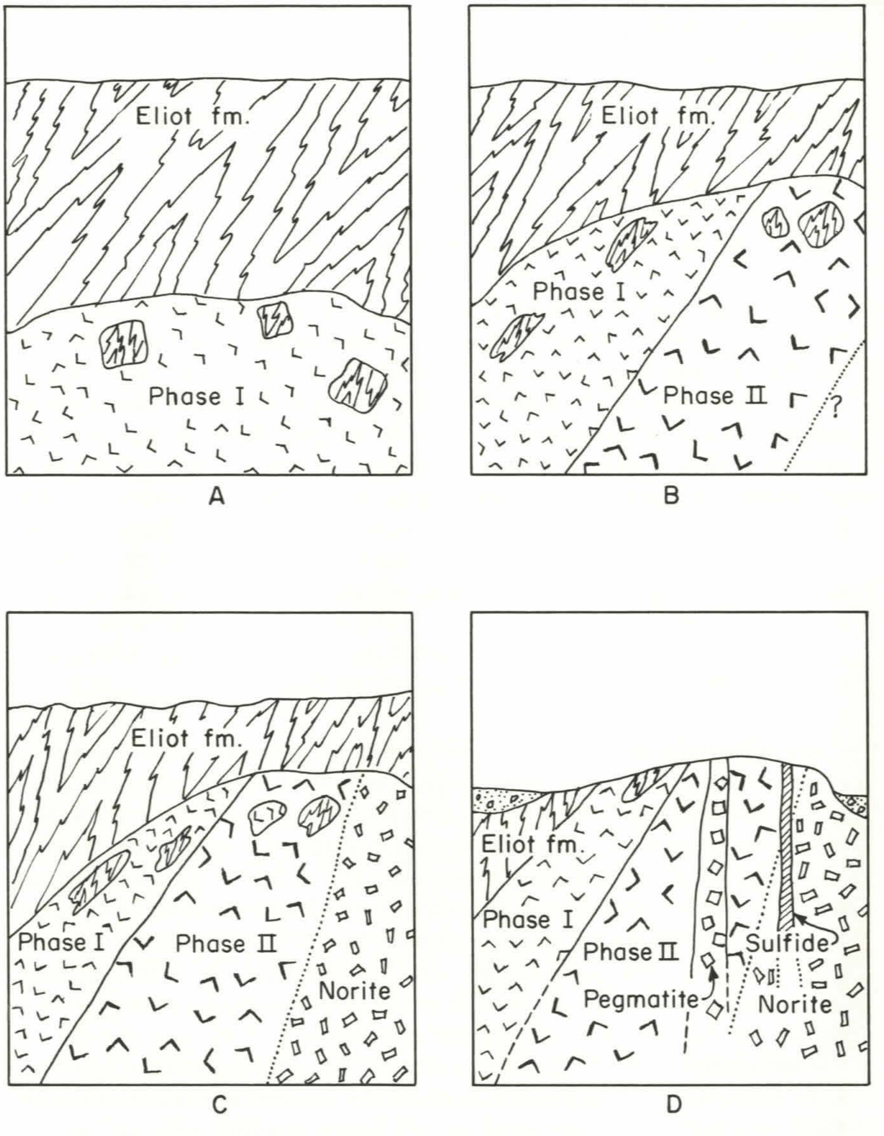

Figure 22. A modal showing series of events in the emplacement of rocks in the Tombstone diorite pluton.
A. Emplacement of biotite-rich diorite (Phase I).
B. Deformation of diorite, xenoliths, and Eliot fm. host rock followed by emplacement of massive hornblende diorite (Phase II).
C. Post-tectonic emplacement of hornblende diorite (Phase II) and norite.
D. Latest events are intrusion of pegmatite and sulfide veins, and erosion of all rock types to present day surface.

the Island Pond and the Sweepstake diorite plutons.

In contrast, partial melting produces melts of granitic composition first during tectonism. Then as the temperature increases, melts from the "de-silicated" source, relatively more basic in composition are emplaced. Finally, when temperature and pressure conditions are sufficiently high, the melts which formed the norites and gabbros are generated and emplaced.

The partial melting model also gives a reasonable explanation for the relatively large amount of granitic rocks compared to the more basic rocks. The source rock may have been crustal material (as opposed to upper mantle) and therefore would have enough silica to produce the granite.

The pegmatites are considered by-products during all stages of the plutonic activity and probably continued to be emplaced throughout the entire plutonic period. They appear to represent pockets of higher volatile content which may have been squeezed out into available spaces at any stage during the crystallization of the plutonic rocks. The presence of both highly deformed and massive pegmatites in the area supports this concept of their position in the paragenetic sequence.

White Mountain plutonic-volcanic series

The White Mountain plutonic-volcanic series (Billings, 1956, p. 69) crops out throughout the state and northern New England. It consists of plutonic and hypabyssal massive rocks ranging from gabbro and diabase to granite and rhyolite. Foliation and banding are lacking. In the Haverhill quadrangle only the hypabyssal rocks are present. They consist of a diabase dike, granitic intrusives, and numerous camptonite dikes. Because there are no criteria present in the Haverhill quadrangle, such as degree of deformation or crosscutting relationships, the sequence of intrusion for these rocks has not been determined.

Camptonite

The distribution of camptonite dikes in the Haverhill 15' quadrangle is shown in Plate I. The trend of the dikes is essentially parallel to the strike of the regional foliation. The dips of the dikes rarely coincide with the foliation of the host rock; most dip steeply (45° - 90°) to the northwest. The thickness of the dikes ranges from less than an inch to about five feet; their length is difficult to determine due to the soil cover, although the writer was able to follow the largest dike (sample no. 132, Plaistow, N.H.) for about 1,200 feet. All of the camptonite bodies have chill margins but the host rock has not been markedly altered.

Megascopically, the camptonite is dark greenish-black to black and weathers to a medium reddish-brown to grayish-brown. The rock generally is aphanitic to fine-grained phaneritic with a few specimens exhibiting a porphyritic texture. Stubby, black augite crystals up to 4 mm across, and white euhedral to subhedral plagioclase crystals up to 15 mm across comprise the majority of phenocrysts. The groundmass minerals are too small to recognize with the unaided eye.

Microscopically, the camptonite is holocrystalline, and ranges from hypidiomorphic granular to trachytoid to ophitic in texture. The essential minerals are plagioclase, titanaugite, and possibly oxyhornblende. The fine-grained groundmass (from submicroscopic to 0.4 mm) is composed primarily of andesine-labradorite, titanaugite, oxyhornblende, and magnetite.

Plagioclase composition varies in rocks from different locations, but all within the limits An(30-60). The small laths in the groundmass of the thin dikes have a lower anorthite content than the phenocrysts in the thicker dikes. In some samples, the plagioclase is nearly completely altered to sericite with some epidote and calcite. The plagioclase phenocrysts An(40-60) exhibit albite-Carlsbad and pericline twinning. Inclusions other than alteration products are rare. In the groundmass, plagioclase An(30-50) occurs as laths and the albite-Carlsbad twinning is distinct.

Titanaugite is pleochroic in light to medium pink. It is seen as both euhedral phenocrysts up to 4 mm across and as subhedral to anhedral matrix crystals ranging in size from 0.05 to 0.4 mm across. Zoning and twinning are common, especially in the larger crystals. It alters to serpentine and-or oxyhornblende. Also, magnetite, biotite, and chlorite surround ragged relicts of augite.

Oxyhornblende is present in varying amounts.[5] It is most commonly seen as an alteration product in association with titanaugite and magnetite. It is intensely pleochroic in medium to dark brown. Euhedral crystals are rare and the oxyhornblende is usually seen as subhedral laths constituting part of the groundmass mineralogy. The oxyhornblende alters to biotite and chlorite.

Magnetite or ilmeno-magnetite is present as both primary and secondary phases. The primary phases are usually larger (up to 1.5 mm) and euhedral to subhedral in form. The secondary minerals

[5]Although they are similar optically, the possibility of this brown amphibole being barkevikite is discredited for two reasons. First, oxyhornblende has a high Fe^{+3} content whereas barkevikite contains primarily Fe^{+2}. Magnetite, $FeFe_2O_4$ is present in significantamounts and it can be concluded that the availability of Fe^{+3} is adequate formation of oxyhornblende. Secondly, barkevikite is characterized by a low SiO_2 content (Heinrich, 1965, p. 266). The camptonites have to be considered a silica saturated rock because of the lack of feldspathoids and the occasional presence of quartz. Therefore, there should be adequate silica for the formation of oxyhornblende.

are smaller and probably more abundant. They appear as small anhedral clusters (0.05-0.1mm) and are usually altered in turn to limonite and-or leucoxene.

The accessory minerals include serpentine, chlorite, biotite, sericite, calcite, epidote, apatite, and pyrite. Serpentine is seen as a medium yellowish- to bluish-green fibrous replacement mineral. Outlines of the large phenocrysts of titanaugite are often completely filled with serpentine. Other titanaugite phenocrysts exhibit highly altered zones along cleavage or parting planes. Chlorite is the alteration product of biotite and oxyhornblende, is pleochroic in light to medium bluish-green and has an anomalous brown interference color. Biotite appears as the product of a reaction between titanaugite and magnetite because it is usually seen in contact with those two minerals. It is pleochroic in light to dark brown and alters to chlorite. Sericite is the alteration product of andesine and labradorite. Calcite and epidote are also present as alteration products of the plagioclase minerals but in lesser amounts. Apatite is ubiquitous but not abundant. It appears as tiny inclusions in plagioclase and also as small, independent prisms in the matrix. Pyrite, when present, appears as both perfect cubes and as massive anhedral clots up to several millimeters across.

The estimated modal analysis of several of the rocks representative of the camptonites is given in Table 9, (p. 77).

Diabase

A large diabase dike crosses the Raymond-Chester townline in the northwestern corner of the Haverhill 15' quadrangle. It strikes north to N. 25° E. and dips steeply at about 60° to the west. It is 50 to 60 feet wide and can be traced for about three-quarters of a mile before it disappears beneath the soil cover. In the northwestern part of the quadrangle it intrudes both the Berwick formation discordantly and the large intensely deformed two-mica granite pluton (pl. 2).

Megascopically, the diabase resembles the camptonite; it is greenish-black to black in color and ranges from aphanitic to fine-grained phaneritic. The only commonly occurring mineral recognizable in the hand specimen is augite which occurs as small, black stubby crystals up to 4 mm across. Occasionally, labradorite crystals are large enough to be seen but they rarely exceed 2 mm in length. Outcrops in which the contact with the host rock are best shown are along the northern end of the dike where it intrudes the foliated two-mica granite which appears unaltered, despite the fact that a chill zone is apparent in the dike.

Microscopically the rock is holocrystalline and the texture varies from hypidiomorphic granular to porphyritic and the contact chill zone shows a porphyritic texture (the two-mica granite does show substantial hydrothermal alteration of biotite to chlorite and oligoclase to sericite, calcite, and clay minerals). The essential minerals are augite and labradorite. Augite is anhedral, pale pinkish-brown and non-pleochroic. It occurs as both phenocrysts and fine-grained matrix, and poikiolitically includes labradorite. Zoning and simple twinning are common. Alteration products are biotite, magnetite and serpentine.

The plagioclase is labradorite An(50-65). The phenocrysts usually have a higher anorthite content than the finer grained matrix crystals. Labradorite is euhedral to subhedral in form, exhibits continuous zoning with a change in anorthite content from core to rim of -9 to -11 per cent, and is twinned according to the albite-Carlsbad and pericline twin laws. The labradorite is usually clear and unaltered. Saussuritization, although present, is not common.

Accessory minerals include biotite, magnetite, serpentine, chlorite, pyrite, and apatite. Biotite, magnetite, and serpentine are commonly seen in association with anhedral augite and are considered as alteration products. Biotite is pleochroic in light to medium brown. Magnetite usually occurs as massive anhedral clots and is considered to be an alteration product when in this form. To a much lesser extent, it occurs in euhedral form and is then presumed to be a primary accessory mineral. Serpentine is pale yellowish-green, has a fibrous texture, occurs with a reddish-brown stain (presumably limonite), and is seen around the rim and cleavages of augite. Chlorite is pleochroic in pale to medium green and is the alteration product of biotite. Pyrite is present in the coarser grained portion of the dike and occurs as small cubic crystals which are sometimes rimmed with deep red hematite. Apatite is detected in trace elements only in the coarser grained samples.

Other elements of petrographic interest are myrmekitic texture in the coarser grained samples and the diabase-rock-fragment "phenocrysts" in the porphyritic phase near the chill zone.

The diabase is treated as a separate rock unit because (a) the anorthite content of the plagioclase is higher in the diabase and the augite is not the pink titaniferous variety common to the camptonite, and (b) the diabase has only a minor amount of biotite and hornblende present (and only along the chill zone) whereas these minerals often constitute a major portion of the camptonite, and (c) the structural orientation of the diabase dike is independent of the regional trend of the foliation whereas the camptonite dikes usually strike parallel to the trend of the regional structure.

Riebeckite granite

The reibeckite granite intrusives are located in the southeastern corner of the Haverhill 15' quadrangle; one at Bugsmouth Hill on the townline of Newton and South Hampton about 200 feet south of Chase Road, the other on and to the west of Route 108 in the extreme southeastern corner of Plaistow township less than half a mile from the Massachusetts stateline. The Bugsmouth Hill riebeckite granite was first mentioned by Illsley (1934) and referred to by Dennen (1943, p. 31-32). Billings (1956, p. 75) refers to the body as a syenite and it is so designated on the state geologic map. The best outcrops were Bugsmouth Hill which essentially is the topographic manifestation of the intrusive body itself. The northern end of the intrusive may have been quarried at one time for crushed stone or hard fill. The entire body is heavily fractured and jointed. Unfractured specimens larger than a common brick are difficult to find. The joint surfaces are stained with a submetallic bluish-black mineral, probably psilomelane because dendrites are common in the rock.

Megascopically, the rock is a light gray and weathers to a light brown. It is very fine grained with some well-formed phenocrysts (2-5 mm across). The only minerals identifiable in hand specimen are the orthoclase phenocrysts.

In thin section it is holocrystalline and hypidiomorphic granular in texture. The essential minerals which make up the matrix are orthoclase, quartz, oligoclase, and riebeckite. The matrix is generally clouded with alteration products such as sericite and clay. Orthoclase occurs primarily as a fine grained mineral in the matrix and also as phenocrysts. The phenocrysts are usually clear and unaltered. Both the matrix and phenocrysts exhibit Carlsbad twinning. Some of the orthoclase has been replaced by an extremely fine grained mineral mass that looks like chalcedony. Quartz is present as both an interstitial primary mineral and a secondary replacement mineral. The plagioclase is andesine, An(12-17), exhibits albite-Carlsbad twinning and is partially altered to sericite and clay. The only primary mafic mineral present is riebeckite. It occurs as elongate, ragged subhedral prisms, and is pleochroic from medium brownish-green to deep greenish-blue and black.

Accessory minerals are sericite, limonite, and cristobalite. Sericite and limonite are alteration minerals of the feldspars and riebeckite, respectively, and are seen as tiny sericite blades and as limonite stain. Cristobalite is a secondary mineral replacing orthoclase and appears as an ultrafine-grained mass.

The composition of the intrusive along Route 108 in Plaistow resembles that of the Bugsmouth Hill intrusive. The microscopic textures, however, are different; the Bugsmouth Hill texture is massive, whereas the intrusive along Route 108 has a fluxion structure due to the alignment of the feldspar laths.

Although Billings (1956, p. 75) has referred to the more acid rocks of this series as syenites, the chemical composition and katanorms (tables 13 and 14, pl. 5), and modal analysis (table 9, p. 77) of these rocks in the Haverhill 15' quadrangle indicate that granite is a more appropriate classification.

The estimated modal analysis of the Bugsmouth Hill riebeckite granite and other rocks in the White Mountain plutonic-volcanic series is given in Table 9. (p. 118).

Summary

The relatively fine grained and undeformed nature along with the hypabyssal character of the rocks described above, clearly distinguishes them from the coarser grained and often highly deformed plutonic rocks of the Hillsboro plutonic series. These two intrusive series differ appreciably in both time and depth of emplacement. Isotope geochronology should confirm this view which is held by researchers familiar with the geology of this part of New England.

Table 9

ESTIMATED MODAL ANALYSIS OF ROCKS FROM

THE WHITE MOUNTAIN PLUTONIC-VOLCANIC SERIES

SAMPLE NO.	5	132-B	18*	104*
Quartz	--	--	--	13
Plagioclase	25	20	30	10
% Anorthite	(25-35)	(30-44)	(55-62)	(12-17)
Granophyre	--	--	7	2
Orthoclase	--	--	--	60
Augite	5	30	50	--
Oxyhornblende	47	tr	--	--
Riebeckite	--	--	--	10
Biotite	--	5	tr	--
Chlorite	2	tr	tr	--
Epidote	--	tr	8	tr
Sericite	tr	tr	tr	3
Magnetite	--	--	5	--
Ilmenomagnetite	15	15	--	--
Pyrite	--	tr	--	--
Apatite	1	tr	tr	tr
Carbonate	tr	--	--	tr
Serpentine	tr	tr	tr	--
PHENOCRYSTS				
Plagioclase	--	20	--	--
% Anorthite	--	(37-47)	--	--
Orthoclase	--	--	--	2
Augite	2	10	tr	--
Oxyhornblende	3	--	--	--
GROUNDMASS SIZE (mm)	(0.05-0.5)	(0.05-1.5)	(0.05-0.4)	(0.03-0.4)
PHENOCRYSTS SIZE (mm)	(0.7-1.5)	(2-15)	(1.0-2.0)	(2-4)

TYPE AND FIELD LOCATION OF ROCKS LISTED IN TABLE 9

SAMPLE NO.	ROCK TYPE	LOCATION
5	camptonite	Ledge Road, 2,500 feet south of Lane Road on west edge of quadrangle, Chester, N. H. (pl. 2).
132-B	camptonite	Hill between Old Kingston Road and Route 125, 500 feet south of Kingston-Plaistow townline, Plaistow, N. H.
18*	diabase	Old woods road in foliated two-mica granite, 300 feet north of Chester-Raymond townline, Raymond, N. H.
104*	riebeckite granite	Bugsmouth Hill, 200 feet south of Chase Road, South Hampton, N. H.

* Chemical and rare-earth analyses, Tables 13 (pl. 5) and 21 (pl. 7)

Chapter 5 Structure

General statement

The Haverhill 15' quadrangle is located on the crest of the Rockingham anticlinorium. The strike of the dominant foliation, here and elsewhere in southeastern New Hampshire, is northeast-southwest and coincides with the axial trace of this structure. The orientation of lineation and foliation in the intrusive bodies of the Hillsboro plutonic series is also generally parallel to the regional structural trend. Small folds, lineations, and joints are common throughout the quadrangle.

Three planar elements used for structural analysis are recognized: S_1, compositional banding which may be the same as bedding; S_2, foliation by mineral orientation within and parallel to S_1; S_3, foliation by mineral orientation parallel to the axial planes of mesoscopic folds and not necessarily parallel to S_1 or S_2. S_2 is thought to be caused by an early period of regional or load metamorphism. S^3 is considered a product of a later stage of tectonism occurring primarily in the northwestern portion of the quadrangle. S^3 foliation may have formed synchronously with the earlier stages of the Hillsboro plutonic series.

The major deformation in New Hampshire occurred in Middle to Late Devonian time during the Acadian orogeny (Bilings, 1956, p. 108). Foliation and lineation is some rocks, and the massive texture of other rocks of the Hillsboro plutonic series are evidence that intrusive bodies were emplaced during the latest stages of the orogeny and others following the orogeny.

Inferential evidence of faulting, such as silicified zones and mylonite dikes, is present in the Haverhill 15' quadrangle. The data are neither consistent nor extensive enough, however, to define the extent, orientation, and relative movement of these faults.

A summary of the macroscopic structure in southeastern New Hampshire is given in Figure 23, page 80, and a synoptic diagram of poles to foliation is shown in Figure 81, page 124.

Macroscopic structures[1]

Rockingham anticlinorium

The major large-scale structure in the Haverhill quadrangle is the crest of the northeast-southwest-trending Rockingham anticlinorium (Billings, 1955). The interpretation of this structure is based primarily on stratigraphic relationships in the neighboring quadrangles (Meyers, 1940; Freedman, 1950; Sriramadas, 1966; Novotny, 1963). The sequence starts with the Kittery formation in the Dover quadrangle (Novotny, 1963, map) and is succeeded to the northwest by the progressively younger Eliot, Berwick, and Littleton formations. This sequence represents the northwestern flank of the Rockingham anticlinorium. Only the Eliot and Berwick formations are present in the Haverhill quadrangle (pl. 1; fig. 5-B, p. 15). Also, the Littleton formation overlies the Berwick formation in the Manchester quadrangle (Sriramadas, 1966, map) and the Suncook quadrangle (Billings, 1955).

A similar stratigraphic sequence characterizes the southeastern flank of the anticlinorium except that the stratigraphic section is not as complete; the Eliot formation is the youngest unit exposed. The Kittery formation reappears southeast of the Eliot formation and the Eliot syncline is defined.

The outcrop pattern of the formations above in the Manchester, Dover, and Exeter quadrangles indicates a southwest plunge for these large folds.

The Rockingham anticlinorium is believed to extend into the Haverhill quadrangle because (a) the Berwick formation in the northwestern corner is in contact with the older Eliot formation exposed in the central and southeastern portion of the quadrangle, (b) the Eliot formation is present along both sides of the inferred trace of the fold axis, and (c) the series of exposures of the phyllitic facies (p. 26) suggests a continuous marker bed in the Eliot formation and, if this interpretation of the limited outcrop data is correct, the map configuration of this member indicates a major anticlinal fold plunging to the southwest.

The consistent northeast-southwest strike of the foliation in the Haverhill quadrangle is evidence which appears to contradict the presence of a major fold. If the hinge of the southwesterly plunging Rockingham anticlinorium is in the Haverhill quadrangle, one would expect a change in the strike and dip of the foliation from the northwest flank across the axial trace to the southeast flank. There is no

[1]Macroscopic scale: covering bodies too large or too poorly exposed to be examined directly in their entirety. Such bodies are observed indirectly by extrapolation from and synthesis of smaller structures. Macroscopic structures range in size from groups of isolated exposures to the largest mappable bodies (Turner & Weiss, 1963, p. 16).

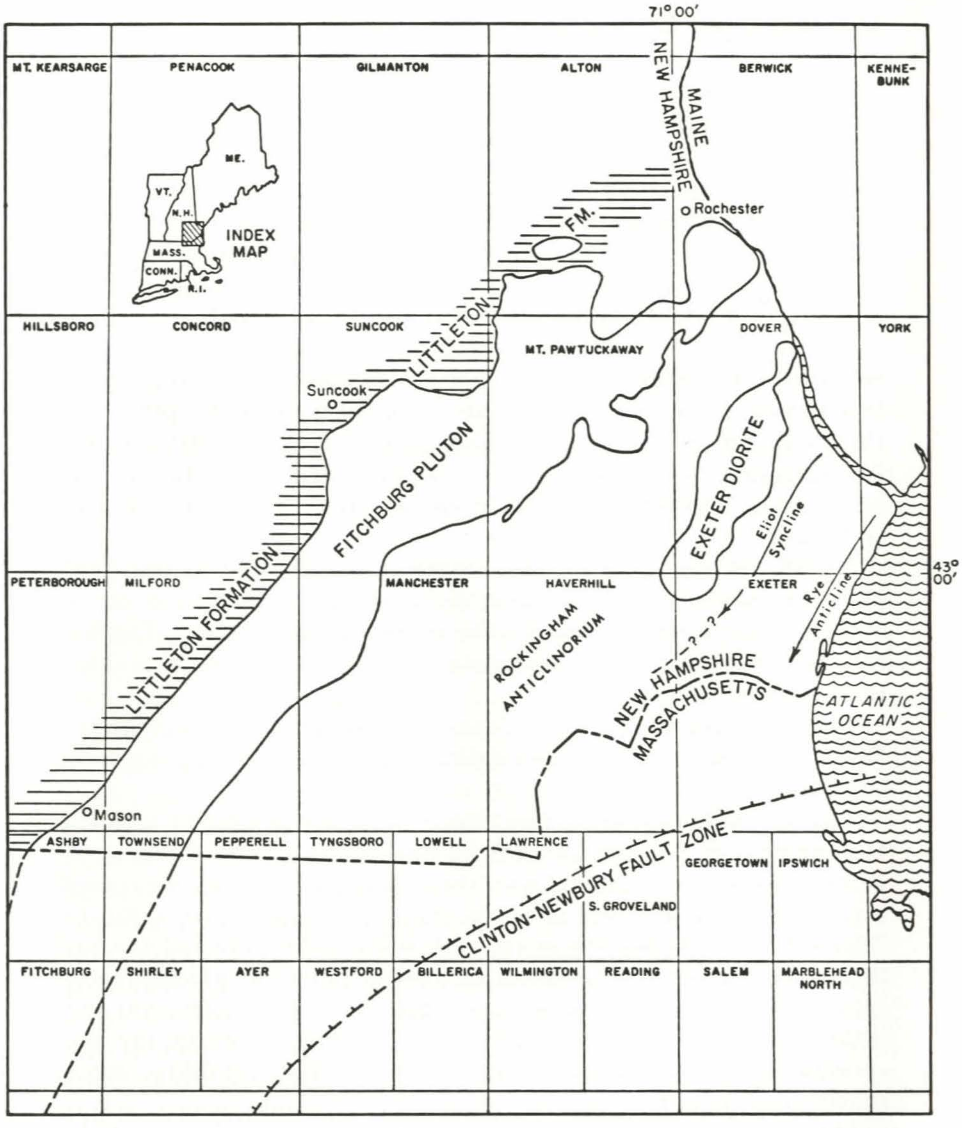

Figure 23. Major structures in the Haverhill 15' quadrangle and in southeastern New Hampshire (Billings, 1955).

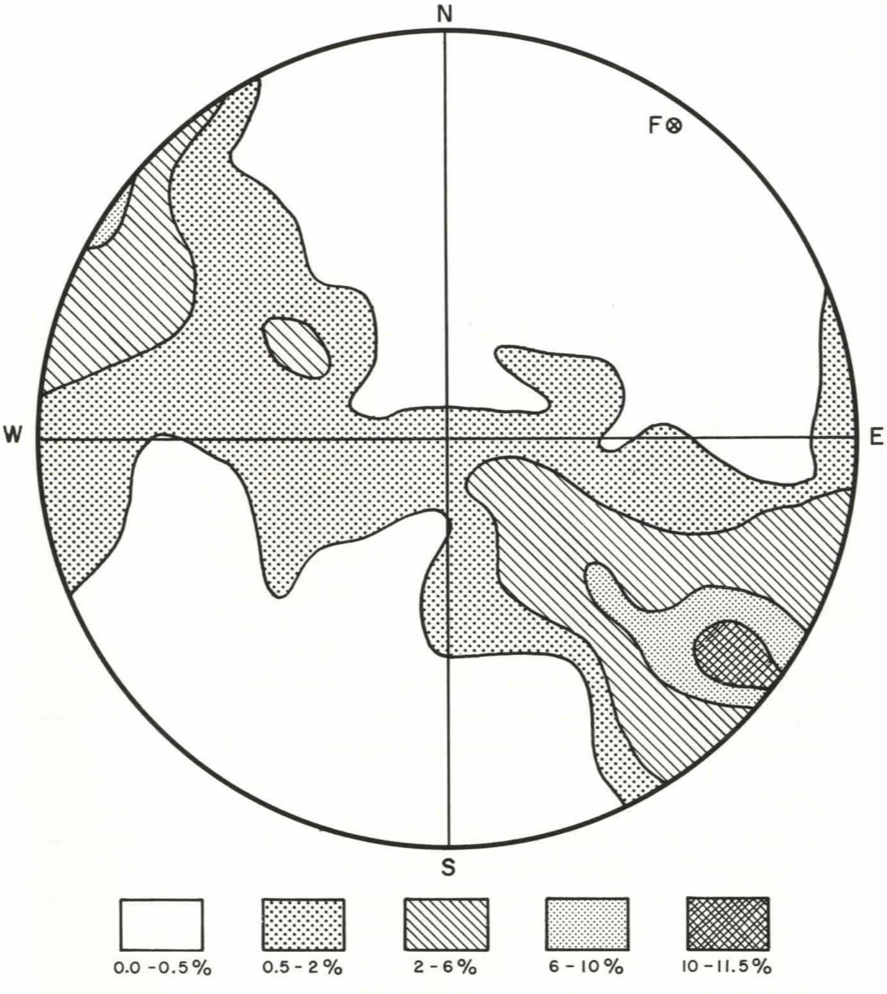

Figure 24. Synoptic diagram of poles to foliation in the Haverhill 15' quadrangle, southeastern New Hampshire (175 readings). Poles to S_1, S_2, and S_3 form a nearly vertical plane striking NW-SE. The pole (F) normal to this vertical plane trends N. 36° E. and plunges 4° NE.

such change in the strike of the foliation anywhere in the Haverhill 15' quadrangle (pl. 1).

In order to account for the data, the writer suggests that the structure occurred in two stages. The first stage produced the broad, open fold systems (S_1 and S_2 were folded) as described by the stratigraphy. Superimposed upon these major, macroscopic southwesterly plunging fold systems was a set of smaller folds and other tectonic elements which are the product of a later, more intense period of tectonism. Tight, isoclinal folds with foliation parallel to fold axial planes (S_3) superimposed on the major fold would account for the trend of the foliation.

Eliot syncline

If the axis of the Eliot syncline is projected southwestward from the Dover and Exeter quadrangles into the Haverhill quadrangle it coincides closely with the axis of a large elongated exposure of phyllite in East Kingston and Newton (pl. 1). Billings noted this (1956, p. 112) and also speculated on the possibility that the phyllite may be part of a northwestward continuation of the Worcester phyllite (Carboniferous ?) from north-central Massachusetts. If so, the phyllite rests unconformably on the Merrimack group (Eliot formation) and is downfolded in a small syncline (Billings, 1956, page 102).

Mesoscopic structures[2]

Structural elements on the mesoscopic scale in the Haverhill 15' quadrangle include minor folds, lineations, foliations, and joints. Each of these will be discussed separately, and then the manner in which they are interrelated will be given in a summary statement.

Foliation

Lenses of calc-silicate rock and compositional banding are usually oriented parallel to the schistosity of the metasedimentary rocks. The term "bedding schistosity" has been applied to describe this type of relationship between bedding and schistosity (Sriramadas, 1966, p. 39). The term is misleading because it tends to equate all types of foliation to bedding. Isoclinal folding of S_1 and S_2 is common in the northwestern half of the Haverhill 15' quadrangle. To what degree macroscopic folding of S_1 and S_2 foliation occurs is undetermined. Therefore, structural and stratigraphic sections based on "bedding schistosity" alone are not reliable.

In the following section on folding, the truncation of folds by slip cleavage is described. It is important to note that the S_3 foliation

[2]Mesoscopic scale . . . . . . bodies that can be effectively studied in three dimensions by direct observation (with or without a low-power hand lens). They range from hand specimens to large but continuous exposures (Turner & Weiss, 1963, pp. 15-16).

as determined by the planar and parallel orientation of the biotite flakes is parallel to the fold axial planes and is not parallel to the folded compositional bands (S_1) especially in the area of the fold nose (fig. 25). Where axial plane foliation (S_3) is pervasive in both macroscopic and microscopic domains, the schistosity and foliation is not controlled by bedding (S_1), but is the result of recrystallization and reorientation of platy minerals in response to the stress applied during the later major tectonic event.

Foliation parallel to bedding (S_2) is predominant in the southeastern half of the quadrangle whereas axial plane foliation (S_3) is a significant structural element in the northwestern half of the quadrangle. Axial plane foliation (S_3) appears to increase with an increase in metamorphic rank and igneous activity.

An excellent example of the change in foliation-compositional layering relationship is seen in an extensive outcrop along Route 101, West Epping in the Mt. Pawtuckaway quadrangle. Gentle, open folds of S_1 and S_2 foliation are present on the western edge of the 600 foot outcrop. The axial plane of these folds dips steeply to the west (fig. 25-A). In the center of the outcrop the folds are fractured and broken. At the eastern end of the outcrop, the foliation (S_3) is nearly vertical. The compositional bands (S_1) are torturously folded and broken (fig. 25-C), the axial planes of the relict folds are nearly vertical and parallel to the foliation (fig. 25-B) and the foliation is no longer consistently parallel to the compositional layering (S_1).

A sequence of events in the development of the structure in the area of the outcrop is suggested from field observations.

The layers (S_1) were originally horizontal and were effected by vertical stress. The compositional layering (S_1) or bedding (?) is considered a primary planar structural element. The pervasive foliation due to the parallel arrangement of micaceous minerals which developed parallel to S_1 during regional or load metamorphism is designated S_2 because it is a planar structural element younger than S_1.

During a later stage of the same tectonic period the direction of the major stress changed from nearly vertical to nearly horizontal and was directed from northwest to southeast. This stress field produced the folds in S_1 and S_2 that are present in the northwestern part of the region. Although folding relieved some of the stress, the rock ruptured and moved along cleavage planes (S_3) parallel to the fold axial plane. Movement of rock in the plane parallel to the fold axial plane had both vertical and horizontal components. The horizontal component was in a direction parallel to the regional structural trend as described by the present foliation and lineation (fig. 24, p. 81). The vertical component of the movement is described in Figure 26, page 86.

A B C

Figure 25. Transition from S_2 to S_3 foliation in the Eliot formation. The outcrop is located half a mile east of the Lamprey River, West Epping, New Hampshire.

A. Gentle open folds of foliation (S_2) parallel to compositional banding (S_1) (note steeply dipping axial plane).

B. Dominant (S_3) foliation parallel to axial plane in Figure 26. S_3 is superimposed on S_1 and S_2.

C. Enlargement of small area in Figure 26 showing remnants of isoclinally folded and sheared S_1 and S_2.

Folds

Minor folds are most abundant in the northwestern half of the Haverhill 15' quadrangle. The most commonly observed folds are small, open, similar folds with wave lengths ranging from 2 to 20 cm and amplitudes ranging from 1 to 10 cm. Less common are isoclinal folds. Both the similar and isoclinal folds are found in schists, calc-silicate rock, and in phyllites.

A third type of fold, small crenulations with wave lengths of 5 to 10 mm and amplitudes of 1 to 3 mm, is found primarily in phyllites. A rather complex fold structure is formed in the phyllites where one or more of the folds above are superimposed. The superimposed folds are seen as intersecting crenulations of the same size. Both fold axes are in the plane of the dominant foliation of the phyllite which coincides with the regional foliation. In the Eliot syncline, in East Kingston and Newton, the plane containing-intersecting crenulations of the phyllite has been folded into broad, open similar folds resembling those described above which occur in the schists and calc-silicate rocks.

Folding is found only within small areas. In all of the outcrops of schists and calc-silicates observed by the writer, fold zones seldom are more than one or several folds wide. There is one exception to the previous observation. Crenulation folding is pervasive throughout the domains of all the phyllite members in the Haverhill 15' quadrangle. In some instances, the crenulation folding has developed to resemble kinking (fig. 8, p. 21).

Truncation of folds by slip cleavage (S_3) parallel to the axial plane may be more common than was visibly apparent to the writer. The compositional changes which make folding in the rock visible are subtle, especially in the biotite schists. Therefore, the folding is most readily observed on fresh exposures in the outcrop. The development and subsequent truncation of a fold is illustrated in Figure 26, page 86.

Lineations

Pervasive lineations in rocks of the Haverhill 15' quadrangle are limited to axes of the phyllite crenulations and elongated minerals in the early phase of the Sweepstake diorite and the deformed two-mica granites (fig. 12-A, 12-B, p. 35).

The elongated minerals in the plutonic rocks are parallel to the line perpendicular to the plane formed by poles to foliation in the synoptic diagram (fig. 24, p. 81). This implies that these plutonic rocks were involved in the orogency which produced the planar structural elements in the metamorphic rocks.

Boudinage, a non-pervasive linear element, occurs in the Haverhill

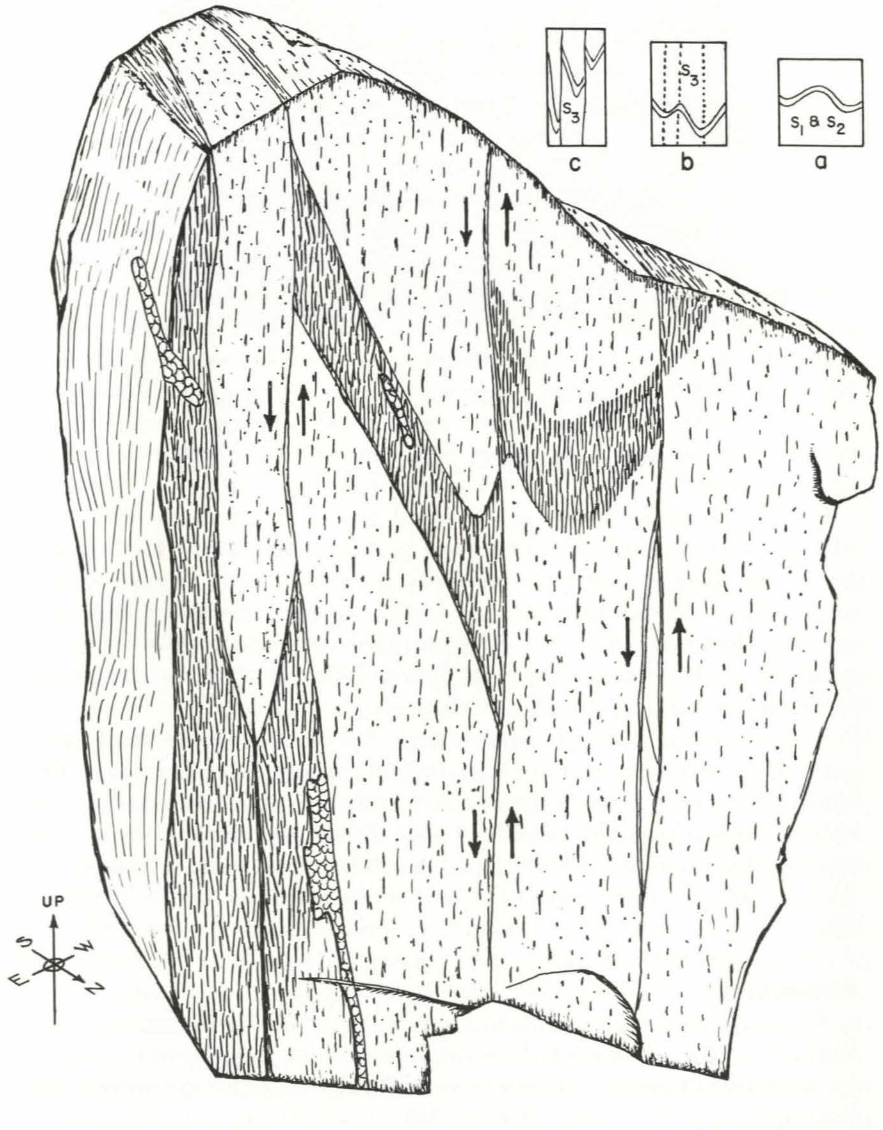

Figure 26. Folding and cleavage in a quartz-biotite-schist. The dark layer is rich in biotite. The light stringers are quartz. The original open folds of S_1 and S_2 (in inset **a**) have been truncated by slippage along cleavage planes (S_3 in inset **c**) parallel to fold axial planes (dotted lines in inset **b**). The outcrop is located on Route 101 east of the Lamprey River, West Epping, New Hampshire. (Scale: approximately 1/3 full size of specimen).

15' quadrangle as small pegmatite bodies. Originally, the pegmatite appears to have been emplaced as a dike. When the host metasedimentary rock responded to stress by ductile flow, the incompetent pegmatite broke into attenuated boudins (fig. 6-A, p. 15). In several outcrops it can be shown that the dike was rotated from its original discordant position to an orientation which is almost concordant with the present foliation.

Faults

A silicified zone about 300 feet long and 50 feet wide was found in the foliated two-mica granite between Lane Road and Route 102 in Chester (pl. 1, 2). It is roughly on a line with a series of silicified zones trending northeast-southwest in the Mt. Pawtuckaway quadrangle and the Manchester quadrangle. These zones are considered to be faults in these quadrangles and are mapped as such (Billings, 1937, p. 526; Freedman, 1950, map; and Sriramadas, 1966, pp. 42-43). Therefore, this silicified zone may be part of an extensive fault system.

An ultramylonite dike was observed by the writer in the southeastern corner of the Haverhill quadrangle (fig. 27). It is less than 10 mm thick, is nearly horizontal, and extends throughout the area of the outcrop. Unfortunately, the writer initially mistook the dike for a small camptonite dike and neglected to record the dip and strike. It is essentially concordant with the foliation, however, which strikes parallel to the regional structure trend and dips gently (23°) to the west.

The ultramylonite has a black, flint-like appearance. In thin section it is very fine grained and is composed of quartz, chlorite and some unidentified opaque mineral.

Outcrops in the southeastern corner of the New Hampshire portion of the Haverhill quadrangle are highly fractured (fig. 28). The fracturing, indicates that this area is in or on the northwestern edge of a fault zone. However, outcrops are too scarce to define the type and location of this fault

Joints

The most common joint set in the metasedimentary rocks of the Haverhill quadrangle is nearly vertical and strikes approximately normal to the regional foliation (fig. 6-B, p. 15).

In the plutonic rocks, two nearly vertical joint sets are seen oriented at approximately right angles to each other. The dominant set is oriented parallel to the joints in the metamorphic rocks and approximately normal to the regional structural trend. The dominant joints in both igneous and metamorphic rocks are spaced 10 cm to 2 meters apart.

Joints in the White Mountain hypabyssal rocks are more closely spaced than either the Hillsboro plutonic or Merrimack metasedimentary rocks. Here the joints occur every 10 to 20 cm, are nearly vertical and mutually perpendicular. The third set is nearly horizontal and could be considered the equivalent to sheeting. One of the major vertical joint sets in the White Mountain hypabyssal rocks is oriented approximately normal to the regional structural trend.

Summary

The interpretations made from the stratigraphic and structural data suggests the following structural history:

1. The metasedimentary rocks involved in the Haverhill quadrangle were deposited during the Silurian (?) period. They were subjected to regional metamorphism probably during Middle Devonian time. The original bedding (S_1) recrystallized forming schistosity (S_2) parallel to the compositional banding. The major stress shifted from vertical to horizontal and folds such as the Rockingham anticlinorium and the Eliot syncline developed.

2. Granite and quartz monzonite of the Hillsboro plutonic series were emplaced in the northwestern portion of both the Haverhill 15' quadrangle and southeastern New Hampshire. The metasedimentary rocks were intensely folded into small, mesoscopic folds whose axes are nearly parallel to the macroscopic fold axes and to the present regional trend. Plutons of the earliest magmas were also subjected to the horizontal stress and responded by flowing which produced elongation of the plutons (note gr in fig. 11, p. 45) and mineral lineations parallel to the present regional structure.

3. When incompetent rocks broke under stress, shearing and slippage occurred along planes parallel to the mesoscopic scale fold axes (S_3). The orientation of the new minerals was parallel to the planes of shear and formed the most recent pervasive structural element (S_3).

4. In the southeastern area which was not intruded by the volatile-rich granitic magmas, the rocks were competent and the deformation by the horizontal stress caused brittle fracturing, brecciation, and possibly thrusting.

5. After the subsidence of the horizontal stress and the intrusion of the Hillsboro magmas, cooling and possibly regional uplift formed a tensional stress which produced the joint systems. The major joint sets are oriented nearly perpendicular to the present regional structural trend.

These events probably began in Middle Devonian and ceased in Late Mississippian, a period of time which coincides approximately with the Acadian orogeny.

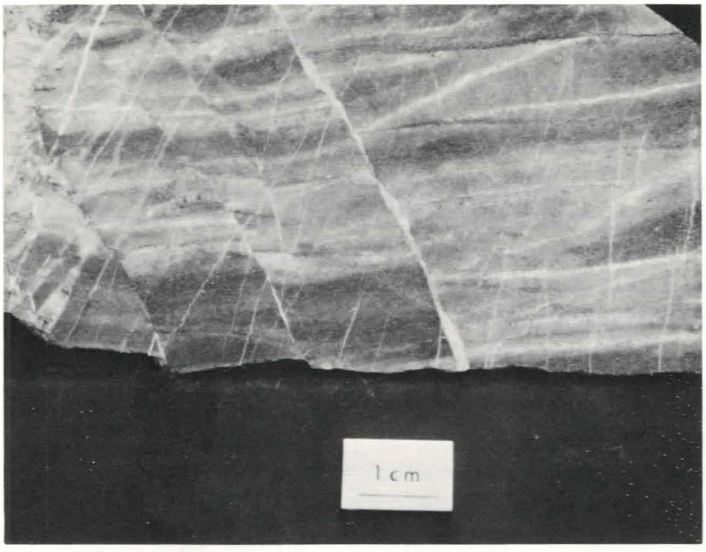

Figure 27. Ultramylonite dike in quartz-biotite-chlorite schist. The outcrop is on the Newton-Plaistow townline north of Sweet Hill.

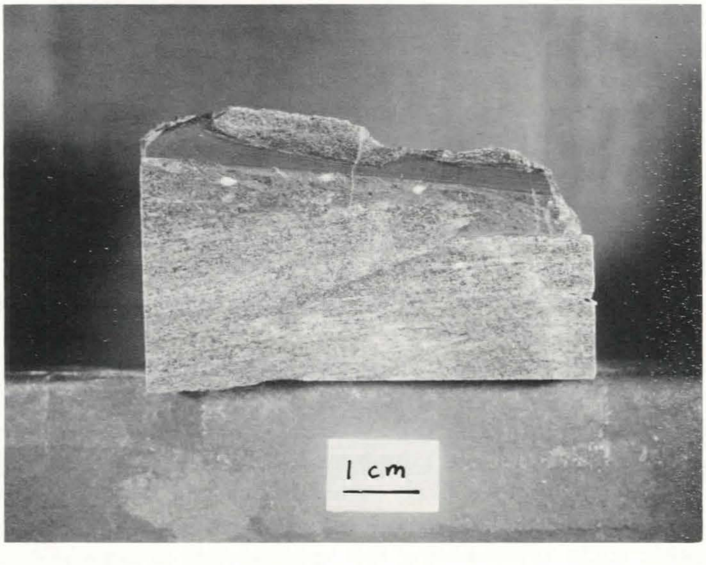

Figure 28. Brittle fracture in fine grained quartz-chlorite-biotite schist. The outcrop is located in the extreme southeastern corner of Plaistow, N. H. on Route 108.

Chapter 6 Geochemistry

Geochemical studies included coventional major and minor element chemical analyses, trace element analyses for strontium and rubidium, qualitative determination of trace amounts of certain metals, and a semi-quantitative determination of seven rare-earth elements and yttrium. The locations of the samples analyzed are shown on a location map and the types of samples are listed in Table 10, plate 5.

Chemical analyses

The samples were selected and prepared for analysis by the author. Determinations of major elements as oxides, CO_2, S, P_2O_5, and free carbon (graphite) are expressed as weight per cent. These and Sr and Rb trace element abundance determinations were made by the Geochemistry Section of the Indiana Geological Survey. The author developed the method for the rare-earth analyses (Sundeen, 1970, p. 185-205).

The results of fifteen whole-rock chemical analyses are tabulated in Tables 11, 13 and 15 (pl. 5). The kataform computations are listed in Tables 12 and 14 (pl. 5). The misonorm computations are listed in Table 16 (pl. 5) for the metamorphic rocks analyzed. The merits and shortcomings of normative calculations will not be discussed in this paper. Barth (1956, 1962) presents a thorough discussion of this subject. AFM and CaNaK plots of the igneous rocks are shown in Figure 29, page 146.

Most of this discussion pertains to the Hillsboro plutonic series although reference is made to the analysis of a metadiorite and two rock analyses from the White Mountain series which are plotted on the variation diagrams.

Although the data plotted on the AFM and CaNaK variation diagrams are limited, the trends (fig. 29, p. 91) are similar to those of other workers studying differentiated rock series (Nockolds and Allen, 1953) and (Reid and Lanphere, 1969). The variation diagrams appear to show the most likely order of differentiation, the granitic rocks representing the composition of the residual end products and the noritic rocks representing the approximate composition of the postulated parent magma.

Two problems remained unsolved by using this interpretation. First,

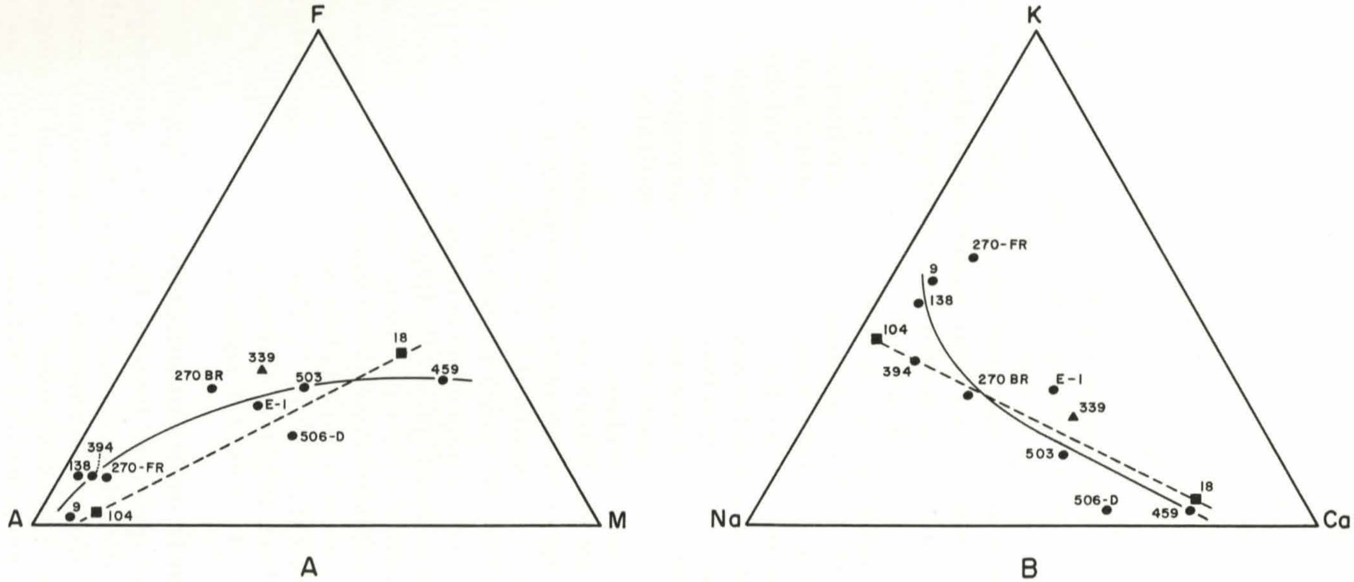

Figure 29. AFM and CaNaK variation diagrams for rocks from the Hillsboro and White Mountain intrusive series. Sample numbers - see Table 10, plate 5 for corresponding rock type. Circle - Hillsboro plutonic series; square - White Mountain plutonic-volcanic series; triangle - metadiorite. Solid line - Hillsboro trend; dashed line - White Mountain trend.

as in most igneous complexes, there is very little rock representing the parent magma relative to the end product differentiate. Secondly, the field evidence indicates that the sequence of intrusion began with granite and was followed by quartz monzonite, diorite and norite.

The AFM and CaNaK variation diagrams show a continuous change in the relative amounts of major elements. Although consistent with a fractionating process, they are consistent also with a partical melting process. The author prefers a partial melting model because it is consistent with both geochemical and field data (see discussion on Hillsboro plutonic series, Petrongenesis, p. 69).

The plotted locations of samples 339, 270-BR, and 270-FR on the variation diagrams require additional explanation. Sample 339 has the mesoscopic properties of a quartz-biotite-garnet schist. However, the microscopic properties, as seen in thin section, are those of a metadiorite. The variation diagram shows that the relative abundance of the major elements in sample 339 is in the same range as that of diorites from the Hillsboro plutonic series. The relative abundances of the rare-earths in sample 339 is strikingly similar to the relative rare-earth abundances in the Exeter and Island Pond diorites. The outcrop from which sample 339 was taken is located roughly on strike between the Exeter and Island Pond diorites (see location map, plate 5). The evidence suggests that the "quartz-biotite-garnet schist" is a diorite related to the Hillsboro plutonic series and had been subjected to a form of autometamorphism.

Samples 270-BR and 270-FR were taken from the same outcrop on the eastern edge of the Island Pond porphyritic quartz monzonite. Both samples have essentially the same physical properties of the Island Pond porphyritic quartz monzonite as described previously (p. 44); however, the samples differ in the amount of biotite present. Therefore, the biotite-rich phase (270-BR), when plotted on the variation diagram, falls in or near the diorite range and the feldspar-rich phase (270-FR) falls within one quartz monzonite and granite range. The relative rare-earth abundances normalized to La =1.0 are practically identical (table 19, pl. 7). The evidence suggests that both samples came from the same magma source but are products of localized differences in mineral segregation.

Trace elements (semi-quantitative analysis)

Seventeen rock specimens from the Haverhill 15' quadrangle have been semi-quantitatively analyzed for 15 trace elements with the use of the optical emission spectrograph. The approximate amount of each of the trace elements present was determined by comparison with simultaneously-processed USGS standard grainte G-1 and standard diabase W-1. The results are tabulated in Table 17 (pl. 6).

The analyses were made to determine if any trace elements appeared consistently in a particular rock type or series. Ba, Cu, Ga, and Y[1] are present in trace amounts (ppm quantities) and Ti is present in minor amounts (0.1 — 3 per cent) in most of the seventeen specimens analyzed. No special significance is given to the presence of these elements because they are commonly found in trace quantities in most igneous and metamorphic rocks.

The presence or absence of Ni in the samples of rock from several sites is significant. For example, an old nickel mine was worked in the Dracut norite (Dennen, 1943), but Ni was detected in only trace amounts in the Dracut norite (sample no. 459). In similar rocks from the same plutonic series, such as the Sweepstake diorite (nos. 503, 506-D) and the Exeter diorite (no. E-1), Ni was not detected. A diorite sample from the contact zone next to a small sulfide vein in the Tombstone diorite (no. 506-B) has a substantial trace quantity of Ni (as well as B, Mn, V, and Cu). This suggests that Ni was not a significant trace constituent of the original intrusives but was introduced later when the nickel-rich deposits were emplaced.

Ni is present in small trace quantities in the phyllites (nos. 85, 110, 458). This result was interesting because the sulfides present in the phyllites have an appearance of pentlandite when observed in thin section using reflected light. However, no chemical data are available on the sulfide mineral phase alone.

Trace elements (quantitative analysis)

Strontium and rubidium abundances were determined quantitatively by X-ray emission spectrometry for 23 rocks from the Haverhill quadrangle. The results are presented in Table 18. The Rb/Sr and K/Rb ratios of eight rocks from the Hillsboro plutonic series are plotted against the Larsen Index (1/3 SiO_2 + K_2O-CaO-MgO-FeO) in Figures 30-A and 30-B and are discussed below.

Rubidium /Strontium

The behavior of strontium in a cogenectic series of rocks is explained by Tauson (1965, p. 228) by comparing their thermochemical properties. According to Tauson, during the formation of solid solutions, the crystalline phase is usually enriched in the components having the higher melting points (CaO has a higher melting point than SrO, 2580°C and 2430°C respectively, at one atmosphere, dry). During the formation of a solid solution of $SrAl_2Si_2O_8$ in $CaAl_2Si_2O_8$, the early crystal fractions might be expected to be richer in calcium while strontium would be relatively enriched in the later plagioclases

[1]Yttrium was also determined quantitatively with the rare-earth elements.

associated with the more silicic rocks.[2] Average Rb/Sr ratios given by Taylor and White (1966) are listed below:
Continental crust

Continental crust	0.23
Basalt	0.056
Granodiorite	0.25
Granite	0.51

In general, the trend of the Rb/Sr ratios shows an increase from the norites to the granites in the Hillsboro plutonic series (fig. 30-A). This is consistent with the trend shown in other rocks that are the products of frational crystallization (Taylor, 1965, and Taylor and White, 1966). Similar results could be expected if these were derived from a fractional (partial) melting process.

Data from pegmatite bodies must be interpreted with caution, especially if the pegmatite is zoned. The pegmatite samples taken from the Sweepstake pluton show an anomalously high set of values of Rb/Sr = 9.0 and 18.0. These results are not surprising because strontium substitutes for calcium in the plagioclase feldspars and the anorthite content of the plagioclase in these zoned pegmatites is low (less than 10 per cent).

The Island Pond pegmatite (no. 262) is unzoned, very coarse grained and composed primarily of pink perthite. This sample was taken from an area adjacent to the host rock, a foliated porphyritic quartz monzonite with microcline phenocrysts. The plagioclase in the pegmatite has an anorthite content of 20 to 30 per cent which provides a greater opportunity for Sr substitution and may in part explain the relatively low Rb/Sr ratio (0.28) compared with the Sweepstake pegmatites.

Potassium/Rubidium

K and Rb are comparable in size (1.33A° and 1.48A°, respectively), charge, electronegativity and ionization potential. The only significant difference is in their size and this property becomes effective in conditions of extreme fractionation, with Rb being slightly concentrated in the later fractions due to the larger radius. According to Taylor (1965, pp. 143-148), the crustal abundance of Rb is about 90 ppm and the average crustal K/Rb ratio is about 230. "Normal" ratios fall within the range of 150 to 350 and ratios definitely outside these limits require special explanations.

The relationship of K/Rb to the Larsen Index in the rocks of the Hillsboro plutonic series show a general trend increasing from the

[2] Ca^{++} is also accepted preferentially into the early-formed crystalline phase because it has a slightly smaller ionic radius than Sr^{++} (0.99A to 1.12Å respectively).

norite to the granites. This trend is reverse to the normal trend shown by rocks that are the products of fractional crystallization as found in other igneous complexes (Taylor, 1965, and Taylor and White, 1966). Except for a marked increase in the zoned Sweepstake pegmatites, the Rb concentration decreases as the rock type becomes more granitic (fig. 30-B). The same general trend is observed in the rocks from the White Mountain plutonic-volcanic series. The writer has no explanation for this anomalous trend.

Trace elements (rare earths and yttrium)

Chemical data of the rare-earth group were obtained for the igneous and metamorphic rocks in the Haverhill 15' quadrangle. The geochemically similar element yttrium was routinely included with the rare-earth analyses. Seven rare earths (La, Ce, Pr, Nd, Sm, Gd, Dy) and yttrium (Y) were quantitatively determined in 17 rocks.

Method

The rare-earth and yttrium oxalates were precipitated and pressed into a pellet after having been concentrated from 10 g of sample. The procedure was monitored for percentage chemical yield by using the radioisotopes Y^{88} and Ce^{139}. X-ray emission spectrography was used to obtain the analytical data from the pellets containing the rare-earth concentrates. The concentration of each of these trace elements was determined from correlation charts (counts per 100 seconds vs. concentration) constructed from standards. A detailed description of the method is given by Sundeen (1970), pages 185 - 205.

Accuracy and precision were poor. Per cent deviation from the mean of a duplicate analysis indicated precision for an individual rare earth averaged ± 22 per cent. Absolute accuracies are very uncertain in that analysis of a rock previously analyzed by neutron activation yields concentrations apparently 75-80 per cent lower. However, the method was relatively rapid (subsequent to initial development) and sufficiently sensitive to detect major trends in lanthanide abundances.

Discussion

A general discussion of the use of rare-earth abundance patterns for geochemical interpretations is given by Coryell, Chase, and Winchester (1963), Haskin, et al. (1966), and Ehrlich (1968). Only a brief résumé will be given here.

The geochemical usefulness of the rare earths is a result of their general similarity but systematic differences in chemical behavior. Except for europium (+2, +3) and cerium (+3, +4), their oxidation states under geological conditions are tripositive; they are also

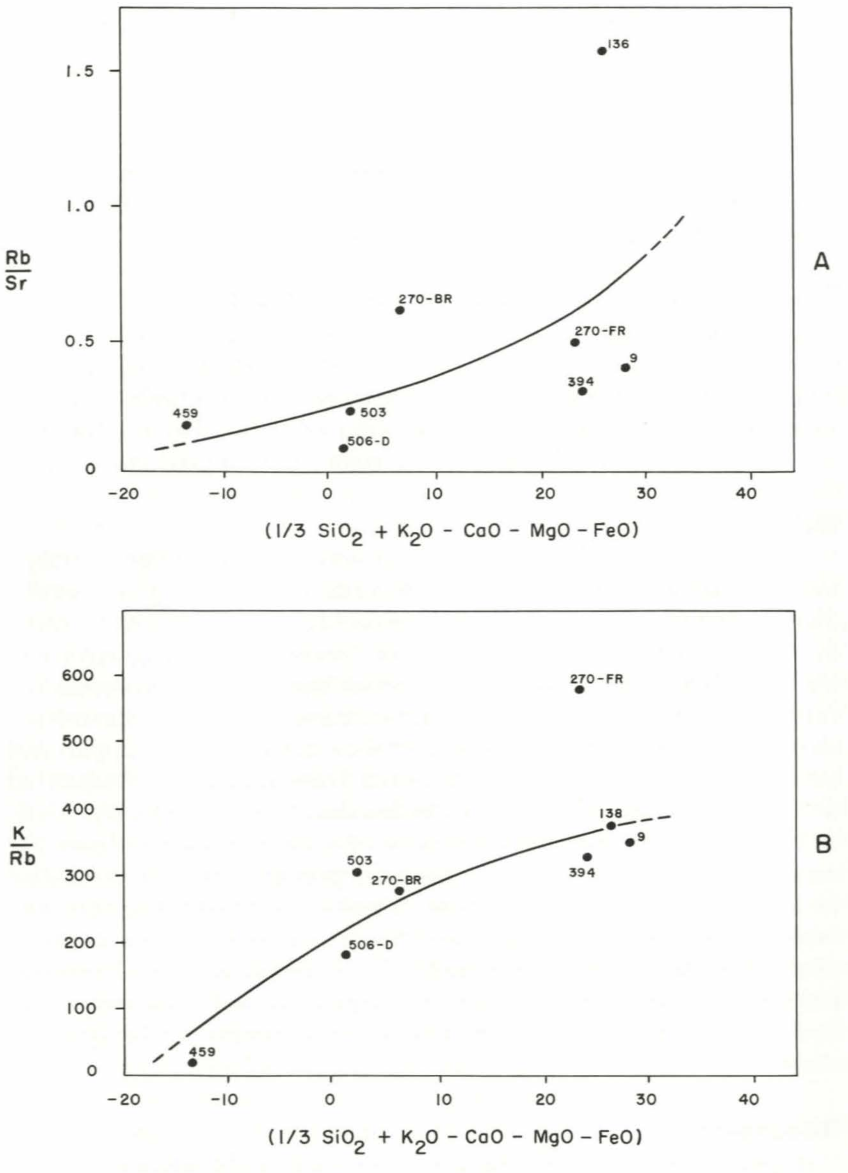

Figure 30. Diagram showing the relationships between rock types, Rb/Sr, and K/Rb from samples of the Hillsboro plutonic series.
A. Larsen Index and Rb/Sr.
B. Larsen Index and K/Rb.

characterized by a gradual decrease in ionic radius with increase in atomic number from lanthanum (r=1.14Å, Z=57) to lutetium (r=0.85Å, Z=71).[3] Therefore, such small systematic differences in the physical and chemical properties from element to element result in regular variations in abundances within the series although the entire series occurs as a group in most materials of geologic interest. Yttrium (r=0.92Å, Z=39) is not a lanthanide but it does have a plus three oxidation state, a similar ionic radius and similar chemical properties. Because the ionic radius of yttrium is approximately the same as that of erbium (r=0.89), it is, for comparitive purposes, plotted in graphical displays at the erbium position with an effective atomic number of 68. According to Towell, et al. (1965), this choice seems to be consistent with the geochemical behavior of yttrium.

Although the rare earths exhibit similar chemical and geochemical properties, their normal absolute abundances display a zigzag pattern plotted against their atomic number (or ionic radii) on a semi-log graph. Figure 31, (p. 98), modified from Towell (1963), strikingly exhibits the Oddo-Harkins rule that the abosolute abundance of an element of even atomic number is greater than that of the elements adjacent having odd atomic numbers. Also, in this figure, the ratio of each of the rare-earth concentrations in the rock sample (Rubidoux Mountain leucogranite) to the corresponding element concentrations in chondritic meteorites (Schmitt and Smith, 1962) is plotted as a function of the atomic number (Z) on a semi-log scale. These "normalized" abundances (i.e. ratios) are plotted as the ordinate (log-scale) against the atomic number as the abscissa. Instead of the zigzag line, a smooth curve or straight line (linear scale) can be drawn. Comparisons of ratios from one sample to another are still valid and the differences between them are more clearly revealed. The chondrites serve as a well-analyzed standard reference.

To further emphasize the relative rather than absolute abundances, these ratios may also be plotted renormalized to La = 1.00. An example of this type of representation of data is shown at the bottom of Figure 31. (p. 98).

The rare-earth data obtained in this study of igneous and metamorphic rocks in the Haverhill 15' quadrangle are given in Tables 19, 20, and 21, plate 7. Figures 32-A, 32-B, and 32-C, pages 100-104 are plots of the renormalized values (La = 1.00).

Although, in this study, only seven rare earths and yttrium were analyzed, major trends are evident. The heavy lanthanides ($Z > 66$) generally behave very similarly (i.e., show little internal fractionation), and their distribution relative to the lighter lanthanides is usually approximated by yttrium.

[3]This property is commonly referred to as the "lanthanide contraction."

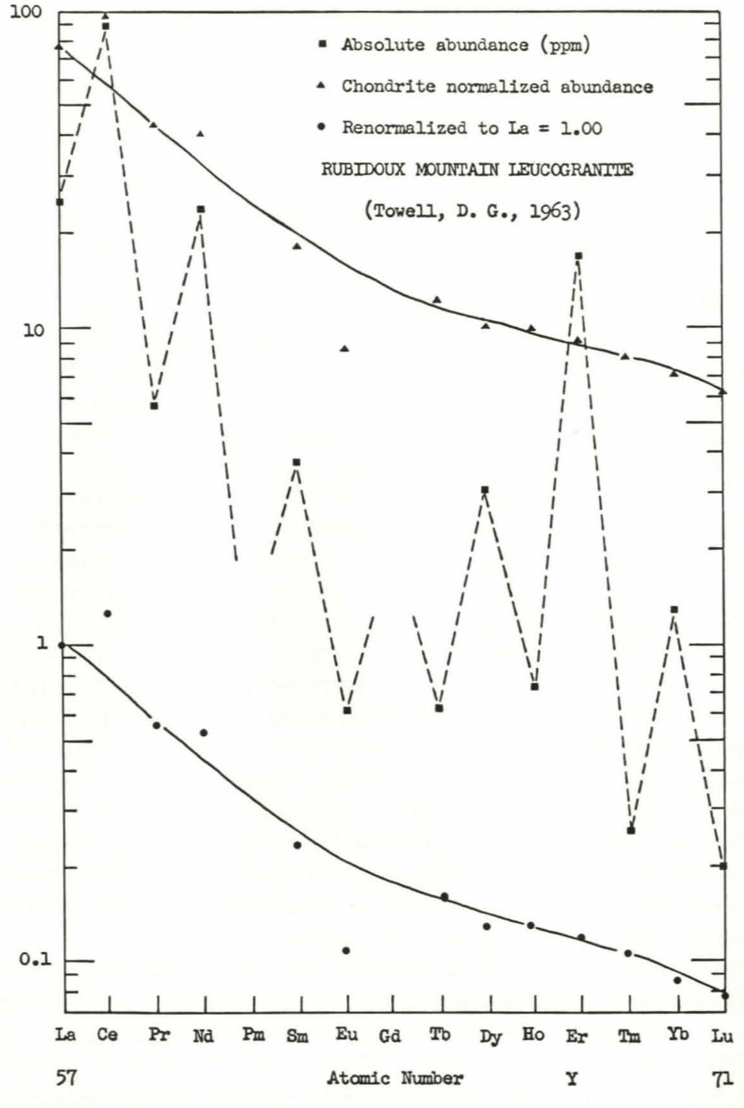

Figure 31. Example of absolute and normalized rare-earth abundances plotted on a logarithmic scale as a function of atomic number.

The squares represent the absolute abundance in ppm as determined analytically. The triangles represent the value of the absolute abundance divided by the average chondrite abundance (from table 19). Notice that the points fall approximately along a continuous curve rather than the zigzag pattern described by the absolute abundance (squares). The solid circles represent the value of the chondritic-normalized re-normalized to La = 1.00. Observe that the lines described by the triangles and circles are parallel and have the same shape.

The data are taken from an analysis of most of the lanthanides. Promethium (Pm) is not present because it is naturally radioactive and has a relatively short half life.

Data from Ph.D. thesis by Towell, 1963.

Two trends in the rare-earth abundances of the igneous rocks of the Hillsboro plutonic series are observed. The most basic rocks in this series tend to have the lowest total lanthanide content (sum of those elements measured). The basic rocks as a group have total rare-earth contents ranging from 6.9 ppm (Sweepstake norite) to 33 ppm (Island Pond diorite). In contrast, the granitic rocks have a total rare-earth content ranging from 174 ppm (Misery Hill quartz monzonite) to 200 ppm (Island Pond biotite-rich porphyritic quartz monzonite), which is more than six times greater than that of the basic rocks.

The other apparent trend observed is the increased relative amount of lighter rare earths (i.e. lower atomic numbers) in the more granitic fractions. This effect is graphically displayed by the "slope"[4] of the line drawn by visual best fit through the points plotted on the graphs in Figures 32-A, 32-B, and 32-C, pages 100-104. The estimated slopes of these lines are given with the associated rare-earth content in Table 22. The scatter of the analytical data plotted on these graphs makes these slopes only semi-quantitative in nature. However, smaller slopes tend to be characteristic of the most basic rocks indicating a more even distribution of the lanthanide series in these rocks. The more acidic or granitic rocks have abundances which plot along a line of steeper slope. The massive Sweepstake diorite is an exception, but in this case the slope is based upon relative concentrations of only three rare earths detected in the sample. In the foliated two-mica granite (no. 9), the heavier rare earths are not detectable although the total concentration is high (190 ppm).

The overall results are grossly similar to those which could be predicted by a fractional crystallization model. Because the ions are all trivalent and presumably proxy for Ca^{+2} (0.99 Å), the earliest-formed crystals would preferentially incorporate the ions with the smallest radii, i.e., the heavy rare earths, Gd to Lu. This process, if continued, would tend to enrich the residual liquid in the lighter rare earths. Generation of magmas by partial melting, however, can also yield similar overall rare-earth patterns from rock to rock.

No separated minerals were analyzed for rare earths. However, two sets of rock samples were chosen in such a manner that the results would have an obvious mineralogical implication. Samples 270-FR and 270-BR were taken from a freshly exposed outcrop of the Island Pond porphyritic quartz monzonite. The samples were located within a meter of each other (fig. 15, p. 46), but they differed in the relative amounts of biotite, apatite, and sphene. The results show

[4]For convenience, the "slope" has been calculated as the reciprocal of the change in atomic number units per log cycle. For instance, if the distribution of the rare earths as determined by the visually fitted line changes by **one** factor of ten over the first nine atomic number units, the slope would equal 1/8 (0.125); over the first four, 1/3 (0.333), etc.

Figure 32. Chondrite-normalized rare-earth abundances of the major rock types in the Haverhill 15' quadrangle of southeastern New Hampshire The abundances have been renormalized to La = 1.00 and plotted on logarithmic scale as a function of atomic number.

Notice yttrium (Y) atomic number 39, is substituted for erbium (ER) atomic number 68 (not analyzed), because Y (for which analytical data were obtained), behaves similarly to Er and adjacent lanthanides.

A - Hillsboro plutonic series
B - White Mountain plutonic-volcanic series
C - Metamorphic rocks

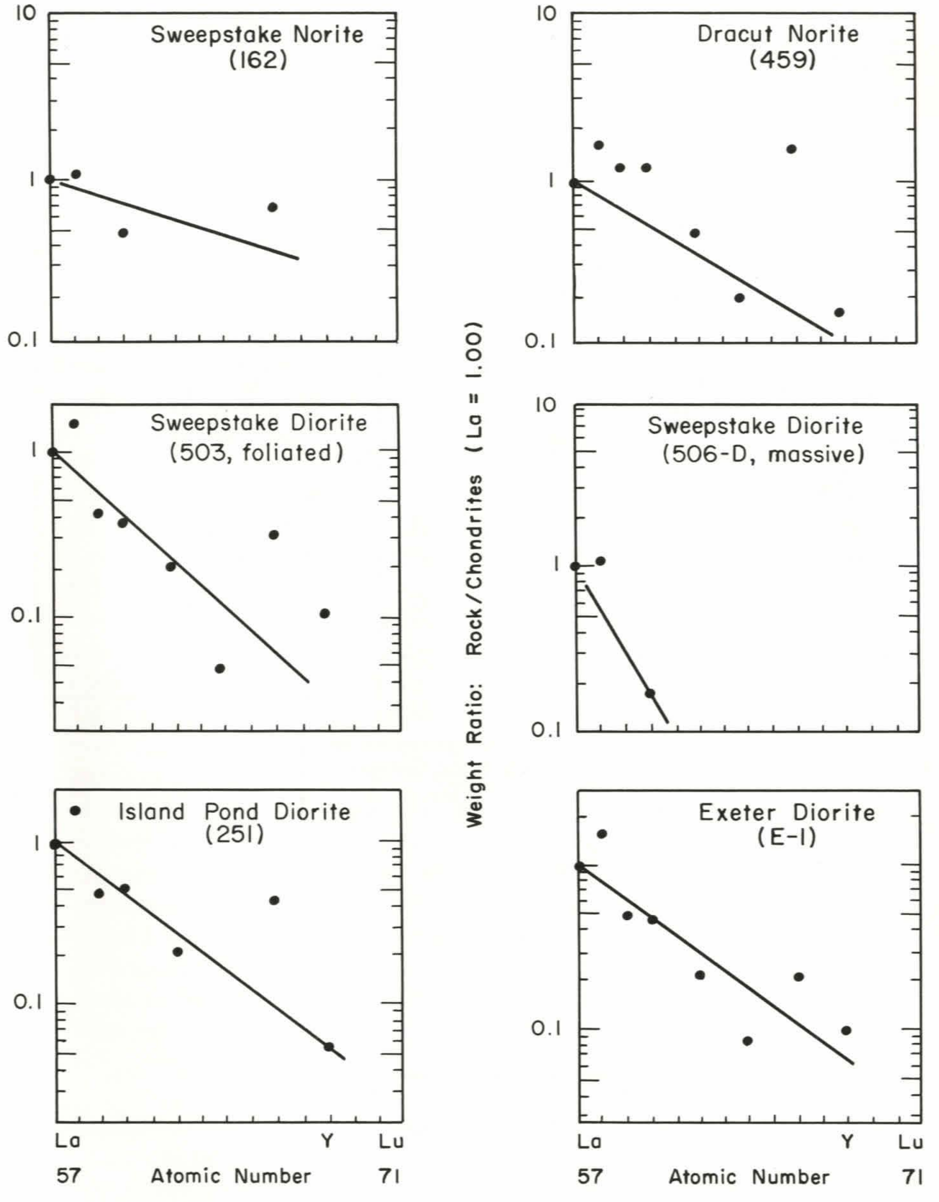

Figure 32-A. Hillsboro Plutonic Series

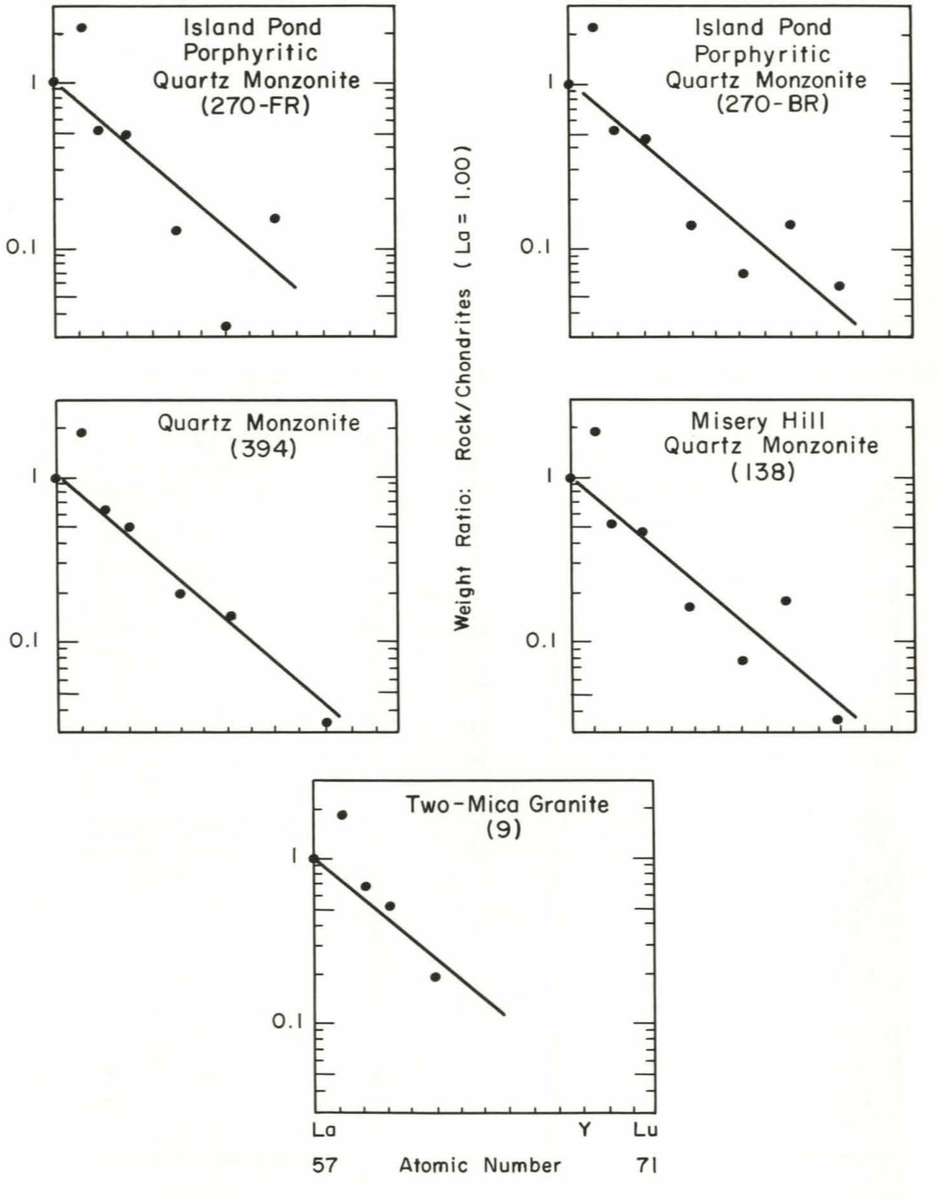

Figure 32-A. (Continued) Hillsboro Plutonic Series

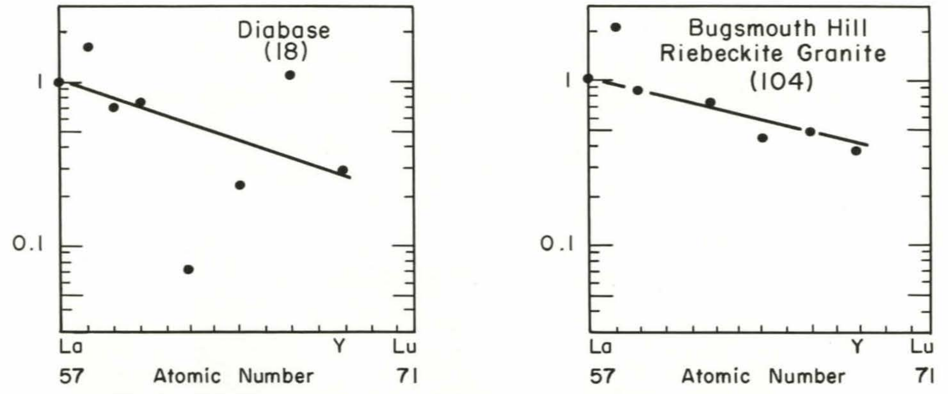

Figure 32-B. White Mountain plutonic-volcanic series

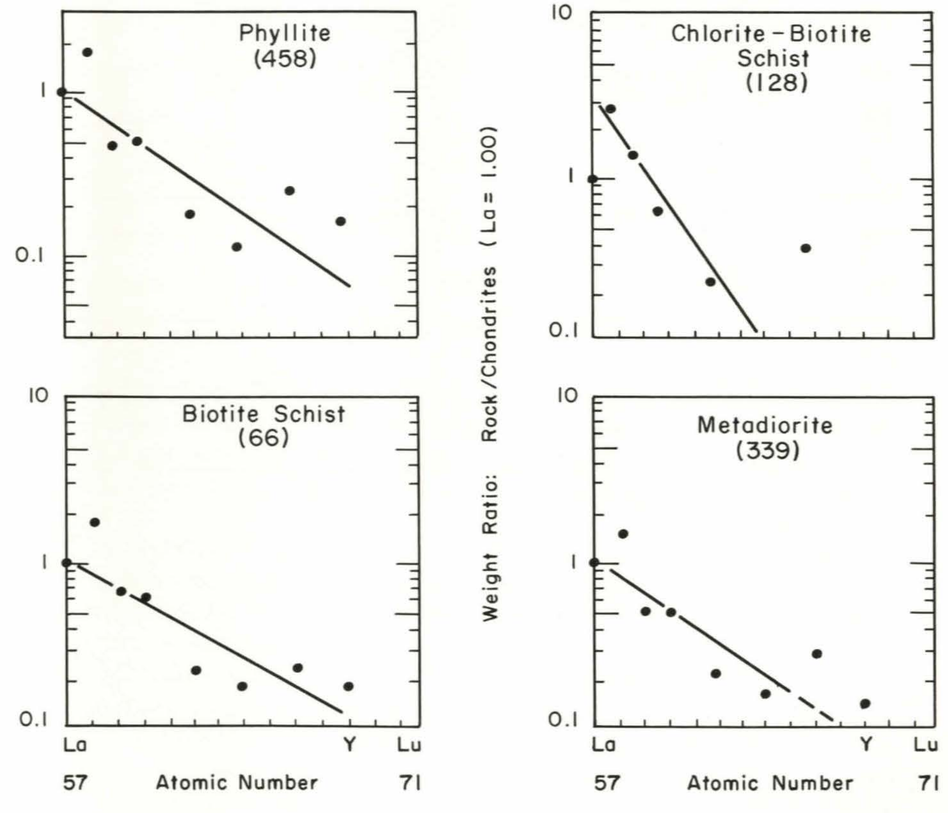

Figure 32-C. Metamorphic rocks

Table 22

TOTAL DETECTABLE RARE EARTHS IN IGNEOUS AND METAMORPHIC ROCKS FROM THE HAVERHILL 15' QUADRANGLE, SOUTHEASTERN NEW HAMPSHIRE

SAMPLE NO.	ROCK TYPE	TOTAL DETECTABLE RE (ppm)	LARSEN INDEX*	"SLOPE"**
	HILLSBORO PLUTONIC SERIES			
459	Dracut norite	22.3	-13.74	0.087
162	Sweepstake norite	6.9	-------	0.051
506-D	diorite (massive)	9.8	0.75	0.250
503	diorite (foliated)	29.0	2.32	0.137
251	Island Pond diorite	32.8	-------	0.118
E-1	Exeter diorite	46.2	9.45	0.107
270-FR	Island Pond (feldspathic) porphyritic monzonite	113.7	23.19	0.125
270-BR	Island Pond (biotitic porphyritic monzonite	199.6	6.28	0.125
138	Misery Hill quartz monzonite	174.0	26.24	0.125
394	Quartz monzonite (massive)	93.9	23.74	0.128
9	Two-mica granite (foliated)	189.5	27.94	0.125
	WHITE MOUNTAIN PLUTONIC-VOLCANIC SERIES			
18	Diabase	22.6	-10.71	0.053
104	Bugsmouth Hill riebeckite granite	135.5	27.11	0.036
	METAMORPHIC ROCKS			
458	Phyllite	42.5	-------	0.109
339	(metadiorite)	114.7	7.22	0.100
66	Quartz-biotite schist	106.7	-------	0.086
128	Chlorite-biotite schist	77.1	-------	0.286

*($1/3\ SiO_2 + K_2O - CaO - MgO - FeO$)

** See Footnote 4, page 99'

that the biotite-rich sample contains almost double the total analyzed rare-earth content of the feldspar-rich sample (table 23, p. 105). However, the relative rare-earth abundances are almost identical (table 19, pl. 7). This implies that the fractionation process that affected the rare earths as individual elements had already occurred and that biotite (or its associated accessory inclusions) provided a more suitable site for the rare earths as a group than plagioclase or microcline. Towell, et al (1965) found that the overall rare-earth abundance pattern associated with biotite from the Rubidoux Mountain leucogranite paralleled the total rock pattern with absolute concentrations by a factor of two or greater in the biotite versus the feldspar fractions. Unfortunately, the multivalent rare earth Europium, which frequently exhibits enrichment in feldspar, was not analyzed.

The biotite-rich Sweepstake diorite (no. 503) has three times the total rare earths found in the amphibole-rich Sweepstake diorite (no. 506-D). The biotite-rich diorite also has about three to five times the TiO_2 and P_2O_5 contents of the amphibole-rich diorite.

Analyses of some rocks and associated minerals of the batholith

Table 23

EFFECT OF MINERALOGY ON THE TOTAL RARE-EARTH CONTENT

SAMPLE	TOTAL RE MEASURED (ppm)	EXCESS MINERALS PRESENT
270-FR	115	Microcline, plagioclase
270-BR	200	Biotite (phene and apatite)
506-D	9.8	Actinolite
503	29	Biotite (sphene and apatite)

of southern California by Towell, et al., (1965) show that not only biotite, but also minerals such as apatite have relatively large amounts of rare earths associated with them. Apatite and sphene are accessory minerals common to both the Island Pond and Sweepstake diorite sample sets. The thin section and chemical analyses of these rock sets show that P_2O_5 and TiO_2 abundances in the biotite-rich facies are more than twice those in the feldspar- and amphibole-rich facies. The potential rare-earth contribution made by these accessory minerals cannot be ignored.

Of the two rock samples from the White Mountain plutonic-volcanic series one trend of rare-earth abundances differs from that of the

Hillsboro plutonic series. The distribution of the rare earths in the diabase dike is "normal" for basic igneous rocks although the individual points show large scatter. However, the distribution pattern for the Bugsmouth Hill riebeckite granite (fig. 33, p. 102) does not resemble that of the granitic rocks (fig. 33, p. 101) of the Hillsboro plutonic series, although the total amount of rare earths (136 ppm) is typical of granites. The Bugsmouth Hill riebeckite granite is a fine-grained hypabyssal rock whereas the granites of the Hillsboro plutonic series are coarse-grained plutonic rock. The writer has no explanation for this apparent distribution anomaly.

Limitations of analytical method

The writer analyzed the rock samples which included one duplicate, one previously analyzed sample (provided by D. G. Towell), and two reagent blanks. The results were somewhat disappointing as the duplicate analysis "A" gave values averaging about 36 per cent lower than "B" (table 24, p. 107). The duplicate set was a diorite of low rare-earth content (sample no. 251). It was found that samples with low total rare-earth contents took much longer to form the oxalate precipitate in the last step of the concentrating procedure (Appendix). Therefore, an incomplete precipitation may have been the cause for the consistent discrepancy in the absolute abundances.

The known sample (Woodson Mountain granodiorite) gave results that were substantially lower (average -77 per cent) than the presumably known values determined by the neutron activiation technique (table 24, p. 107). However, two abundances were in agreement; those of Ce and Dy. The Ce values might be influenced by the +4 oxidation state. The Dy posed a problem in one of the reagent blanks yielding a value of 1.5 ppm (no other rare earths were detected). This particular reagent blank was run with the duplicate known samples. If 1.5 ppm were deducted from the apparent Dy content of the known sample as determined by the X-ray spectrographic method, the **relative** abundances of all the analyzed lanthanides (except Ce) would be in reasonably good agreement. Comparison of results with the activation analysis suggests that the absolute abundances determined in this study may, in some instances, be as much as 75-80 per cent lower than the true contents. Although the absolute abundances of an individual rare earth are probably systematically greater (by as much as 80 per cent) than the results given by the X-ray method, the data give a useful semi-quantitative measure of the **relative** rare earth abundances in the rocks analyzed.

Table 24

ACCURACY AND PRECISION OF ANALYTICAL DATA

DUPLICATE ANALYSES SAMPLE NO. 251

RARE EARTH	CONCENTRATION (ppm) A	B	AVERAGE	% DEVIATION FROM AVERAGE	$\frac{(B-A)}{B}$ 100
La	3.5	4.5	4.0	± 12.5%	22.2%
Ce	13.9	19.2	16.55	± 16.0%	27.6%
Pr	0.6	0.9	0.75	± 20.0%	33.3%
Nd	2.5	4.1	3.30	± 24.5%	39.0%
Sm	0.3	0.6	0.45	± 33.3%	50.0%
Gd	—	0.1	—		—
Dy	1.1	1.9	1.5	± 26.7%	42.1%
Y	—	1.5	—	—	—
AVERAGE				22.1%	35.7%

Comparative analysis with previously analyzed sample (Neutron Activation)

RARE EARTH	CONCENTRATION (ppm) (A) NEUTRON ACTIVATION	(B) X-RAY EMISSION	$\frac{(B-A)}{A}$ 100
La	25.3	7.0	- 72%
Ce	34.2	35.9	+ 5%
Pr	6.96	1.2	- 83%
Nd	22.3	6.2	- 72%
Sm	3.96	0.7	- 82%
Gd	—	0.9	—
Dy	2.99	3.1	+ 3%
Y	24.6	5.7	- 77%
AVERAGE		- 77%*	- 77%*

* Ce and Dy not included

Woodson Mountain granodiorite sample and comparative data supplied by Towell (1963).

Summary of geochemical results

The gross compositions of the rocks in the Hillsboro plutonic series show a trend consistent with other rock series derived from a common source which has undergone a differentiation process (fig. 29, p. 91). The Rb/Sr ratios for these rocks show a trend of increasing values from norite to granite which also is consistent with rocks that are products of fractional crystallization (fig. 30, p. 96). However, the K/Rb ratios show a weak trend of increasing values for the same rocks which is contrary to the values expected from the products of fractional crystallization (fig. 30, p. 96).

Although there is substantial scatter of data, the rare earth concentrations in the rocks from the Hillsboro plutonic series show definite trends. The total rare-earth content increases as the rocks become more granitic. Also, group fractionation seems to favor the lighter rare earths in the more granitic rocks (fig. 33, p. 109). In contrast, although the rocks from the White Mountain plutonic-volcanic series show an increase in the total rare-earth content from diabase to granite, they do not show a concomitant increase in the fractionation within the rare-earth group. (Note, however, that only two samples were analyzed).

Conclusion

The writer has generally implied that the Hillsboro plutonic series is possibly a product of fractional crystallization of an original common magma source. The possibility of the same results being produced by a partial melting process has been suggested and the writer agrees that this model fits the gross field data better, especially in consideration of the sequence of emplacement. The source rock (e.g. diorite ?) would, upon initial heating, yield a relatively granitic melt and as more heat was applied the more basic fractions would become mobile and be emplaced. The author believes that the geochemical data are consistent with the magma genesis either by magmatic differentiation or partial melting at depth.

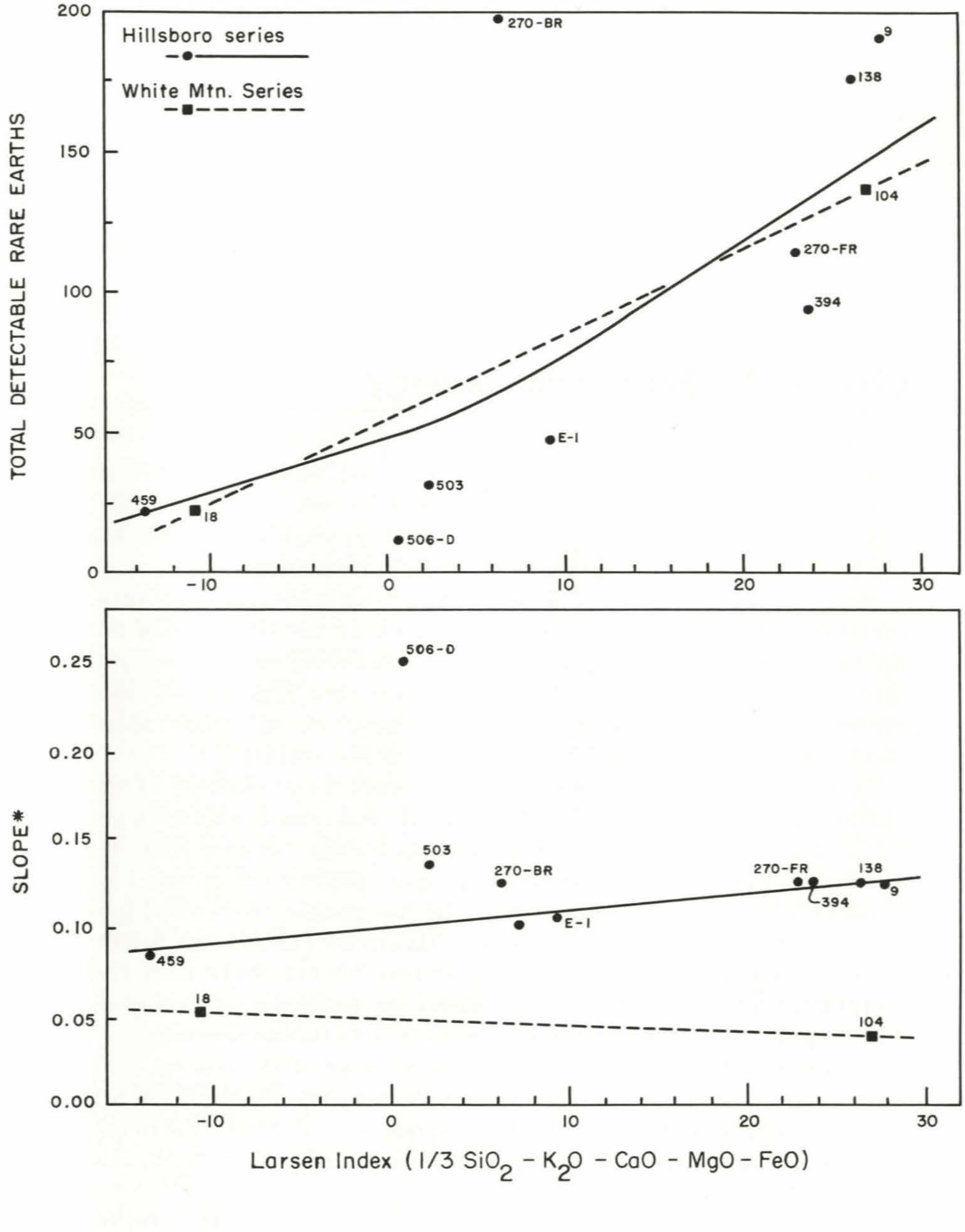

Figure 33. Total detectable rare earths and relative abundance slope plotted against the Larsen Index for igneous rocks in the Haverhill 15' quadrangle, southeastern New Hampshire. (Curves by visual-best-fit)

*For definition of slope, see Footnote 4, page 167.

Chapter 7 Economic Geology

Sand and gravel are, to date, the only profitable raw materials derived from geologic processes in the Haverhill 15' quadrangle. Glaciofluvial deposits, primarily eskers and outwash plains, provide the best sources of sand and gravel for light construction fill.

No extensive bodies of rock of sufficient quality to sustain a commercial building stone operation are present. Small quarries are operated for local consumption, for use in building foundations and stone walls. The largest of these quarries is in a massive two-mica granite located on the south side of the intersection of Pelham Road (Route 97) and Interstate 93 in Salem, New Hampshire.

To date, no record has been made of heavy metal deposits in the Haverhill 15' quadrangle. Ore deposits of chalcophilic elements are difficult to locate in the Haverhill 15' quadrangle because they deteriorate rapidly and are buried by the ever present soil cover. Two small sulfide veins were unearthed in the Sweepstake diorite by highway construction along the Veterans Memorial Parkway in Salem, New Hampshire. The veins are about 30 cm wide and the metasomatized zone is less than a meter on each side of the veins. The original minerals have deteriorated to a sulfurous-smelling gossan. Samples of the gossan and the contact zone of the dioritic rock were taken and the contact rock (sample no. 506-B) was analyzed with the optical spectrograph. The results are listed in Table 17, plate 6; elements present in trace quantities are B, V, Mn, Ni, and Cu.

The large pegmatite bodies in the three-mile wide belt trending northeast-southwestward across the quadrangle are potential sources of elements such as lithium, beryllium, niobium, and tantalum. The writer feels that further investigation of both the sulfide veins and the pegmatite bodies using core sampling methods is necessary to determine their potential for economic development.

Chapter 8 Mineralogy

Potentially interesting locations for collecting mineral specimens are in and near the pegmatite bodies in Kingston, Danville, and Atkinson. The commercial pegmatite deposits in Raymond (presently shut down) are well known to local collectors for rose quartz, beryl, lepidolite, tourmaline, and spodumene (Page and Larrabee, 1962). These mines are located in the Mt. Pawtuckaway quadrangle within two miles of the northern edge of the Haverhill 15' quadrangle. The pegmatites in the Kingston-Danville area make up Rock Rimmon Hill. They are well covered with soil and moss. The local residents have shown more perseverance than the writer in the search for unusual minerals and exhibited several excellent specimens of massive chalcopyrite which were found in the pegmatite area. If any of these pegmatite bodies should be exploited commercially or opened up during highway construction, it would seem reasonable to expect the presence of minerals such as those found in the Raymond pegmatites.

The rock-forming minerals of the Haverhill 15' quadrangle are described in the section on petrography. Only those physical properties which were readily obtained from thin sections using a petrographic microscope are given in the petrography section. The physical properties of the rock-forming minerals in the Haverhill 15' quadrangle fall within the same range as those in the Manchester quadrangle. The results of detailed studies on the major rock-forming minerals of the latter quadrangle, namely, alkali-feldspars, plagioclases, pyroxenes, amphiboles, micas, and garnets, are tabulated in the chapter on its mineralogy by Sriramadas (1966, pp. 46-53).

Several specimens of garnet from the Haverhill 15' quadrangle were studied by the writer. Garnets occur in metamorphic and plutonic rocks in the northern and central portions of the western part of the Haverhill quadrangle. The garnets vary in size from microscopic dimension to about one centimeter. The larger garnets are normally

Table 25

Physical properties of garnets from the Haverhill 15' Quadrangle, southeastern New Hampshire

SAMPLE NO.	ROCK TYPE	LOCATION	COLOR	REFRACTIVE INDEX	CELL EDGE
338	Metadiorite	1.9 miles north Hampstead Center, New Hampshire on Route 121.	Brownish-red	1.780± 0.005	11.62± 0.01
506-F	Aplite (core zone of pegmatite in Sweepstake diorite	Geremonty Drive and Veterans Memorial Parkway, Salem, New Hampshire.	Red	1.830± 0.005	11.53± 0.01

found in metamorphic rocks and usually are filled with inclusions such as biotite and quartz. The largest garnets observed in igneous rocks were less than 5 mm in diameter.

The heavy minerals were separated using heavy liquids. The garnets were isolated and selected under a binocular microscope.

The procedure for determining the approximate composition of the garnets involved the determination of the cell edge and the refractive index. The correlation of unit cell edges and refractive indices with the chemical composition was done using diagrams constructed by Sriramadas (1957).

The garnet from the metadiorite (see page 106), sample no. 338, has a composition of 51 per cent almandine, 16 per cent pyrope, and 33 per cent grossularite. The garnet in the aplite core of a pegmatite from the Sweepstake diorite pluton, sample no. 506-F, is essentially pure almandine (greater than 97 per cent almandine). The physical properties of these two garnets are given in Table 25.

Chapter 9 Summary of Conclusions

The Eliot and Berwick formations were deposited during Silurian (?) time. The initial planar structure is bedding and is designated S_1. During the early stages of the Acadian orogeny, the formations underwent regional metamorphism and developed a schistose texture. The mineral assemblages which developed are in the greenschist-amphibolite transition and amphibolite facies. These areas are designated on the geologic map by biotite and garnet isograds respectively. The schistosity developed parallel to S_1 and is designated S_2. Large-scale folding produced the Rockingham anticlinorium and later intense folding produced small isoclinal folds in the western portion of the quadrangle. Along with the isoclinal folding, metamorphic minerals recrystallized parallel to the axial plane. This latest planar structure is designated S_3, and is often observed in an orientation oblique to folded relicts of S_1.

During the later stages of the Acadian orogeny, acidic magmas of the Hillsboro plutonic series (probably generated by a partial melting process) were emplaced. The earlier plutons were stretched or sheared by the tectonic forces which produced the isoclinal folds. Post-tectonic intrusions of these plutonic rocks were of a more basic composition and have an undeformed, massive texture. Evidence from field relationships, petrography, rare earth, Rb/Sr and K/Rb trends suggests that all coarsely-crystalline plutonic rocks in the Haverhill 15' quadrangle belong to the Hillsboro plutonic series.

The White Mountain plutonic-volcanic series was emplaced during Late Triassic-Early Jurassic time. These are fine-grained hypabyssal rocks which occur generally as diabase and camptonite dikes throughout the Haverhill 15' quadrangle. The juxtaposition of hypabyssal and plutonic rocks suggests a substantial uplift and erosion during the interval between the emplacement of the two igneous series.

Numerous acidic plutons and S_3 structures occur within the area of the garnet isograd. The area enclosed by the biotite isograd has no major granitic outcrops or S_3 foliation. The increases in metamorphic rank and tectonic deformation appear to be related to the acidic phase of the Hillsboro plutonic igneous activity in the Haverhill 15' quadrangle.

Chapter 10 Historical Geology

Much of the evidence which would yield a more complete geologic history of the Haverhill 15' quadrangle is either buried or has been removed by erosion. In order to more completely describe the sequence of events in the quadrangle, data from all the quadrangles in southeastern New Hampshire are presented in Figure 34 on a geologic time scale. One column contains the chronology and sequence of events that are verified by data from the Haverhill quadrangle. A separate column is used to include information from the adjacent quadrangles and events of regional magnitude.

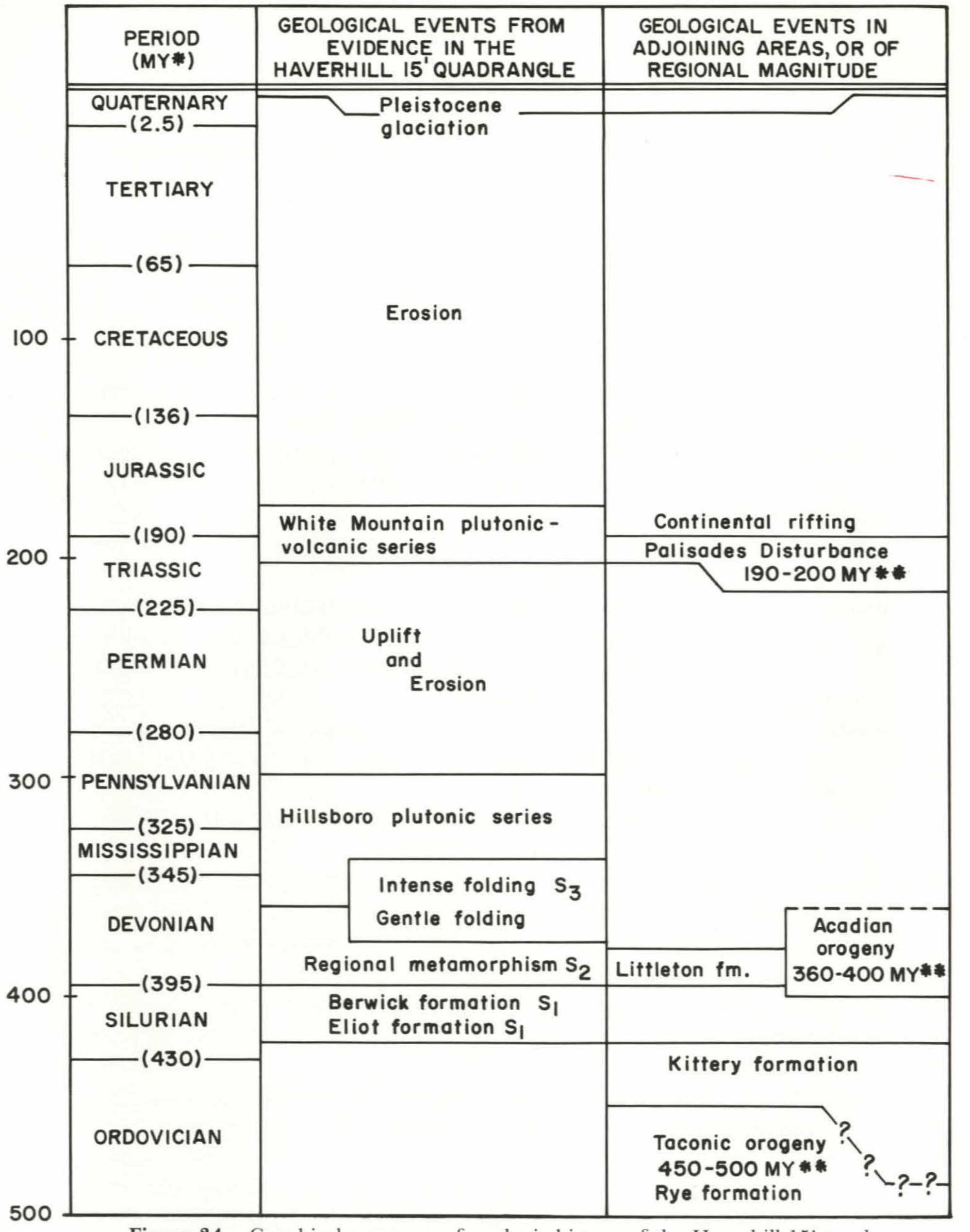

Figure 34. Graphical summary of geologic history of the Haverhill 15' quadrangle, southeastern New Hampshire.

* Absolute ages of Periods, Eicher (1968)
** Absolute ages of Events, Rodgers (1967)

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PART XVII. LIGHTWEIGHT AGGREGATE RAW MATERIALS IN NEW HAMPSHIRE. Preliminary Report. Glenn W. Stewart. 1959. 30 p. $1.00.
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PART XX. DRILLED WATER WELLS IN NEW HAMPSHIRE. Glenn W. Stewart. 1968. 58 p. 50 cents.

MISCELLANEOUS REPORTS AND REFERENCES

GEOLOGICAL STORY OF FRANCONIA NOTCH AND THE FLUME. Andrew H. McNair. 1949. 14 p. illus. 20 cents.
GEOLOGY STORY OF KINSMAN NOTCH AND LOST RIVER. Andrew H. McNair. 1949. 14 p. illus. 20 cents.
THE MOUNTAINS OF NEW HAMPSHIRE. A directory locating the mountains and prominent elevations of the State. 1949. 145 p. illus. 50 cents.
ORE HILL ZINC MINE, WARREN, NEW HAMPSHIRE. H. M. Bannerman. 1943. Reprinted 1962. 2 p. Map. 10 cents. **Out of print.**
MICA-BEARING PEGMATITES OF NEW HAMPSHIRE. U. S. Geological Survey Bulletin. 931 p. Preliminary report. J. C. Olson. 1941. 41 p. Maps. Free. **Out of print.**
ROCK-WELL SURVEY IN NEW HAMPSHIRE. Progress Report. Glenn W. Stewart. 1964. 10 p. 30 cents.

The following reports should be purchased directly from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402.
PEGMATITE INVESTIGATIONS, 1942-45, NEW ENGLAND. U. S. Geological Survey Professional Paper 255. Eugene N. Cameron and others. 1954.
BERYL RESOURCES OF NEW HAMPSHIRE. U. S. Geological Survey Professional Paper 353. James J. Page and David M. Larrabee. 1962. Price: $4.00.

MINERAL DEPOSITS AND OCCURENCES IN NEW HAMPSHIRE, EXCLUSIVE OF CLAY, SAND, GRAVEL AND PEAT. Mineral investigations. Resources map MR 6. Nancy C. Pearre and James A. Calkins. 1957. 50 cents.

The following are available in limited supply from the New Hampshire Water Resources Board, State House Annex, Concord, New Hampshire:

GEOLOGY AND GROUND-WATER RESOURCES OF SOUTHEASTERN NEW HAMPSHIRE. U. S. Geological Survey Water Supply Paper 1695., Edward Bradley. 1964. 80 p. Maps. $1.00.

NEW HAMPSHIRE BASIC-DATA REPORT NO. I, GROUND WATER SERIES, SOUTHEASTERN AREA. Edward Bradley and Richard G. Petersen. Prepared by the U. S. Geological Survey in cooperation with the New Hampshire Water Resources Board. 1962. 53 p. Maps.

NEW HAMPSHIRE BASIC-DATA REPORT NO. II, GROUND WATER SERIES, LOWER MERRIMACK RIVER VALLEY. James P. Weigle and Richard Kranes. Prepared by the U. S. Geological Survey in cooperation with the N. H. Water Resources Board. 1966. 44 p. Map.

GROUND-WATER FAVORABILITY MAP OF THE NASHUA-MERRIMACK AREA, NEW HAMPSHIRE. James M. Weigle. Prepared by U.S.G.S. in cooperation with the N. H. Water Resources Board. 1963.

GROUND-WATER FAVORABILITY MAP OF THE SALEM-PLAISTOW AREA, NEW HAMPSHIRE. James M. Weigle. Prepared by the U.S.G.S. in cooperation with the N. H. Water Resources Board. 1964.

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STRATIGRAPHY AND STRUCTURE OF THE BOUNDARY MOUNTAIN ANTICLINORIUM IN THE ERROL QUADRANGLE, NEW HAMPSHIRE-MAINE. Geological Society of America Special Paper 77. John C. Greene. 1964. $3.50.

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