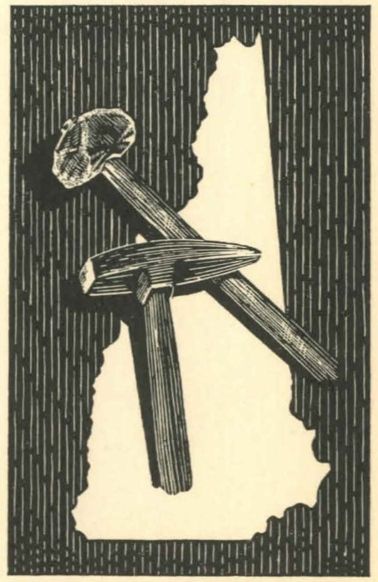
# The Bedrock Geology of the HILLSBORO QUADRANGLE New Hampshire

By Dennis L. Nielson



Bulletin No. 8

PUBLISHED BY THE STATE OF NEW HAMPSHIRE
DEPARTMENT OF RESOURCES AND ECONOMIC DEVELOPMENT

# The Bedrock Geology of the HILLSBORO QUADRANGLE New Hampshire

## Bulletin No. 8

By Dennis L. Nielsen

Published by the State of New Hampshire
Department of Resources and
Economic Development
Concord, N.H.
1981

**NEW HAMPSHIRE**
**DEPARTMENT of RESOURCES and**
**ECONOMIC DEVELOPMENT**
**DIVISION OF FORESTS and LANDS**

George Gilman, Commissioner
Theodore Natti, Director, Forests and Lands
Robert I. Davis, State Geologist

## ACKNOWLEDGMENTS

Acknowledgment is given to Donald Jacobs and Alec Nicholas, Graphic Arts Section, Department of Resources and Economic Development, for the drafting of maps and preparation of the manuscript for printing.

# ABSTRACT

The Hillsboro 15′ quadrangle, New Hampshire, is located in the highly deformed and metamorphosed belt of the northern Appalachians. In this study, the metasedimentary rocks have been broken down into four units which are, from oldest to youngest: 1) the Crotched Mountain Formation, 2) the Francestown Formation, 3) the Warner Formation, and 4) the Littleton Formation. It is suggested here on the basis of lithologic similarities with units along strike in Maine, that the Crotched Mountain Formation is Ordovician or Silurian in age, that the Francestown and Warner Formations are Silurian. The Littleton Formation is lower Devonian in age.

The plutonic rocks of the Hillsboro quadrangle are members of the New Hampshire Plutonic Series, and were emplaced during and slightly after kinematic episodes of the Early Devonian Acadian Orogeny. The oldest unit is the Kinsman Quartz Monzonite which underlies much of the western half of the quadrangle. A previously unreported biotite granodiorite forms five plutons in the area and apparently grades into rocks which are similar to the Spaulding Quartz Diorite described by Fowler-Billings (1949). These quartz diorites are also associated with hypersthene quartz diorites and actinolite gabbros. A group of rocks ranging in composition from binary tonalite to binary granite have been mapped as plutons of Concord Granite. These rocks are post-kinematic and often show flow banding. Two small bodies of aplite have also been mapped in the southwest corner of the quadrangle.

The metasediments of the Hillsboro quadrangle reached a metamorphic climax ($M_1$) in the silimanite-K-feldspar zone of regional metamorphism. Possibly as a result of the buffering effects of $H_2O$, some of these rocks only developed assemblages characteristic of the upper sillimanite zone. The emplacement of biotite granodiorite plutons provided the heat and fluids necessary to recrystallize many of the rocks to lower grade assemblages ($M_2$). These rocks are often characterized by the presence of andalusite and occasionally by staurolite. Late fluids, possibly from the biotite granodiorite, resulted in widespread retrograde metamorphism which produced assemblages characteristic of the greenschist facies.

Rocks of the Hillsboro quadrangle have undergone three periods of folding. The $F_1$ folds were recumbent isoclinal folds about northwest-trending fold axes. This folding was accompanied by the intrusion of the Kinsman Quartz Monzonite and, in areas to the west,

the Bethlehem Gneiss. The $M_1$ metamorphic climax also probably occurred at this time. The $F_2$ folding was about northwest-trending axes, but this time the axial planes were upright. The $F_3$ folding event resulted in upright to overturned folding about northeast-trending axes. This event was accompanied by the intrusion of biotite granodiorite plutons and $M_2$ metamorphism.

# TABLE OF CONTENTS

page

## ILLUSTRATIONS

### PLATES

### FIGURES

## FIGURES (cont.)

## TABLES

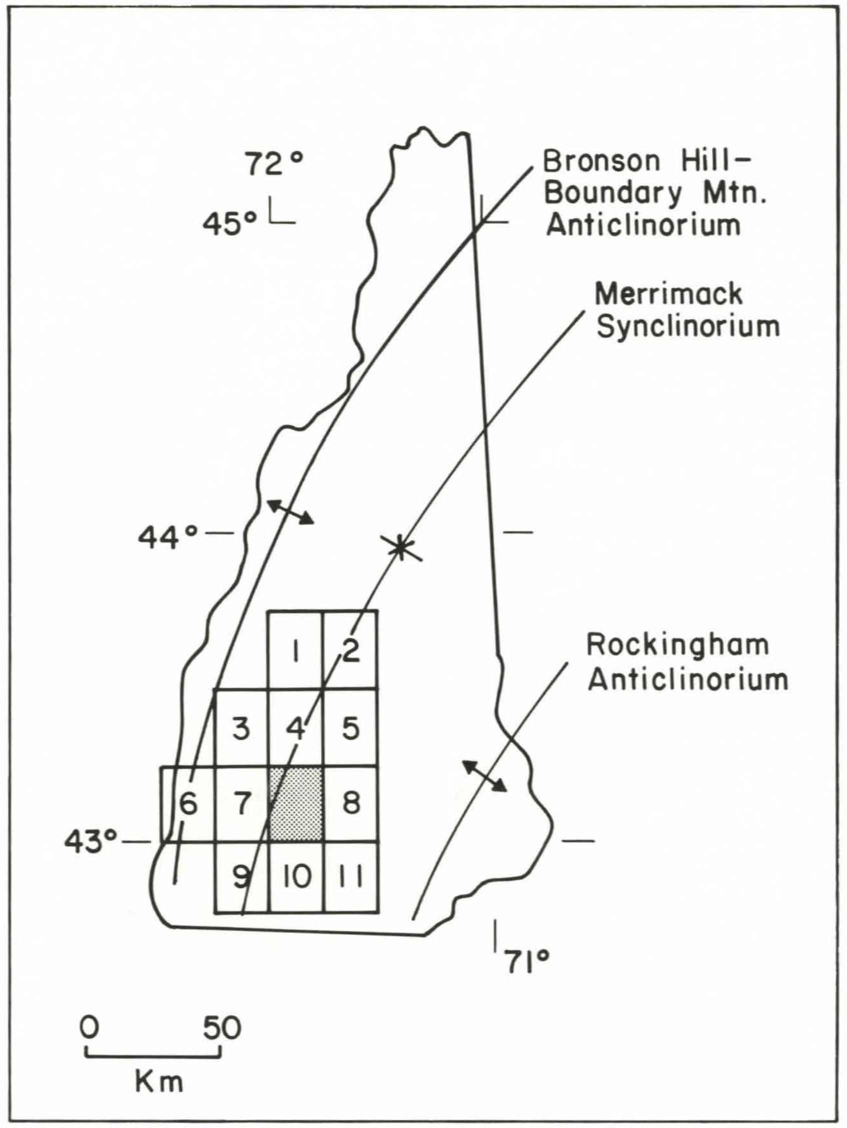


**Figure 1.**
Index map of New Hampshire showing the location of the Hillsboro 15′ quadrangle (shaded) as well as the major structural features of New Hampshire (Billings, 1956). Nearby quadrangles are: 1. Cardigan, 2. Holderness, 3. Sunapee, 4. Mt. Kearsarge, 5. Penacook, 6. Bellows Falls, 7. Lovewell Mtn., 8. Concord, 9. Monadnock, 10. Peterborough, 11. Milford.

# INTRODUCTION

## Location

The Hillsboro 15-minute quadrangle covers an area of about 220 square miles in south-central New Hampshire (Fig. 1) lying within portions of Hillsboro and Merrimack counties. The region is more than 90 percent forested and is moderately hilly. The highest point, Knights Hill in the northwest corner of the quadrangle, has an elevation of about 1940 feet. The lowest point has an elevation of about 380 feet and is located on the Contoocook River at the border between the Concord and Hillsboro quadrangles. The principal industries in the area are tourism, agriculture, and logging.

## Acknowledgements

The author would especially like to acknowledge Professor John B. Lyons of Dartmouth College for his continued interest and encouragement in this project. This paper has benefited from reviews by Drs. J.B. Lyons and D.R. Nielson. Mr. G.A. Hahn assisted in the field during 1972, and Dr. D.R. Nielson provided assistance during both the 1972 and 1973 field seasons.

Financial assistance for this project was provided by two Penrose Grants (numbers 1567-72 and 1752-73) from the Geological Society of America and a Grant-in-Aid of Research from the Society of the Sigma Xi. These monies are gratefully acknowledged. During this study the author was supported at Dartmouth College by an N.D.E.A. Title IV Fellowship.

The manuscript was prepared with the assistance of the Earth Science Laboratory, University of Utah Research Institute.

## Regional Geology

The Hillsboro quadrangle lies within the highly deformed eugeosynclinal belt of the Appalachian Mountain system. Specifically, the quadrangle lies near what is presumed to be the axis of the Merrimack synclinorium (Fig. 1) of Billings (1956). It is probable that the Merrimack synclinorium in New Hampshire was a depositional basin throughout Silurian and into Devonian time as has been shown to be the case in Maine (Osberg and others, 1968).

The paleogeographic relations in northern New England during the Silurian and Early Devonian have been summarized by Boucot (1968). Throughout much of this time, most of New Hampshire was submerged, with a land area to the west. The shore of this land area was approximately located along the Bronson Hill anticlinorium in the Early Silurian. According to Boucot (1968), the shore line transgressed westward to the Green Mountain anticlinorium during the Middle Silurian and then disappeared altogether as the area was inundated in the Early Devonian. To the east, roughly along the present Atlantic coast, there was a positive area which was a site of volcanism from the Early Silurian into the Early Devonian (Naylor and Boucot, 1965; Boucot, 1968; Brookins and others, 1973). Brookins and others (1973) have dated three volcanic complexes in this Maine Coastal Volcanic Belt which have yielded Rb/Sr ages of 390 m.y., i.e., close to the Silurian-Devonian time boundary. Thus, during much of Silurian time the Merrimack synclinorium was a depositional basin receiving influxes of terrigenous detritus from positive areas to both the east and west. The sedimentation in the area was terminated in Early Devonian time by the onset of the Acadian Orogeny.

Billings (1956) has shown the metasediments of the Hillsboro quadrangle and much of the area to the west as a part of the Lower Devonian Littleton Formation with Silurian and Ordovician metasediments and metavolcanics cropping out around the Oliverian domes of the Bronson Hill anticlinorium. The geology along and to either side of the Bronson Hill anticlinorium has recently been remapped and the structure reinterpreted by Thompson and others (1968). Much of their interpretation was based upon a reassignment of units originally mapped as Lower Devonian Littleton Formation to the Middle Ordovician Partridge, or to the Silurian Clough and Fitch Formations. If one accepts the stratigraphic correlations of Thompson and others (1968), the structural geology of the Bronson Hill anticlinorium consists of three large nappes rooting at an uncertain distance to the east. The remapping of Thompson and others (1968) was carried as far as the Lovewell Mtn. quadrangle.

Recently, Englund (1971,1974,1976) has demonstrated the presence of an initial recumbent folding event followed by two successive cycles of upright folding in the Holderness quadrangle of central New Hampshire where some of the formations resemble those of the Hillsboro quadrangle.

# STRATIGRAPHY

## Regional Stratigraphy

The Paleozoic stratigraphy of New Hampshire has been defined by Billings (1956) with type sections established along the Bronson Hill anticlinorium. In southwestern New Hampshire the Middle Ordovician Ammonoosuc Volcanics surround the Ordovician Oliverian gneiss domes and are themselves conformably overlain by the Middle Ordovician Partridge Formation. There is an angular unconformity above the Partridge Formation, and above this there is a thin Silurian section consisting of the Clough and Fitch Formations. The Clough is a quartzite and quartz pebble conglomerate which ranges from 0 to 365 meters in thickness and is overlain by the marbles and calc-silicates of the Fitch Formation which ranges from 0 to 234 meters in thickness. These rocks are overlain by the Lower Devonian Littleton Formation which has an estimated thickness in excess of 4.5 km.

Recent work in Maine by Moench and Boudette (1970), Boone (1973), Osberg and others (1968), and in New Hampshire by Hussey (1968) have established probable stratigraphic correlations across the Merrimack synclinorium. In Maine and eastern New Hampshire the metamorphic grade is lower than in central New Hampshire, and rare fossils are present. The above workers have established an extreme thickening of the Silurian section eastward from a possible shoreline along the Bronson Hill - Boundary Mountains anticlinorium. By analogy, it was the opinion of D.L. Nielson (1974) that the Merrimack synclinorium of central New Hampshire was the area of a depositional basin during the Silurian, exhibiting thickening of units as well as facies changes from the type sections along the Bronson Hill anticlinorium.

## Stratigraphy of the Hillsboro Quadrangle

In the following sections, the metasedimentary rocks of the Hillsboro quadrangle will be described in terms of their lithologies and inferred position in the stratigraphic column. It should be pointed out here that the stratigraphic relations depend in large part on the structural interpretations which will be discussed in a later section of this report. The structural interpretation involves an initial period of isoclinal recumbent folding during which the rocks underwent severe plastic deformation. One result of this is to make estimates of original stratigraphic thickness of the units extremely imprecise.

Billings (1956) classified all the metasedimentary rocks of the Hillsboro quadrangle as Lower Devonian Littleton Formation. This designation has been used by all workers in the area (c.f., Greene, 1970; Englund, 1976), and mappable metasedimentary units have been termed members of the Littleton Formation. However, lithologic similarities of metasedimentary units of central New Hampshire with rocks of both the Merrimack synclinorium of Maine and the Bronson Hill anticlinorium of New Hampshire suggest that there are units of Silurian and possibly Ordovician age in the Hillsboro quadrangle. Therefore mappable stratigraphic units will be designated here as formations and their possible age relations will be suggested. Two of the mapped units were originally described as members of the Littleton Formation by Greene (1970) in the Peterborough quadrangle, and two are continuations of units mapped by J.B. Lyons (unpub.) in the Mt. Kearsarge quadrangle. No fossils have been found in any of these rocks. Stratigraphic top has been inferred on the basis of graded bedding in several of the units.

### Crotched Mountain Formation

The term Crotched Mountain Member of the Littleton Formation was introduced by Greene (1970) for "mica and sillimanite schists that occur in the north central part of the Peterborough quadrangle, stratigraphically above the Francestown Member." The type locality of this unit, which will here be designated the Crotched Mountain Formation, is at the summit of Crotched Mountain, just south of the Hillsboro - Peterborough quadrangle boundary. The unit underlies Crotched Mountain and has been mapped extending north into the Hillsboro quadrangle in three belts, one to the west of the Deering Pluton and two to the east of the Deering Pluton (Plate I). A small area of Crotched Mountain Formation has also been mapped in the northeastern part of the quadrangle on the basis of lithology and position in the stratigraphic sequence.

The interpretation of the distribution of this unit presented here differs from that of Greene (1970) in that I have mapped units in the southeast corner of the Hillsboro quadrangle as Crotched Mountain which will be continuous with a portion of Greene's Peterborough Member. In addition, the structural interpretation presented here puts the Crotched Mountain Formation stratigraphically below the Francestown Formation rather than above it as was the interpretation of Greene (1970).

In general, the Crotched Mountain Formation ranges from metaquartzite to biotite-sillimanite-quartz schist. These rock types are often rhythmically interbedded in layers which are about 2 to 3 cm thick. Often the unit shows excellent graded bedding with individual units ranging from 12 to 20 cm thick. The formation also contains more massive units of sillimanite-biotite-quartz schist which are several meters thick, and often contains blocky sillimanite porphyroblasts up to 5 cm long. A thin layer of quartz pebble conglomerate has been found on the southwest flank of Tobey Hill. The Crotched Moun-

Table 1 - Modes of the Crotched Mtn. Formation based on point counts of 1000 grains.

| | Hi-12-72 | Hi-18-72 | Hi-22-72 | Hi-122-72 | Hi-123-72 | Hi-167-73 | Hi-171-73 |
|---|---|---|---|---|---|---|---|
| Quartz | 57.1 | 72.6 | 54.9 | 35.7 | 24.2 | 54.5 | 19.1 |
| Plagioclase* | 3.0 | .1 | 18.1 | tr | .9 | .3 | 11.7 |
| K feldspar | | .3 | | .1 | .3 | | |
| Muscovite | .2 | 15.4 | | 13.8 | 22.7 | 6.3 | 15.2 |
| Biotite | 24.2 | 7.1 | 16.0 | 35.9 | 37.6 | 26.8 | 47.6 |
| Garnet | | tr | | 2.3 | | 1.2 | 3.1 |
| Sillimanite | 12.5 | | | 11.2 | 12.8 | 9.9 | 13.1 |
| Apatite | .3 | tr | .3 | tr | .1 | tr | .1 |
| Graphite | 1.9 | | .5 | .9 | 1.5 | .9 | 2.0 |
| Ilmenite | tr | tr | tr | tr | tr | tr | tr |
| Pyrrhotite | | .6 | | .1 | | | |
| Zircon | | | | tr | .1 | .1 | .1 |
| Sphene | | | 1.8 | | | | |
| Epidote | | | .4 | | | | |
| Chlorite | | 3.9 | | | | | |
| FeOx | .8 | | | | | | |
| *percent An in plagioclase | 26 | 26 | 54 | 30 | 23 | 26 | 33 |

| | |
|---|---|
| Hi-12-72 | Sillimanite-biotite-quartz schist. To the north of dirt road at top of Bradford Hill, Town of Francestown. |
| Hi-18-72 | Thinly bedded muscovite-biotite-quartz granofels. 0.1 mi. N of Francestown outcrop in road .7 mi. NW of Kingsbury Hill, Town of Francestown. |
| Hi-22-72 | Biotite-plagioclase-quartz granofels. From cellar hole along dirt road on E flank of Kingsbury Hill, Town of Francestown. |
| Hi-122-72 | Sillimanite-biotite-quartz schist. Along dirt road .2 mi. NW of intersection with paved road, SE of Lincoln Hill, Town of Francestown. |
| Hi-123-72 | Sillimanite-muscovite-biotite-quartz schist. At fork in road S of Kingsbury Hill, Town of Francestown. |
| Hi-167-73 | Sillimanite-biotite-quartz schist. 0.4 mi. SW of highway 149 along dirt road through woods, SW of Toby Hill, Town of Weare. |
| Hi-171-73 | Garnet-Sillimanite-biotite-schist. .05 mi. E of Hi-22-72, Town of Francestown. |

tain Formation generally develops a gray weathered surface, but immediately east of the Deering Pluton it is characterized by a rusty brown weathered surface because of an increased abundance of pyrrhotite.

Occasionally biotite-plagioclase-quartz granofels are found within the Crotched Mountain Formation. These units may also contain zoned calc-silicate boudins. Table 1 gives some representative modes of the Crotched Mountain Formation, and Table 2 lists some chemical analyses. Its structural thickness is estimated to be about 950 meters (3100 feet) on the basis of outcrops in the southeastern corner of the quadrangle. Greene (1970) has estimated that the stratigraphic thickness of the Crotched Mountain Member is 5300 feet.

Table 2 - Chemical analysis of the Crotched Mtn. Formation. Descriptions and locations are listed in Table 1. All analyses were by the author.

|  | Hi-22-72 | Hi-122-72 | Hi-171-72 |
|---|---|---|---|
| $SiO_2$ | 73.5 | 58.2 | 53.8 |
| $TiO_2$ | .66 | 1.19 | 1.14 |
| $Al_2O_3$ | 12.0 | 20.5 | 22.5 |
| FeO* | 3.71 | 8.54 | 8.79 |
| MnO | .07 | .12 | .17 |
| MgO | 2.00 | 2.84 | 2.81 |
| CaO | 3.14 | .29 | 1.11 |
| $Na_2O$ | 1.95 | .70 | 1.27 |
| $K_2O$ | 1.71 | 3.93 | 4.80 |
| $H_2O^+$ | .21 | .48 | 1.24 |
| $H_2O^-$ | .06 | .06 | .01 |
| $P_2O_5$ | .16 | .08 | .27 |
| Total | 99.2 | 96.9 | 97.9 |

*Total Fe calculated as FeO

## Francestown Formation

The Francestown Formation was defined by Greene (1970) in the Peterborough quadrangle as a member of the Littleton Formation. The type locality for this unit is along Quarry Road in the Peterborough and Hillsboro quadrangle; the exposures run from about 300 meters north to about 600 meters south of the Hillsboro-Peterborough quadrangle boundary. This unit is lithologically similar to and probably correlative with the Rusty Quartzite Member of the Littleton Formation in the Monadnock quadrangle (Fowler-Billings, 1949) and with the Clay Brook Member of the Littleton Formation in the Holderness quadrangle (Englund, 1971, 1976). This unit also crops out over large areas in the Concord quadrangle and has been observed in the Penacook and Mt. Kearsarge quadrangles (J.B. Lyons, personal communication). It is possible that beds which are assigned to the Francestown represent similar lithologies at different stratigraphic horizons. Due to sparse outcrop the author was unable to establish detailed stratigraphic relationships to positively confirm or deny this possibility, but the interpretation favored here is that lithologies assigned to the Francestown do represent a unique stratigraphic horizon. It is therefore proposed here that the Francestown be given formation status. The Francestown is one of the most distinctive units in central New Hampshire and will be the key to unlocking the structure and stratigraphy of the area.

The Francestown Formation is a rusty weathering, thinly-bedded, light- to dark-gray, quartz-rich calc-silicate. The unit characteristically shows thin, rhythmic layering. On good exposures or polished samples it is often possible to see graded bedding.

The composition of the Francestown is quite variable, but in general it is a graphite-pyrrhotite-plagioclase-quartz granofels plus or minus variable amounts of diopsode, actinolite, muscovite, biotite, and microcline. Some representative modes and chemical analyses are given in Tables 3 and 4. Several samples have been found which contain coexisting pyrrhotite and pyrite.

The stratigraphic thickness of the Francestown Formation is here estimated to be 340 meters (1100 feet). This estimate is based on the broad belt of Francestown in the southeast corner of the Hillsboro quadrangle. As will be shown later, this belt contains the axial area of a recumbent synform. Thus it was assumed that the unit had been doubled in thickness by the recumbent folding event. Englund (1974, 1976) has estimated the thickness of the Clay Brook Member in the Holderness quadrangle to be 1400 feet. Greene (1970) suggests that the unit ranges from 0 to 500 feet thick in the Peterborough quadrangle, and Fowler-Billings (1949) estimates thicknesses from 0 to 600 feet "or more" in the Monadnock quadrangle.

Table 3 - Modal Analyses of the Francestown Formation based on 1000 point counts. Modes by Hahn (1973).

| | Hi-<br>65-72 | Hi-<br>66-72 | Hi-<br>66b-72 | Hi-<br>67-72 | Hi-<br>68-72 | Hi-<br>72-72 | Hi-<br>73-72 | Hi-<br>88-72 | Hi-<br>89-72 | C-<br>101-72 | Pb-<br>101-72 | Pb-<br>102-72 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quartz | 19.6 | 62.7 | 6.6 | 46.1 | 68.6 | 45.4 | 40.8 | 3.5 | 35.3 | 26.9 | 36.7 | 56.1 |
| Plagioclase* | 26.8 | 19.2 | | 14.3 | 13.0 | 17.8 | 36.9 | | 16.1 | | 21.5 | 22.2 |
| Microcline | | | 78.8 | 2.8 | | | | 22.3 | | | | |
| Diopside | | 5.2 | | 11.0 | 7.5 | 5.6 | | | | 1.1 | | |
| Actinolite | | 2.1 | | 1.0 | .3 | 3.1 | .4 | 58.2 | | 11.9 | | |
| Clinozoisite | .9 | 5.0 | 1.0 | 1.0 | | 17.7 | 1.3 | 1.0 | | 35.4 | 1.0 | 1.0 |
| Muscovite | 17.3 | | 4.2 | 5.0 | .6 | | 7.4 | 3.1 | | | | |
| Biotite | 19.7 | | | 5.3 | | | | | 36.8 | | 22.6 | |
| Phlogopite | | .6 | | | | | | | | | | 7.8 |
| Sphene | 2.6 | 2.3 | 3.6 | 4.1 | 1.5 | 2.6 | 2.1 | 2.3 | 3.0 | 5.1 | 3.4 | 2.8 |
| Graphite | 3.0 | 1.0 | 2.0 | 1.8 | 2.9 | 2.4 | 3.5 | 3.3 | 3.6 | 7.3 | 5.0 | 1.0 |
| Pyrrhotite | 9.0 | 1.5 | 3.8 | 7.6 | 5.6 | 5.1 | 6.9 | 6.3 | 5.0 | 12.3 | 8.8 | 4.1 |
| Pyrite | tr | | | | tr | | .1 | | | | | |
| Garnet | 1.1 | | | | | | tr | | tr | | 1.0 | |
| Apatite | | .4 | | | | | .6 | | .2 | | .5 | .2 |
| *percent An in plagioclase | 45 | 54 | | 68 | 70 | 58 | 66 | | 45 | | 48 | 64 |

| | |
|---|---|
| Hi-65-72 | Pyrrhotite-graphite-plagioclase-biotite-quartz granofels. Blasted outcrop on E side of road S of Deering Reservoir and NW of Fulton Pond, Town of Deering. |
| Hi-66-72 | Pyrrhotite-graphite-diopside-plagioclase quartz granoferls. Same locallity as Hi-65-72. |
| Hi-67-72 | Pyrrhotite-graphite-diopside-plagioclase-quartz granofels. In ditch on S side of dirt road across from farm and .1 mi. SW of intersection, SW of Cove Hill, Town of Deering. |
| Hi-68-72 | Pyrrhotite-graphite-diopside-plagioclase-quartz granofels. At T-junction in roads E of Vincent State Forest, Town of Weare. |
| Hi-72-72 | Pyrrhotite-graphite-diopside-clinozoisite-plagioclase-quartz granofels. Along S shore of Deering Reservoir, Town of Deering. |
| Hi-73-73 | Pyrrhotite-graphite-muscovite-plagiclase-quartz granofels. Outcrops along road 15 mi. NW of summit of Cove Hill, Town of Deering. |
| Hi-88-72 | Graphite-pyrrhotite-microcline-actinolite granofels. Outcrop in E-W road E of Bell Ledges, in Town of Francestown .1 mi. E of boundary with the Town of Bennington. |
| Hi-89-72 | Graphite-pyrrhotite-plagioclase-quartz-biotite granofels. Same locality as Hi-88-72. |
| C-101-72 | Pyrrhotite-graphite-actinolite-clinozoisite-quartz granofels. Concord quadrangle, Town of Weare, Along Hwy 149 at intersection of E end of Perkins Pond Marsh. |
| Pb-101-72 | Graphite-pyrrhotite-plagioclase-biotite-quartz granofels. Type locality along Quarry Road, Town of Francetown, Peterborough-Hillsboro quadrangle boundary. |
| Pb-102-72 | Pyrrhotite-graphite-plagioclase-quartz granofels. Same locality as Pb-101-72. |

Table 4 - Chemical analyses of the Francestown Formation. Descriptions and locations are listed in Table 3. All analyses were by the author.

| | Hi-65-72 | Hi-73-72 | Hi-88-72 |
|---|---|---|---|
| $SiO_2$ | 62.3 | 64.8 | 52.9 |
| $TiO_2$ | .88 | .65 | .79 |
| $Al_2O_3$ | 16.3 | 14.2 | 15.0 |
| FeO* | 4.84 | 5.27 | 5.09 |
| MnO | .14 | .03 | .28 |
| MgO | 1.84 | 1.29 | 7.48 |
| CaO | 3.70 | 5.28 | 7.89 |
| $Na_2O$ | 2.49 | 1.74 | 1.31 |
| $K_2O$ | 2.36 | .66 | 4.93 |
| $H_2O^+$ | .68 | .56 | .54 |
| $H_2O^-$ | .52 | .53 | .41 |
| $P_2O_5$ | .16 | .14 | .20 |
| Total | 96.2 | 96.0 | 96.8 |

*Total Fe calculated as FeO
Note: C and S not analyzed

## Warner Formation

The term Warner Formation is introduced here for calc-silicate granofels and sillimanite-biotite schists which are stratigraphically above the Francestown Formation. The type locality for these rocks is along I-89 south of the village of Warner in the Mt. Kearsarge quadrangle. The unit is found in the Hillsboro quadrangle in a northeast-trending belt west of Deering Reservoir (Plate I). It also crops out in the northeast corner of the quadrangle in a belt which can be traced northward to the type locality in the Mt. Kearsarge quadrangle.

The calc-silicate rocks are diopside-actinolite-plagioclase-quartz granofels with variable amounts of K-feldspar, grossularite, and biotite. The diopsides often form large porphyroblasts. These calc-silicates occur in layers which range in thickness from several centimeters to several meters. The intervening rock type is biotite-plagioclase-quartz granofels which often contains abundant fibrolite and/or garnet. This rock type is generally quite massive and forms somewhat rounded outcrops with a gray weathered surface. The fresh surfaces are dark gray to brown. Table 5 gives modes of the Warner Formation, and Table 6 gives chemical analyses.

In places, this unit also contains abundant zoned calc-silicate boudins or isolated zoned calc-silicate concretions. These boudins are found in both the calc-silicate rocks and the biotite-quartz granofels and probably result from the extension and boudinage of brittle, calc-silicate beds. The cores of the boudins may be composed of carbonate and weather to a punky, porous surface, or they may contain grossularite, in which case they are salmon pink. This core may grade outward to a grossularite + clinozoisite zone, followed by an actinolite zone, followed by a phlogopite + actinolite zone. These boudins are not diagnostic of the Warner Formation since they are occasionally found in the Crotched Mountain and Littleton Formations. But the vast majority of all calc-silicate boudins found in the Hillsboro quadrangle are in the Warner Formation.

This unit at times contains cordierite-rich layers and also flecky gneisses. The latter are segregations within pelitic granofels which consist of a garnet core surrounded by a leucosome, or mantle, of quartzo-feldspathic material. The flecks have been studied by D.R. Nielson (1973, 1974) who concludes that they are formed by metamorphic differentiation. Three of the analyses in Table 6 (128, 131, 159) are whole rock analyses of fleck-bearing rocks. The relatively low $SiO_2$, and high FeO and $Al_2O_3$ show that the flecks form in rocks which were originally deposited as iron-rich muds. Four of the modes in Table 5 are of matrices of flecky gneisses.

As a whole, the Warner Formation was deposited as a series of iron-magnesium carbonates and muds rich in iron, magnesium, and aluminum with variable amounts of quartz detritus. Sulfides are locally abundant within the unit in central New Hampshire; however, they are relatively rare in the Hillsboro quadrangle. The calc-silicate units tend to decrease in abundance toward the south end of the Hillsboro quadrangle. Correlation with units in adjacent quadrangles is tenuous. Heald (1950) and Chapman (1952) have mapped "lime-silicate granulites" within the Hubbard Hill Member of the Littleton Formation in the Lovewell Mountain and Sunapee quadrangles. Fowler-Billings (1949) mentions the presence of calc-silicate "concretions" within the Littleton Formation in the Monadnock quadrangle. However, it has already been suggested that the presence of concretions is not unique to the Warner Formation. Greene (1970) has noted the occurence of "lime-silicate granulites" in all four of his members of the Littleton Formation. Vernon (1971) and Englund (1976) also mention the presence of calc-silicate rocks in the Concord and Holderness quadrangles. If this unit were everywhere as spectacular as it is in the southern part of the Mt. Kearsarge quadrangle, then it certainly would have received more attention by the above mentioned workers. It is quite probable, therefore, that the Warner area was the center of carbonate deposition for this unit, and that there is a sedimentary facies change to more pelitic rock types away from the type locality. The estimated maximum structural thickness of the Warner Member in the Hillsboro quadrangle is 940 meters (3000 feet).

Table 5 - Modes of the Warner Formation based on 1000 point counts. Analyses of Hi-92-72, Hi-128-72, Hi-131-72, and Hi-159-72 from D.R. Nielson (1974).

| | Hi-6-72 | Hi-40-72 | Hi-92-72 | Hi-95-72 | Hi-96-72 | Hi-128-72 | Hi-131-72 | Hi-147-73 | Hi-159-73 |
|---|---|---|---|---|---|---|---|---|---|
| Quartz | 57.5 | 26.4 | 62.4 | 28.3 | 13 | 14 | 31 | 25.9 | 23 |
| Plagioclase* | 21.1 | 20.0 | 24.3 | 4.6 | 6 | 25 | 15 | 12.9 | 11 |
| K feldspar | | | | .1 | 14 | 8 | | 1.9 | 2 |
| Diopside | | | 12.8 | 14.2 | | | | 10.3 | |
| Actinolite | | | | 18.8 | | | | 47.5 | |
| Muscovite | | .2 | | 4.1 | 27 | tr | 1 | | 2 |
| Biotite | 19.5 | 23.7 | | .8 | 37 | 25 | 25 | | 34 |
| Garnet | .1 | 11.4 | | | 3 | | 5 | | |
| Sillimanite | | | | | | 1 | 2 | | 7 |
| Andalusite | | | | | | 14 | 1 | | 18 |
| Apatite | .4 | .2 | | | | | | .6 | |
| Sphene | | | .4 | | | | | .7 | |
| Graphite | 1.4 | .4 | .1 | .6 | tr | 1 | 1 | .3 | tr |
| Ilmenite | tr | tr | tr | .4 | tr | 1 | 1 | tr | tr |
| Clinozoisite | | 1.3 | | 3.6 | | | | tr | |
| Staurolite | | | | | | 10 | 17 | | |
| Chlorite | | | | 24.4 | | | | | 2 |
| Hypersthene | | 16.4 | | | | | | | |
| FeOx | | | | .1 | | | | | |
| *percent An of plagioclase | 49 | 61 | 45 | 50 | 60 | 36 | | 66 | 25 |

| | |
|---|---|
| Hi-6-72 | Biotite-plagioclase quartz granofels. Blasted outcrop on W side of paved road .3 mi. S of old cemetery SW of Deering Reservoir, Town of Deering. |
| Hi-40-72 | Garnet-hypersthene-biotite granofels. Along dirt road .2 mi. NE of Bear Pond, Town of Warner. |
| Hi-92-72 | Diopside-plagioclase-quartz granofels. .6 mi. W of Stanley Hill, Town of Warner. |
| Hi-95-72 | Actinolite-diopside- calc-silicate. W side of hill just E of Clark Hill, Town of Warner. |
| Hi-96-72 | Flecky gneiss. Same location as Hi-95-72. |
| Hi-128-72 | Flecky gneiss. Along access road to the W side of Deering Reservoir, .3 mi. from fork in road at the head of the lake, Town of Deering. |
| Hi-131-72 | Flecky gneiss. Along access road to W side of Deering Reservoir, 14 mi. from fork in road at the head of the lake, Town of Deering. |
| Hi-147-73 | Diopside-actinolite calc-silicate. 100 feet S into woods from farm SW of Cove Hill, Town of Deering. |
| Hi-159-73 | Flecky gneiss. Behind Sprague house, .3 mi. due W of Deering Reservoir, Town of Deering. |

Table 6 - Chemical analyses of the Warner Formation. Descriptions and locations are listed in Table 5. All the analyses were by the author.

| | Hi-95-72 | Hi-128-72 | Hi-131-72 | Hi-159-73 |
|---|---|---|---|---|
| $SiO_2$ | 56.0 | 52.9 | 53.9 | 54.4 |
| $TiO_2$ | .77 | 1.15 | 1.17 | 1.21 |
| $Al_2O_3$ | 14.1 | 23.3 | 21.4 | 23.3 |
| FeO* | 7.13 | 9.05 | 9.88 | 8.35 |
| MnO | .54 | .20 | .14 | .10 |
| MgO | 7.42 | 3.24 | 3.36 | 2.52 |
| CaO | 11.29 | 2.47 | 1.19 | .77 |
| $Na_2O$ | .51 | 1.52 | 1.11 | 1.11 |
| $K_2O$ | .65 | 3.14 | 3.76 | 4.40 |
| $H_2O^+$ | 1.40 | .87 | 1.46 | 1.47 |
| $H_2O^-$ | .03 | .04 | .03 | .01 |
| $P_2O_5$ | .26 | .13 | .23 | .16 |
| Total | 100.4 | 98.0 | 97.6 | 97.8 |

* Total Fe calculated as FeO

## Littleton Formation

The Littleton Formation contains a thick sequence of alternating metasandstones and metashales which lie stratigraphically above the Warner Formation.

This unit is identical to that which forms the northern and western slopes of Mt. Kearsarge in the Mt. Kearsarge quadrangle. From here it has been traced to the flanks of Mt. Moosilauke by J.B. Lyons (personal communication). Rumble and Boucot (in press) have found Lower Devonian fossils here. The rock types grade from metaquartzite to biotite-sillimanite-quartz schist with variable amounts of andalusite, oligoclase, K-feldspar, muscovite, cordierite, and garnet (Table 7). Graphite and ilmenite are common accessory minerals with pyrrhotite being a rare accessory. Chemical analyses of the Littleton Formation are given in Table 8. The rock often shows graded bedding or is rhythmically-bedded. It also contains rather massive layers of sillimanite-garnet-biotite-quartz schist. Some isolated calc-silicate concretions have been found.

Figure 2 shows a typical rhythmically bedded outcrop from near the top of Craney Hill in the Hillsboro quadrangle. Here the metasandstone layers are massive and separated from one another by

Table 6 - Chemical analyses of the Warner Formation. Descriptions and locations are listed in Table 5. All the analyses were by the author.

| | Hi-95-72 | Hi-128-72 | Hi-131-72 | Hi-159-73 |
|---|---|---|---|---|
| $SiO_2$ | 56.0 | 52.9 | 53.9 | 54.4 |
| $TiO_2$ | .77 | 1.15 | 1.17 | 1.21 |
| $Al_2O_3$ | 14.1 | 23.3 | 21.4 | 23.3 |
| FeO* | 7.13 | 9.05 | 9.88 | 8.35 |
| MnO | .54 | .20 | .14 | .10 |
| MgO | 7.42 | 3.24 | 3.36 | 2.52 |
| CaO | 11.29 | 2.47 | 1.19 | .77 |
| $Na_2O$ | .51 | 1.52 | 1.11 | 1.11 |
| $K_2O$ | .65 | 3.14 | 3.76 | 4.40 |
| $H_2O^+$ | 1.40 | .87 | 1.46 | 1.47 |
| $H_2O^-$ | .03 | .04 | .03 | .01 |
| $P_2O_5$ | .26 | .13 | .23 | .16 |
| Total | 100.4 | 98.0 | 97.6 | 97.8 |

* Total Fe calculated as FeO

## Littleton Formation

The Littleton Formation contains a thick sequence of alternating metasandstones and metashales which lie stratigraphically above the Warner Formation.

This unit is identical to that which forms the northern and western slopes of Mt. Kearsarge in the Mt. Kearsarge quadrangle. From here it has been traced to the flanks of Mt. Moosilauke by J.B. Lyons (personal communication). Rumble and Boucot (in press) have found Lower Devonian fossils here. The rock types grade from metaquartzite to biotite-sillimanite-quartz schist with variable amounts of andalusite, oligoclase, K-feldspar, muscovite, cordierite, and garnet (Table 7). Graphite and ilmenite are common accessory minerals with pyrrhotite being a rare accessory. Chemical analyses of the Littleton Formation are given in Table 8. The rock often shows graded bedding or is rhythmically-bedded. It also contains rather massive layers of sillimanite-garnet-biotite-quartz schist. Some isolated calc-silicate concretions have been found.

Figure 2 shows a typical rhythmically bedded outcrop from near the top of Craney Hill in the Hillsboro quadrangle. Here the metasandstone layers are massive and separated from one another by

Table 7 - Modes of the Littleton Formation based on point counts of 1000 grains.

|  | Hi-44-72 | Hi-46-72 | Hi-125-72 | Hi-144-73 | Hi-149-73 | Hi-177-73 | Hi-180-73 |
|---|---|---|---|---|---|---|---|
| Quartz | 69.3 | 50.3 | 54.1 | 30.7 | 26.7 | 43.4 | 39.4 |
| Plagioclase* | 2.9 | .6 | 3.0 |  | .5 | .7 | .7 |
| K feldspar | 1.0 |  | .2 |  | 14.7 | 3.7 | 1.6 |
| Muscovite | 2.5 | 16.9 | 5.4 | 37.2 | .3 | 4.5 | 1.4 |
| Biotite | 14.9 | 22.8 | 23.9 | 14.9 | 37.0 | 13.4 | 34.5 |
| Garnet |  | 2.4 | .6 | 8.9 | .1 | 2.1 | .1 |
| Sillimanite | 3.8 | .7 | 11.1 | 5.3 | 19.9 | 28.4 | 21.0 |
| Andalusite | 2.9 | 4.4 |  |  |  |  |  |
| Apatite | tr | tr | tr | tr | tr | .2 | .1 |
| Graphite | tr | .4 | .5 | 2.8 | .5 | 1.2 | 1.0 |
| Pyrrhotite | 1.4 | 1.4 |  | .2 |  |  | .2 |
| Ilmenite | tr | .1 | .7 | tr | .2 | .4 | tr |
| Zircon | tr | tr | tr | tr | tr | tr | tr |
| Cordierite |  |  | .5 |  |  | 2.0 |  |
| *percent An of plagioclase | 23 | 25 | 30 |  | 26 | 25 | 31 |

| | |
|---|---|
| Hi-44-72 | Sillimanite-biotite-quartz granofels. From access road to Craney Hill fire tower, Town of Henniker. |
| Hi-46-72 | Muscovite-biotite-quartz granofels. Same location as Hi-44-72. |
| Hi-125-72 | Sillimanite-biotite-quartz granofels. Outcrop in kink in road at top of Sodom Hill, Town of Deering. |
| Hi-144-73 | Thinly bedded garnet-muscovite-quartz schist. From southern outlet of Mud Pond, SW of Dudley Pond, Town of Deering. |
| Hi-149-73 | Sillimanite-biotite schist. On knoll 1.3 mi. NW of Chase Village, .6 mi. S of Hillsboro Co. line, Town of Weare. |
| Hi-177-73 | Biotite-sillimanite-quartz schist. Above small pegmatite mine on the NNW flank of Wilson Hill, Town of Deering. |
| Hi-180-73 | Sillimanite-biotite-quartz schist. Just W of road at top of hill S of Morrill Pond, Town of Henniker. |

Table 8 - Chemical analyses of the Littleton Formation. Descriptions and locations are listed in Table 7. All analyses were by the author.

| | Hi-44-72 | Hi-46-72 | Hi-144-73 |
|---|---|---|---|
| $SiO_2$ | 76.7 | 65.1 | 59.5 |
| $TiO_2$ | .65 | 1.08 | 1.36 |
| $Al_2O_3$ | 10.0 | 16.7 | 21.2 |
| FeO* | 4.76 | 7.22 | 7.47 |
| MnO | .05 | .09 | .07 |
| MgO | 1.52 | 2.32 | 1.30 |
| CaO | .62 | .23 | .19 |
| $Na_2O$ | 1.78 | .89 | .67 |
| $K_2O$ | 1.08 | 3.08 | 4.13 |
| $H_2O^+$ | .58 | 1.15 | 1.00 |
| $H_2O^-$ | .07 | .09 | -- |
| $P_2O_5$ | .11 | .12 | .05 |
| Total | 97.9 | 98.1 | 96.9 |

* Total Fe calculated as FeO

layers of biotite-sillimanite-quartz schist which represent original shaly layers. Note the large sillimanite porphyroblast in the metashale layer. These large porphyroblasts are common in the Littleton Formation, but are never quite as blocky as those found in the Crotched Mountain Formation. Both were products of a similar tectonic-sedimentary environment which resulted in turbidites and rhythmically-bedded sands and shales. In a qualitative way, the Crotched Mountain Formation contains more metashale and rusty weathering mica schist than the Littleton Formation. As was mentioned with respect to the Warner Formation, the original sedimentary environment was probably characterized by facies variation. Therefore, at this time, the criteria which will best distinguish the Crotched Mountain from the Littleton Formation are its position within the stratigraphic sequence, thickness of the unit, and the abundance of rusty-weathering pelitic units within the Crotched Mountain. The top of the Littleton Formation has not been recognized in the Hillsboro quadrangle. It is therefore not possible to estimate the total thickness of the unit, but the wide areas underlain by this rock type suggest thicknesses of several kilometers.

**Figure 2.**
Photograph of the Littleton Fm. on Craney Hill. Note the massive metasandstone layers separated by thin layers of metashale which contain large sillimanite porphyroblasts. Lens cap for scale.

Correlation of the Littleton Formation with units in adjacent quadrangles is again rather tenuous. It is probably equivalent to the Hubbard Hill Member in the Lovewell Mountain quadrangle (Heald, 1950) and the Sunapee quadrangle (Chapman, 1952), and the extension of these rocks into the Monadnock quadrangle (Fowler-Billings, 1949). It is possible that some parts of the Peterborough Member in the Peterborough quadrangle (Greene, 1970) will correlate with the Littleton Formation.

### Age and Correlation of the Stratigraphic Sequence

The stratigraphic sequence which has been established for the Hillsboro quadragle is summarized in Figure 3. The lithologic character and stratigraphic succession of the metasediments of the Hillsboro quadrangle is quite similar to Paleozoic rocks of the Merrimack Synclinorium in Maine (Moench and Boudette, 1970). The author favors the following correlations on the basis of lithology and stratigraphic succession. The Crotched Mountain Formation is similar to the Perry Mountain Formation of Silurian age. The rusty-weathering portion of the Crotched Mountain is lithologically similar to the Ordivician Partridge Formation, and thus the Crotched Mountain Formation may be in part Ordivician and correlated with the Partridge Formation.

It is clear that a thick sequence of polymictic conglomerate correlative with the Rangely Formation has not been found in central New Hampshire, but the presence of conglomeratic beds in the Crotched Mountain Formation suggests that the unit may also be partly correlative with the Silurian Rangely Formation. The Smalls Falls Formation of Silurian age is strikingly similar to the Francestown Formation as is the Silurian Madrid Formation with the Warner Formation. The Littleton Formation is lithologically similar to, and probably correlative with, the Lower Devonian Seboomook Formation.

Mapping by Boone (1973) in the Little Bigelow Mountain area of Maine suggests another possible but less likely correlation. In this area, the typical Seboomook is underlain by the Lower Devonian Carrabassett Formation. It is therefore possible that the Francestown and Warner Formations could be correlative with the upper member of the Carrabassett, and the Crotched Mountain Formation could be correlated with the middle member of the Carrabassett. The Littleton Formation would still be equivalent to the Seboomook.

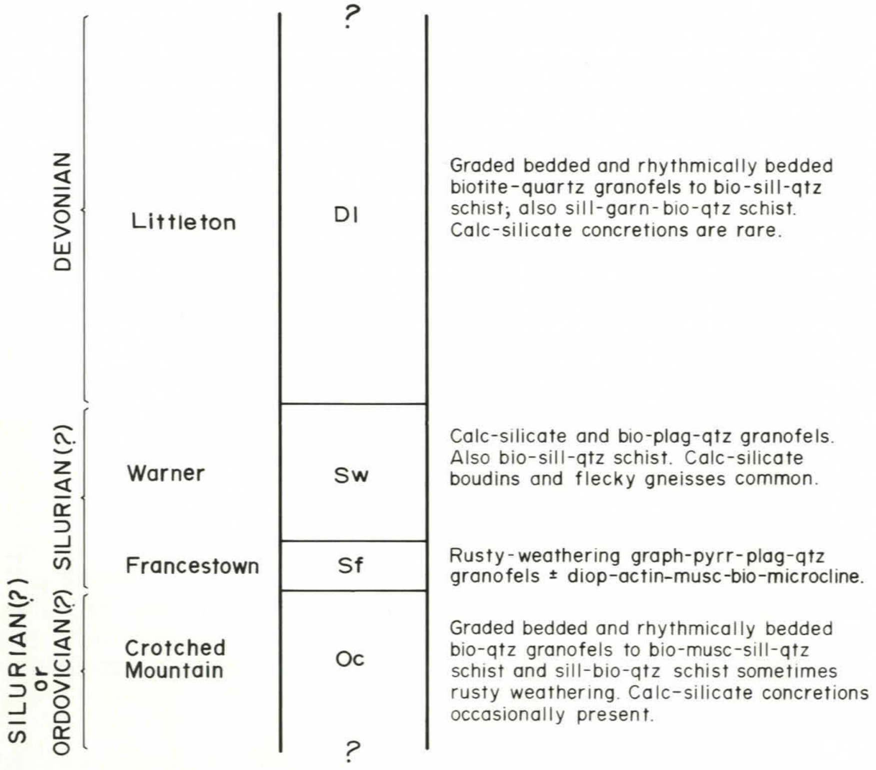


**Figure 3.**
Columnar section of metasedimentary rocks in the Hillsboro quadrangle.

# PLUTONIC ROCKS

## Introduction

The only intrusive rocks in the Hillsboro quadrangle which are not members of the New Hampshire Plutonic Series (Billings, 1956) are unmetamorphosed lamprophyre dikes which are thought to be members of the White Mountain Volcanic-Plutonic Series. The New Hampshire Series rocks are syn-kinematic to post-kinematic, and range in composition from actinolite gabbro to leuco-granite. However, most of the rocks are intermediate to felsic in composition.

The rocks of the New Hampshire Series have been divided into five mappable units in the Hillsboro quadrangle. From oldest to youngest the units are: 1. Kinsman Quartz Monzonite, 2. hypersthene quartz diorites and actinolite gabbros of the Spaulding Series, 3. biotite grandiorites and biotite tonalites of the Spaulding Series, 4. muscovite-biotite tonalites and granites of the Concord Granite, and 5. leuco-granites and aplites. Lyons and Livingstone (1977) have established Rb-Sr ages of 411 + 19 m.y. for the Kinsman Quartz Monzonite, 402 + 5 m.y. for the Spaulding Quartz Diorite, and 330 + 3 m.y. for the Concord Granite.

## Petrography and Field Relations

In this section the plutonic rocks of the Hillsboro quadrangle will be described in terms of mineralogy, textures, and field relations. The classification scheme used is that recommended by the IUGS Subcommission on the Systematics of Igneous Rocks (Streckeisen, 1973).

## Kinsman Quartz Monzonite

Much of the western part of the Hillsboro quadrangle is underlain by a portion of the Cardigan Pluton of the Kinsman Quartz Monzonite. The Kinsman has recently been described in detail by Clark (1972). The rock ranges from granodiorite to granite in composition. Table 9 lists chemical analyses and C.I.P.W. norms of three samples of the Kinsman from the Hillsboro quadrangle. The rock is characterized by the presence of K-feldspar megacrysts which may range up to 13 cm in length. These megacrysts, along with biotite, commonly define a strong foliation, but non-foliated varieties are not uncommon. Microscopically, the feldspars are often perthitic and commonly show microcline twinning. Cell refinements of these feldspars (J.B. Lyons, personal communication) show that the structural state is maximum microcline. Staining of the megacrysts has demonstrated that some are actually non-twinned plagioclase, although the plagioclase grains are generally smaller than the K-feldspar. Megacrysts of antiperthite

Table 9 - Chemical analyses and C.I.P.W. norms of the Kinsman Quartz Monzonite. All analyses by the author.

| | Hi-70-72 | Hi-108-72 | Hi-192-72 |
|---|---|---|---|
| $SiO_2$ | 69.9 | 65.5 | 64.5 |
| $TiO_2$ | .40 | .95 | 1.28 |
| $Al_2O_3$ | 14.8 | 15.6 | 16.4 |
| FeO* | 3.21 | 4.80 | 5.44 |
| MnO | .07 | .06 | .08 |
| MgO | .81 | 1.41 | 1.72 |
| CaO | 1.89 | 2.97 | 3.39 |
| $Na_2O$ | 2.68 | 2.99 | 2.71 |
| $K_2O$ | 4.49 | 3.52 | 3.00 |
| $H_2O^+$ | .73 | .27 | .21 |
| $H_2O^-$ | .03 | .03 | -- |
| $P_2O_5$ | .16 | .36 | .19 |
| Total | 99.2 | 98.5 | 98.9 |

*Total Fe calculated as FeO

| | Hi-70-72 | Hi-108-72 | Hi-192-72 |
|---|---|---|---|
| Q | 29.88 | 23.83 | 24.31 |
| Or | 26.53 | 20.80 | 17.73 |
| Ab | 22.68 | 25.30 | 22.93 |
| An | 8.33 | 12.38 | 15.58 |
| C | 2.48 | 2.33 | 2.99 |
| En | 2.02 | 3.51 | 4.28 |
| Fs | 5.63 | 7.36 | 8.02 |
| Il | .76 | 1.80 | 2.43 |
| Ap | .37 | .83 | .44 |
| Total | 98.41 | 98.16 | 98.71 |

| | |
|---|---|
| Hi-70-72 | Kinsman Quartz Monzonite with some chlorite after garnet. Along Hwy 114, .6 mi. NW of intersection with N-trending dirt road which goes past Windsor Work Peak, Town of Henniker. |
| Hi-108-72 | Biotite-bearing Kinsman Quartz Monzonite. On dirt road E of Loon Pond .6 mi. NW of creek feeding NE corner of pond, Town of Hillsboro. |
| Hi-192-73 | Kinsman Quartz Monzonite with biotite after garnet. Along paved road about 1.1 mi. ESE of Bradford Center, Town of Bradford. |

have also been found. The compositional range of seven samples of plagioclase in Kinsman rocks from the Hillsboro quadrangle is $An_{26}$ to $An_{35}$.

The Kinsman is often characterized by the presence of almandine as a primary igneous phase. Similar garnet-bearing calc-alkaline igneous rocks have been described from the Piscataquis Volcanics in Maine (Rankin, 1968), the Borrowdale Volcanic Group of Northern England (Fitton, 1972), and from Victoria (Green and Ringwood, 1968). Green and Ringwood (1968) have shown that the garnets would be crystallized from an acid calc-alkaline magma at pressures of 9 to 18 kilobars, which corresponds with pressures in the lower crust or upper mantle. The garnets are preserved at lower pressures by rapid ascent to the surface, and chilling in the case of the garnet-bearing volcanic rocks. The presence of graphite in the Kinsman may have lowered the oxygen fugacity sufficiently to stabilize garnet at lower pressures (Hsu, 1968; Clark, 1972). Garnet is apparently less abundant in the Hillsboro quadrangle than it is in areas to the north. In a qualitative way, garnets or biotite pseudomorphs after garnet are more abundant in the northern areas of the quadrangle than in the southern areas. Often the garnets are surrounded by biotite or there are well-formed pseudomorphs of biotite after garnet. The conversion of garnet to biotite has been attributed to the reaction

$$\text{Garnet} + K^{+} = \text{Biotite} + Al^{+++} + O^{--}$$

(Lyons and others, 1973). Many times the rock also contains primary biotite. Also, it is not uncommon to find small garnet concentrations which are roughly tabular and may be 20 cm thick and a meter or more long. These features have been described as restites which are left after the partial fusion of metasedimentary xenoliths (Clark, 1972).

Several percent muscovite may be present within the Kinsman. Common accessory minerals are pyrrhotite, zircon, apatite, and graphite. Sillimanite and cordierite are also found in minor amounts (Heald, 1950; Clark, 1972).

On a regional scale, the Cardigan Pluton is concordant with the enclosing schists. However, Plate I shows its discordant nature in the Hillsboro quadrangle. In contrast to the other intrusives, the Kinsman underlies hilly, high ground. The unit tends to weather into large boulders which have been widely redistributed by Pleistocene glaciation.

## Spaulding Quartz Diorite and Related Rocks

Five plutons of biotite granodiorite have been mapped in the Hillsboro quadrangle. The series has been termed biotite quartz monzonites by Nielson and others (1973; 1976), but this is a field term, and laboratory studies have shown that the rocks are granodiorites. Other plutons of biotite granodiorites have been found in the Mt. Kearsarge, Penacook, Concord, Milford, and Peterborough quadrangles. The rock type is generally a biotite granodiorite by the classification of Streckeisen (1973); however, associated rocks range in composition from actinolite gabbro to biotite granites. The rocks have a medium grain size and may be either foliated or massive. Chemical analyses and C.I.P.W. norms of some of these rocks are given in Table 10. Table 11 lists some representative modes.

The biotite granodiorites are principally made up of quartz, K-feldspar, and plagioclase with up to 16 percent biotite. They are recognized in the field by the predominance of biotite over muscovite, which serves to distinguish these rocks from the Concord Granite. The non-porphyritic texture distinguishes it from the Kinsman. The plagioclases are oligoclase-andesine; the K-feldspars are microcline, commonly perthitic. Hypersthene or garnet are sporadically present, and some aggregates of biotite are probable pseudomorphs after garnet. Texturally the rocks are allotriomorphic or hypidiomorphic granular; cataclastic textures are not uncommon.

The biotite granodiorites are similar to the Spaulding Quartz Diorites of the Monadnock quadrangle (Fowler-Billings, 1949) and in many places may grade into Spaulding-type rocks. The biotite granodiorites are distinguished from the Spaulding by the presence of K-feldspar.

Chemical analyses and modes of Spaulding rocks (Tables 10 and 11, Hi-81-72, Hi-172-73, Mon-1-73) show that these rocks contain a high percentage of biotite and little or no K-feldspar. In general they are tonalites, and one (Mon-1-73) plots as a quartz-rich granitoid. The biotite granodiorites are generally deuterically altered, with the feldspars going to white micas, and biotites and garnets altering to chlorite.

These rocks form five separate plutons in the Hillsboro quadrangle (Plate I). The Antrim Pluton lies between the towns of Antrim and Hillsboro along the eastern margin of the Cardigan Pluton. The area underlain by the pluton forms a large valley which has been filled with sands and gravels of Pleistocene outwash. Outcrops of the intrusive are sparse except near the contacts. On the west side of the pluton, on Meetinghouse Hill, inclusions of Kinsman within the biotite granodiorite suggest that at least the margins of the Kinsman were crystallized at the time of injection of the Antrim Pluton.

The Deering Pluton (Plate I) stretches northward from the lower slopes of Crotched Mountain to about 2 km north of the Weare Reservoir. Again, this pluton occupies a valley which is filled with glacial tills and outwash. Outcrops are abundant on Lincoln Hill, but otherwise sparse. Where the contact crosses the road about 1/2 km north of the cemetery north of Weare Reservoir, the rock is made up of zoned plagioclase with a composition of about $An_{46}$ and hornblende. A microprobe analysis of the hornblende is given in Table 12. A small portion of biotite granodiorite just north of the Deering Pluton probably represents a northward extension of that body.

Table 10 - Chemical analyses and C.I.P.W. norms of biotite granodiorite and related rocks. Descriptions and locations of samples are listed in Table 11. All analyses were by the author.

| | Hi-62-72 | Hi-81-72 | Hi-91-72 | Hi-1-72 | Hi-198-72 |
|---|---|---|---|---|---|
| $SiO_2$ | 67.6 | 63.3 | 71.4 | 45.1 | 59.5 |
| $TiO_2$ | .53 | 1.02 | .15 | .25 | .98 |
| $Al_2O_3$ | 16.1 | 16.7 | 14.4 | 15.7 | 16.5 |
| FeO* | 3.45 | 4.54 | 1.67 | 12.78 | 6.57 |
| MnO | .05 | .04 | .03 | .11 | .12 |
| MgO | 1.18 | 2.22 | .43 | 8.08 | 4.49 |
| CaO | 2.23 | 4.38 | .97 | 12.04 | 5.87 |
| $Na_2O$ | 3.35 | 3.08 | 3.26 | 1.08 | 2.82 |
| $K_2O$ | 3.98 | 2.74 | 5.20 | .32 | 2.32 |
| $H_2O^+$ | .41 | .35 | .20 | .74 | .24 |
| $H_2O^-$ | .07 | .03 | .03 | .18 | -- |
| $P_2O_5$ | .27 | .40 | .30 | -- | .20 |
| Total | 99.2 | 98.9 | 98.0 | 96.4 | 99.6 |

*Total Fe calculated as FeO

| | Hi-62-72 | Hi-81-72 | Hi-91-72 | Hi-1-72 | Hi-198-72 |
|---|---|---|---|---|---|
| Q | 24.58 | 20.28 | 29.50 | | 11.15 |
| Or | 23.52 | 16.19 | 30.73 | 1.89 | 13.71 |
| Ab | 28.35 | 26.06 | 27.59 | 9.14 | 23.86 |
| An | 9.30 | 19.12 | 2.46 | 37.05 | 25.51 |
| C | 2.87 | 1.66 | 2.51 | | |
| En | 2.94 | 5.53 | 1.07 | 11.21 | 20.91 |
| Fs | 5.55 | 6.69 | 2.93 | | |
| Il | 1.01 | 1.94 | .28 | .47 | 1.86 |
| Ap | .63 | .93 | .83 | | .46 |
| Di | | | | 18.86 | 1.90 |
| Fo | | | | 7.41 | |
| Fa | | | | 9.44 | |
| | 98.74 | 98.40 | 97.90 | 95.46 | 99.37 |

Table 10 - (cont.)

| | Co-29-72 | Mon-1-73 | Mon-2-73 | Pb-1-73 |
|---|---|---|---|---|
| $SiO_2$ | 48.8 | 67.2 | 63.4 | 68.7 |
| $TiO_2$ | .46 | .76 | .73 | .63 |
| $Al_2O_3$ | 18.2 | 15.9 | 16.4 | 16.3 |
| FeO* | 7.82 | 4.05 | 4.98 | 4.15 |
| MnO | .18 | .08 | .09 | .10 |
| MgO | 10.48 | 1.48 | 3.26 | 1.67 |
| CaO | 10.36 | 1.77 | 3.98 | 2.82 |
| $Na_2O$ | 1.30 | 2.56 | 3.05 | 3.24 |
| $K_2O$ | .33 | 3.92 | 2.55 | 2.88 |
| $H_2O^+$ | .28 | .60 | .58 | .66 |
| $H_2O^-$ | .31 | .12 | .31 | .27 |
| $P_2O_5$ | -- | .19 | .05 | .08 |
| Total | 98.15 | 98.6 | 99.4 | 101.5 |

*Total Fe calculated as FeO

| | Co-29-72 | Mon-1-73 | Mon-2-73 | Pb-1-73 |
|---|---|---|---|---|
| Q | | 28.96 | 18.96 | 27.44 |
| Or | 1.95 | 23.17 | 15.07 | 17.02 |
| Ab | 11.00 | 21.66 | 25.81 | 27.42 |
| An | 42.85 | 7.54 | 19.42 | 13.47 |
| C | | 4.68 | 1.51 | 2.92 |
| En | 28.12 | 3.69 | 8.12 | 4.16 |
| Fs | | 6.33 | 8.11 | 6.77 |
| Il | .87 | 1.44 | 1.39 | 1.20 |
| Ap | | .44 | .12 | .19 |
| Di | 6.93 | | | |
| Fo | 3.91 | | | |
| Fa | 2.30 | | | |
| Total | 97.93 | 97.91 | 98.49 | 100.57 |

Table 11 - Modes of biotite granodiorites and some related rocks, based on 1000 point counts.

| | Hi-9-72 | Hi-13-72 | Hi-34-72 | Hi-62-72 | Hi-81-72 | Hi-87-72 | Hi-91-72 | Hi-94-72 |
|---|---|---|---|---|---|---|---|---|
| Quartz | 41.6 | 39.5 | 38.5 | 31.6 | 36.6 | 39.7 | 43.3 | 38.0 |
| K feldspar | 14.3 | 26.8 | 9.1 | 16.9 | | 38.2 | 25.2 | 5.5 |
| Plagioclase* | 31.4 | 10.4 | 33.5 | 36.2 | 36.0 | 16.4 | 22.5 | 45.6 |
| Biotite | 1.1 | 9.2 | 15.8 | 11.7 | 23.1 | 1.2 | 3.4 | 3.4 |
| Muscovite | .4 | 13.0 | 3.9 | 3.2 | | 3.6 | 1.7 | 6.6 |
| Garnet | .7 | | | | | .1 | tr | |
| Chlorite | 9.1 | | | .2 | 3.0 | .7 | 1.5 | .8 |
| Ilmenite | .4 | 1.0 | .1 | .1 | .5 | .1 | .2 | .1 |
| Calcite | 1.0 | | | | | | | |
| Zircon | | | tr | | | | | |
| Apatite | tr | tr | .2 | .1 | .7 | tr | tr | tr |
| Sillimanite | | | | | | | 2.2 | |
| *percent An of plagioclase | 25 | 30 | 30 | 28 | 40 | 28 | 23 | 21 |

| | Hi-103-72 | Hi-172-73 | Pb-1-73 | Mon-1-72 | Mon-2-73 | Hi-1-72 | Hi-198-73 | Co-29-72 |
|---|---|---|---|---|---|---|---|---|
| Quartz | 26.1 | 34.3 | 43.6 | 44.5 | 37.6 | | 11.3 | 1.5 |
| K Feldspar | 6.2 | | .4 | | | | 1.6 | |
| Plagioclase* | 52.9 | 39.8 | 31.7 | 20.0 | 30.9 | 44.6 | 57.2 | 48.2 |
| Biotite | 10.7 | 23.7 | 15.6 | 20.8 | 30.3 | | 13.1 | |
| Muscovite | 2.7 | | 7.9 | 13.7 | | | | |
| Chlorite | .6 | | .1 | | | | | |
| Ilmenite | .4 | .6 | .2 | .9 | 1.2 | | .4 | |
| Zircon | | | tr | | | | | |
| Apatite | tr | .6 | .4 | .2 | tr | | | |
| Clinozoisite | | 1.1 | | | | 1.9 | | |
| Garnet | | | .1 | | | | | |
| Amphibole | | | | | | 40.7 | | 49.5 |
| Hypersthene | | | | | | | 16.1 | |
| Pyrrhotite | | | | | | 12.8 | | .7 |
| *percent An of plagioclase | 31 | 36 | 29 | 26 | 42 | 70 | 63 | 72 |

Table 11 - (cont.)

| | |
|---|---|
| Hi-1-7 | Actinolite Gabbro. Outcrop along dirt road SE of Clement. Hill, 2 mi. N of intersection with E-W road, Town of Hopkinton. |
| Hi-13-72 | Biotite grandiorite. Outcrop in field .1 mi. SE of fork in road, .6 mi. E of Antrim Center, Town of Antrim. |
| Hi-9-72 | Biotite granodiorite. Blasted outcrop .3 mi. N of Holton, Town of Deering. |
| Hi-34-72 | Biotite granodiorite. NW side of Riley mountain, Town of Antrim. |
| Hi-62-72 | Biotite granodiorite. Along chair lift of Onset Ski area, N flank of Crotched Mtn., Town of Francetown. |
| Hi-81-72 | Biotite tonalite. Outcrops in sand quarry E of Clement Hill, Town of Hopkinton. |
| Hi-87-72 | Biotite granite. E flank of Clough Hill, Town of Hopkinton |
| Hi-91-72 | Biotite granite. Top of Stanley Hill, Town of Warner. |
| Hi-94-72 | Muscovite-biotite granodiorite. S slope of hill NE of Craney Hill, Town of Henniker. |
| Hi-103-72 | Biotite granodiorite. Outcrop along Hwy 202 about 2.3 mi. NE of Antrim, Town of Antrim. |
| Hi-172-73 | Biotite tonalite. Spaulding Quartz Diorite Along New Boston - Weare town line, .25 W of quadrangle boundary. |
| Hi-198-73 | Hypersthene-biotite quartz diorite. Spaulding Quartz Diorite Camp Merrimack, Town of Hopkinston. |
| Pb-1-73 | Biotite tonalite. .2 mi. SE of railroad tracks, in South Lyndeborough, Peterborough quadrangle. |
| Mon-1-73 | Quartz-rich granitoid. Spaulding Quartz Diorite. On dirt road SE flank of Sunset Hill, Town of Dublin, Monadnock quadrangle. |
| Mon-2-73 | Biotite tonalite. Spauling Quartz Diorite .5 mi .W of road lintersection W of Stone Pond, Town of Marlboro, Monadnock quadrangle. |
| Co-29-72 | Actinolite gabbro. On Hwy 127 on W flank of Emerson Hill, Concord quadrangle, Town of Hopkinton. |

Table 12 - Electron microprobe analyses of amphiboles from plutonic rocks in central New Hampshire.

| | Hi-32-72 | Hi-1-72 | Pe-18-72 | Co-1-72 |
|---|---|---|---|---|
| $SiO_2$ | 43.04 | 54.35 | 51.96 | 47.89 |
| $TiO_2$ | .94 | .44 | .55 | 1.04 |
| $Al_2O_3$ | 10.90 | 4.28 | 7.37 | 11.98 |
| FeO* | 18.74 | 7.34 | 4.70 | 8.02 |
| MnO | .18 | .19 | .14 | .25 |
| MgO | 8.78 | 18.78 | 20.43 | 15.62 |
| CaO | 11.15 | 12.29 | 12.65 | 12.38 |
| $Na_2O$ | 1.38 | .67 | 1.54 | 1.84 |
| $K_2O$ | .33 | .27 | .02 | .18 |
| $Cr_2O_3$ | .04 | .11 | .82 | .04 |
| Total | 97.48 | 98.73 | 100.18 | 99.24 |

*Total Fe calculated as FeO

Formula on basis of 23 oxygens:

| | Hi-32-72 | Hi-1-72 | Pe-18-72 | Co-1-72 |
|---|---|---|---|---|
| Si | 6.475 | 7.560 | 7.097 | 6.716 |
| Al | 1.525 | .440 | .903 | 1.284 |
| | 8.000 | 8.000 | 8.000 | 8.000 |
| Al | .761 | .260 | .279 | .695 |
| Fe | 2.357 | .850 | .533 | .938 |
| Ti | .105 | .046 | .056 | .107 |
| Mn | .022 | .022 | .012 | .028 |
| Mg | 1.968 | 3.918 | 4.156 | 3.263 |
| Cr | .004 | .008 | | |
| | 5.217 | 5.104 | 5.036 | 5.031 |
| Na | .401 | .180 | .404 | .498 |
| Ca | 1.796 | 1.832 | 1.847 | 1.860 |
| K | .062 | .080 | .004 | .028 |
| | 2.259 | 2.092 | 2.255 | 2.386 |

| | |
|---|---|
| Hi-1-72 | Actinolite from actinolite gabbro. Outcrop along dirt road SE of Clement Hill, .2 mi. N of intersection with E-W road, Town of Hopkinton. D.L. Nielson, analyst. |
| Hi-32-72 | Hornblende from contact zone of biotite granodiorite. On road about .5 Km north of the cemetery which is N of Weare Reservoir, Town of Weare, Hillsboro quadrangle. D.L. Nielson, analyst. |
| Pe-18-72 | Pargasite from slightly altered ultramafic, probably a result of the reaction augite → pargasite. From Canterbury Quarry, Penacook quadrangle. D.R. Nielson, analyst. (D.R. Nielson, 1974) |
| Co-1-72 | Hornblende from monzo-diorite associated with soapstone. From Mt. Misery Quarry, Concord quadrangle. D.R. Nielson, analyst. (D.R. Nielson, 1974). |

The extreme southeast corner of the quadrangle is cut by another biotite granodiorite pluton which continues into the Concord, Peterborough, and Milford quadrangles. The only sample collected from this body shows that the lithology is very similar to the Spaulding Quartz Diorite, but this sample may represent a contact phase since many of the other rocks observed in this pluton are lighter in color.

The Hopkinton Pluton of the Spaulding Quartz Diorite is located in the northeast corner of the quadrangle. Again, exposures are poor, and the pluton underlies a topographic low which now contains copious amounts of Pleistocene outwash sands. In contrast with the other plutons which have been mapped as biotite granodiorites, this pluton exhibits an extremely varied lithology; rocks both more felsic and more mafic than the normal biotite granodiorites have been found. A second phase has been mapped within the Hopkinton Pluton. This phase is basically a hypersthene-biotite quartz diorite (Table 11, Hi-198-73) but does include phases of amphibole gabbro (Table 11, Hi-1-72, Co-29-72). As seen in Table 11, the amphibole gabbros are essentially equal mixtures of plagioclase and amphibole. A microprobe analysis of the amphibole from Hi-1-72 is given in Table 12. The analyses appear to be that of an actinolite, suggesting that these amphibole gabbros may be reworked inclusions of mafic or ultramafic rocks. The differences in $Al_2O_3$, FeO, and MgO contents between the chemistry of this amphibole and the contact phase of the Deering Pluton (Table 12, Hi-32-72) are quite striking. It is probable that the amphibole from the Deering contact zone is an igneous hornblende. It should be noted that amphiboles are quite rare in rocks of the New Hampshire Series, and that the mafic phase of the Hopkinton Pluton contains the first hypersthene-bearing rocks reported from the New Hampshire Series.

The hypersthene quartz diorites appear to grade into biotite tonalites which are essentially the same as the Spaulding Quartz Diorite of Fowler-Billings (1949). These Spaulding-type rocks grade into normal biotite granodiorites which in turn seem to grade into biotite-muscovite granites such as Hi-92-72 and Hi-87-72 (Table 11). In terms of biotite content, these rocks are similar to the Concord Granites (Table 14), but the absence of flow banding and the presence of garnet in some of the rocks suggest that they are felsic derivatives of the biotite grandiorite series.

## Concord Granite

The Concord Granite ranges in composition from muscovite-biotite tonalite to muscovite-biotite granite and forms three plutons in the Hillsboro quadrangle. The type locality of the Concord Granite is the large Concord Pluton in the Concord quadrangle. The rock is identified in the field by the occurrence of both primary biotite and muscovite, the absence of a metamorphic foliation, and the presence of good flow banding, especially near contacts (Fig. 4). Where the contacts are exposed, such as along Highway 114 west of Lake Massasecum, the pluton has brecciated the wall rocks during injection and it is clearly discordant.

Chemical analyses and C.I.P.W. norms of Concord rocks are given in Table 13, with modes given in Table 14. It appears that two types of binary rocks are present. The rocks from the Massasecum Pluton are binary tonalites. They contain oligoclase which makes up much of the rock. The K-feldspar is non-perthitic microcline and is not an abundant phase. The other type of Concord rock is typified by sample Hi-55-72 (Tables 13 and 14) from the Clinton Grove Pluton (Plate I). This rock is characterized by abundant microcline perthite, which reflects its high $K_2O$ content. A sample from the Henniker Pluton (Table 14, Hi-47-72) appears to be intermediate between the two major categories of Concord-type rocks. At this time there is not enough evidence to indicate whether there are two separate series of binary rocks or whether these rocks are different end members of the same series.

Like the biotite granodiorites, the binary Concord rocks weather easily and underlie low areas which are typically filled with outwash and ground-moraine material. Gravity studies indicate that these plutons are thicker than the biotite granodiorite plutons, typically reaching depths of about 2 km (Nielson and others, 1976).

## Aplites

Two small bodies of aplite have been mapped topping hills in the southwest corner of the Hillsboro quadrangle. A chemical analysis of one of these rocks is included in Table 13, and three modes are listed in Table 14. Plots of these modes classify the rocks as granites. They have allotriomorphic textures; the dominant feldspar is a microcline mesoperthite. The rocks often show some amount of alteration with white micas replacing the feldspar. They commonly contain a small amount of garnet which may be spessartine-rich (J.B. Lyons, personal communication). One of the bodies continues into the Lovewell Mountain quadrangle (Heald, 1950) where it has been mapped as an altered phase of the Kinsman. However, the unit may represent a late-stage segregation of the Kinsman, or more probably, represents a late-stage injection into it.

## Lamprophyre Dikes

Several small lamprophyre dikes which are thought to be members of the White Mountain Volcanic-Plutonic Series have been found in the Hillsboro quadrangle. The largest of these crops out north of Henniker along Highway 49. The rock has been described and chemically analyzed by Bieler (1973) and is classed as an augite-biotite camptonite. Fission track work on similar rocks from the Holderness quadrangle yields ages of 142 + 8 m.y. (Rice, 1970, unpub. ms.).

**Figure 4.**
Flow banding in binary tonalite of the Massasecum Pluton exposed at the south end of Lake Massasecum. Hammer for scale.

Table 13 - Chemical analyses and C.I.P.W. norms of Concord Granites and an aplite from the Hillsboro quadrangle. Sample descriptions and locations are listed in Table 14. All analyses were by the author.

| | Hi-55-72 | Hi-169-72 | Hi-193-73 | Hi-105-72 |
|---|---|---|---|---|
| $SiO_2$ | 72.8 | 70.3 | 69.9 | 73.8 |
| $TiO_2$ | .14 | .20 | .24 | -- |
| $Al_2O_3$ | 14.8 | 16.5 | 16.6 | 14.6 |
| FeO* | 1.19 | 2.12 | 2.00 | .88 |
| MnO | .03 | .04 | .05 | .08 |
| MgO | .50 | 1.04 | .70 | .20 |
| CaO | .53 | 3.04 | 3.16 | .35 |
| $Na_2O$ | 1.97 | 4.41 | 4.47 | 3.72 |
| $K_2O$ | 6.39 | 1.97 | 1.42 | 4.60 |
| $H_2O^+$ | .55 | .11 | .31 | .35 |
| $H_2O^-$ | .05 | .03 | -- | .02 |
| $P_2O_5$ | .14 | .19 | -- | .28 |
| Total | 99.1 | 100.0 | 98.8 | 99.0 |

*Total Fe calculated ad FeO

| | Hi-55-72 | Hi-169-72 | Hi-193-73 | Hi-105-72 |
|---|---|---|---|---|
| Q | 34.47 | 27.92 | 29.11 | 33.45 |
| Or | 37.76 | 11.64 | 8.39 | 27.18 |
| Ab | 16.67 | 37.32 | 37.82 | 31.48 |
| An | 1.71 | 13.84 | 15.68 | |
| C | 4.01 | 2.04 | 1.96 | 3.50 |
| En | 1.25 | 2.59 | 1.74 | .50 |
| Fs | 2.05 | 3.64 | 3.37 | 1.76 |
| Il | .27 | .38 | .46 | |
| Ap | .32 | .44 | | .65 |
| Total | 98.51 | 99.81 | 98.54 | 98.53 |

Table 14 - Modes of Concord Granites and aplites based on 1000 point counts of thin sections.

| | Hi-47-72 | Hi-55-72 | Hi-169-72 | Hi-193-72 | Hi-21-73 | Hi-104-72 | Hi-105-72 |
|---|---|---|---|---|---|---|---|
| Quartz | 33.9 | 36.1 | 40.1 | 29.8 | 45.6 | 53.3 | 41.6 |
| K feldspar | 15.3 | 41.5 | 3.7 | .3 | 29.3 | 27.6 | 49.6 |
| Plagioclase* | 41.3 | 13.6 | 44.6 | 57.6 | 4.8 | 13.3 | 6.0 |
| Biotite | 5.0 | 1.7 | 7.5 | 7.0 | | | |
| Muscovite | 3.9 | 6.1 | 3.6 | 4.6 | 18.7 | 5.0 | 3.8 |
| Chlorite | .6 | .5 | .2 | .4 | | | |
| Ilmenite | tr | .2 | .3 | .1 | .4 | .3 | tr |
| Apatite | tr | .1 | tr | .2 | tr | tr | tr |
| Zircon | | .1 | | | | | |
| Garnet | | | | | 1.1 | .5 | |
| *percent An of plagioclase | 26 | 17 | 30-31 | 30-21 | 15 | 18 | 14 |

| | |
|---|---|
| Hi-21-72 | Muscovite granite (Aplite). From Ball Hill in the SW corner of the Hillsboro quadrangle, Town of Hancock. |
| Hi-47-72 | Muscovite-biotite granodiorite. In back of house on old Hwy 202, S of intersection with new Hwy 202 about 1.8 mi. E of Henniker, Town of Henniker. |
| Hi-55-72 | Biotite-muscovite granite. At crest of hill .6 mi. S of Slab City, Town of Weare. |
| Hi-69-72 | Muscovite-biotite tonalite. .1 mi. NW of Pond Cemetry along Hwy 114, Town of Bradford. |
| Hi-104-72 | Muscovite granite (Aplite). Same locality as Hi-21-72. |
| Hi-105-72 | Muscovite granite (Aplite). Same locality as Hi-21-72. |
| Hi-193-72 | Muscovite-biotite tonalite. On Hwy 114 about .5 mi NW of access road to S end of Lake Massasecum, Town of Bradford. |

# METAMORPHISM

## Introduction

The Hillsboro quadrangle lies in the approximate center of the regional metamorphic sillimanite-K-feldspar plateau as defined by Thompson and Norton (1968). This plateau is bounded on both the east and the west by very steep gradients where, in the space of a few kilometers, the intensity of metamorphism decreases to biotite or chlorite grade.

## Pelitic Assemblages

As indicated in the section on stratigraphy, the metasedimentary rocks of the Hillsboro quadrangle are largely formed from clastic sediments. The metapelitic rocks contain quartz and biotite with various amounts of sillimanite, andalusite, garnet, muscovite, staurolite, oligoclase, K-feldspar, and cordierite. Accessory phases generally include graphite, ilmenite, and pyrrhotite. Chlorite is a common retrograde metamorphic product, and chloritoid has been identified in some retrograde metamorphic assemblages.

As defined on the basis of the first occurrence of the pair sillimanite + K-feldspar, the pelitic assemblages of the sillimanite-K-feldspar zone in the Hillsboro quadrangle are (see Fig. 5):

1. Quartz + Plagioclase + K-feldspar + Biotite + Sillimanite + Graphite + Ilmenite (+Muscovite),

2. Quartz + Plagioclase + Garnet + K-feldspar + Sillimanite + Muscovite + Cordierite + Graphite + Ilmenite,

3. Quartz + Plagioclase + Biotite + K-feldspar + Sillimanite + Garnet + Graphite + Ilmenite (+Muscovite).

Many of the other assemblages found do not contain the pair sillimanite + K-feldspar and are indicative of the upper sillimanite zone. The principal assemblage in rocks of the upper sillimanite zone is:

4. Quartz + Plagioclase + Muscovite + Biotite ( + Garnet) + Sillimanite + Graphite + Ilmenite.

This assemblage is diagramatically represented in Fig. 6. Other pelitic assemblages are clearly of retrograde origin or indicate a departure from equilibrium.

In general, the rocks of the Hillsboro quadrangle have a schistose texture defined by biotite, muscovite, and sometimes sillimanite. At times this schistosity is poorly defined, and it is evident that there has been some recrystallization of mica minerals. In some samples, quartz and feldspar show undulatory extinction and sutured grain boundaries, suggesting post-metamorphic stressing, while in other samples

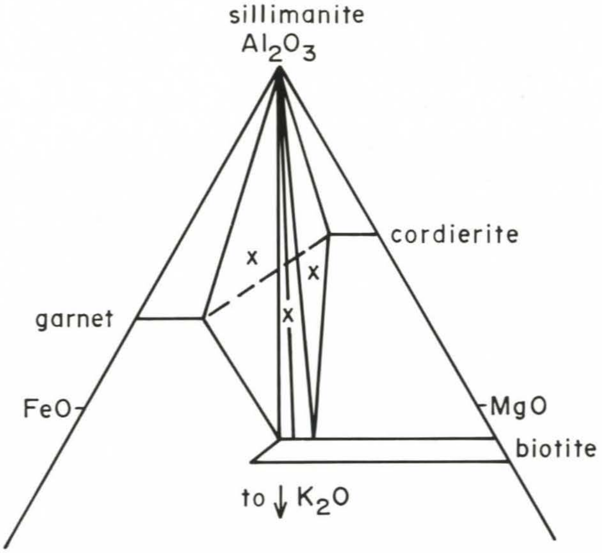


**Figure 5.**
Schematic AFM projection from K-feldspar showing the assemblages of the sillimanite-K-feldspar zone in the Lovewell Mtn. (Heald, 1950) and Hillsboro (this study) quadrangles. Dashed line indicates possible co-existence of garnet and cordierite in assemblages shown.

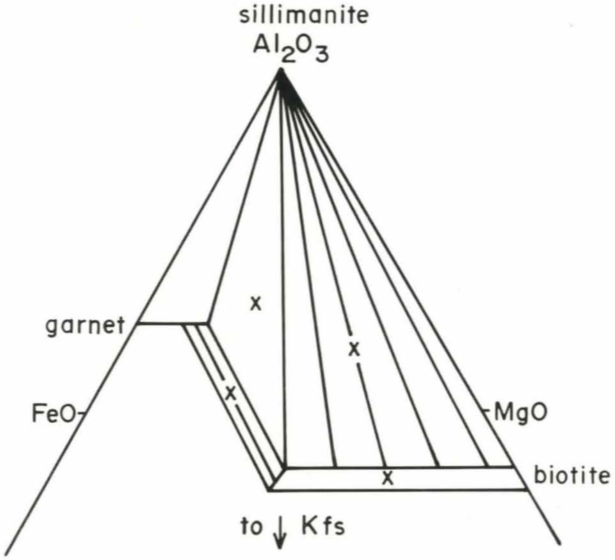


**Figure 6.**
Schematic AFM projection from muscovite showing assemblages of the upper sillimanite zone from the Lovewell Mtn. (Heald, 1950) and Hillsboro (this study) quadrangles.

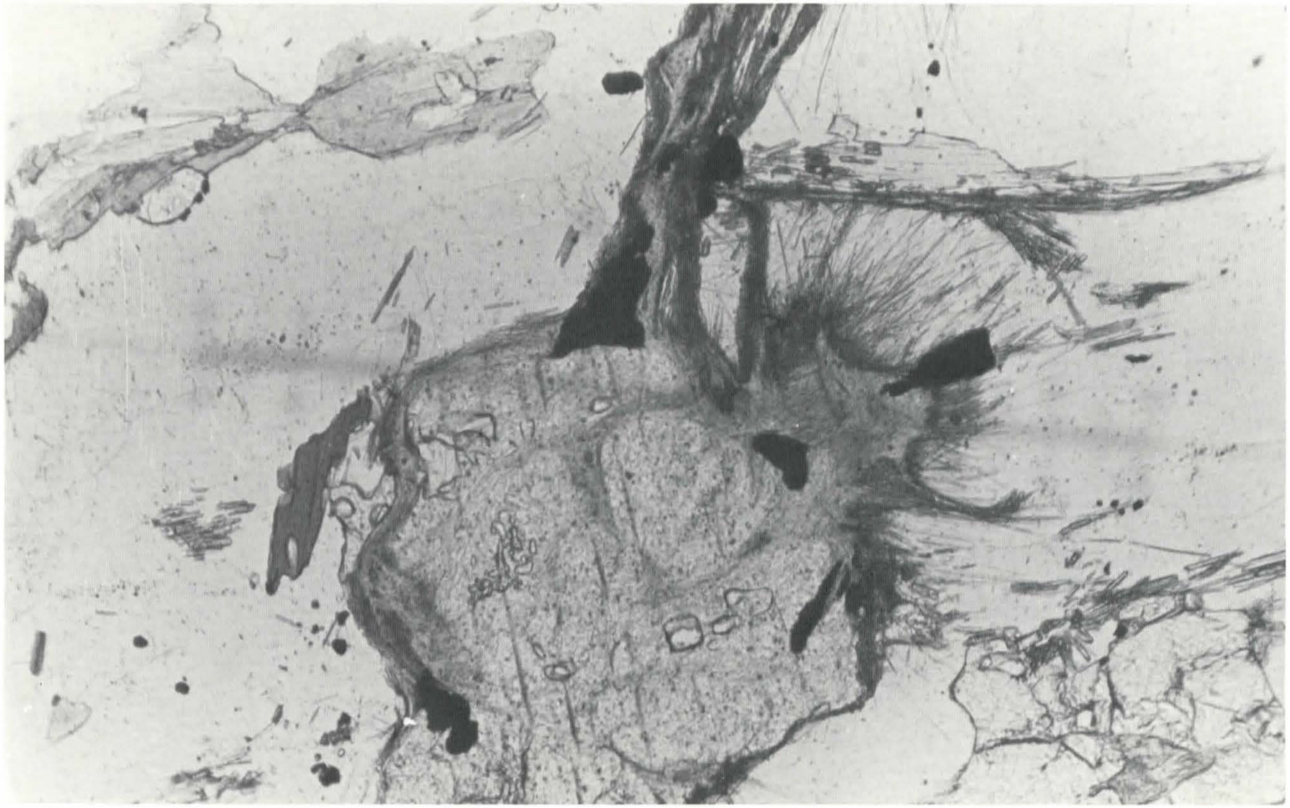


**Figure 7.**
Photomicrograph of fibrolitic silimanite growing on andalusite from sample Hi-44-72. T;he fibrolite forms a vein which can be seen extending from the andalusite grain off the bottom of the photograph (uncrossed nicols).

they show mosaic-textured equilibrium grain boundaries. Several samples show brecciation or extensive cataclasis, which is also post-metamorphic.

The $Al_2SiO_5$ polymorphs sillimanite and andalusite are common in many of the metasediments of the Hillsboro quadrangle. Andalusite is found near the contacts of biotite granodiorite plutons and is considered a contact metamorphic phase. Sillimanite occurs as three textural varieties: fibrolite, prisms, and blocky prisms which are probable pseudomorphs after andalusite. The textural associations of each of the three varieties are different also. The blocky prisms are often surrounded by biotite whereas the fibrolite and prisms often occur within and at the margins of biotite and appear to have formed from or at the same time as the biotite. Fibrolite has also been found growing on andalusite and forming small veinlets within the rock (Fig. 7). This is the only instance found of sillimanite growing on andalusite. The fact that sillimanites grow on andalusite only when the andalusites are cut by the fibrolite vein suggests that the presence of fluids may have played a significant role. Pitcher (1965) has noted a common association of fibrolite with metasomatic activity. The fibrolite itself is found as sprays of acicular crystals, as isolated bundles, and along foliation planes forming what might be characterized as fibrolite mats. At times the bundles appear to have been rolled and possibly represent pseudomorphs after such minerals as staurolite or garnet. In some samples the fibrolite appears to coarsen and probably recrystalizes to form long slender prisms (Fig. 8). It is common to find blocky sillimanite crystals with square cross sections which may be up to 8 cm long and up to 2.5 cm across (Fig. 9). In some of these crystals it is possible to see relict chiastolite crosses, indicating that the grains are sillimanite pseudomorphs after andalusite. In thin section these blocky grains are composed of a series of sillimanite prisms which are not in optical continuity. The prisms are separated from one another by cracks filled with chlorite, muscovite, biotite, and quartz.

It is probable that the sillimanites in the rocks are a product of several different reactions. The large blocky prisms are a result of the polymorphic transformation

$$\text{andalusite} \rightarrow \text{sillimanite}$$

However, it is probable that the fibrolite and prismatic sillimanite have developed during the prograde metamorphism, perhaps by such a reaction as

$$\text{Staur} + \text{Mg Chte} + \text{Na Musc} + (\text{Garn?}) \rightarrow \text{Sill} + \text{Bio} + \text{K-richer Musc} + \text{Ab} + \text{Qtz} + H_2O \quad (1)$$

which defines the transition from the staurolite to the lower sillimanite zone in Maine (Guidotti, 1974). At slightly higher temperatures, sillimanite might continue to be produced by the reaction

$$\text{Staur}+\text{Na Musc}+\text{Qtz}\rightarrow\text{Sill}+\text{Bio}+\text{K-richer Musc}+\text{Ab}+\text{Garn}+H_2O. \quad (2)$$

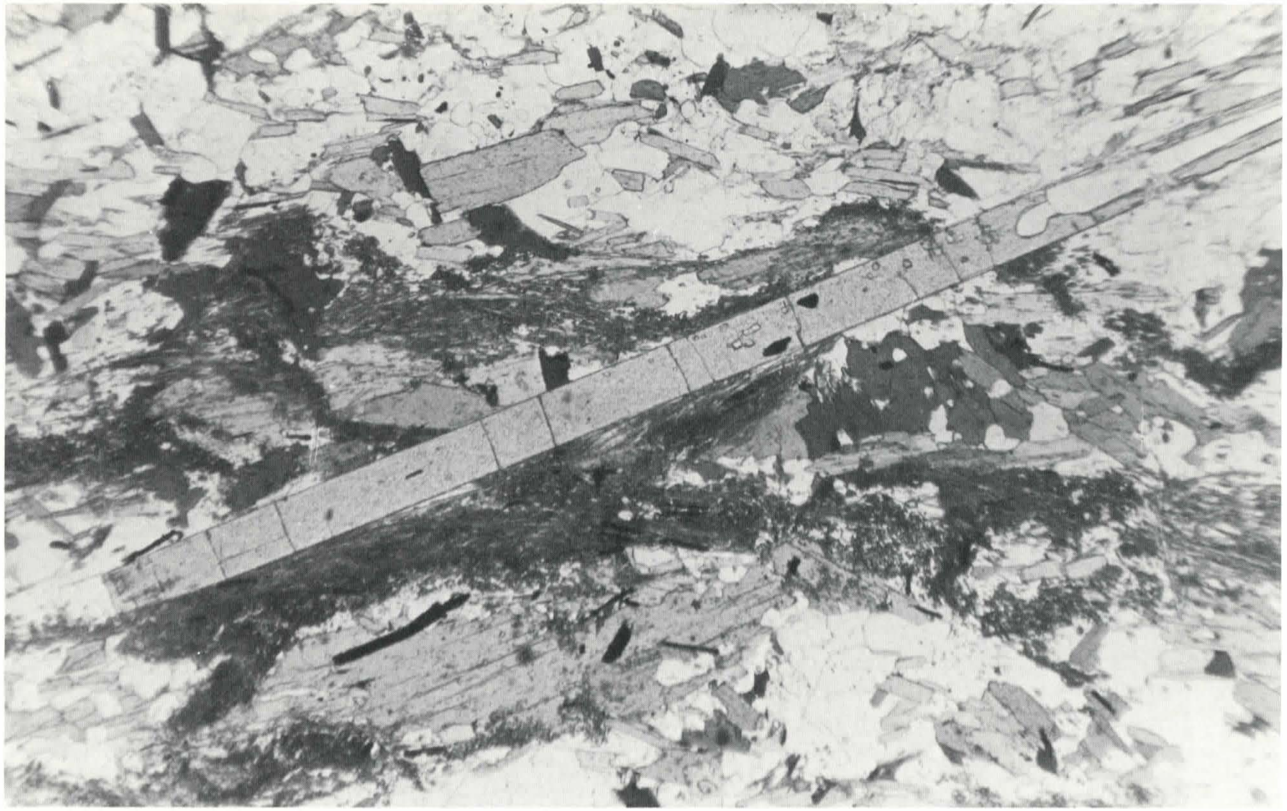


**Figure 8.**
Photomicrograph of prismatic sillimanite surrounded by aggregates of fibrolite. The remainder of the slide is primarily biotite (dark Gray) and quartz. The slide is from sample Hi-180-73, uncrossed nicols.

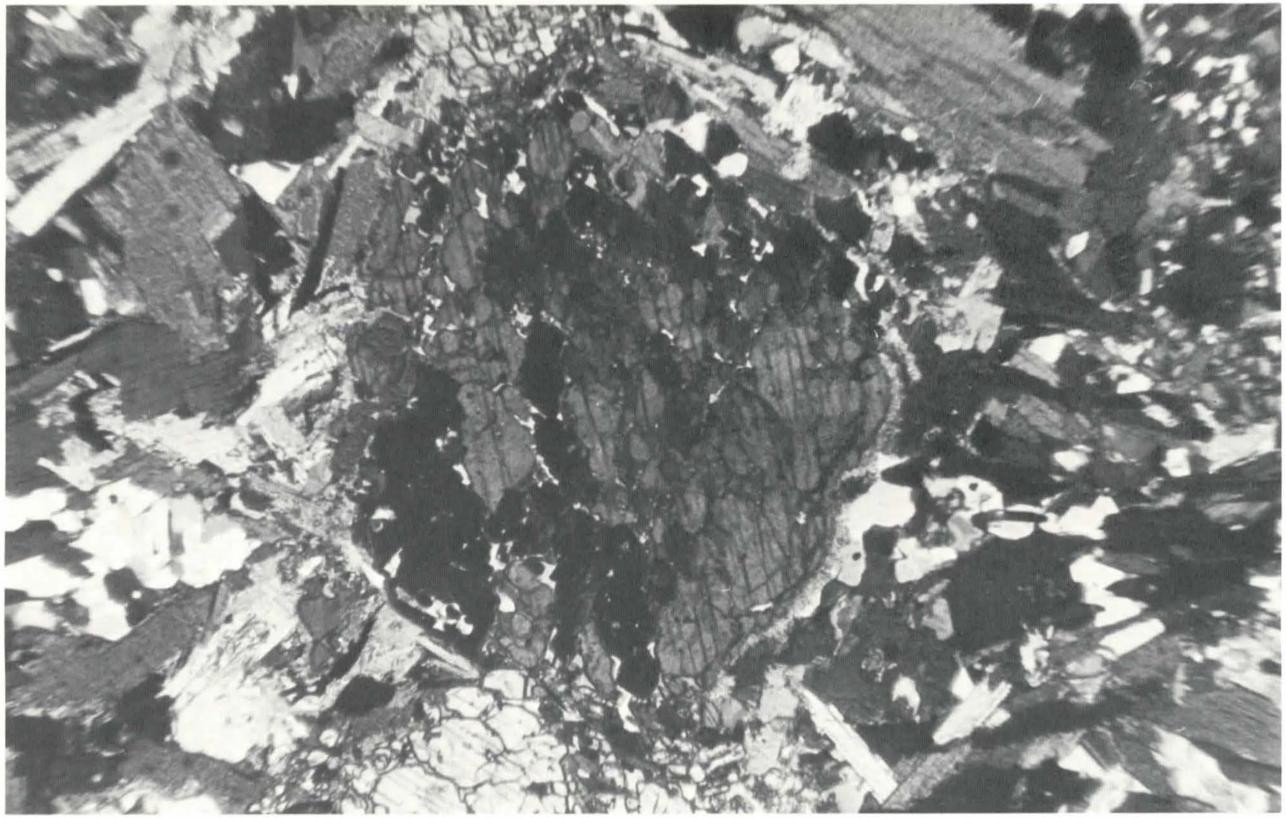


**Figure 9.**
Photomicrograph of blocky sillimanite which is probably a pseudomorph after andalusite. Sample Hi-123-72, crossed nicols.

The production of sillimanite continues into the sillimanite and sillimanite-K-feldspar zones through the continuous reaction

$$\text{Na Musc} + \text{Qtz} \rightarrow \text{Sill} + \text{Ab} + \text{K-richer Musc} + H_2O. \tag{3}$$

The final disappearance of muscovite does not involve pure end member phases and is represented by equation 4:

$$\underset{\text{muscovite}}{K_{.94}Na_{.06}Al_2AlSi_3O_{10}(OH)_2} + SiO_2 + \underset{\text{albite}}{0.1NaAlSi_3O_8} \rightarrow \underset{\text{Kfs}}{1.1K_{.86}Na_{.14}AlSi_3O_8} + \underset{\text{sill.}}{Al_2SiO_5} + H_2O. \tag{4}$$

This reaction may be prevented from going to completion by the buffering effect of $XH_2O$ of the fluid phase. The sillimanite-K-feldspar isograd has been defined by the presence of a muscovite of composition $Mu_{94}P_{96}$ in the presence of sillimanite-K-feldspar (Evans and Guidotti, 1966).

With this in mind, a reconnaissance study of the geochemistry of muscovite from the Bellows Falls, Lovewell Mountain, and Hillsboro quadrangles was undertaken using a MAC-5 electron microprobe. The analyses are listed in Table 15. As in the analyses published by Evans and Guidotti (1966), there are slightly more than four filled octahedral sites ($Al^{VI}$, Fe, Mg, Mn, Ti) and less than the ideal two (K, Na) filled inter-layer sites. This is apparently the normal situation for metamorphic muscovites.

Guidotti (1973) states that the use of paragonite content (Na/Na+K) and phengite content (Fe+Mg) to monitor metamorphic conditions should be done in the context of a limiting assemblage. This is an assemblage where the number of phases present equals the number of components needed to describe those phases. In this situation, the phase compositions will be a function of the intensive variables.

According to Evans and Guidotti (1966), the sillimanite-K-feldspar reaction is initiated at a paragonite content of $6 < 2$ percent. In a subsequent paper, Cheney and Guidotti (1973) suggest that the lower sillimanite zone muscovites contain greater than 20 mole percent paragonite with an average of 21.7, and upper sillimanite zone muscovites contain less than 20 mole percent paragonite with an average of 18.6. Guidotti (1973) shows upper sillimanite zone muscovites with an average of 14.2 mole percent paragonite. The muscovites from the matrix of flecky gneisses (Table 15, Hi-101, Hi-126, MK-14, MK-18) are probably products of retrograde metamorphism of sillimanite (D.R. Nielson, 1974), It can be seen that these are characterized by low paragonite contents (Table 15) which, in most cases, would assign them to the sillimanite-K-feldspar zone. The muscovites which are not of dubious retrograde origin, except BF-3-72, show values consistent with the upper sillimanite zone rather than the sillimanite-K-feldspar zone. With the exception of one sample, all show paragonite contents which are lower than the upper sillimanite zone average of Cheney and Guidotti (1973).

Table 15 - Electron microprobe analyses and formulae of muscovites from south-central New Hampshire.

| | Hi-127-72 | Hi-123-72 | LM-6-67 | LM-46-66 | BF-3-72 | BF-5-72 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 47.57 | 47.36 | 47.50 | 48.19 | 47.40 | 48.13 |
| $TiO_2$ | .94 | .87 | .98 | .05 | .42 | .67 |
| $Al_2O_3$ | 36.42 | 36.44 | 35.69 | 37.82 | 37.12 | 33.02 |
| FeO | 1.06 | .99 | 1.06 | .72 | .91 | 1.88 |
| MnO | .00 | .00 | .00 | .01 | .00 | .02 |
| MgO | .62 | .46 | .60 | .56 | .50 | 1.58 |
| CaO | .00 | .00 | .00 | .00 | .00 | .00 |
| $Na_2O$ | .95 | 1.18 | .73 | 1.40 | 1.72 | .44 |
| $K_2O$ | 9.58 | 9.06 | 9.60 | 9.16 | 8.91 | 10.22 |
| $Cr_2O_3$ | .02 | .00 | .04 | .00 | .00 | .12 |
| Total | 97.16 | 96.36 | 96.20 | 97.91 | 96.98 | 96.08 |
| Formulae based on 22 oxygens: | | | | | | |
| $Si^{IV}$ | 6.169 | 6.168 | 6.206 | 6.164 | 6.133 | 6.357 |
| $Al^{IV}$ | 1.831 | 1.832 | 1.794 | 1.836 | 1.867 | 1.643 |
| | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 |
| $Al^{VI}$ | 3.725 | 3.762 | 3.700 | 3.865 | 3.793 | 3.492 |
| Fe | .115 | .105 | .112 | .075 | .096 | .206 |
| Mg | .122 | .087 | .113 | .106 | .095 | .311 |
| Mn | .000 | .000 | .000 | .000 | .000 | .002 |
| Ti | .071 | .084 | .096 | .002 | .040 | .066 |
| | 4.053 | 4.038 | 4.021 | 4.048 | 4.024 | 4.077 |
| K | 1.584 | 1.503 | 1.596 | 1.494 | 1.468 | 1.721 |
| Na | .239 | .298 | .184 | .345 | .431 | .112 |
| | 1.823 | 1.801 | 1.780 | 1.838 | 1.899 | 1.833 |
| $\Sigma Al$ | 5.556 | 5.594 | 5.494 | 5.702 | 5.660 | 5.136 |
| Mg + Fe | .237 | .193 | .226 | .182 | .192 | .518 |
| Na/Na+K | .131 | .166 | .103 | .188 | .226 | .062 |

Table 15 - (cont.)

| | Hi-101-72 | MK-14-72 | MK-18-70 | BR-2-72 | Hi-126-72 |
|---|---|---|---|---|---|
| $SiO_2$ | 48.04 | 46.52 | 47.96 | 46.20 | 48.16 |
| $TiO_2$ | .04 | .04 | .28 | 1.27 | .22 |
| $Al_2O_3$ | 35.74 | 33.06 | 36.11 | 35.04 | 36.24 |
| FeO | 1.30 | 3.26 | 1.13 | 1.20 | 1.00 |
| MnO | .02 | .01 | .05 | .00 | .03 |
| MgO | 1.30 | 3.14 | .75 | .56 | .46 |
| CaO | .00 | .00 | .00 | .00 | .00 |
| $Na_2O$ | .61 | .38 | .36 | 1.03 | .98 |
| $K_2O$ | 9.95 | 10.06 | 10.18 | 9.57 | 9.38 |
| $Cr_2O_3$ | .09 | .01 | .00 | .03 | .07 |
| Total | 97.54 | 96.50 | 96.83 | 94.91 | 96.54 |
| Formulae based on 22 oxygens: | | | | | |
| $Si^{IV}$ | 6.22 | 6.17 | 6.236 | 6.152 | 6.26 |
| $Al^{IV}$ | 1.78 | 1.83 | 1.764 | 1.848 | 1.74 |
| | 8.00 | 8.00 | 8.000 | 8.000 | 8.00 |
| $Al^{VI}$ | 3.69 | 3.34 | 3.770 | 3.652 | 3.81 |
| Fe | .19 | .36 | .122 | .133 | .11 |
| Mg | .25 | .62 | .145 | .109 | .09 |
| Mn | .00 | .00 | .003 | .000 | .00 |
| Ti | .00 | .00 | .026 | .125 | .02 |
| | 4.13 | 4.32 | 4.066 | 4.019 | 4.03 |
| K | 1.64 | 1.70 | 1.687 | 1.626 | 1.55 |
| Na | .15 | .10 | .087 | .262 | .24 |
| | 1.79 | 1.80 | 1.774 | 1.888 | 1.79 |
| ΣAl | 5.47 | 5.17 | 5.534 | 5.500 | 5.55 |
| Mg + Fe | .44 | .98 | .267 | .242 | .20 |
| Na/Na+K | .08 | .06 | .049 | .139 | .13 |

Table 15 - (cont.)

| | |
|---|---|
| Hi-101-72 | Fleck matrix with assemblage: quartz-plagioclase-biotite-chlorite-muscovite-graphite. Outcrop along Hwy 202, .25 mi. S of old mill at Antrim and across from Tenny Farm, Town of Antrim, Hillsboro quadrangle. Analysis #28, Table 4 from D.R. Nielson (1974). D.R. Nielson, analyst. |
| Hi-123-72 | Assemblage: muscovite-quartz-plagioclase-biotite-sillimanite, At fork in road S of Kingsbury Hill and .1 mi. N of the quadrangle boundary, Town of Francestown, Hillsboro quadrangle. D.L. Nielson, analyst. |
| Hi-126-72 | Assemblage: quartz-garnet-biotite-chlorite-muscovite-plagioclase (Fleck matrix). From outcrop in kink in road at top of Sodom Hill, Town of Deering, Hillsboro quadrangle. Average of analyses #32 and #33, Table 4 quadrangle. Average of in D.R. Nielson (1974). D.R. Nielson, analyst. |
| Hi-127-72 | Assemblage: biotite-muscovite-garnet-quartz-plagioclase-andalusite-sillimanite. Along access road to the W side of Deering Reservoir, .3 mi. S of intersection at head of lake, Town of Deering. D.L. Nielson, analyst. |
| BF-3-72 | Assemblage: quartz-muscovite-chlorite-plagioclase-garnet-staurolite-pyrrhotite. Collected about .1 mi. N of intersection of Hwy 123 and 123-A in Bellows Falls quadrangle. D.L. Nielson, analyst. |
| LM-6-67 | Assemblage: quartz-muscovite-biotite-plagioclase-chlorite-chlorite-garnet. Sample collected by J.B. Lyons from outcrops along Dartmouth College Hwy about .25 miles south of the intersection with Forrest Road, Lovewell Mtn. quadrangle. D.L. Nielson, analyst. |
| LM-46-66 | Assemblage: quartz-muscovite-biotite-plagioclase-chlorite-staurolite-sillimanite. Sample collected by J.B. Lyons S side of Hwy 9, about 1.1 mi. NE of intersection at W end of Granite Lake, Lovewell Mtn. quadrangle. D.L. Nielson, analyst. |
| MK-14-72 | Assemblage: quartz-plagioclase-muscovite-biotite-garnet sillimanite-K feldspar (Fleck matrix). Outcrop along Hwy 103 at Warner Lower Village. Analysis #26, Table 4 in D.R. Nielson (1974). D.R. Nielson, analyst. |
| MK-18-70 | Assemblage, K feldspar-quartz-plagioclase-muscovite (Flecky gneiss). Muscovite replacing K feldspar. Collected by R.G. Clark, S side of S lane of I-89, 2.2 mi. SE of Sutton exit, Mt. Kearsarge quadrangle. R.G. Clark and J.B. Lyons, analysts. |
| BR-2-72 | Assemblage: biotite-muscovite-quartz-plagioclase-garnet-ilmenite-graphite-sillimanite. Collected by R.G. Clark on Hwy 103 in Bradford, .25 mi. E of Todd Lake. R.G. Clark and J.B. Lyons, analysts. |

Sample BR-2-72 is from the Bradford garnet concentration (Clark, 1972) and represents a restite from anatexis of pelitic schist within the Kinsman Quartz Monzonite. Therefore, it is evident that this rock should have reached near-magmatic temperatures and have been above the sillimanite-K-feldspar isograd. However, the muscovite contains 13.9 percent paragonite. It is suggested that this sample and other samples from the area which show paragonite contents indicative of the upper sillimanite zone are a result of re-equilibration of the muscovite at lower temperature, i.e., those of the sillimanite zone. This is true for all analyzed samples from the Hillsboro quadrangle where the climax of metamorphism was definitely at P-T conditions characteristic of the sillimanite-K-feldspar zone. The rocks now have higher paragonite contents than those typical of that zone (Evans and Guidotti, 1966). Another possibility is that the $X_{H_2O}$ in these rocks was high enough so that equation (4) was never realized.

The phengite contents of muscovites have also been used to deduce metamorphic conditions. Cipriani and others (1971) report that phengites are intermediate in composition between ideal muscovite and a hypothetical end member celadonite. They are characterized by a decrease in $Al^{VI}$ and a concommittant increase in Fe and Mg. The above authors find that, at a given temperature the phengite content increases with increasing pressure, but with increasing temperature, the phengite content decreases and the composition trends toward ideal muscovite. The atomic total Mg + Fe content of the analyzed muscovites (Table 15) suggests that there may be an increase of phengite content toward the central areas of the sillimanite-K-feldspar plateau, but additional samples will be needed to confirm this trend. Since the paragonite content seems to have re-equilibrated after the main metamorphic event, it would be expected that the phengite content may have also.

Cheney and Guidotti (1973) have also noted that the $TiO_2$ contents of muscovites increase with temperature, and they find an average of 0.75 weight percent for muscovites from the upper sillimanite zone. With the exception of Lm-46-66, most are above the average for muscovites from the upper sillimanite zone, suggesting equilibration at higher temperatures. It will be noted that those samples in Table 15 which are of probable retrograde origin have very low $TiO_2$ contents. This in turn suggests that the muscovite in Lm-46-66 may also be retrogressive.

## Calcic Assemblages

Calc-silicate rocks are most common in the Warner and Francestown Formations. The calcic assemblages (including plagioclase and quartz) in rocks of the Warner Formation are:

1. Actinolite + Biotite ( + Clinozoisite),
2. Actinolite + Diopside ( + Microcline + Chlorite).

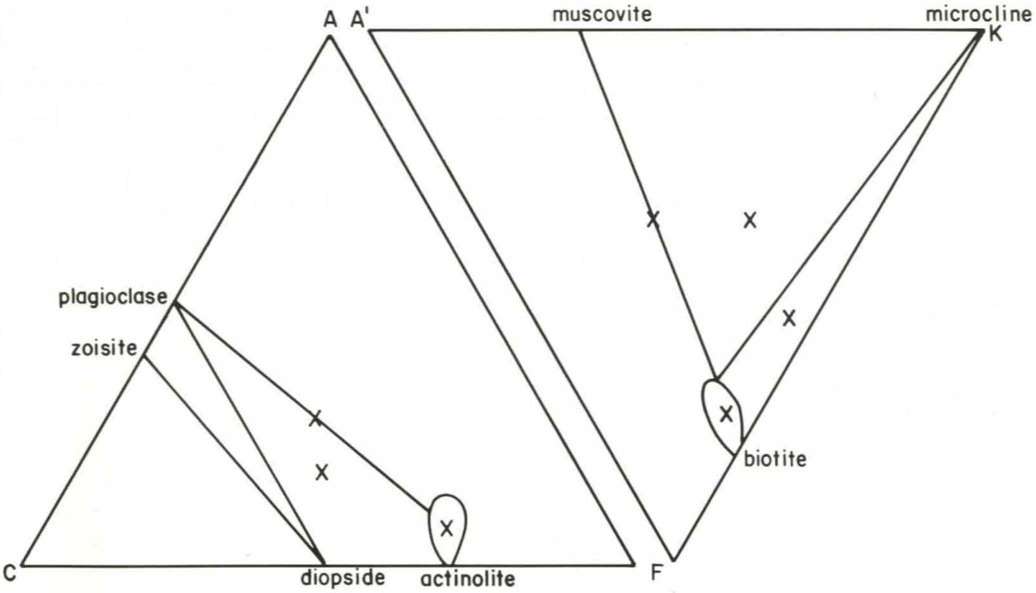


**Figure 10.**
ACF-A'KF diagram of calcareous assemblages from the Hillsboro quadrangle. Excess quartz present.

The Francestown Formation contains the following calcic assemblages (again quartz and plagioclase are present):

3. Clinozoisite + Biotite ( + Muscovite),
4. Actinolite + Diopside ( + Clinozoisite + Microcline + Muscovite + Biotite),
5. Actinolite + Clinozoisite + Muscovite.

These calcic assemblages are schematically illustrated in Figure 10.

In general the calcareous rocks show a granofelsic texture and only take on a schistosity in those rocks which contain a high proportion of biotite. It is not uncommon, however, to find excellent lineations defined by actinolite crystals.

## Metamorphic Equilibrium

The criteria used to evaluate the degree to which equilibrium was attained in the metasediments of the Hillsboro quadrangle are: satisfaction of the phase rule, presence of equilibrium textures, and documentation of similar assemblages from other areas.

At first glance, it is conceivable that some of the assemblages of the Hillsboro quadrangle are not in equilibrium because they violate the phase rule. For instance, a common assemblage in the calcareous rocks is Plagioclase + Diopside + Actinolite + Clinozoisite. Reference to an ACF diagram (Fig. 10) indicates that this assemblage represents the presence of four phases in a three component system. However, some of the clinozoisite shows textural evidence of being a retrograde metamorphic phase. If it is eliminated from consideration, the calcareous phases present are those shown in Figure 10. These assemblages are compatible with the upper amphibolite facies as shown by Winkler (1967) and they are also the calcareous assemblages reported by Heald (1950) from the sillimanite-K-feldspar zone of the Lovewell Mountain quadrangle. On the other hand, since the plagioclase in these samples is never pure anorthite, one more component ($Na_2O$) must be considered. Thus it is possible that the Plagioclase + Clinozoisite + Diopside + Actinolite assemblages are in equilibrium.

Many of the pelitic schists of the quadrangle also do not seem to satisfy the phase rule. The coexistence of two $Al_2SiO_5$ polymorphs, andalusite and sillimanite, indicate either that metamorphic conditions were right on the univariant line separating the divariant andalusite and sillimanite fields, or that the polymorphic transition was a sluggish reaction. The rocks in which both polymorphs are found are near contacts with biotite granodiorite plutons, and the textures generally suggest that the andalusite has formed after sillimanite. Therefore, it is probable that the andalusite is a retrograde phase which formed near the margins of the biotite granodiorite intrusives, and the polymorphic transition of sillimanite to andalusite was sluggish enough that it left the two phases present in some of the rocks.

Another assemblage which contains too many phases to satisfy the phase rule is Quartz + Muscovite + Biotite + Garnet + Staurolite + Sillimanite + Andalusite. In addition to the two $Al_2SiO_5$ polymorphs, the assemblage Biotite + Garnet + Staurolite + $Al_2SiO_5$ involves one phase too many in the three component system AFM. However, garnet is the only mineral which can contain much MnO, and the addition of MnO to the system will stabilize the above assemblage. This assemblage is more characteristic of the lower sillimanite zone than it is the sillimanite-K-feldspar zone. It is also important to note that staurolite is a hydrated phase. Thus, in order for this rock to start to reequilibrate at lower temperatures, an influx of water is also necessary. Crystallization of adjacent biotite granodiorites may have supplied the needed water.

Another assemblage which seems to be in violation of the phase rule is Biotite + Cordierite + Garnet + Sillimanite + K-feldspar, since this represents four phases on an AFM projection (Fig. 5). However, this assemblage has been reported from other high-grade metamorphic terranes (cf. Dallmeyer and Dodd, 1971). This apparent contradiction is due to the fact that the reaction

$$3\text{Cord} \rightarrow 2\text{Garn} + 4\text{Sill} + 5\text{Qtz}$$

(Hensen and Green, 1971) is a continuous reaction which occurs over a range of temperatures and pressures and forms a divariant field on a petrogenetic grid. Also, it must again be considered that garnet is the only mineral here which accepts MnO, thus adding another component to the system.

Other assemblages commonly found in the Hillsboro quadrangle represent grades of metamorphism which are lower than the sillimanite-K-feldspar zone. These include:

1. Biotite + Muscovite + Garnet + Andalusite + Quartz (Andalusite Zone),
2. Sillimanite + Muscovite + Garnet + Plagiocase + Quartz (Upper Sillimanite Zone),
3. Quartz + Muscovite + Chlorite + Biotite (Chlorite Zone).

Thus it is evident that several assemblages have re-equilibrated to form lower temperature associations.

It is also the case that $X_{H_2O}$ would have been quite variable during prograde metamorphism as evidenced by the differing amounts of sulfide and graphite present in the quadrangle. Thus the development of K-feldspar was probably controlled by local $XH_2O$ conditions.

It is important to note that the rocks which are mineralogically characteristic of the sillimanite-K-feldspar zone have been found randomly scattered about the quadrangle, and thus there is no apparent zonation with respect to a higher-temperature core area. As was mentioned previously, the occurrence of andalusite is associated with proximity to plutons of biotite granodiorite. Some greenschist facies rocks are found at a distance from the contacts, but they are also common near the contacts and apparently represent low-temperature hydrothermal metamorphism. It is concluded that most of the rocks do show equilibrium assemblages. However, it is apparent that many of the rocks have re-equilibrated at lower temperatures following a metamorphic climax in the sillimanite-K-feldspar zone.

## Polymetamorphism

It is suggested here that the metasedimentary rocks of the Hillsboro quadrangle have had a polymetamorphic history. The large, well-formed pseudomorphs of sillimanite after andalusite indicate either passage through the andalusite divariant field during prograde metamorphism or a previous andalusite-grade metamorphic event. Temperature and pressures rose to the point where the metasedimentary rocks of the Hillsboro quadrangle reached metamorphic equilibrium in the sillimanite-K-feldspar zone ($M_1$). After this metamorphic climax, the intrusion of the biotite granodiorite plutons produced the heat and fluids necessary for recrystallization and partial re-equilibration at lower temperatures ($M_2$). Thus there has been one prograde and one retrograde metamorphic episode. These episodes were most likely portions of a continuous metamorphic process rather than distinct pulses followed by later periods of cooling. Somewhat the same sequence of events has been reported by Rumble (1973) in the Mt. Moosilauke Region, New Hampshire. In this area he has demonstrated the reaction sequence andalusite-sillimanite-andalusite, involving an up and down temperature sequence during the same cycle of Acadian metamorphism. Specific P-T conditions realized during the $M_1$ event can be approximated by the use of Figure 11.

It is clear from the mineralogy of the pelitic schists that $P_{H_2O}$ was not equal to $P_{fluid}$ during metamorphism. This is shown by the presence of graphite and/or sulfides in most of the rock which indicates the presence of carbon and sulfur compounds in the fluid phase in addition to $H_2O$. French (1966) has demonstrated the importance of such components as $CO_2$, $CO$, $H_2$, and $CH_4$ in the fluid phase. On the basis of experimental work by Eugster and Skippen, Kerrick (1972) has concluded that, in pelitic assemblages in equilibrium with graphite, the $X_{H_2O}$ will lie between 0.5 and 0.8. The univariant curves in Figure 11 are for the ideal reaction

$$\text{Qtz} + \text{Musc} \rightarrow \text{Sill} + \text{Kfs} + H_2O,$$

although the actual breakdown of muscovite involves $Ms_{94}Pg_6$. Evans and Guidotti (1966) felt that the univariant lines for the reaction involving $Ms_{94}Pg_6$ would lie 20° to 30° below the curves for the breakdown of pure muscovite in the presence of quartz.

Another possible thermal control on the $M_1$ event is the reaction

$$\text{Musc} + \text{Calcite} + \text{Qtz} \rightarrow \text{Kfs} + \text{An} + CO_2 + H_2O$$

(Hewitt, 1973). The assemblage K-feldspar + anorthite is common in the calcareous rocks, and muscovite + quartz associations have not been found in the presence of calcite. The univariant curve for this reaction is plotted in Figure 11.

An upper limit to the maximum temperatures in the area can be estimated by plotting the minimum melting curves of granite as a function of $X_{H_2O}$ (Kerrick, 1972) in Figure 11. The only possible candidates for fusion in the Hillsboro quadrangle are the flecky gneisses. However, D.R. Nielson (1973, 1974) has demonstrated that these segregations were formed by metamorphic differentiation and are not products of partial melting.

It is apparent from the $Al_2SiO_5$ triple point isobar mapped by Thompson and Norton (1968), and the fact that kyanite has been observed several kilometers north of the Hillsboro quadrangle, that the maximum P-T conditions of metamorphism in the Hillsboro quadrangle were near the sillimanite-kyanite univariant line but not far from the triple point. Since the sillimanite-K-feldspar reaction line was crossed at the metamorphic peak and since P-T conditions were very near the $Al_2SiO_5$ triple point, the experimental results of Richardson and others (1969) are preferred over Holdaway's (1971).

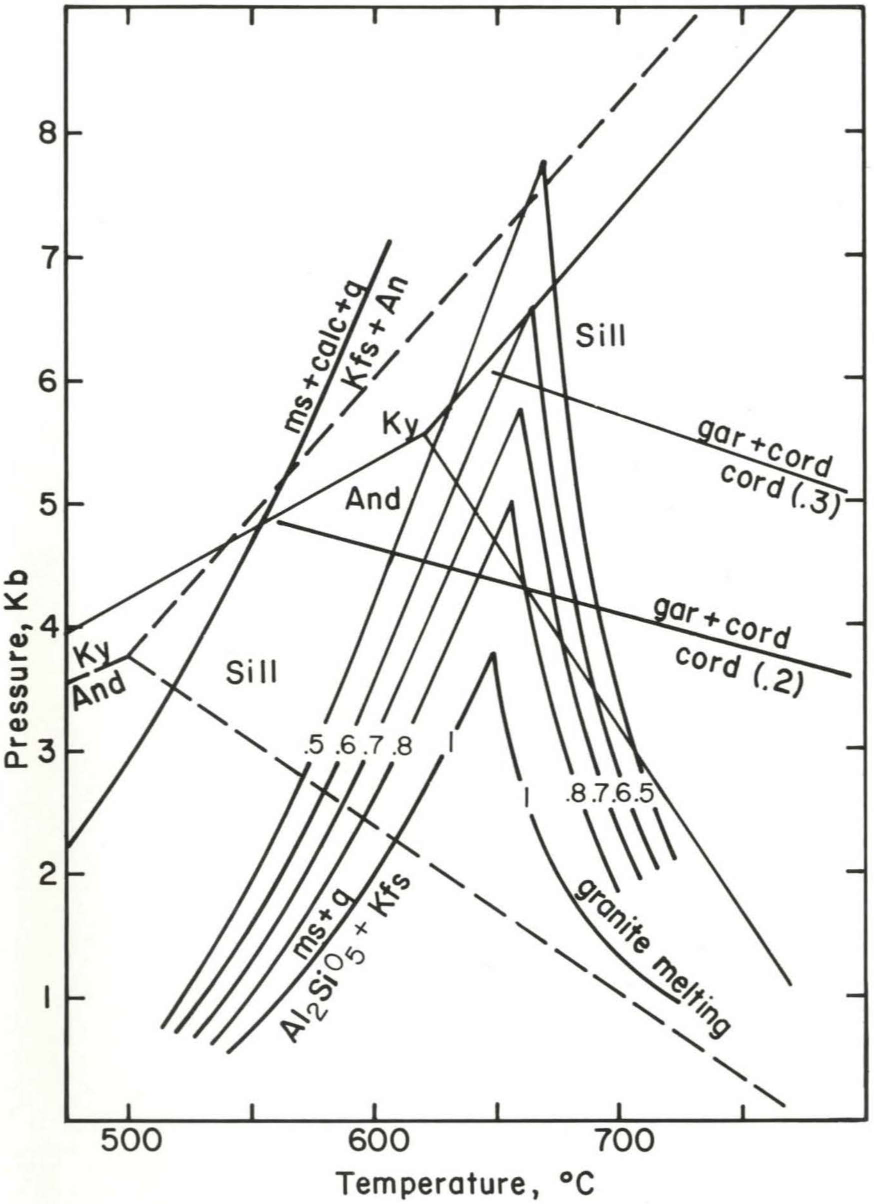


**Figure 11.**
P-T diagram showing the univariant curves for the breakdown of musc + qtz and minimum melting curves of granite as a function of $X_{H_2O}$ (values on curves) from Kerrick (1972). Solid $Al_2SiO_5$ phase relations from Richardson and others (1969), and dashed, from Holdaway (1971). Breakdown of musc + calcite + qtz (Hewitt, 1973) plotted at $X_{CO_2}=X_{H_2O}=0.5$. Cordierite-almandine curves from Currie (1971), number in parentheses is Mg/Mg + Fe ratio.

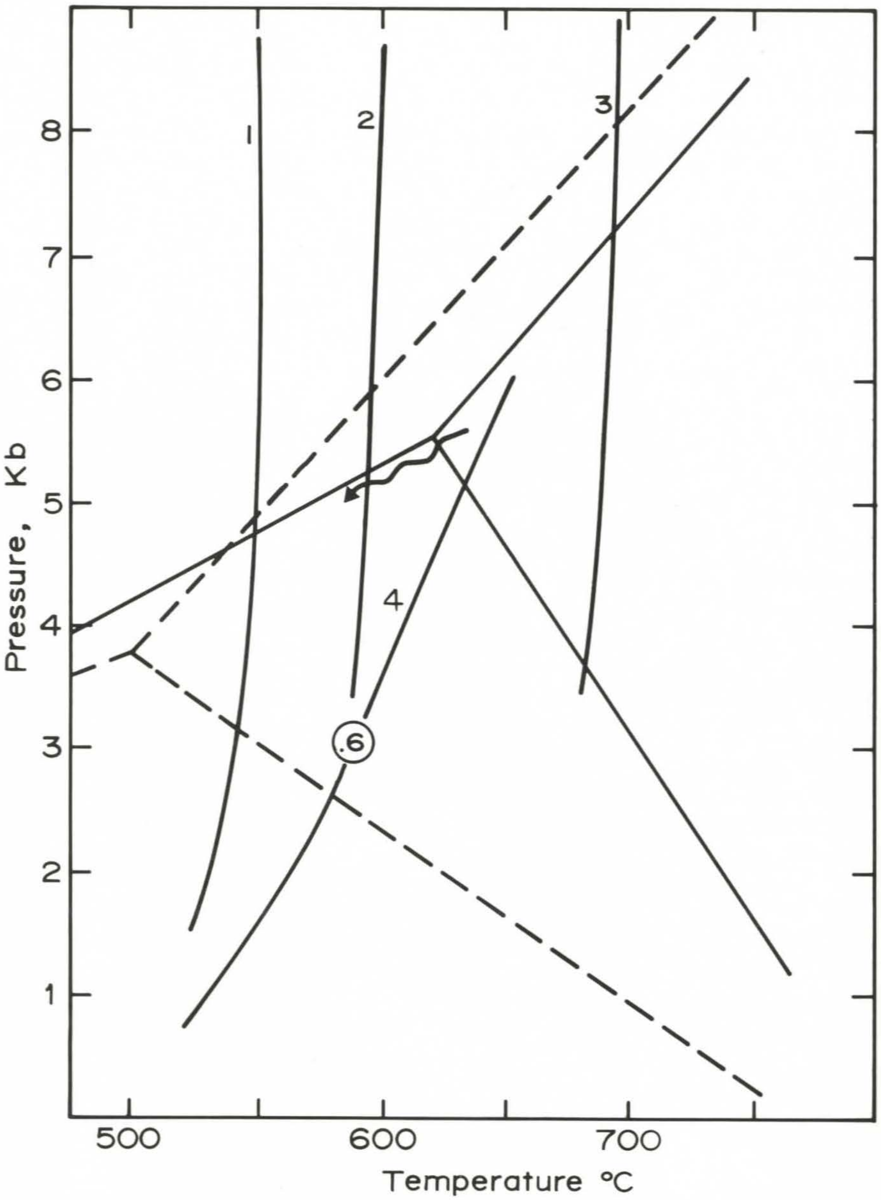


**Figure 12.**
P-T diagram suggesting conditions during $M_2$. Curves 1 to 3 from Richardson (1968).

1. 8Fe–Chtd + 10Sill = 2Fe–Staur + 3Qtz + $4H_2O$
2. 23Chtd + 7Qtz = 2Staur + 5Garn + $19H_2O$
3. 6Fe–Staur + 25Qtz = 8Garn + 46Sill + $12H_2O$
4. Musc + Qtz = $Al_2SiO_5$ + Kfs + $H_2O$ ($X_{H_2O} = 0.6$) (Kerrick, 1972)

These data indicate pressures in the range of 5.5 kilobars with temperatures of about 650°C assuming $X_{H_2O} = 0.6$.

The second metamorphic event ($M_2$) was caused by the intrusion of biotite granodiorite plutons. It produced recrystallization of sillimanite near the contacts and the formation of andalusite and staurolite farther away from the intrusive boundaries. Water evolved during the crystallization of the biotite granodiorites and the plutons of Concord Granite produced retrograde metamorphism to some phases characteristic of the greenschist facies. In the Hillsboro quadrangle, some chloritoid was also formed during this event, probably by a reaction such as

$$\text{Bio} + \text{Sill} + \text{Garn} + 5O_2 + 7H_2O \rightarrow \text{Chtd} + \text{Musc} + \text{Chte}.$$

J.B. Lyons (personal communication) has found chloritoid developing after staurolite in the Mt. Kearsarge quadrangle perhaps by reaction (1) or (2) in Figure 12. It is also apparent that in all rocks which have undergone the $M_2$ transition, sillimanite + K-feldspar has been retrogressed to muscovite + quartz. Since water was introduced during this event, the univariant curve for the sillimanite - K-feldspar reaction at $X_{H_2O} = 0.6$ is also plotted on Figure 12.

It is clear from the distribution of the retrograde phases that the temperature in the area decreased with distance from the biotite granodiorite plutons. Thus it is suggested that the P-T conditions during $M_2$ lay generally along the wavy line shown in Figure 12. The $M_2$ event documents decreases in both temperature and pressure as compared with the $M_1$ metamorphic climax.

The presence of cordierite + almandine in some of the sillimanite -K-feldspar assemblages may provide a valuable check on the pressure conditions realized during the $M_1$ episode. The most reliable data presently available is a whole-rock analysis of a cordierite-biotite-almandine schist from the Lovewell Mountain quadrangle (Heald, 1950) which has a $Mg/Mg + Fe = .27$. However, the annite content of the biotite is unknown and the ratios of the whole rock will probably differ somewhat from those of the cordierite.

# STRUCTURE

## Introduction

This section will present evidence bearing on the character of the penetrative deformations and the structural relationships of the plutonic and metasedimentary rocks of the Hillsboro quadrangle. Billings (1956) recognized one phase of folding in New Hampshire which produced north-northeast trending folds that parallel the trend of the Appalachian Mountains. The effect of this folding was to produce a series of large anticlinoria and synclinoria which are shown in Figure 1. As shown in Figure 1, the Hillsboro quadrangle is located along or close to the axis of the Merrimack synclinorium. This synclinorium was identified in New Hampshire (Billings, 1956, p. 114) using the criterion that the Littleton Formation, which was mapped as underlying all of central New Hampshire, is bounded on either side by older strata, and therefore must lie within a synclinorium. West of the Merrimack synclinorium lies the Bronson Hill anticlinorium whose axial region is defined by the Ordovician gneiss domes of the Oliverian Plutonic Series (Billings, 1956; Naylor, 1968). The Rockingham anticlinorium lies to the east of the Merrimack synclinorium in southeastern New Hampshire (Billings, 1956).

Thompson and others (1968) have remapped several quadrangles along the Bronson Hill anticlinorium in western New Hampshire. Their reinterpretation of the structure shows an initial stage of nappe formation with large-scale nappes being transported to the west from a heated area in the east. These nappes were later arched by the Oliverian domes that form the core of the Bronson Hill anticlinorium.

Structural studies published since the reinterpretation by Thompson and others (1968) include Greene's (1970) map of the Peterborough quadrangle, Englund's (1971, 1976) study of the Holderness quadrangle, and Vernon's (1971) preliminary interpretation of the geology of the Concord quadrangle, and the interpretations of Nielson and others (1976) of gravity data from central New Hampshire. Greene and Vernon recognize one period of folding which is the major north-northeast trending folding recognized by Billings (1956). However, Englund (1971, 1974) has recognized three periods of folding in central New Hampshire. The first folding event ($F_1$) produced recumbent folding about northwest-trending axes. The second folding event ($F_2$) superimposed open folding about northwest-trending axes on the earlier recumbent folds. The final folding event ($F_3$) produced open to isoclinal folding about northeast-trending fold axes. Englund's third folding event accounts for the northeast-trending structural grain in this section of the Appalachians, and his initial recumbent folding event is presumably the same event which produced the nappes reported by Thompson and others (1968).

## Nomenclature

Sander (1966) termed all penetrative structures in a rock "s-surfaces." In following this practice, the original bedding in a rock will be labeled $S_0$, and subsequently imposed foliations will be designated $S_1$, $S_2$, and $S_3$. Folds are designated $F_1$, $F_2$, and $F_3$ such that the $S_1$ foliation is the axial plane foliation of the $F_1$ folds. Lineations are abbreviated L, and are discussed in a subsequent section of this paper.

It is customary to plot structural data on the lower hemisphere of an equal area or Schmidt projection. Descriptions of the use of such projeections can be found in any structural geology text (e.g., Turner and Weiss, 1963, p. 49; Ramsay, 1967, p. 1).

It is also common practice to designate a, b, and c fabric axes when making reference to a fold. The b fabric axis is parallel with the fold axis. The major direction of transport is designated a, and the c direction is normal to the ab plane but has no meaning as a fabric axis.

## Structural Analyses of the Metasedimentary Rocks

In order to decipher the sequence of deformations in the Hillsboro quadrangle, a number of field observations were made whenever possible. These were: 1) measurements of all penetrative foliations in the rock, 2) observations of character and orientations of the minor folds within the rocks, and 3) observations of the relationships between the minor folds and the s-surfaces. During the field work, minor folds were carefully measured. These are mesoscopic folds generally not more than one meter in amplitude, which duplicate the geometry of the much larger folds (de Sitter, 1964, p. 59). The following structural analysis is based on the interpretation of minor folds reflecting the geometry and orientations of the macroscopic folds and the assignment of lineations and foliations to individual folding episodes. The penetrative fabric of the rocks have been assigned as $S_1$, $S_2$, or $S_3$ on the basis of their relationships to the mesoscopic folds.

Three types of minor folds were found in the Hillsboro quadrangle. The earliest of these are tight isoclinal folds which fold the relict bedding ($S_0$). Sketches of these folds are shown in Figure 13; they have been designated $F_1$ folds. The prominent schistosity of the area is the axial plane foliation of the $F_1$ folds and has therefore been designated as $S_1$ foliation. When both this foliation and the relict bedding are exposed, it is seen that $S_1$ is parallel or subparallel $S_0$, consistent with as interpretation of isoclinal folding. $F_1$ fold axes from the Hillsboro quadrangle are plotted in Figure 14 which shows that the $F_1$ folds plunge in a westerly direction at steep to shallow angles.

The second type of minor fold shows open folding about nearly vertical axial planes which have generally westerly-plunging fold axes. They fold both $S_0$ and $S_1$ and have been designated $F_2$ folds. Foliations parallel to the axial planes of the $F_2$ folds ($S_2$) have been

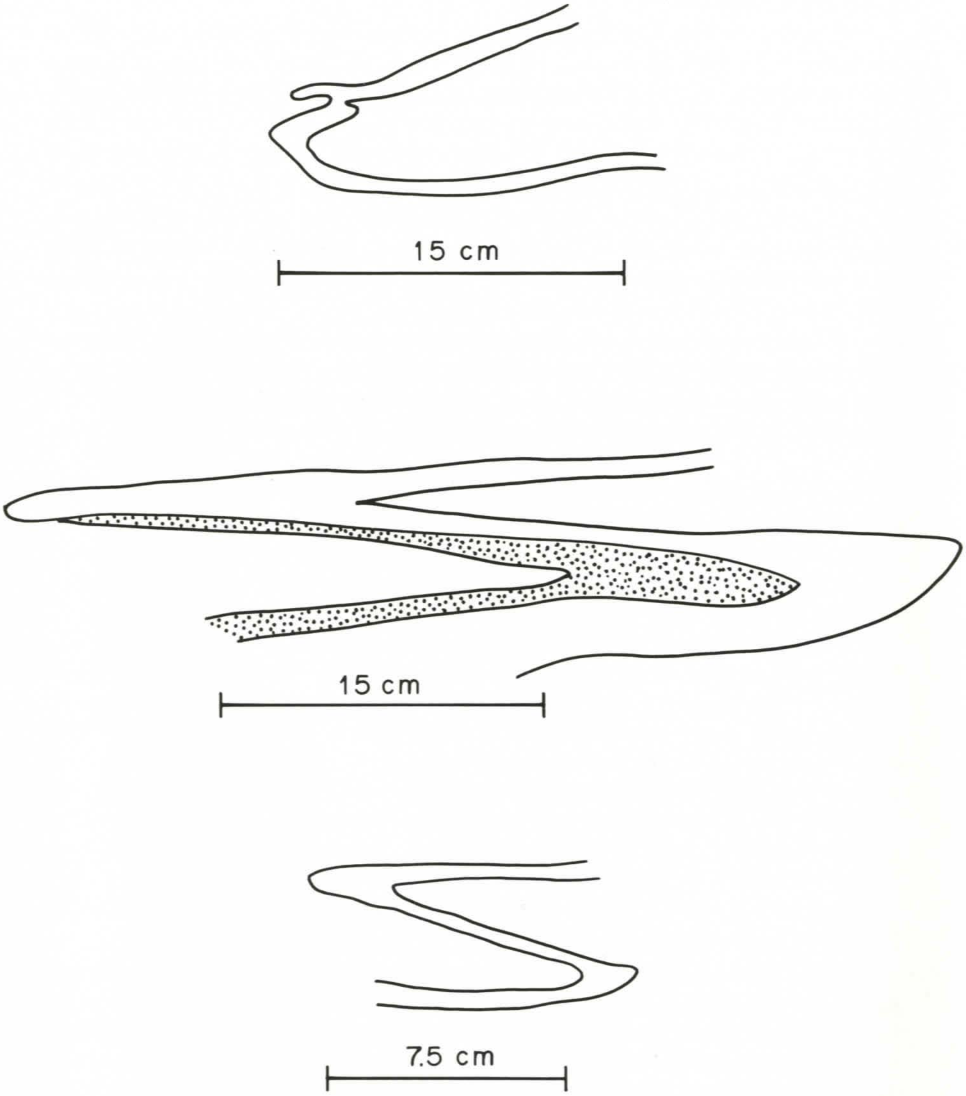


**Figure 13.**
Sketches of $F_1$ folds.

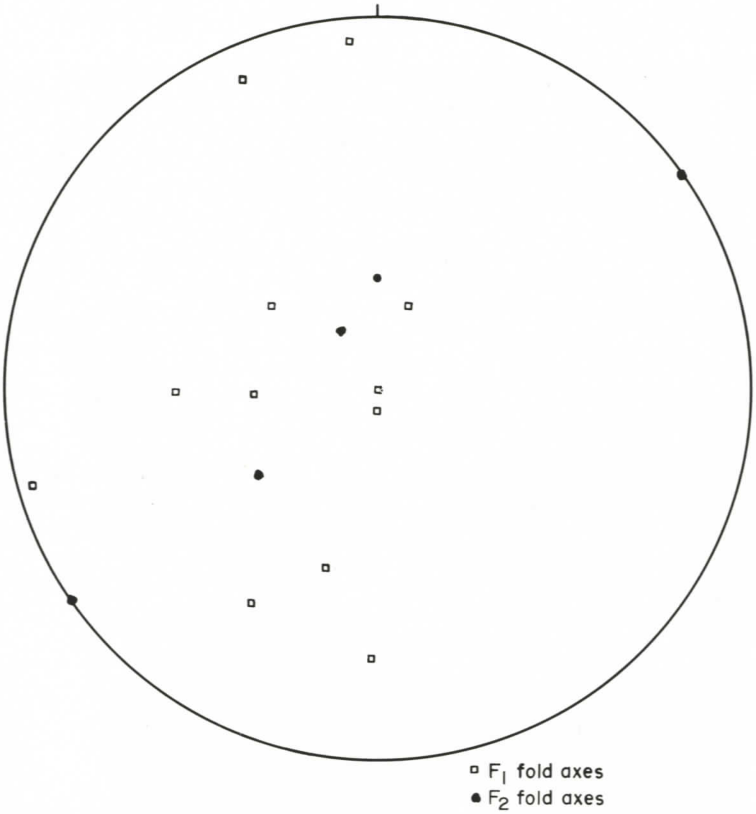


**Figure 14.**
Point diagram of minor $F_1$ and $F_2$ fold axes from the Hillsboro quadrangle.

observed only locally at the noses of some minor $F_2$ folds. The $F_2$ fold axes are also plotted on Figure 14.

The third type of folding ($F_3$) observed is open to tight folding about northeast-trending fold axes. These are the most common minor folds observed in the quadrangle and represent the phase of folding which has been recognized by most workers in the area (e.g., Billings, 1956; Greene, 1970) and which has also been identified as $F_3$ folding by Englund (1971, 1974). These folds also deform both $S_0$ and $S_1$ and their axes generally plunge to the northeast at shallow angles (Fig. 15). Figure 16 shows poles to axial planes of the minor $F_3$ folds and demonstrates that the axial planes of these folds vary in dip from vertical to as little as 20° to the northwest, and that the $F_3$ axial planes are generally overturned to the east. The overturning of the $F_3$ structures is systematic throughout the quadrangle with the axial planes being vertical at the north end of the Deering Pluton and becoming progressively more overturned toward the south.

The $F_3$ folding was the major deformation event which gave the Appalachians their northeasterly trend. Therefore, it is not surprising that a pi-diagram showing poles to $S_0$ and $S_1$ of the metasediments from the entire quadrangle (Fig 17) would reflect the $F_3$ folding. Figure 17 has been contoured by the Schmidt or grid method (Turner and Weiss, 1963, p. 61). This diagram indicates that, on the average, the foliations of the metasediments of the Hillsboro quadrangle strike to the north-northeast and dip to the west at high angles. The weak girdle across the center of the diagram suggests that the orientation of the metasediments largely reflects the $F_3$ folding event. The fact that many of these poles are of $S_1$ surfaces speaks against the conclusion that the metasediments form a simple west-northwest dipping homoclinal sequence as was concluded by Greene (1970).

The isoclinal $F_1$ event cannot be distinguished on Figure 17. If the $F_1$ event were isoclinal about horizontal axial planes and there were no subsequent deformations, the pi-diagram of $S_0$ and $S_1$ foliations would plot as a maximum in the center of the diagram, except for $S_0$ foliations at the noses of the folds. The broadening of the distribution of the poles about the perimeter of the diagram of Figure 17 is consistent with the folding of $S_0$ and $S_1$ foliations by upright $F_2$ folding about northwest-trending axes which would take an initial concentration near the center of the projection and scatter it into a northeast-southwest girdle. Subsequent folding about $F_3$ would then produce the pattern shown by Figure 17.

Greene (1970) has not constructed a composite diagram of the foliations of the metasediments of the Peterborough quadrangle, but he has shown pi-diagrams of numerous structural domains. These diagrams suggest that the metasediments of the Peterborough quadrangle have the same general orientations and structural features as the rocks of the Hillsboro quadrangle and are thus part of the same fold system. Englund (1971, Fig. 2a) shows an equal area diagram of poles to foliations of metasediments of the Holderness quadrangle. The points form a broad northwest-southeast girdle similar to that of Figure 17 but without the eastern point maximum. This indicates that the $F_3$ folding in the Holderness quadrangle is about approximately vertical axial planes.

Lineations are common in rocks of the Hillsboro quadrangle and can be of use in interpreting the structure of the area. The most common lineations are a result of preferred orientation of mineral grains, commonly sillimanite. Lineations may be developed parallel to fold axes and then are termed 'b' lineations as a result of their conicidence with the b fabric axis of the fold. However, Cloos (1946) states that lineations are also developed perpendicular to 'b' in the 'a' direction. Cloos warns that many geologists have assumed that two sets of lineations at right angles to each other were both 'b' lineations and therefore represent two periods of folding at right angles to one another. Both 'a' and 'b' lineations have been observed in the Hillsboro

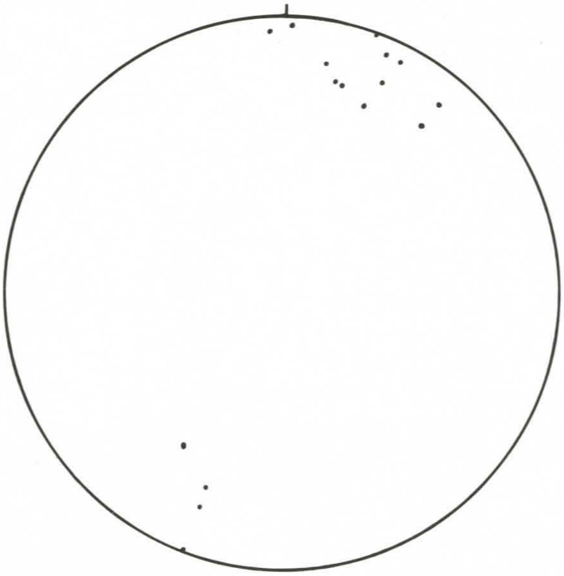


**Figure 15.**
Point diagram of minor $F_3$ fold axes in the Hillsboro quadrangle.

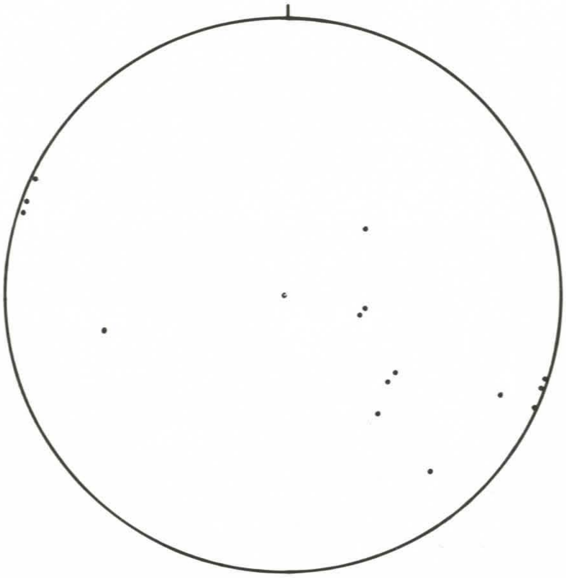


**Figure 16.**
Poles to axial planes of minor $F_3$ folds in the Hillsboro quadrangle.

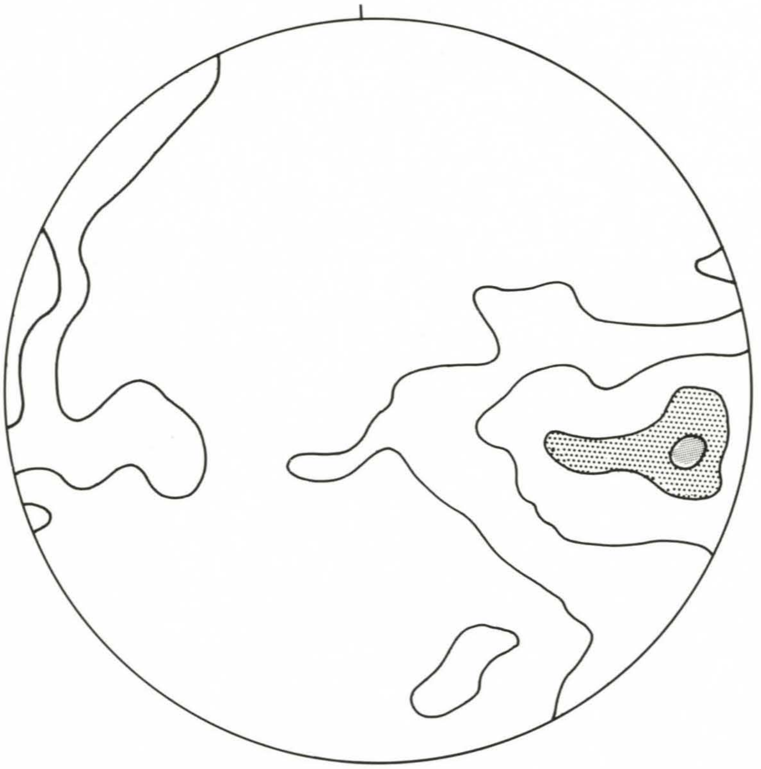


**Figure 17.**
Pi-diagram of $S_0$ and $S_1$ foliations in metasediments of the Hillsboro quadrangle. Contours: 1%, 3%, 6%, and 9% of 1% area; 375 points.

quadrangle, but 'a' lineations, normally found as streaks or "streimung" on foliation surfaces, are less abundant than 'b' lineations, which are either mineral lineations or lineations produced by the intersections of $S_0$ and $S_1$.

Figure 18 is a point diagram of fold axes and Figure 19 a point diagram of lineations from the Hillsboro quadrangle. The similarity of Figures 18 and 19 supports the field observation that most lineations measured were 'b' lineations rather than 'a' lineations. The point to be observed with respect to both fold axes and lineations is that they are not concentrated in only one or two point maxima as they would be if the rocks underwent only one period of deformation. Instead, their scattered distribution and particularly their relative abundance in the western quadrants of both Figures 18 and 19 imply an earlier set of northwest-trending folds, now refolded about northeast-trending axes.

Plots of fold axes (Fig. 18) and lineations (Fig. 19) from the Hillsboro quadrangle are essentially the same as those measured by Greene (1970) in the Peterborough quadrangle. Figure 18 is also quite similar to a point diagram of fold axes measured by Englund (1974, Fig. 19) in the Holderness quadrangle.

It is clear, when the lineations from the Hillsboro quadrangle (Fig. 19) are compared with the point diagram of $F_3$ fold axes (Fig. 15), that many of the lineations measured were 'b' lineations of the $F_3$ folds. The numerous shallow northeast-trending lineations in the Peterborough quadrangle suggest that this is also true in that area. However, Englund (1974, Figs. 20 and 21) has shown that the lineations in the Holderness quadrangle are generally parallel with $F_1$ and $F_2$ fold axes, and that there are no mineral lineations parallel with $F_3$ fold axes. Thus all of Englund's mineral lineations are either 'a' lineations of $F_3$ folds or 'b' lineations of $F_1$ and/or $F_2$ folds. Englund prefers the latter interpretation. The different distribution of mineral lineations between the Hillsboro-Peterborough and Holderness quadrangles is probably a result of the fact that in the southern area of the Hillsboro quadrangle the formation of the $F_3$ folds was accompanied by the intrusion of biotite granodiorite plutons while there are no such intrusions accompanying $F_3$ folding in the Holderness quadrangle. Thus the heat and perhaps fluids from these biotite granodiorite plutons aided in mineral recrystallization during folding to form $F_3$ 'b' lineations.

As stated previously, Greene's (1970) point diagrams of fold axes and lineations are similar to Figures 18 and 19; however, his interpretations are different from those presented here. Greene (1970, p. 23) states that the northwest-southeast fold axes in the Peterborough quadrangle are, "cross folds which...may have formed later than the regional structure, although some may result from heterogeneity in the rocks." He regards the northwest-trending mineral lineations as 'a' lineations of the major northeast-trending folds.

In order to better quantify the attitudes of $S_0$ and $S_1$ and to define the fold styles in the different parts of the Hillsboro quadrangle, the metasediments have been divided into 10 structural domains (Plate II). $S_2$ and $S_3$ foliations have only been identified locally at the noses of minor folds and are not discussed here. The domains are areas which show relatively uniform attitudes of $S_0$ and $S_1$ foliations or style of folding which distinguish each area from adjacent areas. The pi-diagrams and point diagrams of fold axes and lineations for these domains are shown in Figure 20-I through 20-X. Different contour intervals were chosen for the pi-diagrams in Figure 20 in order to emphasize maximum concentrations. The lowest contour was drawn such that it encompasses all points of concentration greater than 0 percent for each 1 percent area of the diagram. This was done to show the total orientation within each domain.

Domain I (Fig. 20-Ia) consists of rocks of the Littleton Formation which strike northerly and dip to the west at high angles. The lineations and fold axes measured in this zone have also been plotted (Fig. 20-Ib). The four lineations plotted are either sillimanite lineations or a lineation produced by the intersection of $S_0$ and $S_1$. These lineations are therefore 'b' lineations of the $F_1$ isoclinal folding. One $F_1$ fold axis was observed in this area, and it is vertical. The fold axis which plunges to the southeast is probably an $F_3$ axis.

Domain II (Fig. 20-II) has been established primarily on the basis of diversity of orientation. This heterogeneity is probably enhanced by the fact that this area contains representatives of all four mapped metasedimentary units, and the different behavior of the different lithologies during folding would help account for the variations. In general the foliations strike about N10° to N30° and dip to the west at moderately high angles. In comparison with Domain I, the foliations of Domain II strike more to the northeast and do not dip as steeply. The similarity of Figure 20-IIa and Figure 17, the pi-diagram of metasediments for the entire quadrangle, should be noted. In fact, in Figure 20-IIa the broadening of poles about the perimeter of the diagram which is ascribed to $F_2$ folding is more pronounced than it is for the quadrangle as a whole. Figure 20-IIb shows the fold axes and lineations for this domain; fold axes plunge at low angles to the northeast. The $F_1$ and $F_2$ fold axes have a rather variable distribution, generally westerly at high angles.

Domain III (Fig. 20-III) is developed in metasediments of the Littleton Formation on the eastern flank of the Antrim Pluton. It is seen that the steep foliations generally strike north-south and dip to the east at high angles more often than to the west. Graded beds in this area indicate that stratigraphic tops are to the west, so the metasediments are overturned. This is the only area where $F_3$ minor folds are overturned to the west. This is possibly a result of the intrusion of the Antrim Pluton which appears to have spread out laterally from a central area of injection (Nielson and others, 1976). This could have exerted a lateral compressive stress on the metasediments which resulted in their overturning to the west. In this domain, measured $F_1$ and $F_3$ fold axes plunge to the northeast at low angles.

The pi-diagram of Domain IV (Fig. 20-IVa) indicates that the metasediments of this domain dip to the northwest at angles of 20 to 50 degrees. It can be seen by comparing this area with Domains I and II and by reference to Plate I that, as the Deering Pluton is approached, the dips become more gentle. The point diagram of lineations and fold axes from this domain indicates that the $F_3$ folding event is strongly represented both as fold axes and lineations. These $F_3$ fold axes plunge at gentle angles to the northeast and southwest. The mineral lineations here represent 'b' lineations of $F_3$ folds. They are well developed in this area due to their proximity to the Deering Pluton which was injected during the $F_3$ folding event. Two $F_1$ fold axes were recognized

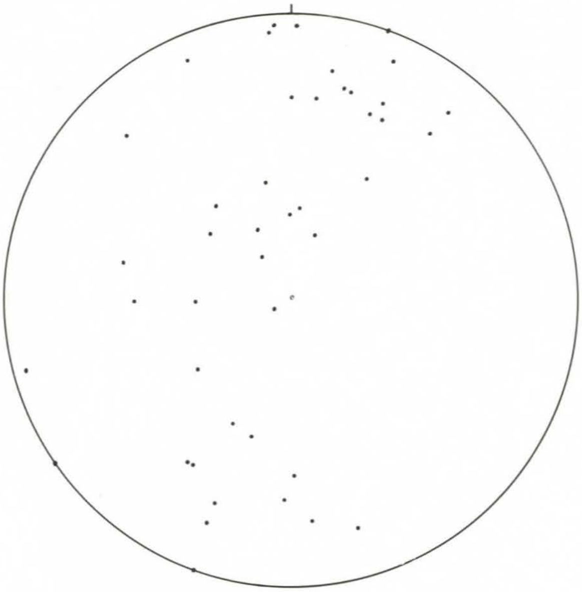


**Figure 18.**
Point diagram of minor fold axes measured in the Hillsboro quadrangle, (44 points).

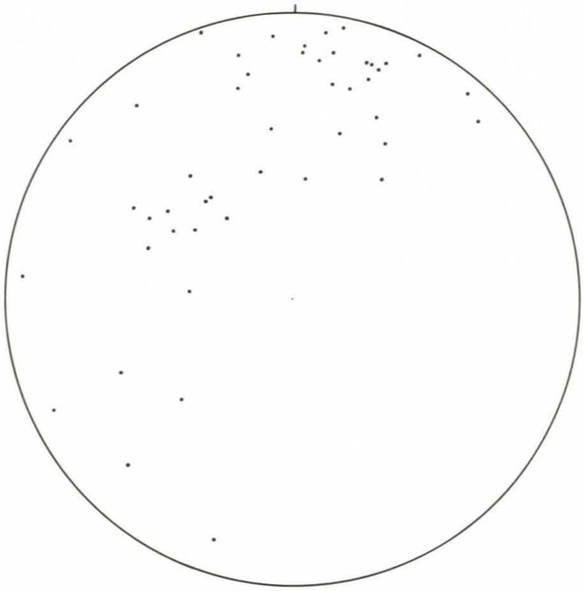
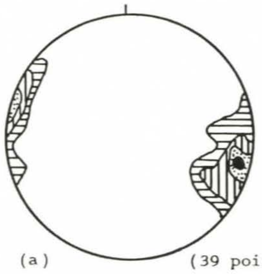
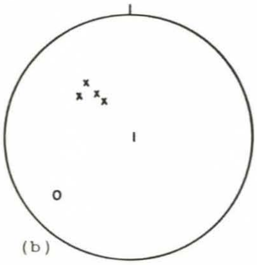


**Figure 19.**
Point diagram of lineations measured in the Hillsboro quadrangle (48 points).



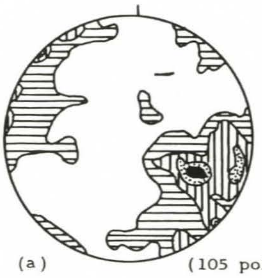
(a) (39 points)

Contours: 2.6%,10%,20%,30%



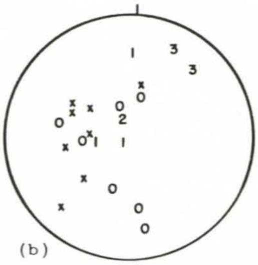
(b)

Figure 20-I Domain I



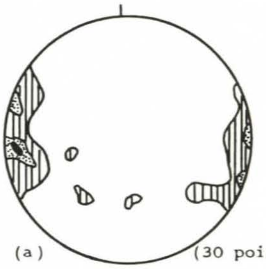
(a) (105 points)

Contours: .95%,3%,6%,9%



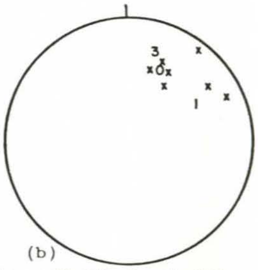
(b)

Figure 20-II Domain II



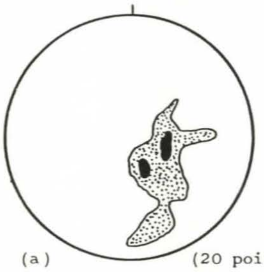
(a) (30 points)

Contours: 3.3%,10%,15%



(b)

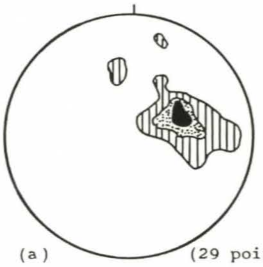
Figure 20-III Domain III



(a) (20 points)

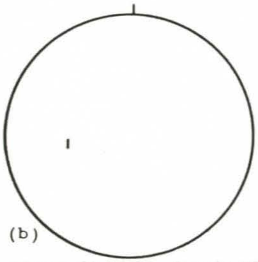
Contours: 5%,15%

Figure 20-VII Domain VII



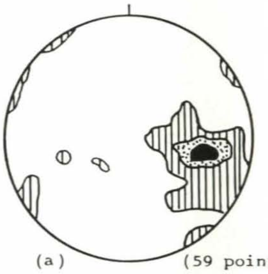
(a) (29 points)

Contours: 3.4%,10%,20%,



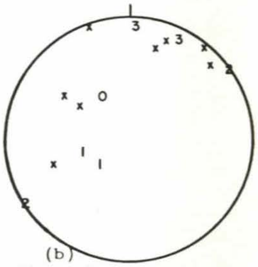
(b)

Figure 20-VIII Domain VIII



(a) (59 points)

Contours: 1.7%,10%,15%



(b)

Figure 20-IX Domain IX

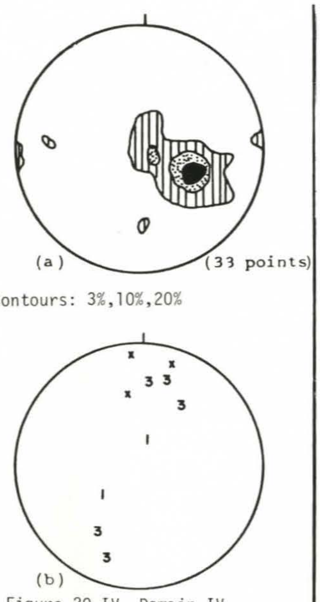


Figure 20-IV Domain IV

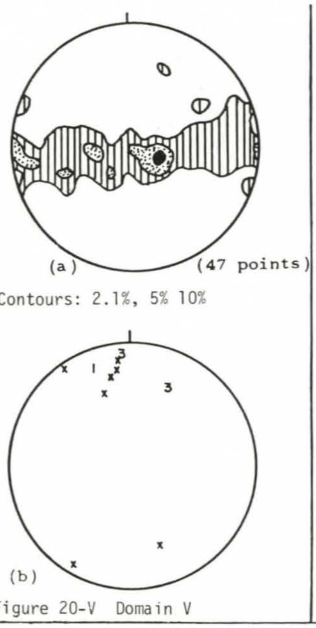


Figure 20-V Domain V

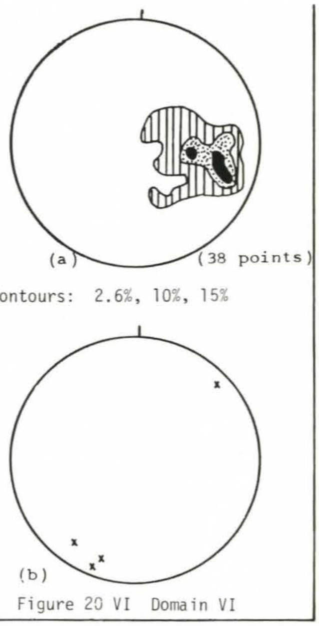


Figure 20 VI Domain VI

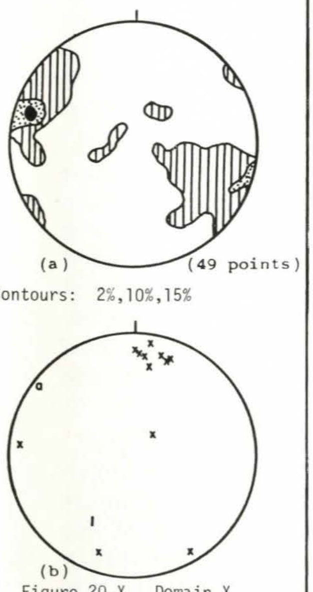


Figure 20-X Domain X

**Figure 20.**
Pi-diagrams of foliations ($S_0$ and $S_1$) and point diagrams of lineations and fold axes of structural domains in the Hillsboro quadrangle. The structural domains are shown in Plate II. Contours per 1% area are listed below diagrams.

x mineral lineations
a 'a' lineation
0 unassigned fold axis
1 $F_1$ fold axis
2 $F_2$ fold axis
3 $F_3$ fold axis

in this domain, and they plunge at high angles to the northeast and southwest.

Domain V (Fig. 20-V) is characterized by gentle $F_3$ folding which forms an east/west-trending girdle on the pi-diagram (Fig. 20-Va). The diagram also indicates that this is the axial area of a major $F_3$ fold. The slightly off-center 10 percent maximum indicates that the folding is only slightly overturned to the east. The $F_3$ fold axes of this area (Fig. 20-Vb) plunge at small angles to the north and northeast.

Figure 20-VIa is a pi-diagram of foliations in Domain VI. It can be seen that the foliations again strike to the northeast and dip to the west. The lineations found in this domain (Fig. 20-VIb) are probably 'b' lineations of $F_3$ folds. Thus, after crossing the axis of a major $F_3$ fold, the foliations are again dipping steeply to the west. These relations indicate that the major $F_3$ fold is overturned to the east. Note by comparing Domains IV and VI that the west limbs of these $F_3$ folds dip to the west at lower angles than the east limbs.

Domain VII is characterized by east-northeast-trending foliations which dip at shallow to steep angles to the north and northwest (Fig. 20-VII). The zone surrounds a small pluton of Concord Granite, and it is proposed that these unusual orientations are a result of arching of the metasediments by the injection of this pluton.

Domain VIII (Fig. 20-VIII) is a small area between Domain VII and the Deering Pluton which is characterized by northwest strikes and dips of about 40° to the southwest. The only fold axis found in this area was an $F_1$ axis which plunges to the west at 45°. The reason for the orientation in this area is not clear, but it may be a result of $F_2$ folding.

The southeast corner of the Hillsboro quadrangle forms Domain IX (Fig. 20-IX). Here the metasediments again strike to the northeast and dip to the west generally at angles of 50° to 60° but vary from vertical to nearly horizontal. It can be seen here once again that there has been some amount of spreading out of poles along the perimeter of the circle which is probably a result of $F_2$ folding. Once again, there is a group of $F_3$ fold axes and lineations parallel with $F_3$ fold axes. Accompanying these is a group of $F_1$ and $F_2$ axes and 'b' lineations of $F_1$ or $F_2$ folds which are rather scattered but generally plunge to the west at moderate angles.

The metasediments of the northeast corner of the Hillsboro quadrangle form Domain X (Fig. 20-X). Here it is seen that the metasediments generally strike northeasterly and are vertical or dip to the east at high angles. The spreading of points about the perimeter of the diagram due to $F_2$ folding is again suggested, and the rather spotty northwest-southeast girdle is a result of the $F_3$ folding. Again there is a strong 'b' lineation parallel with $F_3$ fold axes. One 'a' lineation, produced by slipping during $F_3$ folding, was observed, and it is labeled "a" on Figure 20-Xb. One $F_1$ fold axis and several lineations which are probably parallel with $F_1$ fold axes are also located on Figure 20-Xb.

## Interpretation of Structural Analysis

It has been shown (Fig. 15) that $F_3$ fold axes and 'b' lineations parallel to the $F_3$ fold axes have remarkably uniform trends throughout the metasediments of the Hillsboro quadrangle. It has also been seen that the attitudes of the metasediments (Fig. 17) also largely reflect the effects of this major northeast folding. Thus the $F_3$ event was the last major folding of these rocks.

In contrast, the $F_1$ and $F_2$ fold axes and 'b' lineations parallel with these fold axes have quite variable attitudes but are largely confined to the northwest and southwest quadrants of the stereo net (Figs. 14, 20-I to 20-X). This diffuse orientation is a result of three factors: 1) original variations in the orientation of $F_1$ and $F_2$ fold axes; 2)$F_1$ axes have been deformed by $F_2$ and both $F_1$ and $F_2$ fold axes have been rotated during folding; 3) the effects of the $F_3$ folding have not been uniform throughout the entire quadrangle.

The southwestern orientations of $F_1$ and $F_2$ fold axes are largely a result of the overturned nature of the $F_3$ folding. The folding of a northwest-trending $F_1$ lineation about a northeast-trending, westward dipping axial plane produces lineations which plunge to both the northwest and southwest.

In a general way, the orientations of the lineations are compatible with the deformation of northwest-trending $F_1$ and $F_2$ axes about northeast-trending $F_3$ axes. This is in agreement with the conclusions of Englund (1974).

It is possible that the westward overturning of the $F_3$ folds is a result of flowage beneath a sheet of Kinsman Quartz Monzonite. It is the conclusion of Nielson and others (1973; 1976) that the Cardigan and Weare Plutons (to the east of the Hillsboro quadrangle) of the Kinsman were once continuous and are now separated as a result of erosion of the $F_3$ antiformal arch between the two plutons. In the Hillsboro quadrangle and northward into the Mt. Kearsarge quadrangle it is apparent that the $F_3$ axes are largely parallel to the Kinsman - wallrock contact (J.B. Lyons, personal communication). This suggests that the $F_3$ folding may have been confined by the overlying Kinsman sheet and developed by flowage beneath this sheet.

Figure 20-V shows that Domain V is a well-developed axial zone as indicated by the broad girdle. Thus it is apparent that the Deering Pluton (Plate I) occupies the core of a large $F_3$ antiform. This $F_3$ structure has refolded a large $F_1$ isoclinal recumbent fold which is defined by the outcrop pattern of the Francestown Member. The outcrop pattern and the axes of the minor folds indicate that this large isoclinal recumbent fold was developed about northwest-trending fold axes, and that the direction of overfolding was toward the northeast. These orientations are in agreement with those deduced by Englund (1974) in the Holderness quadrangle.

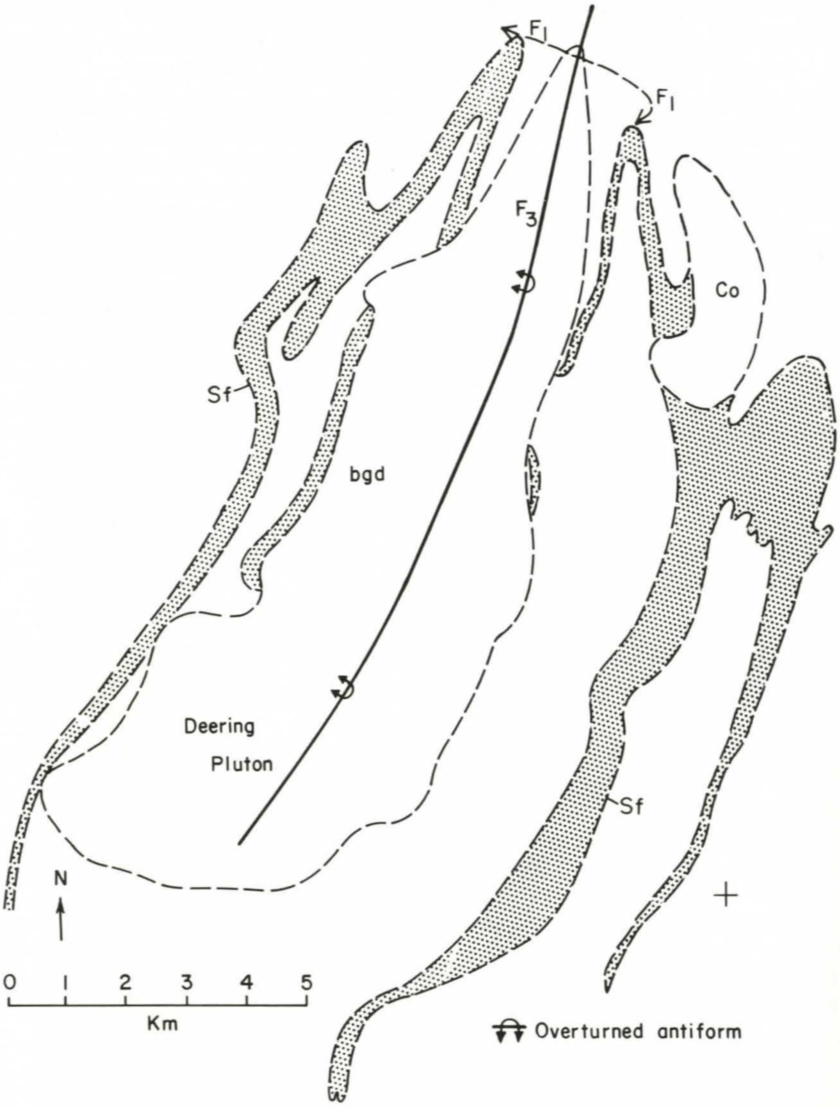


**Figure 21.**
Tectonic map of the southeast quadrant of the Hillsboro quadrangle and adjacent areas in the Peterborough and Concord quadrangles showing the outcrop pattern of the Francestown Formation (Sf) and biotite granodiorite (bgd) and Concord Granite (Co) plutons.

Figure 21 is a tectonic map of the southeast quadrant of the Hillsboro quadrangle and adjacent areas of the Concord and Peterborough quadrangles. The outcrop pattern of the Francestown Member is shown on Figure 21 and was determined outside the Hillsboro quadrangle partly from Greene's (1970) map of the Peterborough quadrangle, and partly by reconnaissance mapping by the author in the Peterborough and Concord quadrangles. Superimposed on the tectonic map are the traces of the fold axis of the major $F_3$ antiform and the trace of the major $F_1$ fold axis projected to the horizontal.

The development of this structure is illustrated by the schematic representation of the Francestown Member in Figures 22a and b. Figure 22a depicts the Francestown at the end of the $F_1$ folding event. The entire structure consists of two recumbent antiforms with a very tight recumbent synform sandwiched between them. In the synform, the Francestown has been folded back on itself. Note that the $F_1$ fold axes are not parallel although they were undoubtedly formed at the same time. The $F_2$ event in this area was minor and produced a small amount of folding about vertical, northwest-trending axial planes.

During the third period of deformation the recumbent structures shown in Figure 22a were refolded about the major north-northeast-trending $F_3$ fold axis. The folding is shown schematically in Figure 22b. As already described, the folding is nearly upright at the nose and becomes progressively overturned to the east toward the southern portion of the fold. It is important to note the trends of the different fold axes. The $F_3$ fold axis plunges to the north at low angles. The $F_1$ fold axes have now assumed orientations which are much different than in Figure 22a; their present orientations are as shown in Figure 22b. It is seen that the $F_1$ axes which are on the west limb of the $F_3$ fold plunge to the west at moderate angles. The $F_1$ axes which are on the eastern limb of the $F_3$ fold, however, plunge to the southwest at steep angles. The outcrop pattern of the Francestown in Figure 21 is thus a result of the superposition of these three fold systems.

West of the Deering Pluton (Plate I, Fig. 21), the double belt of Francestown is a result of an isoclinal $F_1$ fold plunging at a moderate angle to the northwest. The axis of this fold is traced eastward on Figure 21 across the Deering Pluton and is shown plunging to the southwest at a steep angle. The outcrop pattern of the Francestown east of the Deering Pluton is also a result of plunging $F_1$ folds. The discontinuous belt of Francestown exposed directly east of the Deering Pluton and lying on the lower inverted limb of the recumbent structure is very attenuated and generally has a thickness of only about 50 feet. In contrast, the upper limb of the recumbent fold, which is exposed in the next belt to the east, ranges up to 1 km in thickness. This broad belt is traceable into the Peterborough quadrangle where it has been shown by Greene (1970) to terminate. This entire belt is therefore interpreted as defining a tight $F_1$ synformal axis, now overturned to the east with both limbs of the $F_1$ fold sandwiched against

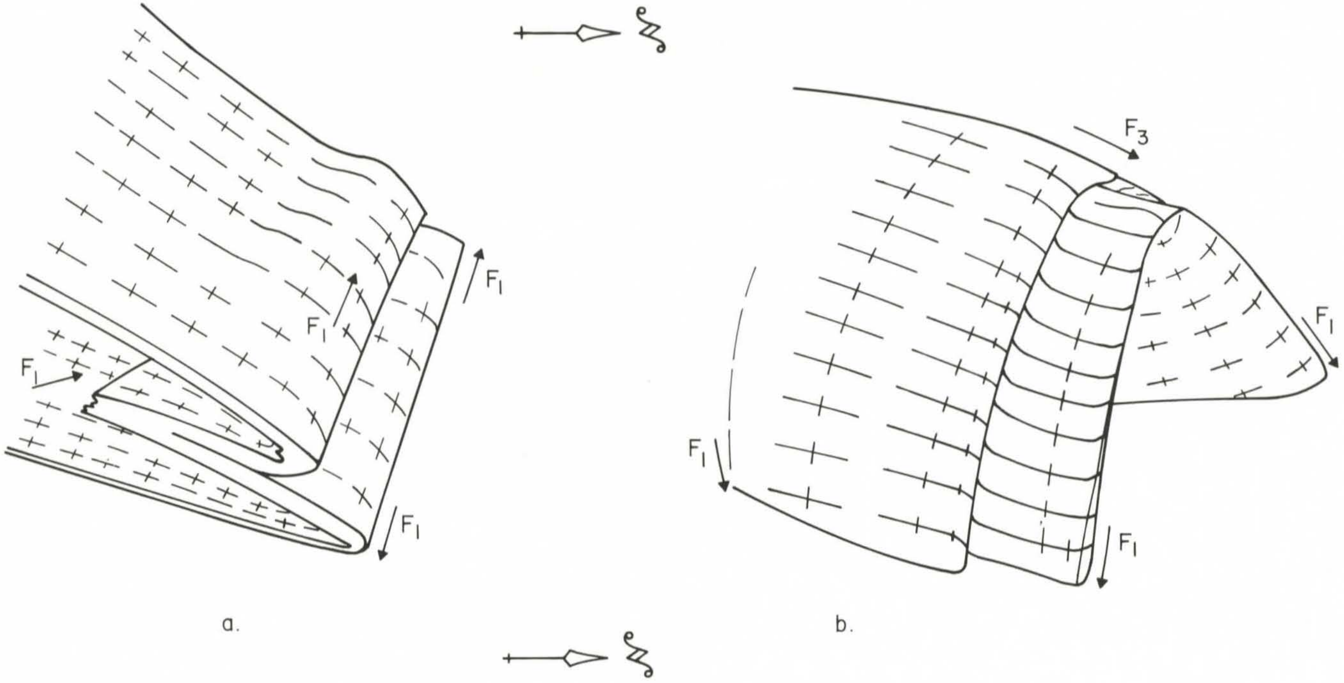


**Figure 22.**
Schematic drawing of the Francestown Member, a) at the end of the $F_1$ folding event and, b) at the end of the $F_3$ folding event.

one another. This belt is similar in appearance to a belt of the Clay Brook Member mapped by Englund (1974) in the Holderness quadrangle and may represent the same type of structure. The Francestown then passes into an $F_1$ antiformal axis which is interpreted on the basis of reconnaissance mapping in the Concord quadrangle. The upper (eastern) limb of the $F_1$ antiform abuts against a biotite granodiorite pluton which underlies the extreme southeast corner of the Hillsboro quadrangle and continues into the Concord, Milford, and Peterborough quadrangles.

It has been shown that the outcrop pattern of the Francestown Member in the Hillsboro quadrangle defines an $F_1$ recumbent structure which has been refolded about a major $F_3$ fold axis. However, the true size of this recumbent structure is not clear; there is no definite indication of the extent of this fold above or below the Francestown. Some lower limits to the fold's size can be set. West of the Deering Pluton, the original thickness of the recumbent sheet, as defined by the Francestown, was at least 2.4 km. It then thickens to about 4.8 km (as defined by the Francestown) to the east of the Deering Pluton as a result of the stacking of two recumbent folds. The length of the entire structure along its axis and the amplitude of the antiformal recumbent folds are not known at this time and will have to await addition mapping in the Peterborough, Milford, and Concord quadrangles.

On a regional scale, the superposition of the two major fold systems ($F_1$ and $F_3$) will produce a "basin and dome" interference pattern (Type 2 of Ramsay, 1967). Note that this explains the occurrence of the same stratigraphy in two separate areas of the Hillsboro quadrangle. That is, the northeastern corner of the quadrangle (Plate I) represents a portion of a "dome" similar to the one described in the southeastern portion of the quadrangle. Figure 23 shows the outcrop pattern of the Francestown in Monadnock, Peterborough, Hillsboro, and parts of the Concord quadrangles; the "basin and dome" interference pattern is obvious. Thus the Francestown does crop out in a series of disconnected "domes" throughout south-central New Hampshire. As a result of this, it will probably not be possible to trace this marker horizon continuously through central New Hampshire. Correlation must be based on lithologic similarities and stratigraphic position.

The precise nature of the Merrimack synclinorium as a structural entity in central New Hampshire is quite uncertain at this time. This area was a basin of sedimentation during late Silurian and early Devonian time and accumulated a thick sequence of marine sediments. This thick section gives way to older rocks of the Bronson Hill anticlinorium on the west and to the Rockingham anticlinorium on the east, but whether a single axis of downwarping can be identified within this synclinorium is doubtful.

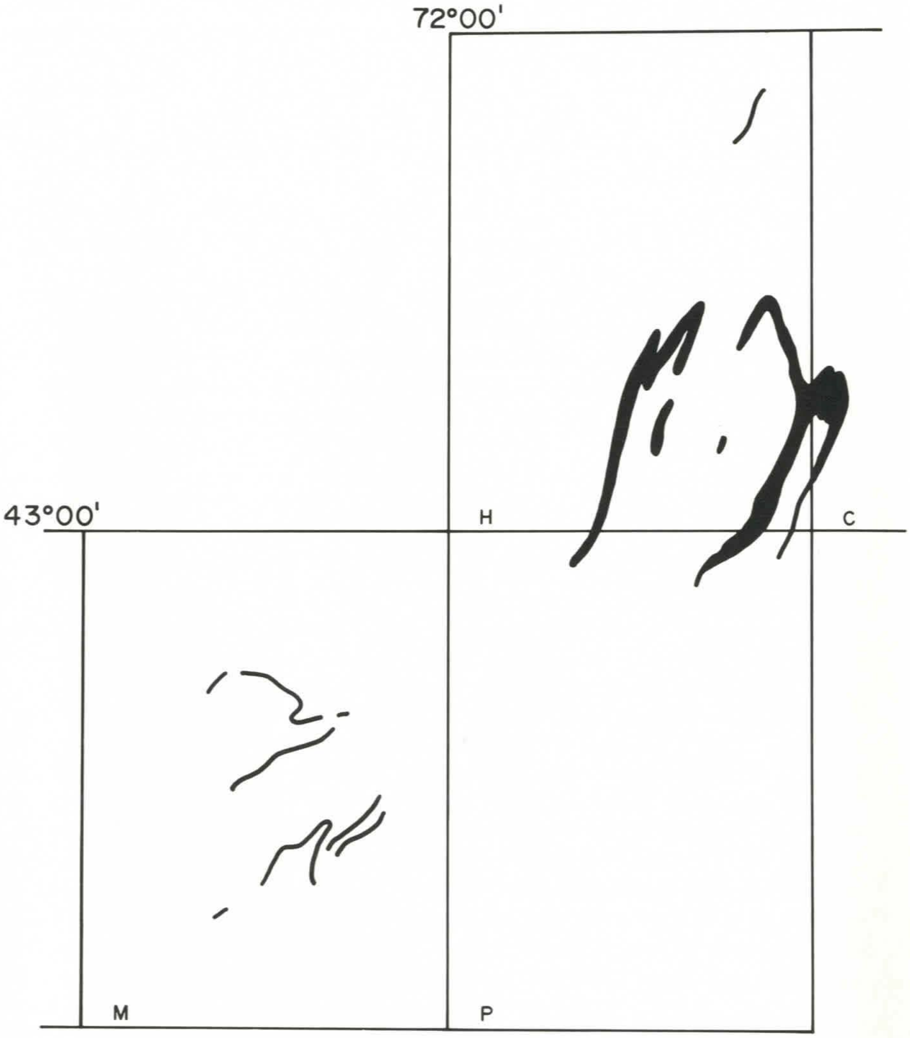


**Figure 23.**
Sketch map of the outcrop pattern of the Francestown Formation in Monadnock (M), Peterborough (P), Hillsboro (H), and part of the Concord (C) quadrangles showing the "basin and dome" interference pattern.

## Structural Analysis of the Plutonic Rocks

The structural relationships of the plutonic rocks of the Hillsboro quadrangle have been studied by measuring the foliations and mapping the outcrop patterns of the intrusive rocks. In addition, gravity studies over central and southern New Hampshire (Nielson and others, 1973, 1976) have defined the three-dimensional configurations of the rocks of the New Hampshire Plutonic series. The observed plutons occur as subhorizontal sheets which are all less than 2.5 km thick. It was concluded by Nielson and others (1973, 1976) that the Kinsman Quartz Monzonite was emplaced as a sheet during the $F_1$ nappe development, with biotite granodiorite and Spaulding Quartz Diorite emplaced during $F_3$ folding. The Concord Granite was emplaced as the metamorphic temperature cooled to permit brittle fracturing of the wall rocks. The formation of these plutonic sheets reflected the high temperature and existing planar structural features of an infrastructural tectonic zone.

Of the plutonic rocks exposed in the quadrangle, the Kinsman Quartz Monzonite is the oldest and the only plutonic rock to have preserved evidences of the three penentrative deformations. The most obvious foliations in the Kinsman are defined by oriented megacrysts of K-feldspar. The K-feldspar foliations may be either $S_1$ or $S_3$. Both foliations have been observed, and Clark (1972, Fig. 11) has shown a picture of both foliations in the same outcrop. Commonly, however, it is not possible to differentiate between $S_1$ and $S_3$ foliations in the Kinsman. This is because the $F_3$ folding becomes more isoclinal and upright as the contact with the Kinsman is approached (Fig. 20-I). Evidently the same structural style that characterizes the metasedimentary rocks is continued within the Kinsman (c.f., Figs. 20-I and 24), and thus it is difficult to determine whether the foliations are $S_1$ or $S_3$. For this reason, $S_1$ and $S_3$ are not differentiated within the Kinsman and both are plotted in Figure 24. As in the pi-diagrams of the metasediments, there is a spreading about the perimeter of the diagram which may be a result of $F_2$ folding. Also, there are some points which suggest a spotty east-west girdle which are a result of $F_3$ folding.

Norwick (1967, Fig. 12) has constructed pi-diagrams from structure maps of the Lovewell Mountain (Heald, 1950) and Sunapee (Chapman, 1952) quadrangles. In these diagrams, the foliations of the Cardigan Pluton have much the same orientations as in Figure 24, but strike more to the northeast. His diagrams show that the metasediments of these quadrangles dip steeply to the east, and that the dips steepen as the Cardigan Pluton is approached. Thus the Cardigan Pluton appears to occupy a synform.

There is a second type of foliation which is seen at times in the Cardigan Pluton. This foliation is defined by aggregates of quartz or biotite and cuts the $S_1$ or $S_3$ foliations defined by the K-feldspar megacrysts. This foliation has not been reported in adjacent quadran-

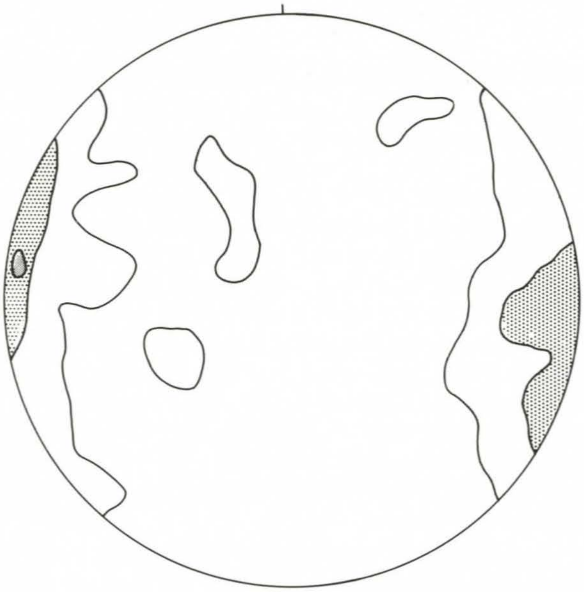


**Figure 24.**
Equal area projection on the lower hemisphere of poles to $S_1$ and $S_3$ (feldspar) foliations of the Cardigan Pluton in the Hillsboro quadrangle. Contours: 1%, 5%, and 10% of 1% area (148 points).

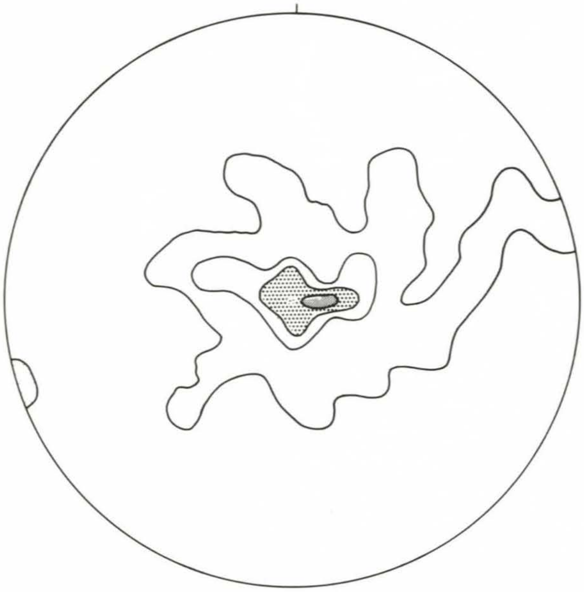


**Figure 25.**
Pi-diagram showing poles to "late" quartz and biotite foliation in the Kinsman Quartz Monzonite. Contours of 1%, 10%, 20%, and 30% of 1% area (87 points).

gles and is primarily, although sporadically, developed in the central and southern areas of the Hillsboro quadrangle. Figure 25 is a pi-diagram of these foliations and indicates that they are remarkably flat when contrasted with the feldspar foliations (Fig. 25) and the foliations of the metasediments (Fig. 17). The origin of these foliations is not clear, but it is later than the $S_3$ foliation which it at times cuts. This relative age and the orientation of the foliation suggest that it may have formed in response to a lessening of overburden pressures and subsequent uplift.

As has been shown previously, the biotite grandiorite plutons were injected during the $F_3$ folding. The number of structural measurements on these rocks has been limited by poor exposure. These rocks are at times massive but at other times have good $S_3$ foliations or even some flow banding.

The Concord Granite is post-kinematic. This rock is generally massive but often shows excellent flow banding, particularly near the margins of the intrusive bodies (Fig. 5).

## Faults

There is no evidence for major faulting in the Hillsboro quadrangle. One silicified zone has been mapped in the northeast corner of the quadrangle (Plate I). It is a "dike" of essentially pure "bull" quartz. Zones such as these are normally attributed to silicification along faults (c.f., Greene, 1970). However, in this area no geologic discontinuities were detected.

There are some foliations which strike north-south and dip vertically near the north end of the Deering Pluton; some of the foliation surfaces show nearly horizontal slickensides. These may represent some small-scale faulting which was associated with the emplacement of that pluton.

# ECONOMIC GEOLOGY

Sand and gravel represent the most valuable mineral commodities within the Hillsboro quadrangle. There are numerous small operations and barrow pits within glacial outwash sands and gravels.

The only evidence of mining in the bedrock of the quadrangle is an abandoned graphite mine located on the northwest flank of Sodom Hill west of the town of Hillsboro (Plate I). There graphite occurs in a silimanite-rich schist as clots which are about 3 cm in diameter, and as disseminations throughout the metasedimentary rock. The mine is reached by going 0.3 miles north through the woods on the old dirt road which cuts off the main east-west road over Sodom Hill. The mine is then approximately 0.1 miles due east. The old mine is a north-south-trending pit which is approximately 20 meters long and 5 meters deep.

# REFERENCES

Bieler, D.B., 1973, A study of some lamprophyre dikes associated with the White Mountain Magma Series: unpub. M.A. thesis, Dartmouth College, 67 p.

Billings, M.P., 1956, The Geology of New Hampshire, Part II, Bedrock Geology: N.H. Dept. Resources and Economic Devel., 200 p.

Boone, G.M., 1973, Metamorphic stratigraphy, petrology, and structural geology of the Little Bigelow Mountain map area western Maine: Maine Geol. Survey Bull. 24, 136 p.

Boucot, A.J., 1968, Silurian and Devonian in the northern Appalachians, in Zen, E-an, White, W.S., Hadley, J.B., and Thompson, J.B., (eds), Studies of Appalachian geology, northern and maritime: Interscience, New York, p. 83-94.

Brookins, D.G., Berdan, J.M., and Stewart, D.B., 1973, Isotopic and paleontologic evidence for correlating three volcanic sequences in the Maine coastal volcanic belt: Geol. Soc. America Bull., v. 84, 1619-1628.

Chapman, C.A., 1952, Structure and petrology of the Sunapee quadrangle, New Hampshire: Geol. Soc. America Bull., v. 63, p. 381-425.

Cheney, J.T. and Guidotti, C.V., 1973, Paragonite contents of coexisting but texturally different muscovites from pelitic schists of the Puzzle Mountain area, Maine: Am. Mineral, v. 58, p. 1076-1079.

Cipriani, C., Sassi, F.P., and Scolari, A., 1971, Metamorphic white micas: definition of paragenetic fields: Schweiz. Mineral. Petrog. Mitt., v. 51, p. 259-302.

Clark, R.G., 1972, Petrologic and structural aspects of the Kinsman Quartz Monzonite and some related rocks: unpub. Ph.D. thesis, Dartmouth College, 225 p.

Cloos, E., 1946, Lineation - A critical review and annotated bibliography: Geol. Soc. America Memoir 18, 122 p.

Currie, K.L., 1971, The reaction 3cordierite = 2garnet + 4sillimanite + 5quartz as a geological thermometer in the Opinicon Lake region, Ontario: Contr. Mineral. Petrol., v. 33, p. 215-226.

Dallmeyer, R.D., and Dodd, R.T., 1971, Distribution and significance of cordierite in paragneisses of the Hudson highlands, S.E. New York: Contr. Mineral. Petrol., v. 33, p. 289-308.

de Sitter, L.U., 1964, Structural Geology: New York, McGraw-Hill, 551 p.

Englund, E.J., 1971, Geology of the Holderness quadrangle, in Lyons, J.B. and Stewart, G.W. (eds.), Guidebook for field trips in central New Hampshire and contiguous areas: New England Intercoll. Geol. Conference, 1971, p. 78-87.

—— 1974, The bedrock geology of the Holderness quadrangle, New Hampshire: unpub. Ph.D. thesis, Dartmouth College, 143 p.

—— 1976, The bedrock geology of the Holderness quadrangle, New Hampshire: N.H. Dept. Res. and Econ. Devel. Bull. 7, 90 p.

Evans, B.W., 1965, Application of a reaction-rate method to the breakdown equilibria of muscovite and muscovite plus quartz: Amer. Jour. Sci., v. 263, p. 647-667.

—— and Guidotti, C.V., 1966, The sillimanite-potash feldspar isograd in western Maine, U.S.A.: Contr. Mineral. Petrol., v. 12, p. 25-62.

Finger, L.W. and Hadidiacos, C.G., 1972, Electron microprobe automation: Carnegie Inst. Washington Yearbook 71, p. 598-600.

Fitton, J.G., 1972, The genetic significance of almandine-pyrope phenocrysts in the calc-alkaline Borrowdale volcanic group, northern England: Contr. Mineral. Petrol., v. 38, p. 231-248.

Fowler-Billings, K., 1949, Geology of the Monadnock region of New Hampshire: Geol. Soc. America Bull., v. 60, p. 1249-1280.

French, B.M., 1966, Some geologic implications of equilibrium between graphite and a C-H-O gas phase at high temperatures and pressures: Rev. Geophys., v. 4, p. 223-253.

Garland, G.D. 1971, Introduction to Geophysics: Philadelphia, Saunders, 420 p.

Green, T.H. and Ringwood, A.E., 1968, Origin of garnet phenocrysts in calc-alkaline rocks: Contr. Mineral. Petrol., v. 18, p. 163-174.

Greene, R., 1970, The geology of the Peterborough quadrangle, New Hampshire: N.H. Dept. of Resources and Econ. Devel., Bull. 4, 88 p.

Guidotti, C.V., 1973, Compositional variation of muscovite as a function of metamorphic grade and assemblage in metapelites from N.W. Maine: Contr. Mineral. Petrol., v. 42, p. 33-42.

—— 1974, Transition from the staurolite to the sillimanite zone, Rangeley quadrangle, Maine: Geol. Soc. America Bull., v. 85, p. 475-490.

Heald, M.T., 1950, Structure and petrology of the Lovewell Mountain quadrangle, New Hampshire: Geol. Soc. America Bull., v. 61, p. 43-89.

Hensen, B.J., and Green, D.H., 1971, Experimental study of the stability of cordierite and garnet at high pressures and temperatures, I. Compositions with excess alumino-silicate: Contr. Mineral. Petrol., v. 33, p. 309-330.

Hewitt, D.A., 1973, Stability of the assemblage muscovite-calcite-quartz: Am. Mineral., v. 58, p. 785-791.

Holdaway, M., 1971, Stability of andalusite and the aluminum silicate phase diagram: Amer. Jour. Sci., v. 271, p. 97-131.

Hsu, L.C., 1968, Selected phase relations in the system A1-Mn-Fe-Si-O-OH: a model for garnet equilibria: Jour. Petrology, v. 9, p. 40-83.

Hussey, A.M., 1968, Stratigraphy and structure of southwestern Maine, in Zen, E-an, White, W.S., Hadley, J.B., and Thompson, J.B., (eds.), Studies of Appalachian geology, northern and maritime: New York, Interscience, p. 291-301.

Kerrick, D.M., 1972, Experimental determination of muscovite + quartz stability with $P_{H_2O}$ $P_{total}$: Amer. Jour. Sci., v. 272, p. 946-958.

Lyons, J.B., and Livingston, D.E., 1977, Rb-Sr ages of the New Hampshire Plutonic Series: Geol. Soc. America Bull., v. 88, p. 1808-1812.

—— Norwick, S., and Lambine, J., 1973, Mantled garnets in plutonic rocks: Geol. Soc. America Abstracts with Programs, Northeastern Section, p. 190.

Moench, R.H., and Boudette, E.L., 1970, Stratigraphy of the northwest limb of the Merrimack synclinorium in the Kennebago Lake, Rangeley, and Phillips quadrangles, western Maine, in Boone, G.M. (ed.), Guidebook for field trips in the Rangeley Lakes-Dead River Basin region, western Maine: New England Intercoll. Geol. Conference 1970, Trip Al, p. 1-25.

Naylor, R.S., 1968, Origin and regional relationships of the core-rocks of the Oliverian domes, in Zen, E-an, White, W.S., Hadley, J.B., (eds.), Studies of Appalachian geology, northern and maritime: New York, Interscience, p. 221-240.

—— 1971, Acadian orogeny: an abrupt and brief event: Science, v. 172, p. 558-559.

—— and Boucot, A.J., 1965, Origin and distribution of Ludlow age (Late Silurian) in the northern Appalachians: Amer. Jour. Sci., v. 263, p. 153-169.

Nielson, D.L., 1974, The structure and petrology of the Hillsboro quadrangle, New Hampshire: unpubl. Ph.D. thesis, Dartmouth College, 254 p.

—— Lyons, J.B., and Clark, R.G., 1973, Gravity and structural interpretation of the mode of emplacement of the New Hampshire Plutonic Series: Geol. Soc. America Abs. with programs, 1973 Ann. Mtg., p. 750.

—— Clark, R.G., Lyons, J.B., Englund, E.J., and Borns, D.J., 1976, Gravity models and mode of emplacement of the New Hampshire Plutonic Series: Geol. Soc. America, Memoir 146, p. 301-318.

Nielson, D.R., 1973, Formation of flecky gneisses by metamorphic differentiation: Geol. Soc. America Abs. with programs, 1973 Ann. Mtg., p. 750.

—— 1974, Metamorphic diffusion in New Hampshire: Soapstone bodies and flecky gneisses: unpub. Ph.D. thesis, Dartmouth College, 262 p.

Norwick, S.A., 1967, The potash feldspars of the Kinsman Quartz Monzonite, New Hampshire: unpub. M.A. thesis, Dartmouth College, 77 p.

Osberg, P.H., Moench, R.H., and Warner, J., 1968, Stratigraphy of the Merrimack synclinorium in west-central Maine, in Zen, E-an, White W.S., Hadley, J.B., and Thompson, J.B. (eds.), Studies of Appalachian geology, northern and maritime: New York, Interscience, p. 241-253.

Pitcher, W.S., 1965, The aluminum silicate polymorphs, in Pitcher, W.S. and Flinn, G.W. (eds.) Controls of Metamorphism: Edinburg, Oliver & Boyd, 368 p.

Ramsay, J.G., 1964, The uses and limitations of beta-diagrams and pi-diagrams in the geometrical analysis of folds: Quart. Jour. Geol. Soc. London, v. 120, p. 435-454.

—— 1967, Folding and Fracturing of Rocks: New York, McGraw-Hill, 568 p.

Rankin, D.W., 1968, Volcanism related to tectonism in the Piscataquis volcanic belt, an island arc of Early Devonian age in north-central Maine, in Zen, E-an, White, W.S., Hadley, J.B. and Thompson, J.B. (eds.), Studies of Appalachian geology, northern and maritime: New York, Interscience, p. 355-369.