STRUCTURE AND STRATIGRAPHY OF BEDROCK IN THE ASHBURNHAM-ASHBY AREA, NORTH-CENTRAL MASSACHUSETTS

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THE STRUCTURE AND STRATIGRAPHY OF THE BEDROCK IN THE ASHBURNHAM-ASHBY AREA, NORTH-CENTRAL MASSACHUSETTS

(M.S. Thesis)

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ABSTRACT

The Ashburnham-Ashby area includes approximately the eastern two-thirds of the Ashburnham and the western third of the Ashby 7 1/2 - minute quadrangles in north - central Massachusetts and adjacent New Hampshire. The area is underlain by Silurian - Early Devonian strata that were folded and metamorphosed during the Devonian Acadian Orogeny and faulted during the Triassic - Jurassic.

Four main stratigraphic units are identified in the area on the basis of field and petrographic observations and correlation with rocks mapped elsewhere in central Massachusetts. These include two members each of the Silurian Paxton Formation and the Lower Devonian Littleton Formation. The Gray Granulite Member of the Paxton Formation is a purplish-gray biotite quartz granulite with interbedded greenish-gray calc-silicate granulite. It has been identified only in the northwest corner of the area where it is in contact only with the Littleton Formation. The Sulfidic Schist Member of the Paxton Formation; also only in contact with the Littleton, is a highly varied unit composed of interlayered rusty-weathering sulfidic schists; extremely rusty-weathering, sulfidic, magnesian white schists; and rusty-weathering, generally sulfidic granulites, quartzites, and calc-silicates. The Lower Devonian Littleton Formation is divided into two members. The Gray Schist Member consists of gray-weathering interbedded pelitic schists and granulites, locally with thin layers or lenses of quartzite or calc-silicate. The Feldspathic Schist Member is, in places, similar to the Gray Schist Member, but is dominated by gray-weathering, gneissic, feldspathic biotite schist that appears to have undergone some partial melting and subsequent recrystallization. West of the Mesozoic Stodge Meadow Pond fault, the two members are separated by the Sulfidic Schist Member of the Paxton Formation. East of the fault, only the Gray Schist Member has been mapped. In terms of stratigraphic correlation with adjacent New Hampshire, the Gray Granulite Member of the Paxton is surely correlated with the Upper Silurian Warner Formation; the Sulfidic Schist Member bears some lithic similarities to the Lower Silurian upper part of the Rangeley Formation, to the Middle Silurian Smalls Falls Formation, and to the uppermost Silurian Andover Formation; and the Littleton Formation correlates with the Littleton or possibly with the Lower Silurian lower part of the Rangeley Formation.

The Granodiorite - Tonalite of the Devonian Fitchburg Plutonic Complex forms a sill-like intrusion that occupies much of the eastern part of the area. It was emplaced during the early stages of the Acadian Orogeny and is the oldest and most deformed member of the Complex.

Five major phases of Acadian deformation have been identified in the area. The first corresponds to the regional nappe stage described in central Massachusetts and is identified on the basis of map-scale repetitions of strata and limited outcrop-scale minor folds. The second and third phases correspond to the regional backfold stage identified in

central Massachusetts. The second phase was the time of development of the predominant foliation in the area, of abundant map-scale folds, and of intrusion of the tonalite. During the third phase, east - west trending folds and mineral lineations were well developed throughout the area, possibly parallel to the transport direction for this phase, and locally mylonites were developed. Fourth phase folds correspond to the regional dome stage of deformation and are abundant at map and outcrop scale in the western part of the area. They generally have moderately west-dipping axial surfaces, a west-over-east rotation sense, and north-trending axes. Fifth phase folds are upright, northeasterly trending folds that warped the previously-existing structural fabrics at the end of the Acadian or during the Alleghenian Orogeny.

A north - northeast-trending, northwest-dipping Mesozoic fault of uncertain displacement, named the Stodge Meadow Pond fault, cuts across the area and is accompanied by intense jointing and cataclasis of the country rock and formation of hydrothermal quartz veins.

Metamorphic mineral assemblages produced in pelitic schists during the peak Acadian metamorphism appear to fall consistently within the sillimanite - muscovite zone. Unfortunately, most of the prograde assemblages have been destroyed by a pervasive, widespread development of retrograde muscovite. A rather unusual assemblage of garnet cordierite - muscovite - biotite ± sillimanite was found in an outcrop of the Gray Schist Member of the Littleton Formation. The metamorphic implications of this assemblage are still under investigation, but preliminary estimates using the garnet - cordierite compositions suggest a temperature of formation of 625° C and a pressure of 5.3 kbar.

INTRODUCTION

Location and Physiography

The Ashburnham and Ashby 7 1/2 - minute quadrangles (Figure 1) lie in north-central Massachusetts and adjacent New Hampshire. The area covered by this study includes approximately the eastern two thirds of the Ashburnham quadrangle and the western third of the Ashby quadrangle. Mount Watatic near the center of the study area (Plate 1), marks the southern extent of the Wapack range of southern New Hampshire. New Ipswich Mountain, at 1881 feet is the highest point in the area and lies near the northern boundary. The range from Mount Watatic to Pratt and New Ipswich Mountains forms part of the watershed boundary between the Connecticut and Merrimack Rivers. The lowest elevation in the area is 927 feet on Water Loom Pond. This empties into the Souhegan River, which drains the area to the north and east into the Merrimack River. Several smaller streams drain west toward the Connecticut River via the Millers River.

The remaining field area is characterized by bedrock hills separated by lower areas covered by glacial deposits and numerous lakes and small

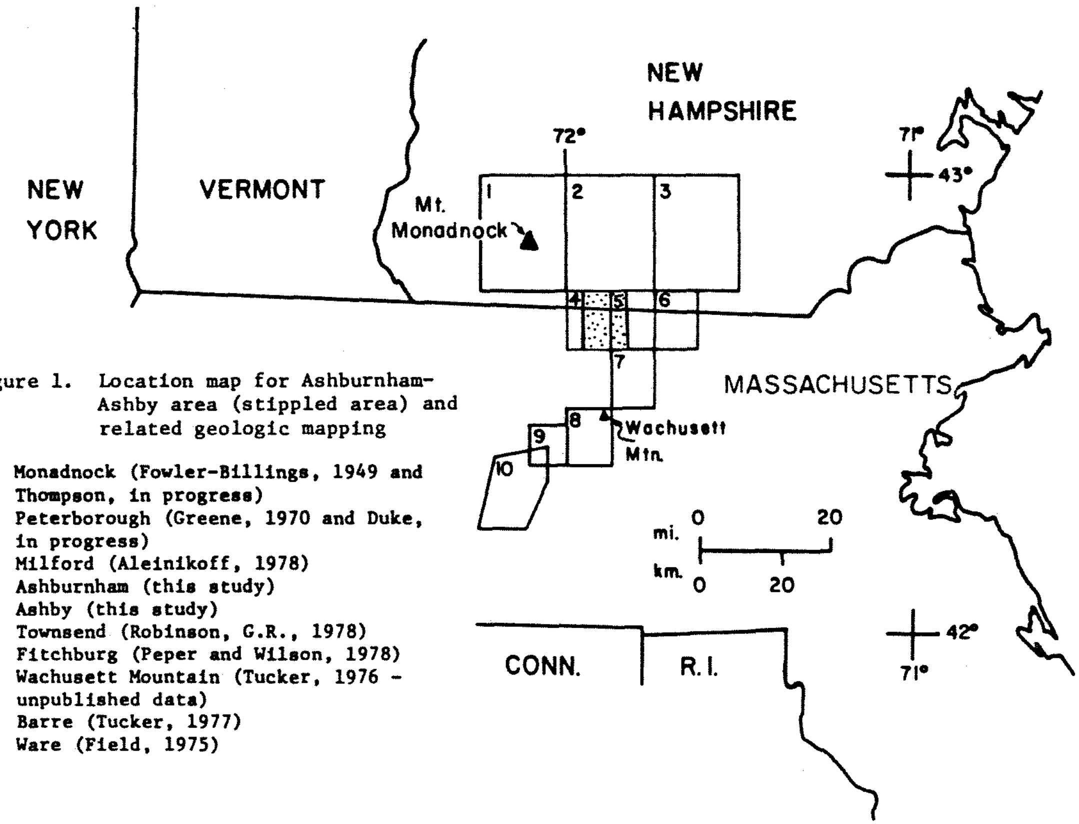

Figure 1. Location map for Ashburnham-Ashby area (stippled area) and related geologic mapping

1. Monadnock (Fowler-Billings, 1949 and Thompson, in progress)
2. Peterborough (Greene, 1970 and Duke, in progress)
3. Milford (Aleinikoff, 1978)
4. Ashburnham (this study)
5. Ashby (this study)
6. Townsend (Robinson, G.R., 1978)
7. Fitchburg (Peper and Wilson, 1978)
8. Wachusett Mountain (Tucker, 1976 - unpublished data)
9. Barre (Tucker, 1977)
10. Ware (Field, 1975)

streams. Due to its bouldery nature, the soil is poor for agriculture. The water stored in the many lakes, however, provides one of the primary resources for the Town of Ashburnham. Notable landmarks visible from Ashburnham are Mount Monadnock, 15 miles to the northwest, and Wachusett Mountain, 15 miles to the south.

Access and Vegetation

Although it is not heavily populated, access to all parts of the area is easy via state highways 12, 119, and 101, as well as improved and unimproved roads and logging trails. The Midstate and Wapack Trails, which connect on Mount Watatic and extend north - south through the center of the area, are helpful in reaching the upland bedrock exposures. At the beginning of the century, most of the area was deforested grazing land. Now it is mainly covered by a young mixed forest of conifers and deciduous trees, commonly with extensive thickets of laurel. Trees generally give way to juniper and bluberries on the large flat outcrops that characterize the tops of many hills.

Regional Geologic Setting

The Appalachian Mountains, which extend from Georgia to Newfoundland along the eastern coast of North America, are a composite product of several orogenic and rift-type tectonic events. Late Precambrian rifting (820 m.y. ago) governed in part by the distribution of pre-existing Grenville-age (1 b.y. old) gneisses, opened the proto-Atlantic (Iapetus) Ocean (Rankin, 1976).

The main deformations observed in the northern Appalachians were produced by the closing of the Iapetus Ocean to merge the North American Plate (billion-year old crust) with the Avalon Plate (600 million-year old crust) (Robinson and Hall, 1980). An initial, widely felt event related to this closing was the Ordovician Taconian Orogeny, This brought island arc rocks of the Bronson Hill "microcontinent", with Late Precambrian basement of possible Avalon affinities (Robinson and Hall, 1980), up onto the North American continent to produce extensive telescoping, deformation, and uplift of the sediments deposited along the Iapetus coast of North America (Osberg, 1978; Robinson and Hall, 1980). Erosion of the North American Taconic uplands produced an unconformity onto which Silurian clastics were deposited.

Eastward on the Bronson Hill plate, a north - northeast-trending basin referred to as the Merrimack-Fredericton trough by Robinson and Hall (1980) received sediment during the Silurian and early Devonian from the Taconic highlands to the west and from an uplifting source on the Avalon plate to the east.

The strata of the Merrimack-Fredericton trough (Figure 2) in general are characterized by a thin Silurian shelf sequence along the west margin

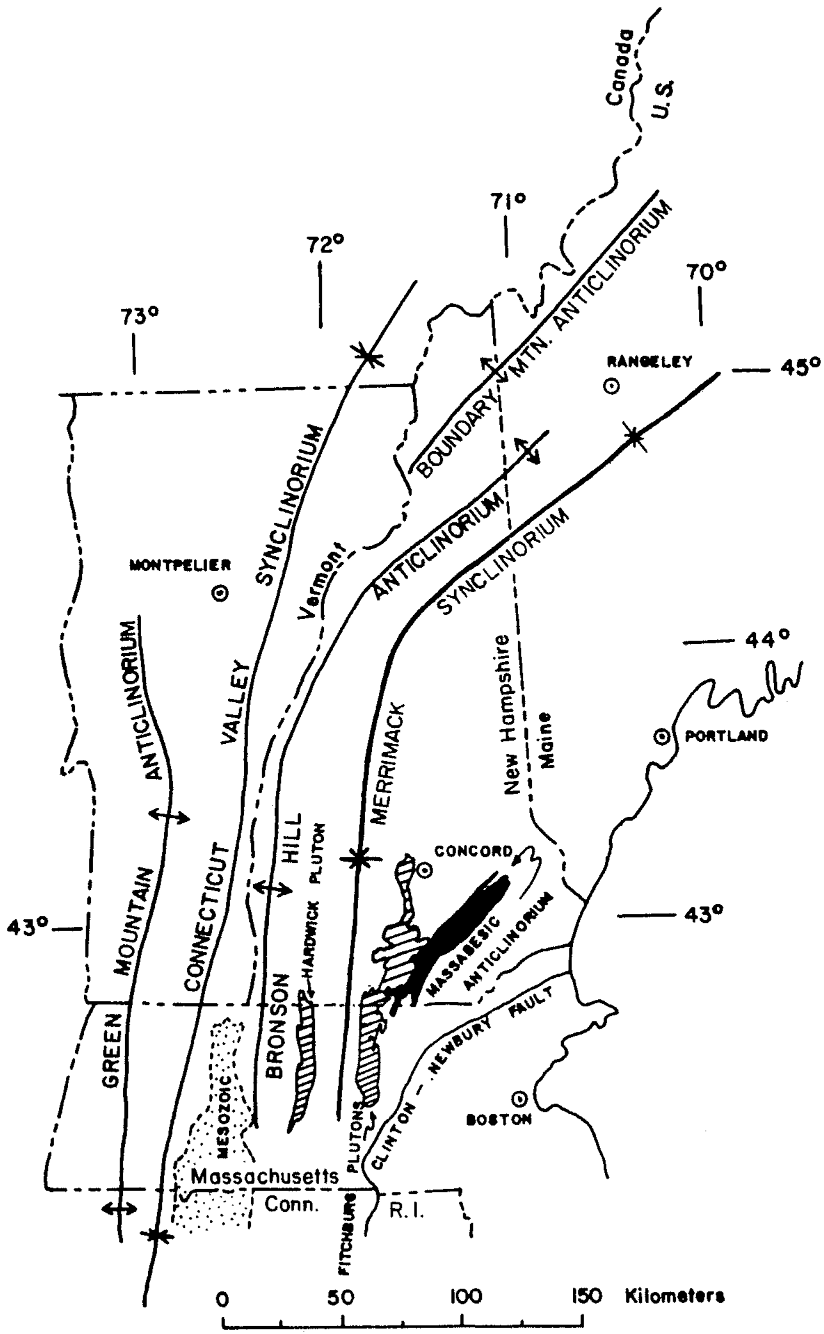

Figure 2. Tectonic framework of central New England showing the axial traces of the major anticlinoria and synclinoria.

which thickens dramatically eastward across a tectonic hinge (Hatch et al, 1983) into a thick clastic sequence. Upward in this Silurian section a decrease in the rate of erosion of the western (North American) source becomes evident and euxinic conditions were widespread by middle Silurian (early Ludlovian) (Pankiwskyj et al., 1976). A fairly thick cover of calcareous sandstones and pelites deposited from the east over much of the Merrimack trough, generally directly on top of the euxinic sediments described above, marks the emergence of a significant source to the east in the Late Silurian (late Ludlovian). This sequence grades into a thick pile of flysch as the eastern source was more rapidly uplifted and eroded in the Early Devonian (Pankiwskyj et al., 1976). These sediments, deposited along the North American shelf and into the Merrimack-Fredericton trough are the predecessors of the schists, quartzites, and calcareous rocks observed in the Bronson Hill anticlinorium and Merrimack synclinorium (Figure 2).

In central Massachusetts the Silurian - Devonian sediments, the pre-unconformity Ordovician sediments and volcanics, and the underlying basement rocks have been intensely metamorphosed and deformed into a series of tight overturned and refolded isoclinal folds. Robinson (1963, 1979) has recognized three major stages of Acadian deformation: 1) Early large-scale, west-directed, recumbent nappes, 2) East-directed, recumbent backfolds, commonly associated with a strong, east-west trending mineral lineation, and 3) Late, upright to overturned, north-trending folds of the dome stage formed during movement of the basement rocks in the gneiss domes of the Bronson Hill anticlinorium. Early syntectonic intrusions, probably emplaced during the nappe stage or early in the backfold stage, are intimately involved in the deformation. Both stratified and plutonic rocks have been metamorphosed during the Acadian Orogeny. Metamorphic conditions range from temperatures and pressures characteristic of the zone of staurolite stability to those suitable for sillimanite - orthoclase - cordierite - garnet stability in pelitic schists.

In the late Paleozoic, deformation associated with the Alleghenian Orogeny affected portions of eastern and southern New England and the Maritimes as well as much of the central and southern Appalachians (Rodgers, 1972). The extent to which this event affected central Massachusetts is not really known, but may be substantial.

Opening of the Atlantic Ocean, beginning in the Mesozoic, produced several, generally north - south trending fault basins filled with Triassic and Jurassic sediments and mafic volcanics such as the Mesozoic basin shown in Figure 2. Diabase dikes, late faults, shearing, silicification, and extensive jointing of the country rock are also products of this Mesozoic rifting evident throughout New England.

The Ashburnham-Ashby area crosses the Massachusetts - New Hampshire border in the center of the Merrimack synclinorium where the stratigraphic correlation with southern New Hampshire to the north and central Massachusetts to the south is uncertain. It lies along the west margin of the Fitchburg Plutonic complex, a series of tonalite granodiorite and granite sills intruded into the Silurian - Devonian strata in the early stages of the Acadian Orogeny. Both stratified and plutonic rocks have been metamorphosed to sillimanite grade and are extremely deformed. Several phases of ductile Acadian deformation as well as Mesozoic faulting and brittle deformation are evident in the area.

Purpose of Study

The specific goals of this study are as follows: 1) To describe the Silurian - Devonian stratigraphy in the Ashhurnham-Ashby area, 2) To correlate the stratigraphy mapped in the Ashhurnham-Ashby area with that described by Tucker (1976) in the Wachusett Mountain area to the south and by Edward Duke (in progress) in the Peterborough quadrangle to the north in New Hampshire, 3) To understand and describe the structural geometry of the rock bodies observed in the Ashburnham-Ashby area and to compare this with the regional structural history. 4) To understand and describe the geometry and contact relations of the tonalite "sill" member of the Fitchburg Plutonic complex with the Silurian - Devonian country rocks and to relate this to what is seen to the south, particularly in the Wachusett Mountain area. 5) To prepare a geologic map and cross sections for the Ashburnham-Ashby area using the stratigraphic and structural information collected. 6) To describe the metamorphic history based on mineral assemblages and reactions observed in the field and in thin section.

Previous Work

Until now the Ashburnham and Ashby quadrangles have only been mapped by reconnaissance field mapping. The earliest published map known to cover parts of the Ashburnham-Ashby area accompanies Hitchcock's. Geology of New Hampshire (1877).

Although the Ashburnham-Ashby area is included on Emerson's 1916 geologic map of Massachusetts and Rhode Island, he makes no specific mention of it in his text (Emerson, 1917). On his map, this study area is mainly underlain by Hubbardston Granite with inclusions of Brimfield Schist (rusty-weathering) and Paxton Quartz Schist. In contact to the east is the Fitchburg Granite: which is described by Emerson (1917) as a medium-grained, biotite, or biotite-muscovite granite. He also describes a dark, biotite granodiorite that outcrops in an irregular pattern along the outer border of the Fitchburg Granite.

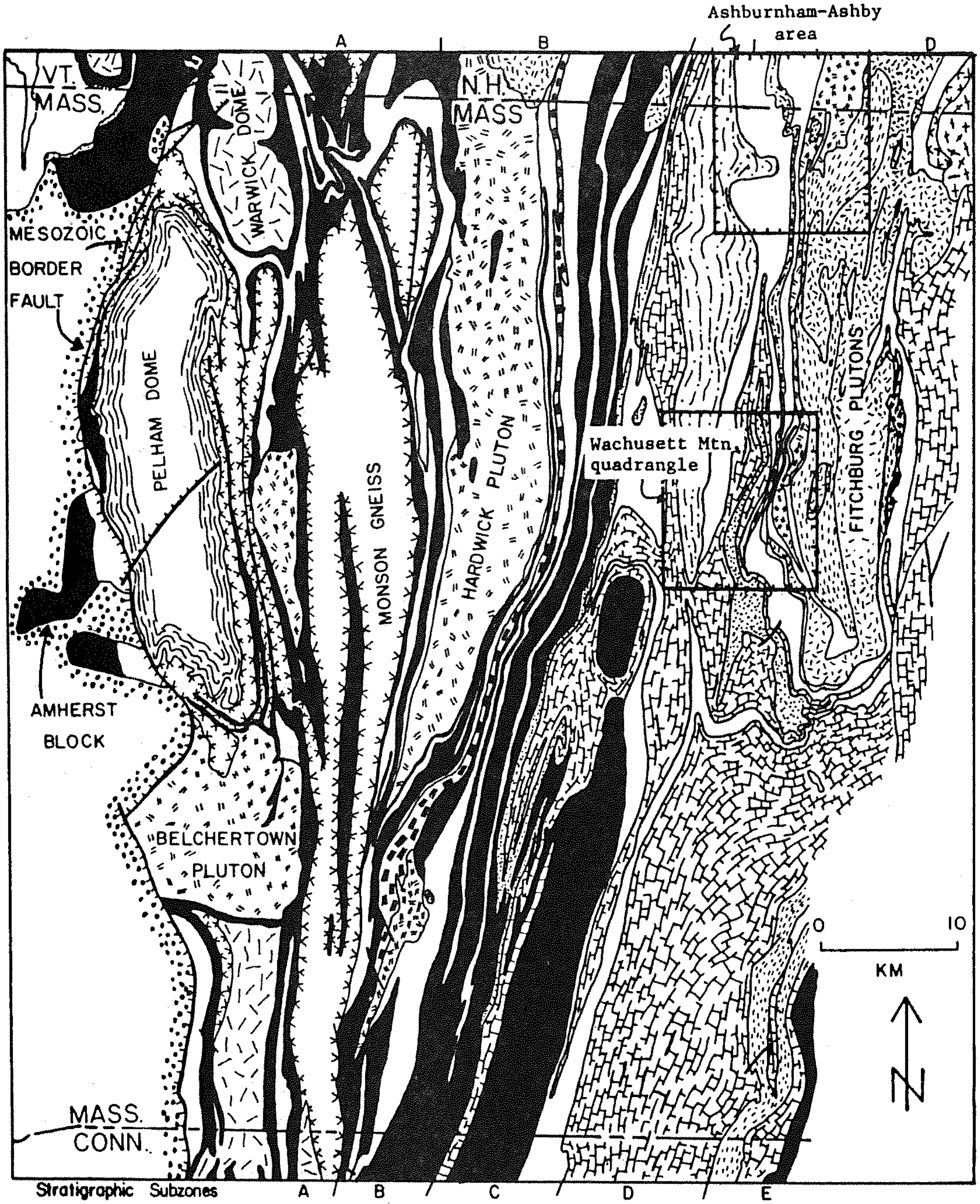
Ashburnham-Ashby
area
A
B
D
VT.
MASS.
N.H.
MASS.
WARWICK DOME
MESOZOIC
BORDER
FAULT
PELHAM DOME
MONSON GNEISS
HARDWICK PLUTON
Wachusett Mtn.
quadrangle
FITCHBURG PLUTONS
AMHERST
BLOCK
BELCHERTOWN
PLUTON
0
10
KM
N
MASS.
CONN.
Stratigraphic Subzones
A
B
C
D
E

Figure 3. Generalized bedrock geologic map of central Massachusetts showing major stratigraphic and plutonic units. (from Robinson, 1979)

Lower Jurassic-Upper Triassic	Conglomerate, sandstone, shale, and basalt.
Upper Pennsylvanian	Weakly foliated biotite granite.
Devonian	Weakly foliated muscovite granite.
	Foliated muscovite granite gneiss.
	Coys Hill porphyritic granite.
	Granodiorite, quartz diorite, diorite, and gabbro.
Lower Devonian	Littleton, Erving, and Waits River Formations.
Silurian	Paxton Formation-Sulfidic schist where separately mapped.
	Paxton Formation, Granulite Member, includes extensive sulfidic schist.
	Zone A-Clough Quartzite where thick enough to show separately. Zone C-Paxton Formation, White Schist Member, sulfidic cordierite schist, and quartzite. Zone D-Paxton Formation, Quartzite-Rusty Schist Member.
Middle Ordovician	Ammonoosuc Volcanics and Partridge Formation, also Tatnic Hill Formation in extreme southeast corner of map.
Ordovician	Massive gneiss of plutonic derivation in cores of domes.
Ordovician? Late Precambrian?	Monson and related layered gneisses.
Late Precambrian	Dry Hill and related gneisses, schists, and quartzites.
	Major normal fault, hachures on downthrown side.

Reconnaissance mapping for the bedrock map of Massachusetts was done in the Ashburnham quadrangle by Robinson and Tucker (1976), and in the Ashby quadrangle by Peper (1976), Peper and Wilson (1978), and Robinson (1962-78) (Figure 3). The Fitchburg Plutonic complex, which occurs in the eastern portion of this study area, was characterized by Maczuga (1981) in the Wachusett Mountain area in terms of its petrology and geochemistry.

Major structural differences noted by Peter Robinson (personal communication) between this study area and the Wachusett Mountain area mapped by Tucker (1976) provided the initial impetus for this project. Remapping of the bedrock geology of the Peterborough quadrangle, New Hampshire, north of this study area (Figure 1), initially mapped by Greene (1970), is being done by Edward Duke (Dartmouth College) and should provide important stratigraphic links between Massachusetts and New Hampshire.

Present Work

Detailed field work in the summer and fall of 1981 and 1982 and early spring of 1983 covered the eastern two-thirds of the Ashburnham quadrangle and the western third of the Ashby quadrangle. Outcrops, plotted directly on a 1 : 24,000 USGS topographic base map, were located with the assistance of a brunton compass, pocket aneroid altimeter, and pacing. Field work included description of rock units, collection of representative samples, discrimination and mapping of stratigraphic contacts, and measurement of structural data. Some data has been taken from the reconnaissance notes of Robinson (1962-78) and Tucker (1976).

Samples of the various units in the study area were collected on a daily basis in the course of field mapping. Representative samples of each unit were chosen for petrographic examination on the basis of general distribution and freshness. A few samples were chosen for textural reasons. Thin sections were prepared bv A. Kudrikow and A. Leavitt using the facilities in the University of Massachusetts Department of Geology and Geography. Approximately 100 thin sections were examined and described using a polarizing microscope. The anorthite content of plagioclase was determined using the Michel - Levy extinction angle of albite twins measured in thin section and was applied to the chart on page 188 in Shelley (1975). The actual anorthite content of the very calcic plagioclases in the calc-silicates examined were difficult to determine by this method. Electron microprobe analyses of one of the calc-silicate samples examined (PAM 1005C) shows the plagioclase to have a composition around An 83. The Michel - Levy method gave An 60. Modes were estimated visually using an area sheet to determine the amount of each mineral in the slide for most of the samples, unless coarse grain size or textural inhomogeneity would have given meaningless results. Identification of a few of the minerals was facilitated by oil immersion. Two samples (including the one mentioned above) were analyzed by R. Durig and D. Elbert using the Electron Microprobe facility at the University of Massachusetts.

Acknowledgements

This report is submitted in partial fulfillment of the requirements for the degree of Master of Science at the University of Massachusetts, Amherst, in May, 1984. Peter Robinson suggested the project and served as my advisor for its duration. His help in the field, his willingness to share his insights into the regional geology of the area and to discuss problems, his time spent assisting with preparation of this manuscript, and most of all his enthusiasm and interest made this project possible. Along with Peter Robinson, Leo M. Hall and John F. Hubert reviewed this manuscript and provided helpful suggestions. Leo Hall also provided valuable assistance in understanding the complicated structure.

Rachel Wing was an invaluable field assistant, remaining cheerful and providing moral support throughout the long hours and many gypsy moths of the summer of 1981. Wayne Arruda served as field assistant on Pratt and New Ipswich Mountains for a week in August, 1982. Rachel Wing and Jon Burr helped to prepare the detailed map of the east peak of Mount Watatic (Plate 6). Observations made on field trips in this study area by P.J. Thompson, E. Duke, N.L. Hatch, J.B. Lyons, and P. Chamberlain were particularly helpful in making the correlations suggested by this study.

Kurt Hollocher and John Schumacher provided patient instruction and helped solve many of the petrologic problems encountered. Renate Durig and Dave Elbert provided the microprobe analyses. Page Fallon helped me sort out my many ideas on the structural deformation. Patty Weisse and Steve Field assisted me in identification of the opaque minerals in some thin sections. John Allison instructed me in the use of the computer facility at the University of Massachusetts and Farinaz Danesh drafted circles for the equal area nets used in this thesis. M. Laforet typed the final copy of this manuscript.

The general enthusiasm and love of the field of the late Gloria Radke inspired me and kept me working on this project to its completion. The following also provided invaluable friendship and moral support during my time at the University of Massachusetts making it easier to complete this thesis: J. Burr, S. Walen, P. Weisse, L. Tompkins, R. Durig, G. Thomas, J. Sparks, J. Allison, J. Bailey, J. Castro, C. Commons, N. Danesh, D. DeNatale, P. Eberly, P. Fallon, S. Field, K. Hollocher, J. Josephson, B. Miranda, M. Retelle, J. Retelle, J. R. Schumacher, the Sargent family, and my cat - Gypsy. I would especially like to thank all the members of my family for their love and support. I also wish to acknowledge the faithful service of my 1968 Pontiac and Vista cruiser bicycle for getting me in and out of the field.

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STRATIGRAPHY

The stratigraphy in the Ashburnham-Ashby area is defined on the basis of correlations with units mapped along strike to the south in the Wachusett Mountain quadrangle (Tucker, 1976). The older units in the area are included in the Silurian Paxton Formation. Gray-weathering schists of the Lower Devonian Littleton Formation overlie the Paxton rock types. The stratified rocks in the area are intruded by the Tonalite Member of the Fitchburg Plutonic complex (Figure 4). A steeply dipping north - northeast trending Mesozoic (?) fault named the Stodge Meadow Pond Fault divides the area so that the general character of the stratigraphic units (Figure 4) and the style of deformation differs on either side of this fault.

West of the fault zone, tonalite is relatively insignificant (see Plates 1 and 2). The Paxton Formation is divided into two main members. The Gray Granulite Member (Sp) occurs in a tight isoclinal fold along the west side of Pratt and New Ipswich Mountains. The Sulfidic Schist Member, a rusty-weathering rock of variable lithologic character, is more widespread and occurs in two main belts. These two members of the Paxton are not in contact in the study area and thus their relative age is uncertain. Each of the belts of Paxton Formation are separated by gray-weathering schist of the Littleton Formation and are interpreted as being nappes which have undergone extreme transport. Each nappe contains a different facies of the Paxton Formation. West of the fault the gray-weathering schists of the Littleton Formation are separated into two members (Figure 4). These differences may only be due to metamorphism in that the Gray Schist Member (Dl) and the Feldspathic Schist Member (Dlf) may differ only in the degree of partial melting that they have undergone.

Only the Sulfidic Schist Member of the Paxton Formation is known east of the fault zone. This is overlain by the gray-weathering schists of the Littleton Formation (Figure 4). Due to pervasive intrusion of pegmatite and partial melting in the vicinity of the tonalite, it was not possible to differentiate the Littleton, so that all of the gray-weathering schists east of the fault have been placed within the Gray Schist Member (Dl). The Tonalite Member of the Fitchburg Plutonic complex dominates the areas of outcrop east of the fault zone (Plate 1). The tonalite cross cuts the stratified rocks in the area and is wildly deformed along with them. No other members of the Fitchburg complex

	West of Fault zone	East of Fault zone
Devonian		Tonalite Member - Fitchburg Plutonic Complex (Dfgt)
Devonian	Littleton Formation Feldspathic Schist Member (Dlf); Gray Schist Member (Dl)	Littleton Formation Gray Schist Member (Dl)
Silurian	Paxton Formation Sulfidic Schist Member (Sps); Gray Granulite Member (Sp)	Paxton Formation Sulfidic Schist Member (Sps)

Figure 4. Simplified stratigraphic column showing the main stratigraphic and intrusive units in the Ashburnham-Ashby area.

have been mapped separately, however, the abundant pegmatite and granite intruding the country rock has largely been ignored in order to focus on the structural pattern of the Silurian and Devonian rocks.

PAXTON FORMATION

The Paxton Formation in east-central Massachusetts includes gray biotite granulites, calcareous granulites, rusty-weathering sulfidic schists, and sulfidic, magnesian "white" schists. It constitutes the Silurian stratigraphy in the area between the Hardwick pluton (Figure 3) and the Fitchburg intrusive complex. To the south and east, the Paxton Formation thickens and is increasingly dominated by gray biotite granulite.

Emerson (1898, 1917) first described the Paxton Schist, near the Town of Paxton, as a gray, flaggy quartz schist with more biotite than its "equivalent" Oakdale Quartzite. It also has fewer aluminum-silicate minerals and less graphite than is characteristic of the adjacent pelitic schists. Beautifully exposed ledges of slabby, biotite-quartz-feldspar granulite in Turkey Hill Brook, downstream from Eames Pond and within Paxton Township, are thought by Robinson et al. (1982b) to represent Emerson's type locality of the Paxton Formation.

Emerson (1917) does not describe any rusty-weathering schist within the Paxton Quartz Schist, however, some areas shown on his map as Paxton are actually interbedded with rusty schist. Interbedded gray biotite granulites and rusty schists were first described as members of the Paxton Formation by Field (1975) in the Ware area and by Tucker (1977) in the Barre area. Detailed mapping by Tucker (1976) in the Wachusett Mountain area and reconnaissance mapping by Robinson (1962-78) and Tucker (1976) have shown these rusty-weathering schists to be a persistent part of the Paxton Formation.

Members of the Paxton Formation described on the state map of Massachusetts (Zen et al., 1983) and of interest to this study include: 1) Gray biotite granulite including undifferentiated rusty schists and calc-silicate granulites (Sp); 2) Separately mapped sulfidic mica schist, possibly at the top of the formation (Spss); 3) Rusty, sulfidic quartzite and schist (Spqr); and 4) Sulfidic, magnesian, "white" schist and sillimanite quartzite (Spsq). Spqr and Spsq may occupy the same stratigraphic position at the base of the Paxton Formation, but in different structural belts. The distribution of the Paxton Formation and its major members is shown in Figure 3.

In the Ashburnham-Ashby area, the Paxton Formation is divided into two main members. The Gray Granulite Member (Sp), is interbedded biotite granulite and calc-silicate granulite similar to the gray biotite granulite described above. The rather inhomogeneous Sulfidic Schist Member (Sps), is a rusty-weathering, sulfidic schist with some characteristics of each of the rusty units (Spss, Spqr, and Spsq) described above for the Paxton of central Massachusetts.

Gray Granulite Member

Distribution. Within the Ashburnham-Ashby area, the Gray Granulite Member of the Paxton Formation is only found in the northwest corner of the map area along the western base of Pratt and New Ipswich Mountains (Plate 1). This occurs in a narrow belt which thins dramatically and appears to hinge out southward in a north-plunging isoclinal fold. Few occurrences of the Paxton Granulite have been noted this far north in Massachusetts (Peter Robinson - personal communication). The Massachusetts state geologic map (Zen et al., 1983) shows a belt of this rock skimming the west side of the Ashburnham quadrangle (outside of this study area) (see also Figure 3). A small road outcrop just north of the center of East Rindge marks the furthest known northern extension of this belt. Another exposure on Route 2, east of Gardner, Massachusetts and five miles south of Ashburnham, is the northernmost known extension of another belt of granulite, interpreted by Robinson (personal communication) as the southeast-plunging hingeline of an east-diricted anticlinal nappe. These two belts of granulite appear to connect to the south in an area of confusing geology (Zen et al., 1983; see Figure 3).

Lithology. Although the Gray Granulite Member as a whole is quite distinctive from the surrounding schists, it is internally variable. The westernmost exposures of the granulite along the base of the mountain slope are dominated by biotite granulite with only minor calc-silicate granulite beds and, locally, some layers of a distinctive "lump" rock. In general, outcrops of the granulite are distinctive slabby ledges which hug the west base of the mountain (Figure 5).

Toward its eastern (upper) contact with gray schist, the Paxton granulite is increasingly enriched in calc-silicate granulites, locally with lenses of pitted, punky-brown-weathering, calcite-bearing calc-silicate. If the Paxton granulite does, indeed, occur in a tight fold, it should also be rich in calc-silicates along its western contact, which is unfortunately very poorly exposed. There is one outcrop of granulite with abundant calc-silicates at the western contact with schist.

The biotite granulite is purplish-gray with slightly rounded outcrop surfaces which stand out as more resistant than the adjacent interbedded calc-silicates. The granulite is bedded on a scale of 1 - 10 cm with rare graded beds and a poorly developed foliation, Fine-grained, granular, quartz, plagioclase, microcline, and biotite make up the bulk of the rock and are evenly distributed throughout to give it a homogeneous texture (Table 1). The granular minerals, quartz and feldspar, make up at least 70% of the rock and are typically equant grains averaging .25 - .35 mm in diameter. Quartz is slightly strained. Microcline, more abundant than plagioclase, has low relief

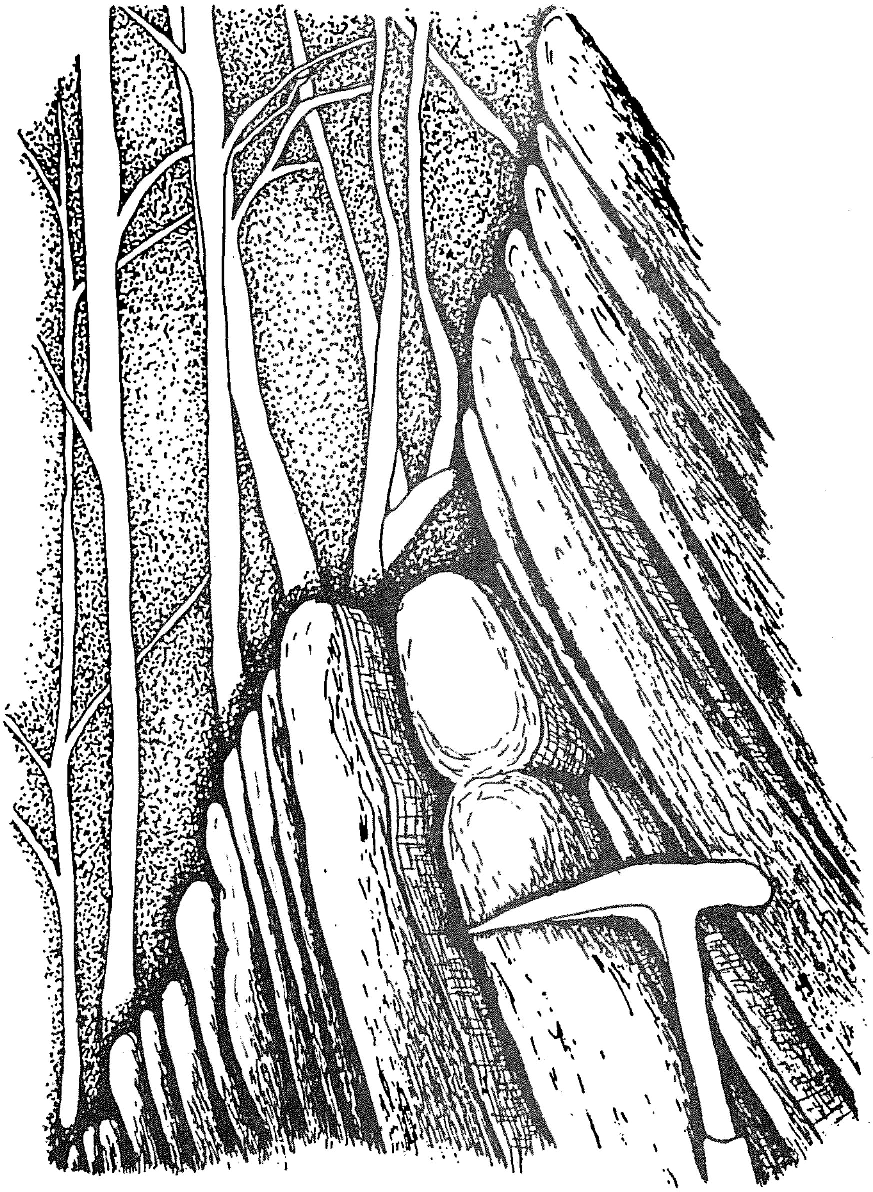


Figure 5. Sketch of a typical flaggy outcrop of the Gray Granulite Member of the Paxton Formation. Taken from a photograph looking northeast toward a large west-facing outcrop at locality PAM 990 on the west side of Pratt Mountain. The beds here strike N 21 E and dip 45 southeast.

next to quartz, and commonly displays grid twinning or repeated pericline twins. Plagioclase, An 37 - 40, has sharp albite twins and a refractive index only slightly higher than quartz. Biotite occurs as slightly elongate orange- to red-brown grains averaging .5 - .6 mm in length, No muscovite occurs in the typical granulite, however, minor retrograde Fe-rich chlorite replaces biotite in some samples. Other minerals present in small amounts are sphene, apatite, zircon, rutile, allanite, ilmenite, and minor undifferentiated opaques (Table 1).

Locally oriented lumps, up to 1 cm in diameter, of quartz and feldspar with coarse secondary muscovite at their core occur within the biotite granulite. The muscovite cores are evident in outcrop, giving the lumps an eye-like appearance. Figure 6 is a sketch of several of these lumps in their biotite granulite matrix. This matrix (Table 1 - PAM 999 and PAM 1037) is very similar in appearance and mineralogy to the typical biotite granulite, however, it does have fine secondary muscovite which may have formed at the same time as the muscovite within the lumps. The anorthite content of the plagioclase (An 23 - 28) is a bit lower in the lump rocks and they also contain green tourmaline and abundant graphite, not observed in the typical biotite granulite. The texture and mineralogy of these lumps indicate that they may have initially contained cores of an aluminum silicate mineral such as sillimanite, which has undergone a retrograde reaction with quartz and feldspar to form muscovite.

The typically greenish beds of calc-silicate granulite contain abundant quartz, calcic plagioclase, diopside, hornblende, and clinozoisite. Orange-brown biotite is present in small amounts in the less pure calc-silicates. Equant, interlocking grains of weakly strained quartz and plagioclase (0.2 - 0.3 mm in diameter) make up the light-colored matrix of these calc-silicates. The plagioclase composition determined by the Michel - Levy extinction angle method is approximately An 60, whereas microprobe analyses of the same or similar sections give An 83.5 (see Tables 1 and 9). The diopside is colorless with high relief, moderate to low birefringence, and 2V = 50. It is generally equant or slightly elongate, 0.4 - 0.7 mm in diameter (up to 1.3 mm in diameter in some cases), and commonly rimmed by epidote. Hornblende is the most abundant colored mineral with Z = pale green or bluish green, and X = Y = pale olive green or greenish-yellow to nearly colorless. Typically it occurs as slightly elongate embayed or poikilitic grains, 0.6 - 1.4 mm long. Clinozoisite is colorless with very high relief and abnormal blue to lemon yellow interference colors. It occurs as discrete grains, 0.2 - 0.25 mm in diameter, which are commonly strongly zoned, and as rims around diopside. Ferrian zoisite is also found in sample PAM 1005C, and may be present in minor amounts in the other calc-silicates. Although not abundant overall, beautiful, pleochroic, pink and brown sphene, 0.25 mm in diameter, is ubiquitous in the calc-silicates observed. Other minerals present in minor amounts include apatite, zircon, rutile, deep blue tourmaline (0.15 mm long), ilmenite, and graphite (Table 1).

Table 1. Estimated modes for samples from the Paxton Formation - Gray Granulite Member.

	BIOTITE GRANULITE		BIO-CALC GRANULITE		CALC-SILICATE		"LUMP ROCK" **	
	PAM 990B	PAM 1005	PAM 986	PAM 990G	PAM 990P	PAM 1005C	PAM 999	PAM 1037
Quartz	54	12	48	x	38	28	38	38
Plagioclase	5	23	14	x		17	15	11
(mol.% An)	(37-40)	(37)	(64-70)	(55)		(83)	(23-26)	(28)
Orthoclase		38						
Microcline	24			x			14	10
Diopside			5	x	20	22		
Hornblende			23	x		21		
Tremolite					10 *			
Garnet					2			
Biotite	14	24	2	x			27	27
Muscovite							2	10
Fe-Chlorite		2					1	
Calcite					5			
Clinozoisite			5	x	23	8		
Fe-Zoisite					tr			
Allanite		1						
Sphene	2		1	x	2	3	tr	1
Tourmaline			tr-b			tr-b	1-g	1-g
Apatite	1	tr	1	x	tr	tr	tr	1
Zircon	tr	tr	tr	x	tr	tr	tr	tr
Rutile		tr	tr	x		tr		tr
Ilmenite		tr		x		1		
Graphite				x			2	1
Undiff. Opaques	tr		1					

** Estimated mode of matrix, excluding lumps. * 4 % of this tremolite is secondary.
b Indicates blue tourmaline. g Indicates green tourmaline.
x Indicates that the mineral is present in the rock, but no mode is estimated.

List of Specimens in Table 1

Note: For all samples examined, PAM indicates a locality within the Ashburnham quadrangle and PAY indicates a locality within the Ashby quadrangle.

PAM 990B - Fine-grained, well bedded, quartz-feldspar-biotite granulite, interbedded with calcareous granulite, and calcite-bearing granulite (see PAM 990G, 990P). Sampled from a long west-facing cliff along the west side of the Pratt Mountain ridge at 1550 feet elevation, N 19 W of the western Pratt Mountain summit.

PAM 1005 - Well bedded, medium- to fine-grained, quartz-feldspar-biotite granulite. Taken from a long low outcrop along the west base of New Ipswich Mountain at 1330 feet elevation. The outcrop is 1600 feet (.3 miles) S 25 E of the southernmost end of Mountain Pond.

PAM 986 - Well bedded, fine- to medium-grained, calcareous, diopside-hornblende-epidote-biotite granulite. This beautiful, folded, north-facing wall is at 1520 feet elevation along the base of Pratt Mountain, N 45 W of its western summit.

PAM 990G - Fine-grained, interbedded, quartz-biotite granulite and calcareous, diopside-hornblende-epidote granulite. Same outcrop as PAM 990B, but collected about 10 feet higher.

PAM 990P - Punky-brown, pitted-weathering, diopside-garnet-tremolite-epidote granulite with calcite preserved in fresh samples. Fresh surface is mottled pink, tan, green, and white. Pits are reminiscent of holes left by leaching of carbonate where fossils were present in high grade rocks. Collected at same outcrop as PAM 990B, but 15 feet lower.

PAM 1005C - Bedded, dark green, hornblende-diopside-epidote calc-silicate interbedded with the biotite granulite of PAM 1005. See PAM 1005 for location of the outcrop.

PAM 999 - Well bedded, graphitic, quartz-feldspar-biotite granulite with strange zoned lumps of quartz and feldspar cored by coarse muscovite. The lumps are oriented within the plane of foliation. Graded bedding is evident within the granulite matrix. This long, low outcrop is located at 1450 feet elevation along the base of Pratt Mountain ridge, 1800 feet (.34 miles) N 18 W of the west summit of Pratt Mountain.

PAM 1037 - Medium-grained, quartz-muscovite-biotite granulite with oriented lumps of quartz and feldspar cored by coarse muscovite (same as PAM 999). This is more muscovite-rich than the lump rock sampled at PAM 999, but is otherwise very similar. Sample is taken from a small outcrop at 1615 feet elevation, 1050 feet (.19 miles) S 19 of the west summit of Pratt Mountain.

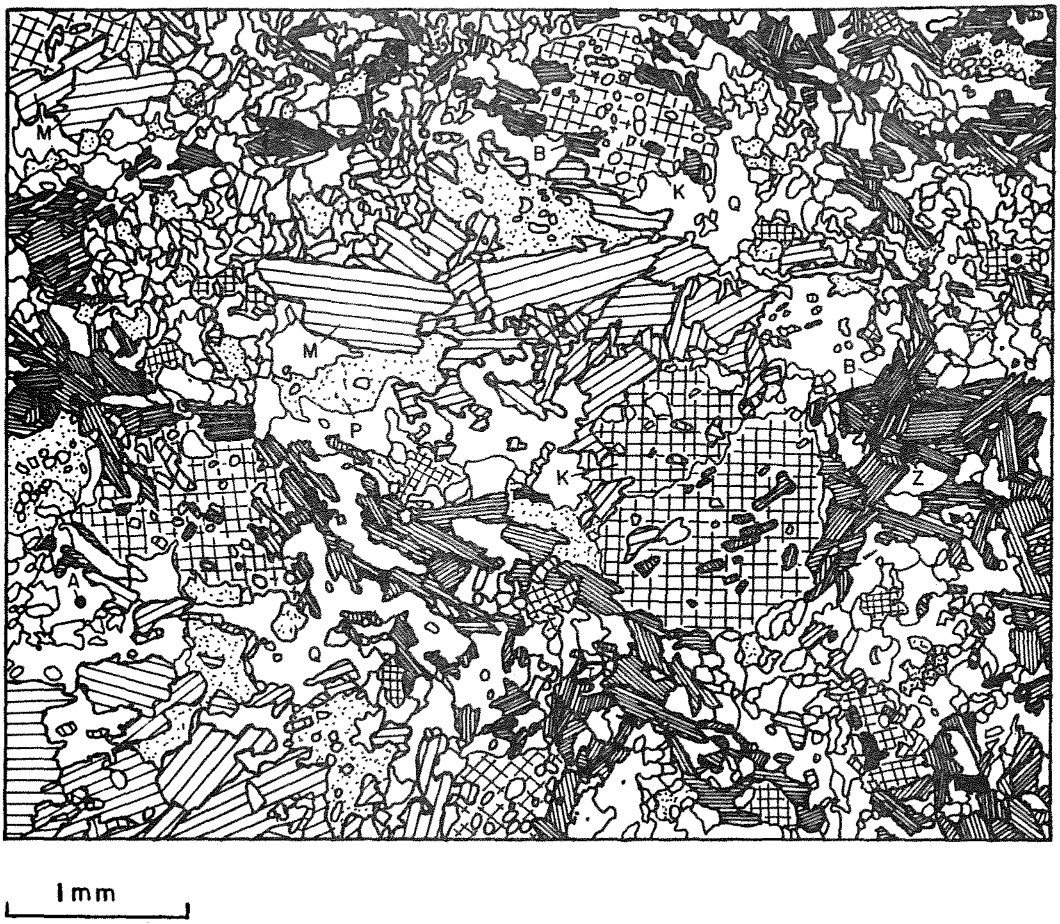


Figure 6. Sketch of a thin section of "lump" rock within the Gray Granulite Member of the Paxton Formation - sample PAM 999. Several muscovite-quartz-feldspar "eyes" are shown in a biotite granulite matrix. These are patches essentially devoid of biotite. Q = quartz (unpatterned), P = plagioclase (stippled), K = K-feldspar (cross-hatched), B = biotite (heavy-lined), M = muscovite (light-lined), Z = zircon, A = apatite. Tourmaline is black.

A pitted, punky-brown-weathering calcite-bearing calc-silicate (PAM 990P) is locally present within the calc-silicate granulite. This calc-silicate contains calcite, quartz, diopside, tremolite, grossular, and clinozoisite. Accessory minerals include sphene, zircon, and apatite. Much of the calcite is rimmed or being replaced by diopside and/or clinozoisite. The calcite generally occurs as fairly coarse, equant grains up to 2 mm in diameter. Diopside is colorless and occurs as coarse equant grains (0.65 mm in diameter) which are being replaced by secondary fibrous tremolite. It also occurs as rims around calcite. Clinozoisite is tan, but colorless in thin section with very high relief and abnormal blue to yellow (or rarely brown) interference colors. It occurs as rims around calcite and as clumps of coarser, zoned grains which may represent totally replaced calcite. Pistacite is present in the cores of some of these coarser grains. A large single white grain of primary (?) tremolite, greater than 1.5 cm long, poikilitically encloses several round grains, mainly of quartz and diopside, in one portion of the thin section. Sphene is fairly abundant in small (0.35 mm in diameter), round or diamond-shaped, brown grains. Grossular is present, but not abundant. At another locality, idocrase is present in a low outcrop of calc-silicate, 720 feet S 30 W of the summit of Pratt Mountain.

The pitted nature of these granulite outcrops may be due to small local concentrations of calcite, possibly attributed to the former presence of fossils. Unfortunately, none could be identified.

In general, the granular texture and moderately calcareous nature of the Gray Granulite Member of the Paxton Formation causes it to erode more easily than the adjacent pelitic schists. The structural attitude of the granulite in this area (see Plate 2, Cross Section A - A') coupled with its easy weathering character are probably responsible for formation of the steep west slope of Pratt and New Ipswich Mountains.

Contacts. The restricted areal extent of the Gray Granulite Member of the Paxton Formation in this area means that there are few exposed contacts with adjacent gray-weathering schist of the Littleton Formation. Although no contact is exposed within a single outcrop, the eastern contact can be pinned down to within 20 feet in a few places along the west base of Pratt Mountain. The transition to gray, moderately to well bedded schist appears to be slightly gradational. Granulite beds up to 20 - 30 cm thick are present within the schist near the Paxton Granulite contact. The western contact is only approximately located to within about 200 feet in the low saddle (1510 feet elevation - Plate 1) southwest of the summit of Pratt Mountain. North of this, most of the outcrops of Paxton Granulite are at the base of the mountain slope so that only a few outcrops of gray schist, well to the west, help to constrain the location of the western contact.

Derivation. The calcareous nature and relatively high ratio of quartz plus feldspar to biotite in the Paxton granulite indicate that the initial sediment may have been deposited in a relatively high-energy environment, which removed clay and may have allowed deposition of calcareous layers or lenses. This may indicate shallow-water depositional conditions in the Merrimack trough. Alternatively, the predecessor of the granulite may have been a low-energy calcareous shale in which the clays reacted with calcite and quartz to produce Ca-plagioclase and microcline. For similar rocks in Maine, McKerrow and Ziegler (1972) suggest a volcanic feldspar contribution from the east.

Thickness. The belt of Paxton Granulite exposed along the west side of Pratt and New Ipswich Mountains is interpreted as a possible first phase, eastward-directed, anticlinal nappe. Gray schist is exposed on either side of the unit, however, no bottom of the unit is known in this area. The measured double thickness on the map is 800 feet (244 meters). Given the vertical dip of strata in this area, the minimum true thickness for the Gray Granulite Member of the Paxton Formation in this area is 400 feet (122 meters).

Sulfidic Schist Member

This inhomogeneous unit is composed of red- to rusty-weathering, commonly sulfidic schists and granulites which have been mapped further south in central Massachusetts as members of the Paxton Formation (Field, 1975; Tucker, 1976; Tucker, 1977; and Robinson, 1962-78). In the Ashburnham-Ashby area, many different rocks are mapped within this unit. This variability can be easily observed in the outcrops at station PAY 519 (Plate 3) on the north side of Route 119 across from Flint Street.

Distribution and lithology. On the east side of the Stodge Meadow Pond Fault, the Sulfidic Schist Member is not widely exposed. In this portion of the area, one main belt of rusty-weathering, sulfidic schist trends roughly north-northeast through the area and is cut by the tonalite. The wildly folded meanderings of the tonalite make it difficult to trace the rusty schist connections. Excellent exposures within this belt of very rusty-weathering, sulfidic, biotite-poor, quartz-muscovite schists interbedded with rusty quartzose granulites can be seen on the Rindge Turnpike (PAY 473A), north and west of the radio tower on Byfield Road (PAY 82), on Route 119 (PAY 519), and on West Road at the intersection with Jones Hill Hoad (PAY 233) (see Plate 3 for these locations). A fresh surface of these extremely rusty-weathering schists is almost white, due to the lack of dark Fe-bearing minerals. This is similar to the Smalls Falls-type white schist (Spsq) mapped in central Massachusetts. Interlayered with these white schists are sulfidic muscovite-biotite-quartz schists and orange- to red-rusty-weathering, biotite-quartz granulites. To the south in this belt, outcrops of rusty schist are sparse. The rusty units mapped in the vicinity of Pillsbury Road and to the north include thinly interbedded rusty-weathering, sulfidic schists, and schistose granulites. These are cut off from the main rusty belt by the tonalite, but are interpreted to connect through folding (see cross sections - Plate 2, especially D - D'). Rusty-weathering schist on Jewell Hill And on the northwest side of the Fitchburg Reservoir appears to belong to yet another belt.

West of the fault zone, two belts of rusty-weathering schist are mapped. The area shown as underlain by the easternmost of these two belts is one of very poor bedrock exposure and limited control. Rusty-weathering graphitic schists and granulites of the Sulfidic Schist Member are exposed in outcrops northeast of Mount Watatic, on Page Hill and Parmenter Road, and in the vicinity of Smithville. The westernmost mapped belt of rusty-weathering sulfidic schist is also highly variable. The southern part of this belt has undergone extensive partial melting during peak metamorphism, or intrusion of the tonalite. Thinly interbedded, sulfidic, biotite-poor schist, red- to orange-rusty-weathering, biotite schist, and rusty-weathering, schistose granulite occur in outcrops along the west base of Mount Hunger. Further south exposure is poor, but there are some outcrops, south of River Styx Road, of sulfidic, rusty-weathering, biotite schist that has undergone some partial melting.

In the vicinity of Camp Split Rock, Fisher Hill, and Little Watatic Mountain the Sulfidic Schist Member is a rusty-weathering, muscovite-biotite-quartz schist, locally interbedded with quartzose granulite. On Little Watatic Mountain, the Sulfidic Schist includes rotten, rusty-weathering outcrops of sulfidic, graphite-quartz-muscovite-tourmaline schist which bear resemblance to the Smalls Falls-like white schist. No thin sections were made from samples of these outcrops due to their friable nature. Interbedded sulfidic, muscovite-biotite schist and red- to orange-rusty-weathering granulite underlie much of Mount Watatic. Flat, extremely rusty-weathering, pitted outcrops of sulfidic schist are well exposed in the ski slopes on the north side of the mountain (PAM 962 - see Plate 3).

North of Mount Watatic, along the state line, the schists are extremely graphitic and very rusty. On Emerson Hill, these schists are thickly interbedded with red-orange-weathering, thinly laminated, biotite-quartz granulite and well bedded, slightly rusty-weathering, graphitic quartzite. This somewhat gritty quartzite, at sample locality PAM 202 is the "type locality" of the "Emerson Hill Quartzite" - a name suggested by Peter Robinson in the course of reconnaissance mapping in the area.

The Sulfidic Schist Member of the Paxton Formation mapped on the east slope of New Ipswich Mountain is highly variable. It includes a distinctive, red-orange-weathering, coarse-grained, muscovite-biotite schist; slightly sulfidic, graphitic rusty-weathering schist; reddish, quartz-biotite granulite; and thickly bedded calc-silicate quartzite, The thin rusty unit mapped on the west side of Pratt and New Ipswich Mountains is a biotite-poor, graphitic, muscovite-quartz schist (PAM 969 and PAM 1008) interbedded with rusty schist and granulite.

Off to the west, on Route 119, and in the vicinity of East Rindge, west of Bancroft Reservoir, reconnaissance mapping has revealed the presence of a large area of rusty-weathering, sulfidic, garnet-biotite-muscovite-quartz schist.

Calc-silicate quartzite horizons and lenses are scattered throughout the Sulfidic Schist Member of the Paxton Formation. These are mainly associated with the red-rusty-weathering quartz granulites.

Four main rock types can be identified within this inhomogeneous Sulfidic Schist Member of the Paxton Formation. These include: 1) Rusty-weathering, sulfidic, biotite-muscovite-quartz schist; 2) Extremely rusty-weathering, sulfidic, magnesian, muscovite-quartz "white" schist; 3) Slightly rusty-weathering, calc-silicate quartzite in thick beds, lenses, or pods; and 4) Red-orange, rusty-weathering, biotite-quartz granulite and well bedded quartzite. Although they will be described here as distinct end members, they are commonly interbedded and gradational into one another.

Mineralogically, the rusty sulfidic schist is composed mainly of quartz and muscovite with lesser amounts of biotite and plagioclase. Locally, chlorite replaces biotite (see sample PAY 208C - Table 2). Accessory minerals or minerals present in small amounts include garnet, sillimanite, tourmaline, zircon, apatite, rutile, ilmenite, graphite, and pyrite. A goethite-like phase is locally present replacing Fe-sulfides that were deposited as an insoluble residue, probably related to solution cleavage. The opaques have not been differentiated in all of the samples (Tables 2a, 2b).

Quartz and plagioclase are generally concentrated in thin layers or lenses separated by mica-rich layers. Quartz is commonly slightly strained and equant or recrystallized and elongate. Plagioclase (An 23 - 29) is not abundant and is commonly twinned with a refractive index close to or slightly above that of quartz.

Fine-grained (0.4 - 1.0 mm long), red- to orange-brown biotite is present, but not abundant in these sulfidic schists. Fe-rich chlorite almost totally replaces biotite at locality PAY 208C, but is present only in trace amounts in the other samples examined. Muscovite, more abundant than biotite in these schists, occurs both as a primary and a secondary mineral. The primary muscovite is intimate with and texturally similar to the biotite in the rock. Secondary muscovite occurs as both relatively coarse recrystallized grains and in masses of very fine grains. The coarser muscovite, up to 2 - 3 mm long and random in orientation, may contain small oriented inclusions of relict sillimanite or ilmenite. The fine secondary muscovite commonly occurs in monomineralic lenses which are elongate parallel to foliation.

Small round garnets, generally 1 mm in diameter, are common but not abundant in the rusty schist. Typically, the garnets have inclusions and are at least slightly embayed. In a few cases they cause pressure shadows in which oriented micas and feldspar form parallel to foliation. Sillimanite is present in very fine needles, only where protected inside of coarse garnet or quartz grains. In the field, sillimanite appears to be much more abundant than it actually is in the thin sections examined. This is due to its replacement by muscovite. Tourmaline, present in the schists throughout the area, occurs in very fine to coarse, elongate, randomly oriented grains, which are black in the field and a variety of colors in transmitted light in thin section (mostly green-brown). Rutile is sparingly present in deep-red, rounded grains.

The "white" schist is similar to the rusty sulfidic schist, in outcrop appearance and in basic mineralogy, but it is typically more sulfidic and has a more rotten weathering surface than the rusty schist. A fresh surface of the sample is very pale gray or almost white, thus the name "white" schist. This is due to the paucity of Fe-bearing silicates. The darkest mineral present is commonly graphite. Biotite appears almost colorless in hand specimen and is pale orange to yellow in thin section. Muscovite and quartz are very abundant, Rutile, present in relative abundance in a few of the samples examined, is characteristic of these highly magnesian rocks. Ilmenite is more usual where significant FeO is present. Sample PAY 473A (Figure 7), an exceptional example of these rocks, is made up of interlayered schist and granulite. The schist contains coarse sillimanite, very pale biotite, muscovite, graphite, quartz, and relatively coarse rutile. The granulite is predominantly quartz and plagioclase (andesine) with pale biotite and graphite. Samples PAM 969 and PAM 1008, taken from a belt of the Sulfidic Schist on the west side of New Ipswich Mountain are extremely rusty-weathering, light-gray schists with very magnesian silicates including tourmaline with a pale yellow color characteristic of the Mg-rich end-member tourmaline, dravite (Winchell and Winchell, 1951).

Sample 373A (Table 2b) has a different character than the other "white" schists in that it contains only muscovite, quartz, and graphite. This sample and PAY 473A (Figure 7) both display beautifully developed crenulation cleavage. In general, the rusty schists in this area are strongly crenulated, possibly due to the abundance of white mica, or possibly because this rock may be more susceptible to solution.

The rusty quartzose granulites within the Sulfidic Schist Member of the Paxton Formation are either thinly interbedded with rusty schist, as at locality PAY 519, or occur as fairly thick layers, as observed on Emerson Hill (locality PAM 201). These granulites are much richer in quartz, poorer in biotite, and lack the flaggy outcrop appearance of the Granulite Member of the Paxton Formation. They are typically red-brown-weathering and are intimately associated with sulfidic schist. In the thicker horizons, the granulites also contain

Table 2a. Estimated modes for samples examined of typical rusty-weathering schists and granulites from the Paxton Formation - Sulfidic Schist Member. Samples collected in the Ashby quadrangle.

		RUSTY SULFIDIC SCHIST				GRANULITE	WHITE SCHIST
	PAY 82	PAY 233	PAY 467	PAY 519R	PAY 208C	PAY 519G	PAY 473A
Quartz	50	x	x	56	47	44	x
Plagioclase	10	x	x		11	39	x
(mol.% An)	(29)	(23)			(28)	(25)	(38)
K-feldspar	tr						
Biotite	14	x	x	9	1	6	x
Muscovite (Prim.)	24	x	x	27	19	2	x
Muscovite (Sec.)	tr					1	
Fe-chlorite					14	3	
Garnet		x	x	1	5	4	
Sillimanite			x				x
Tourmaline				5-g			
Zircon	tr	x	x	tr	tr	tr	x
Apatite	tr	x		tr	tr		
Rutile	tr						x
Ilmenite	2	x					
Graphite			x		3		x
Pyrite	tr						x
Chalcopyrite							x
Goethite (Sec.)			x	1			
Undiff. Opaques		x	x	1		1	

x Indicates that the mineral is present in the rock, but no mode is estimated.
g Indicates green tourmaline.

<u>List of specimens in Table 2a</u>.

PAY 82 - Rotten, rusty-weathering, sulfidic, quartz-muscovite schist with minor pale biotite. The flat outcrops sampled lie on the northwest side of the radio tower building on Byfield Road.

PAY 233 - Rusty-weathering, sulfidic, extremely sheared, muscovite-biotite schist with biotite-rich layers, muscovite-rich layers, secondary muscovite lenses, and quartz-feldspar lenses. Everything is strongly smeared out parallel to foliation. Taken from a long rusty roadcut on the west side of West Road where it intersects Jones Hill Road.

PAY 467 - Rusty-weathering, coarse-grained, garnet-biotite-muscovite schist interlayered with quartz-feldspar-rich pegmatitic material. Big garnets, present in the schist, host relict sillimanite needles. This sample is taken from an outcrop 3950 feet (.75 miles) N 27 E from the intersection of Pillsbury Road and Route 119. The outcrop lies at the southwest end of a long northeast-trending ridge upheld mainly by pegmatite.

PAY 519R - Rusty-weathering, sulfidic, garnet-tourmaline-quartz-muscovite schist with minor biotite. The schist is interlayered with granulite in the outcrop (PAY 519G). The sample is taken from a long low outcrop in the north side of Route 119 across from Flint Street.

PAY 208C - Rusty-weathering, graphitic, garnet-muscovite schist with secondary chlorite replacing biotite and garnet. The sample is taken from a low outcrop in and along the north side of the stream that flows east from Smithville where it takes a sharp bend to the south toward Gibson Pond.

PAY 519G - Slightly rusty-weathering, sulfidic, garnet-biotite-quartz-feldspar granulite. Garnets are at the core of quartz-feldspar lenses. The granulite is interlayered in the outcrop with rusty schist. See PAY 519R for location.

PAY 473A - Sulfidic, rusty-weathering, graphite-bearing, quartz-muscovite schist interlayered with quartzose granulite. Gray schist shares the south end of this outcrop (see PAM 473B - Table 3a) which lies on the east side of Rindge Turnpike, near the top of the hill, .46 miles (2440 feet) north of the intersection with Wilker Road.

Table 2b. Estimated modes for samples of rusty-weathering granulite, quartzite, and sulfidic "white" schist from the Paxton Formation - Sulfidic Schist Member. Samples were collected west of the fault in the Ashburnham quadrangle.

	GRANULITE		QUARTZITE		WHITE SCHIST		
	PAM 841G	PAM 201A	PAM 202	PAM 373A	PAM 962	PAM 969	PAM 1008
Quartz	72	53	81	45	47	58	53
Plagioclase	18	22	10		10	5	10
(mol.% An)	(23)	(16-18)	(23)		(<15)	(26)	(22)
Biotite	7	19	7	tr	8	7	6
Muscovite (Prim.)	1	4	2	45	18	28	26
Muscovite (Sec.)		1			12	1	
Fe-chlorite (Sec.)	tr						
Sillimanite					tr	tr	
Tourmaline	tr-g					tr-y	1-y
Sphene						1	1
Zircon	tr	1	tr		tr		tr
Apatite	tr	tr	tr			tr	tr
Rutile					tr		
Ilmenite	1		tr		2	tr	1
Graphite				10	2	tr	1
Pyrite	1				1	tr	1
Chalcopyrite	tr				tr	tr	
Undiff. Opaques		tr					

g Indicates green tourmaline. y Indicates yellow tourmaline.

List of Specimens in Table 2b.

PAM 841G - Slightly rusty, red-weathering, biotite-quartz-feldspar granulite. Interlayered in the outcrop with rusty-weathering schist and calcareous quartzite (see also PAM 841Q, QZ1, QZ2 - Table 2c). Sample is taken from a long east-facing cliff at elevation 1550 feet, 1330 feet (.25 miles) S 73 E of the New Ipswich Mountain summit.

PAM 201A - Well bedded, red-weathering, sandy, biotite-quartz-feldspar granulite, interbedded in the outcrop with rusty-weathering schist. This sample is taken from a long west-facing outcrop, 335 feet (.06 miles) S 4 W of the summit of Emerson Hill.

PAM 202 - Red-rusty-weathering, bedded quartzite with minor biotite and feldspar. Interbedded in the outcrop with rusty-weathering schist and granulite. From a large, broken west-facing outcrop, 335 feet (.06 miles) S 50 W of the summit of Emerson Hill. This is the "type locality" of the Emerson Hill quartzite.

PAM 373A - Rusty-weathering, strongly-foliated, graphitic, quartz-muscovite schist, with well developed crenulation cleavage. Muscovite and graphite are folded by the late folds. Taken from a large flat outcrop on the east slope of a knob, 1500 feet (.28 miles) N 40 W of the intersection of the Massachusetts - New Hampshire state line with Page Hill Road.

PAM 962 - Sulfidic, rusty-weathering, graphite-pale biotite-muscovite-quartz schist. One of several flat pitted outcrops underlying the main ski slope on the north side of Mount Watatic. This sample was collected at 1560 feet elevation, N 13 E of the main Mount Watatic summit.

PAM 969 - Sulfidic, rusty-weathering, graphite-bearing, pale biotite-muscovite-quartz "white" schist. Sample is taken from a low outcrop at 1560 feet elevation in the gully to the west of the main saddle between New Ipswich and Pratt Mountains.

PAM 1008 - Rusty-weathering, sulfidic, muscovite-quartz schist with pale biotite. Very similar to PAM 969. This outcrop is at 1560 feet elevation, S 69 W of the summit of New Ipswich Mountain.

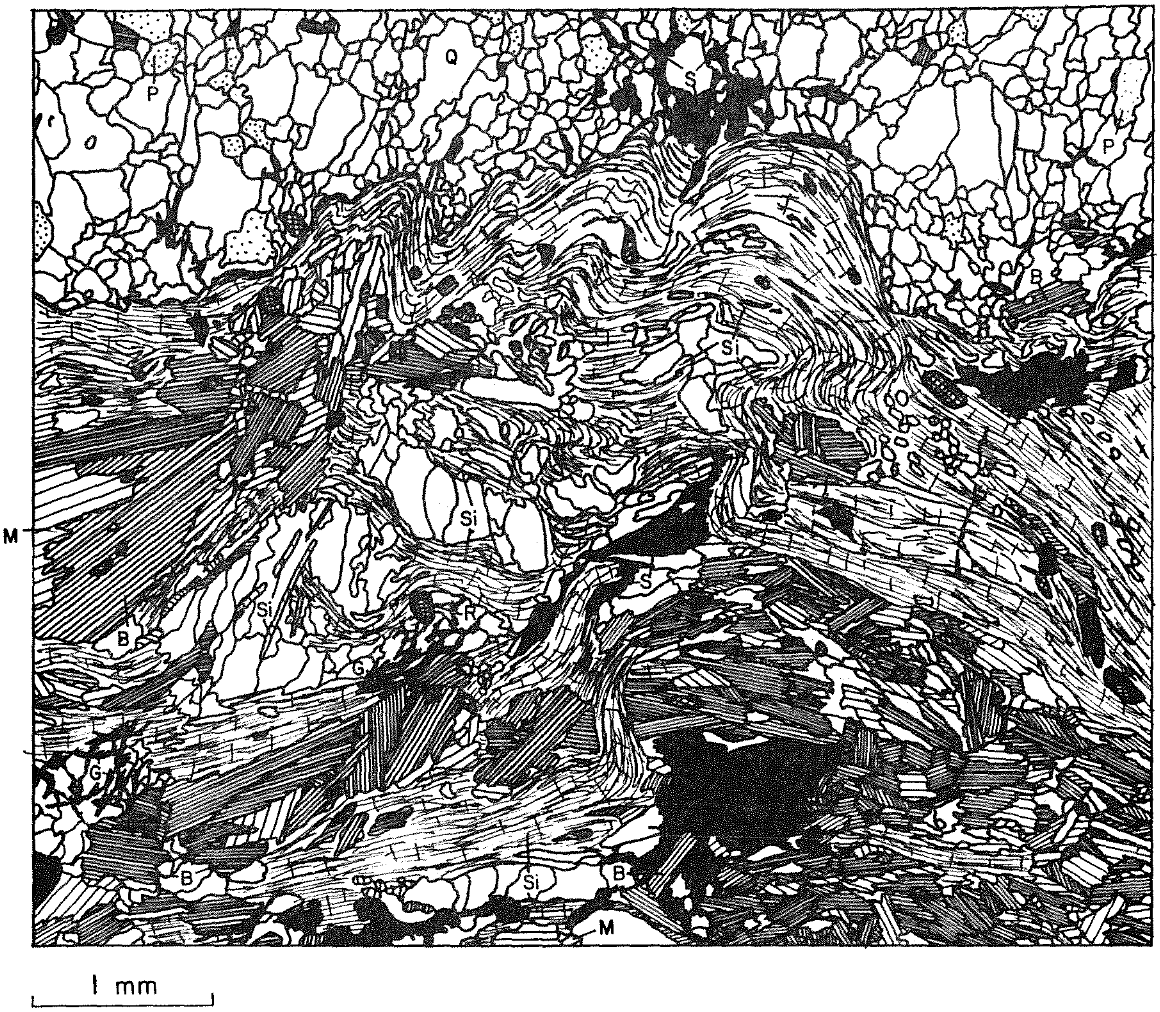


Figure 7. Sketch of a thin section of an extremely rusty-weathering "white" schist from sample PAY 473A. Note the contrast between the mica-sillimanite-rich schistose layer (bottom) and the quartz-plagioclase-rich granulite layer (top). Q = quartz (unpatterned), P = plagioclase (stippled), B = pale orange biotite (heavy-lined), M = muscovite (light-lined), Si = sillimanite (irregular lines), Rutile (cross-hatch), S = sulfide - generally pyrite (solid black), G = graphite (black needles).

well bedded quartzite. On Emerson Hill (PAM 202 - Table 2b), the quartzite is generally fine-grained (average grain size = 0.5 mm in diameter), however, it includes coarser sandy or gritty layers and some calc-silicate cemented quartzites. Figure 8 is a representative thin section sketch of this quartzite. On the east slope of New Ipswich Mountain, sample locality PAM 841 (Table 2c) is an extensive east facing wall of interbedded, red-rusty-weathering, quartz granulite and thick-bedded calc-silicate quartzite interbedded with rusty schist. The granulite (PAM 841G) is very similar to that described on Emerson Hill (PAM 201A), however, the calc-silicate component of the quartzite is much greater on New Ipswich Mountain than on Emerson Hill (see Table 2c).

These calc-silicate quartzites are similar mineralogically to the thin calc-silicate layers and small pods scattered throughout the rusty schist. They are predominantly quartz-rich, with a preponderance of calc-silicate minerals. In the field, they look like gray massive quartzites with thin horizons rich in pink garnet and green diopside, hornblende, and epidote. The samples for which estimated modes are given in Table 2c are all from continuous calc-silicate beds.

The calc-silicate matrix is made up of granular quartz and calcic plagioclase approximately 0.4 - 0.5 mm in diameter. The plagioclase is labradorite - bytownite based on relief and very limited measurements of extinction angles. Grains of garnet, diopside, and hornblende are slightly larger, 0.5 - 0.7 mm in diameter, poikilitic, and heavily embayed. Garnet is pinkish and commonly has so many inclusions and embayments that it appears to be interstitial. Diopside occurs in equant, colorless grains. Hornblende is pleochroic, with Z = green to blue-green, Y = X = pale green to yellow green.

Either pistacite or clinozoisite, are ubiquitous, interstitially or as rims around diopside, hornblende, or plagioclase and locally as discrete grains, up to 0.7 mm in diameter. Actinolite occurs as a secondary fibrous replacement of diopside or hornblende. Red- to orange-brown biotite is rare in the calc-silicates and occurs only near contacts with granulite. Accessory minerals include pinkish-brown sphene, up to 0.4 mm in diameter, minor apatite and zircon, blue tourmaline, and allanite. Opaque minerals, where differentiated, include coarse pyrrhotite, up to 1 mm in diameter, with chalcopyrite inclusions, needle-like graphite grains up to 0.25 mm long, and minor ilmenite up to 0.3 mm in diameter.

Contacts. The contact between the rusty-weathering, Sulfidic Schist Member of the Paxton Formation and the gray-weathering schists of the Littleton Formation, where exposed, is fairly sharp. Locally, the gray schist takes on a brown-weathering character near the rusty schist, making the contact difficult to pin down. In the thin belt of rusty schist on the west slope of Pratt Mountain, thinly-bedded, gray-weathering, biotite-quartz granulites are interlayered with the schist near its upper (eastern) contact. A similar granulite horizon is

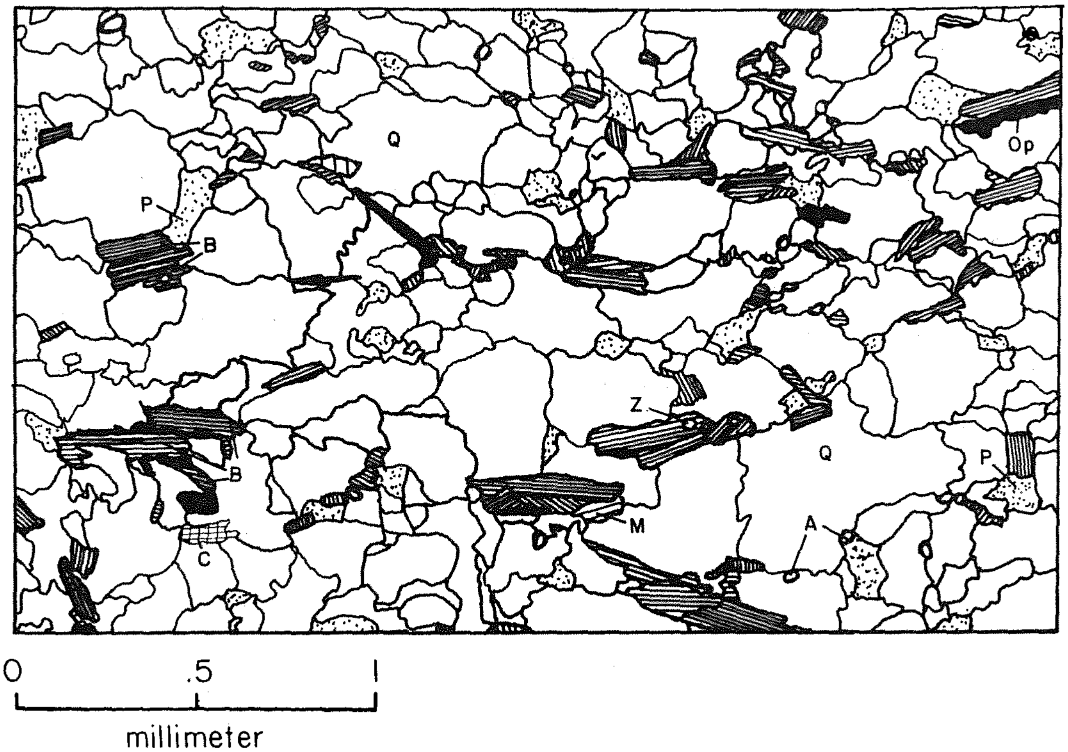


Figure 8. Sketch of a thin section of the quartzite at Emerson Hill, sample PAM 202. Q = quartz (unpatterned), P = plagioclase (stippled), B = biotite (heavy-lined), M = muscovite (light-lined), C = chlorite (cross-hatched), A = apatite, Z = zircon, Op = opaque minerals - undifferentiated (black).

Table 2c. Estimated modes for samples of calc-silicate granulites within the Sulfidic Schist Member of the Paxton Formation.

		NEW IPSWICH MOUNTAIN		
	PAY 505	PAM 841Q	PAM 841QZ1	PAM 841QZ2
Quartz	59	x	63	x
Plagioclase	7	x	8	x
(mol.% An)	(64)	(>70)		(>70)
Diopside	7	x	3	x
Actinolite	1		3	x
Hornblende		x		x
Garnet			8	x
Biotite				x
Sphene	1	x	1	x
Apatite	tr	x	tr	x
Zircon	tr	x	tr	x
Tourmaline			tr-b	
Allanite				x
Clinozoisite	16	x		
Pistacite	3	x	14	x
Ilmenite		x	tr	
Graphite	1			
Pyrrhotite	5			
Chalcopyrite	tr			
Undiff. Opaques		x		x

X Indicates that the mineral is present in the rock, but no mode is estimated. b Indicates blue tourmaline.

<u>List of Specimens in Table 2c</u>.

PAY 505 - Gray, well bedded, graphite-pyrrhotite-bearing, calcareous quartzite with minor diopside, actinolite, and epidote. Sampled from the north end of a large knob of rusty-weathering schist, 1050 feet (.19 miles) from the intersection of Old Ashby Road with Rindge Turnpike.

PAM 841Q - Gray, well bedded, diopside-hornblende-epidote-garnet calc-silicate quartzite. Interlayered in the outcrop with rusty-weathering schist and granulite. See PAM 841G for location.

PAM 841QZ1 - PAM 841QZ2 - Together these slices represent one bed with varied mineralogy within a gray, calc-silicate quartzite matrix (see PAM 841Q). QZ1 is a diopside-actinolite-garnet-epidote calc-silicate. QZ2 grades from a diopside-hornblende-actinolite-garnet-epidote calc-silicate into an almost pure quartzite with minor biotite. See PAM 841G for location.

present along the structurally lower (western) contact, but is not so well exposed. Unfortunately, the gray schist - rusty schist contact is not so continuously exposed in any other part of the study area. On Mount Watatic, a late granite intrudes the schists and more or less follows the contact between them. Where the granite has left the contact intact, it is generally distinct.

On Little Watatic Mountain, bedrock exposure is good on the south slope, however, the complexity of the structure and lithic variability within the rusty schist unit make characterization of the contact in this area difficult. On the small knoll south of Fisher Hill, the gray schist - rusty schist contact is well exposed and sharp.

The cross-cutting nature of the tonalite in the eastern part of the area brings it into contact with both rusty- and gray-weathering schist. The rusty schist exposed near the tonalite is extremely sulfidic and rotten-weathering. Whether this is a contact phenomenon or just coincidence is not known. The general nature of the contact between the tonalite and the schistose country rocks is discussed in the section on intrusive rocks.

Derivation. The predecessor for the interbedded sulfidic schists and granulites of the Paxton Formation was probably a mudrock interlayered with coarser sandy material. The rusty-weathering character of this unit is due to abundant sulfides, especially pyrite and pyrrhotite. The formation of pyrite in muds requires a sulfur source. This is provided in small amounts by organic material or by the reduction of sulfate from sea water by sulfur-fixing bacteria (Blatt et al., 1980). The reducing environment necessary for the production of sulfides is present in the marine environment just below the ocean - sediment interface. It would also be present in a shallow, restricted marine basin. In the early stages of diagenesis, fluids or sulfur-reducing bacteria interact with these interlayered muds and fine sands, removing Fe from the Fe- and Mg-bearing minerals to form pyrite and Fe-depleted (Mg-enriched) sediment. The amount of pyrite formed, or the degree of Fe-depletion depends on the degree that the detrital ferromagnesian grains are reactive. Fine detrital grains have more reactive surfaces than coarse ones due to greater surface area and tend to react more completely. During metamorphism, the unreacted Fe - Mg silicates re-equilibrate with the Mg-enriched silicates to give the final bulk Fe - Mg silicate composition (Robinson et al., 1982a).

The higher the initial post-diagenetic ratio of Mg-enriched reacted grains to Fe - Mg unreacted grains, the greater will be the bulk Mg/(Mg + Fe) ratio of the silicates in the rock following metamorphism. Also, with increasing metamorphic grade, pyrite is converted to pyrrhotite so that at the highest grade, only the rocks with the most Mg-rich silicates have pyrite remaining in them (Robinson et al., 1982a). The variation in the final Mg - Fe bulk composition of silicates in these sulfide-bearing rusty schists is dependent, in part, on the initial sediment size and distribution. A source rock with an initial sediment-size distribution ranging over a short distance from fine mud to fine to coarse sand could easily explain the inhomogeneity presently observed within the rusty schist unit. Pockets of very fine detritus would produce the "white" schist lithologies, slightly coarser muds would produce the more typical rusty sulfidic schists, and more sandy detritus would be the predecessor of the quartzites and quartzose granulites.

Thickness. If all of the rusty-weathering schists mapped in this area are interpreted as the same Sulfidic Schist Member of the Paxton Formation, an explanation is necessary for the repeated belts of gray- and rusty-weathering schists. Field (1975), in the Ware area, and Tucker (1977, 1978), in the Barre and Wachusett Mountain areas, have interpreted similar repetitions of strata as tight isoclinal folds formed during the nappe stage of regional deformation, Assuming this interpretation for the Ashburnham-Ashby area implies that the separate mapped belts of rusty schist are actually doubled in thickness with an anticlinal surface running through them. Since the base of the unit is not seen, only a minimum true thickness can be obtained from half of the maximum thickness calculated from the map (Plate 1) or cross sections (Plate 2). This thickness ranges from 26 feet for the thin belt east of Pillsbury Road, to 185 feet thick in the vicinity of Emerson Hill.

LITTLETON FORMATION

The Littleton Formation was first described by Ross (1923) and later by Billings (1937) in the Littleton and Moosilauke quadrangles in northern New Hampshire. It is predominantly interbedded black slate and gray sandstone in areas which have undergone relatively low grade metamorphism. In the vicinity of Littleton, New Hampshire, fossils found in the upper part of the Littleton Formation indicate it is Lower Devonian, Onondaga (Billings and Cleaves, 1934; Billings, 1937; Billings, 1956; Boucot and Arndt, 1960). Fossils collected near Whitefield, New Hampshire, close to the base of the Littleton Formation, give the same age (Boucot and Arndt, 1960). In the same area, at slightly higher grades of metamorphism, the Littleton is a layered, aluminous, biotite-quartz schist. Based on mapping in eastern and central New Hampshire, Billings (1956) described most of the stratified rock in the Merrimack synclinorium as members of the Littleton Formation. Recent mapping in northern and central New Hampshire has redefined much of what was initially mapped as Littleton as correlative with Silurian formations mapped in Maine (Nielson, 1974; Malinconico 1982; Hatch et al., 1983).

The Littleton Formation described by Hatch et al. (1983) in northern and central New Hampshire is gray-weathering, cyclically-bedded schist and granulite, typically with good graded bedding. It is divided into an upper Kearsarge Member which is thick-bedded on a scale of 25 cm to

2 - 3 meters thick and a Lower Member which is more pelitic and considerably thinner bedded, with 5 - 25 cm thick beds. Coticule horizons are common in the Littleton. Calc-silicate pods or layers are rare.

Remapping in progress by Peter Thompson in the Monadnock quadrangle and by Edward Duke in the Peterborough quadrangle, New Hampshire, previously mapped by Fowler-Billings (1949) and Greene (1970) respectively, has demonstrated a Silurian - Devonian stratigraphy in these areas, very similar to that described further north (Hatch et al., 1983). Many of the rocks previously mapped as Littleton Formation in these quadrangles are now interpreted to be part of the Silurian stratigraphy. One of the more extensive exposures of Littleton in these areas is at Mount Monadnock. This Littleton includes interbedded gray-weathering pelitic schists and quartzites. The base of the unit is dominated by schist with widely-spaced quartzite beds which become increasingly more predominant upward in the unit.

In central Massachusetts, the Littleton described by Field (1975), Tucker (1977), and Robinson (1979) is an interbedded gray-weathering pelitic schist and granulite. This overlies the various members of the Silurian Paxton Formation. Across central Massachusetts, the Littleton is mapped in thin belts separated by Silurian and further west by Ordovician and Silurian strata (Figure 3). These belts are interpreted to be tight isoclinal folds formed during the nappe stage of regional deformation (Field, 1975; Tucker, 1977; Robinson, 1979; Zen et al., 1983).

Assignment of the gray-weathering schists in the Ashburnham-Ashby area to members of the Littleton Formation is based on correlations with the rocks mapped to the south in central Massachusetts (Tucker, 1976; Robinson, 1962-78; Field, 1975; Tucker, 1977). Alternative stratigraphic interpretations of these rocks are discussed in the section on correlation.

Two different gray-weathering schists, the Gray Schist Member and the Feldspathic Schist Member of the Littleton Formation, are differentiated in this area. They are described here as separate members for convenience, however, they may be part of the same unit which has undergone different degrees of partial melting. On the east side of the fault zone in this area, the proximity of the tonalite makes differentiation of the gray schists into these "members" uncertain. These eastern gray-weathering schists are all assigned to the Gray Schist Member.

Distribution and Lithology

Gray Schist Member. In the northwest corner of the Ashby quadrangle, east of the fault, bedrock outcrop is poor or scattered. A low ridge west of and roughly parallel to Ashburnham Road (Plate 1) is underlain by mainly feldspathic gray schist and tonalite. The same schist crops out to the north, in the vicinity of Willard Road. To the south, the hill bounded by Pillsbury Road, West Road, and Rindge State Road (Route 119), referred to here as "Gypsy Hill", is underlain predominantly by gray schist that is extensively intruded by pegmatite and granite. Although much of this schist is quite feldspathic, in places bedding is well preserved and some outcrops are dominated by thick-bedded quartz granulite and schist. The tightly folded rocks in the vicinity of Byfield, Wagg, and Old Marble Roads ("Heartbreak Corners") and in the area to the north of Whitney Road and west of Erickson Road (Plate 1 - south of Jones Hill) are predominantly gray-weathering schists and tonalite. The gray schist is gradational from a feldspathic biotite-muscovite schist to an aluminous, garnet-biotite-muscovite-quartz schist.

Numerous exposures of gray schist, heavily intruded by pegmatite, on the small hill southwest of Blood Hill are mainly fairly gneissic. In a few outcrops, schist that has not undergone extensive partial melting is rich in biotite, muscovite, and garnet and strongly crenulated.

The gray schist exposed on the east side of Jewell Hill includes beautiful, thinly-interbedded, biotite-muscovite schist and sandy quartz granulite. In the low outcrops along the northern shore of Fitchburg Reservoir, the granulite beds are thicker and more predominant. These rocks also include calc-silicate pods and thin coticules. Unfortunately, shortage of outcrop in extensive areas surrounding the Jewell Hill and Fitchburg Reservoir exposures makes correlation to the rest of the area tenuous.

West of the fault zone in the Ashburnham-Ashby area, the Gray Schist Member of the Littleton Formation is dominated by thinly bedded quartzose granulites and garnet-muscovite-biotite schists. Along the west base of Pratt Mountain, the gray schist east of the Paxton Granulite is composed of well bedded clean quartz granulite grading on a scale of 10 - 20 cm into biotite-muscovite schist. Along the Pratt Mountain ridge top the gray-weathering schist, Dl, is characterized by a slightly gneissic schist with recognizable interbedded granulites. This schist contains distinctive white calc-silicate pods that range in length from 20 cm to over 1 meter. These moderately to well bedded, fairly clean, gray-weathering schists interspersed with calc-silicate pods or "footballs" are also typical of the Gray Schist Member on the top of Nutting Hill, on the south and west sides of Mount Watatic, and in the area south of Fisher Hill. On Little Watatic Mountain and to the south, the Gray Schist Member is a bit more gneissic, however, there are outcrops of thinly interbedded schist and granulite. Calc-silicate "footballs" are not abundant.

The Gray Schist Member of the Littleton Formation is dominated by relatively thinly interbedded biotite-quartz-muscovite schist and quartzose granulite. These rocks are typically light gray-weathering and thinly laminated or bedded on a scale of 6 - 20 cm. Graded bedding is present locally, although it is rarely definitive in determining the direction of tops for the unit as a whole. Outcrops of the schist are commonly flat and rounded, capping many of the hills in the area. They also occur as low ledges and rarely as steep cliffs.

Mineralogically, these schists are dominated by quartz, biotite, and muscovite with lesser plagioclase. Garnet, cordierite, beryl, tourmaline, and relict sillimanite are present locally. Accessory minerals include apatite, zircon, sphene, allanite, and rutile. Where they have been identified, the opaque minerals are ilmenite and graphite. Secondary minerals include muscovite, chlorite, and Fe-sulfides replaced by goethite (see Tables 3a, 3b, 3c).

In the granulite layers, quartz is equant and slightly strained. In the more schistose layers it tends to occur in recrystallized elongate aggregates. Quartz grain size ranges from 1 - 4 mm in diameter. Plagioclase is generally present, but not abundant. It is equant or slightly elongate and intergrown with quartz. The anorthite content generally ranges between An 18 and An 26 so that the refractive index overlaps quartz. Slight alteration or sericitization is typical.

Biotite occurs as elongate grains, generally 0.5 - 1 mm long, which are commonly segregated into layers parallel to foliation. It is typically red- to orange-brown. Pale-green to colorless, Fe-rich chlorite locally replaces some of the biotite. Muscovite, although not present in the granulite layers, is ubiquitous in the schists. Primary muscovite is parallel to foliation and is intimately associated with and similar in size to biotite. Secondary muscovite occurs in two forms. Very coarse muscovite, either randomly oriented or controlled in attitude to some degree by the metamorphic fabric, may represent an early stage of muscovite replacement of an aluminum silicate mineral or feldspar. These coarse grains typically include ilmenite plates parallel to the muscovite cleavage or relict sillimanite needles. Fine felt-like masses of muscovite occur as a replacement of individual feldspar grains, as a replacement of coarse secondary muscovite, or as distinct lenses or layers. An example of this fine muscovite replacing coarse secondary muscovite is shown in sample PAM 923A (Figure 9). Here relict sillimanite needles are protected at the core of the coarser muscovite. Elsewhere the lenses of fine secondary muscovite commonly have distinctly shaped boundaries suggesting that they may represent former andalusite.

Garnet is fairly common. The grains are generally round, 2 mm in diameter, and slightly embayed, with minor inclusions. Locally the garnets are elongate parallel to foliation as in sample PAY 702, where mica beards are growing in the pressure shadows at the ends of the garnet grains. Within these garnets, needle-like grains of sillimanite and quartz have grown or been included in a concentric pattern or at a high angle to the present foliation.

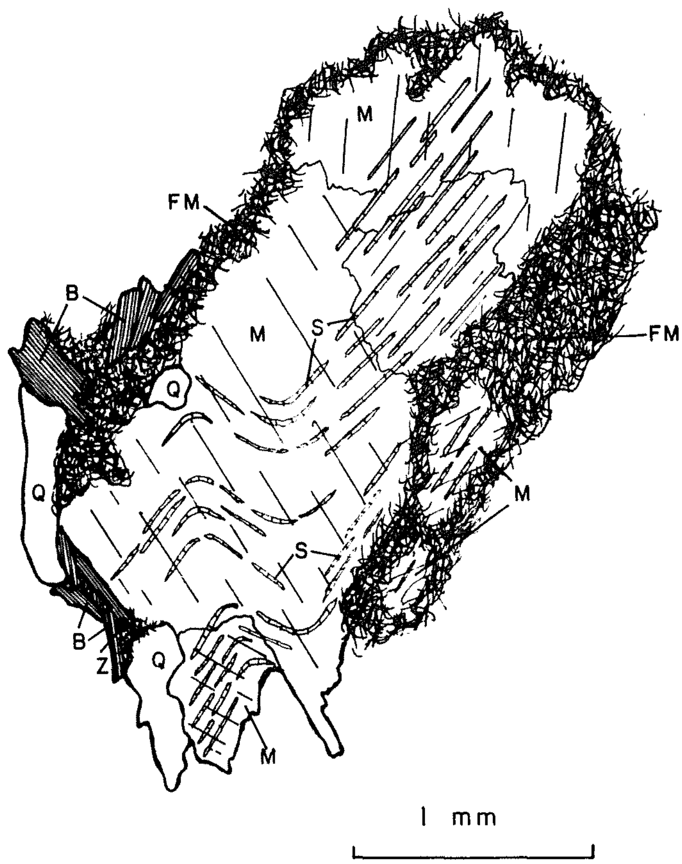


Figure 9. Sketch of portion of a thin section from sample PAM 923A. This shows coarse secondary muscovite enclosing relict folded sillimanite needles. The coarse muscovite is in turn being replaced by a second growth of very fine platelets of muscovite. S = sillimanite, M = coarse muscovite, FM = fine replacement muscovite, Q = quartz, B = biotite, Z = zircon.

Table 3a. Estimated modes for samples of the Gray Schist Member of the Littleton Formation taken from outcrops on the east side of the fault zone.

				EAST OF FAULT ZONE				
	PAM 7A	PAY 84B	PAY 90G	PAY 91S	PAY 157	PAY 158A	PAY 162	PAY 361B
Quartz	x	61	25	58	37	34	8	x
Plagioclase		4		6	16	30	11	x
(mol.% An)				(24)	(18)	(40)	(20)	
Biotite	x	15	30	10	15	30	58	x
Muscovite (Prim.)	x	20	45	24	2		19	x
Muscovite (Sec.)					28			
Fe-chlorite (Sec.)								x
Sillimanite	x							
Garnet	x	tr	tr	tr				
Cordierite	x							
Beryl	x							
Tourmaline	x-g							
Apatite	x	tr		tr	1	2	2	x
Zircon	x	tr	tr	1	tr	1	2	x
Allanite						tr		
Rutile								
Ilmenite	x		tr	1	1	3	tr	
Graphite						tr		
Goethite (Sec.)			tr				tr	
Undiff. Opaques		tr	tr					x

x Indicates that the mineral is present in the rock, but no mode is estimated.
g Indicates green tourmaline.

Table 3b. Estimated modes for samples of the Gray Schist Member of the Littleton Formation taken from outcrops on the east side of the fault zone.

	EAST OF FAULT ZONE								
	PAY 452	PAY 473B	PAY 536	PAY 556	PAY 581	PAY 606	PAY 700	PAY 702	PAY 784
Quartz		30	40	54	25	75	78	37	47
Plagioclase		2	9	6	50		2	7	29
(mol.% An)			(22)	(23)	(26)		(20)	(24)	(22.5)
Biotite	x	20	13	20	19	7	3	23	16
Muscovite (Prim.)	x	42	4	15		17	7	26	2
Muscovite (Sec.)			25				4		
Chlorite (Sec.)			1(Fe)	tr(F/M)	3(Fe)			1(Fe)	1(F/M)
Sillimanite		tr					tr	tr	
Garnet			4	3			4	5	3
Tourmaline		1-g		tr-g					
Apatite	x	tr	1	tr	2	tr	1	tr	tr
Zircon	x	tr	tr	tr	tr	tr	tr	tr	1
Sphene					1				
Allanite				tr	tr				
Rutile									tr
Ilmenite	x		2	2	tr	1	1	1	1
Graphite		5					tr		
Goethite (Sec.)	x		1						
Undiff. Opaques	x				tr	tr			

x Indicates that the mineral is present in the rock, but no mode is estimated. (Fe) Indicates Fe-rich chlorite. (F/M) Indicates the presence of both Fe- and Mg-rich chlorite. g Indicates green tourmaline.

Table 3c. Estimated modes for samples from the western belt of the Gray Schist Member of the Littleton Formation.

	SOUTH		LITTLE WATATIC MOUNTAIN			NORTH	
	PAM 657	PAM 351	PAM 921	PAM 923A	PAM 931	PAM 956S	PAM 982
Quartz	26	34	28	48	42	73	56
Plagioclase	7	30	2	2	28	5	20
(mol.% An)	(18-22)	(18-22)	(24)	(23)	(22.5)		(12)
Biotite	24	16	27	6	22	6	12
Muscovite (Prim.)	36	14	37	14	2	8	10
Muscovite (Sec.)	3			21	1		
Fe-chlorite (Sec.)		3	3	7	1	3	tr
Sillimanite		1	1	1			
Garnet	2				3	3	tr
Apatite		tr	tr		tr		tr
Zircon	1	tr	1	1	tr	tr	1
Allanite			tr				tr
Rutile					tr		
Ilmenite	1	2	1	tr	1	1	1
Graphite				tr		1	
Goethite (Sec.)	tr						

<u>List of Specimens in Table 3a</u>.

PAM 7A - Gray-weathering, strongly foliated, muscovite-rich schist with coexisting garnet, cordierite, and biotite. Sillimanite is found in the cores of some garnets. Microprobe analysis of this section indicates very Fe-rich cordierite and Fe- and Mn-rich garnet compositions. The cordierite may also have significant Na and Be substitution. This sample is collected from a low outcrop on the west side of Rindge Turnpike, 530 feet (.1 miles south of the intersection with Marble Road. No mode is estimated for this sample due to its imhomogeneity.

PAY 84B - Gray-weathering, garnetiferous, muscovite-biotite schist with relict bedding and muscovite-rich lenses, which may replace former sillimanite or andalusite. Taken from a low knob 630 feet (.12 miles) S 50 W of the radio tower on Byfield Road.

PAY 90G - Coarse, strongly foliated, gray-weathering, biotite-muscovite schist. Some evidence for solution cleavage can be seen in this thin section. Sample collected from the base of a large rounded outcrop knob 950 feet (.18 miles) S 65 W of the radio tower on Byfield Road.

PAY 91S - Gray-weathering, garnetiferous, mica schist near the contact with tonalite. Heavily intruded by pegmatite and strongly foliated. Collected from a new roadcut on the north side of Route 119, west of the intersection with West Road. The outcrop has been partially covered since it was sampled.

PAY 157 - Coarsely foliated, gray-weathering, biotite-muscovite schist with quartz-feldspar aggregate knots. Micas are loaded with oriented ilmenite grains. Sample collected south of the summit of "Gypsy Hill" (not labelled on map), 3920 feet (.74 miles) N 56 E of the intersection between Route 119 and Pillsbury Road.

PAY 158A - Fine-grained, gray-weathering quartz-feldspar-biotite granulite interbedded with schist. Outcrop sampled is about 400 feet S 23 E of PAY 157 and 3840 feet (.725 miles) N 63 E of the intersection of Route 119 and Pillsbury Road.

PAY 162 - Strongly crenulated, biotite-rich, gray-weathering schist with insoluable iron residue (goethite) left along cleavage planes. Sample is taken from a low outcrop to the north of an old west-northwest-trending logging road and 2510 feet (.475 miles) N 83 E of the Pillsbury Road - Route 119 intersection.

Table 3a - continued

PAY 361B - Extremely sheared, quartz-mica schist with abundant chlorite veins, slickensided fault surfaces, and mylonite. Micas are strongly oriented parallel to shearing and refolded by a late warping. This slightly overgrown outcrop is along the west side of Willard Road at the top of a small hill approximately 2820 feet (.535 miles) north of Route 123. No mode is estimated due to the inhomogeneity of the sample.

List of Specimens in Table 3b.

PAY 452 - Coarse-grained, gray-weathering, biotite-muscovite schist with very well developed crenulation cleavage. Insoluable Fe-rich residue (replaced by goethite) is depostied along cleavage planes. Sample collected along the northeast shore of Watatic Pond, 180 feet (.35 miles) south of Route 119 behind a house. No mode is estimated due to inhomogeneity of the sample.

PAY 473B - Gray-weathering, graphitic, quartz-rich schist with more abundant muscovite than biotite. Very sulfidic, rusty-weathering schist shares the north end of the same outcrop. See PAY 473A - Table 3a for location.

PAY 536 - Gray-weathering, garnetiferous, biotite-muscovite schist at the contact with tonalite. The rock is strongly foliated with an insoluable residue deposited parallel to a weakly developed crenulation cleavage. Sample is taken from a northeast-trending outcrop 780 feet (.15 miles) S 70 E of the intersection of Old Ashby Road and Rindge Turnpike. To the east lies an outcrop of tonalite (locality PAY 537).

PAY 556 - Spectacular, clean gray-weathering, garnetiferous, biotite-muscovite, quartz-rich schist with small, quartz-feldspar knots. Sample is taken from a long low ledge atop a small knob, 2290 feet (.43 miles) N 86 W of the intersection of Route 119 and West Road.

PAY 581 - Medium-grained, gray-weathering, feldspathic granulite with some interbedded schist and calc-silicate pods. Biotite is strongly retrograded to chlorite. This long, low outcrop is located along the base of a small knob on the east side of "Laurel Hill" (unnamed on the map), 1350 feet (.25 miles) S 19 W of the intersection between Rindge Turnpike and Wagg Road.

PAY 606 - Weakly foliated, gray-weathering, quartz-rich schist near the contact with tonalite. Sample is taken from a small hillside outcrop, 3075 feet (.58 miles) from the intersection of Pillsbury Road with Route 119.

Table 3b - continued

PAY 700 - Quartz-rich, gray-weathering, garnetiferous schist with moderate foliation reoriented by later crenulation cleavage. Sample 680 (not shown in Table 4, but represented in the thin section sketch in Figure 12), sampled nearby, is similar mineralogically to this sample, but is coarsely inhomogeneous with a well developed crenulation cleavage wrapping around coarse rounded garnets. Sillimanite needles are preserved within the garnets as well as in the schist matrix. The outcrop is located 400 feet (.075 miles) N 60 W of the northern end of Wilker Road.

PAY 702 - Gray-weathering, garnetiferous, quartz-rich schist interbedded with granulite. Sillimanite needles are preserved within the larger garnets. Sample is taken from a large outcrop, 320 feet (.06 miles) S 30 E of the Piper Road - Richardson Road intersection on the west side of the peninsula on the northeast shore of the Fitchburg Reservoir.

PAY 784 - Interbedded, garnet-bearing, quartz-rich, gray-weathering schist and granulite. Abundant calc-silicate "footballs" and coarse tourmaline in the outcrop. Approximately .4 miles northeast along Route 119 from its intersection with Flint Road is a small intersection. This sample of schist is taken from a rather large sprawling outcrop, 530 feet (0.1 miles) S 32 E of this intersection.

List of Specimens in Table 3c.

PAM 657 - Gray-weathering, garnet-biotite-muscovite schist interbedded with sandy quartzose granulite. Taken from one of several long low ledges at 1210 feet elevation along the southwest side of the southern summit of Brown Hill.

PAM 351 - Feldspathic, gray-weathering, biotite-muscovite schist. Relict sillimanite needles are preserved in large quartz grains. Outcrop sampled is on top of a small knob, southwest of Camp Split Rock and 1260 feet (0.24 miles) N 40 W of the intersection of Stowell Road with Route 101.

PAM 921 - Interbedded gray-weathering, coarse-grained, muscovite-biotite schist and granulite. Although the rock is heavily retrograded, sillimanite is still present in the cores of coarse secondary muscovite grains. This low outcrop, near the contact with rusty schist, is 1160 feet (.22 miles) S 85 E of the summit of Little Watatic Mountain.

Table 3c - continued

PAM 923A - Gray-weathering, slightly graphitic, quartz-muscovite-biotite schist with small calc-silicate "footballs" (see PAM 923B). Biotite is mostly replaced by chlorite. This large east-facing outcrop is 790 feet (.15 miles) due east of the summit of Little Watatic Mountain at 1435 feet elevation.

PAM 931 - Gray-weathering, feldspathic, garnet-muscovite-biotite schist. Taken from one of several low ledges and flat outcrops located N 80 E of the Little Watatic Mountain summit at 1550 feet elevation.

PAM 956S - Medium-grained, gray-weathering, quartz-rich, garnet-biotite-muscovite schist with good to moderate foliation. Sample is taken from a calc-silicate-bearing outcrop on the southwest slope of Mount Watatic at 1530 feet elevation, 1020 feet (.19 miles) west of the fire tower atop the Watatic summit (see also PAM 956C and PAM 956R - Tables 4a and 4b).

PAM 982 - Gray-weathering, finely-laminated, garnet-muscovite-biotite schist with quartz-feldspar lenses stretched-out parallel to foliation and interbedded calc-silicate "footballs" (see PAM 982C - Table 4a). Sampled outcrop is 790 feet (.15 miles) N 40 E of the eastern Pratt Mountain summit at elevation 1630 feet. Most of the outcrops along this east face are heavily intruded by thin pegmatite stringers.

The garnet-cordierite-muscovite-biotite-beryl association found in sample PAM 7A has not been observed elsewhere in this area. Its significance will be discussed briefly in the section on metamorphism.

Although not well represented in Tables 3a, 3b, and 3c, tourmaline is present in the schists throughout the area and is commonly observed in outcrop. It is typically up to 2 cm long. Apatite and zircon are common accessories. Sphene, allanite, and rutile are rare. Ilmenite commonly occurs as inclusions in mica, Graphite is generally in tiny platelets. A typical example of the gray schist in thin section is shown in Figure 10.

Most of the calc-silicates examined from the Littleton Formation are in the rocks mapped as the Gray Schist Member. Estimated modes of the calc-silicates are shown in Table 4a. These calc-silicate pods are typically surrounded by a fine-grained, plagioclase-biotite-quartz granulite. Estimated modes of these rim rocks are given in Table 4b.

In general, the calc-silicate pods observed in the Gray Schist Member of the Littleton are very similar to those in the rusty-weathering schists of the Paxton Formation. Calc-silicates within the gray schist rarely occur in beds and the pods or "footballs" tend to be larger than those in the rusty schists. Equant granular quartz and plagioclase (generally An 63 - An 70) make up the matrix of the "footballs". Pink garnet, probably near grossular in composition is present in all of the calc-silicates examined. In two of these, PAM 956C and PAM 982C, the garnet core is a fine-grained orange-pink mass. Toward the outer edge of these fairly small pods, the garnets are coarser, reddish-pink, and euhedral.

Diopside, hornblende, and actinolite are all fairly coarse, round or slightly elongate, highly embayed, and poikilitic. Diopside is colorless. Actinolite is more fibrous and generally pale-green to yellow-green. Hornblende is more strongly colored with Z = blue-green, and X = Y = pale green.

The epidote mineral present is most commonly pistacite, however, in PAM 401 it is ferrian zoisite. The epidotes occur in discrete grains or commonly as rims around diopside, hornblende, and plagioclase. Sphene is present in all of the calc-silicates. It occurs in round, high relief, pleochroic, pink - brown colored grains. Other accessories include apatite, zircon, rutile, and ilmenite.

The granulites rimming the calc-silicate footballs are rich in quartz, plagioclase, and biotite (Table 4b). Minor calc-silicate minerals include grossular, diopside, pistacite, and sphene. Also present in minor amounts are muscovite, secondary chlorite, tourmaline, apatite, zircon, and ilmenite.

Table 4a. Estimated modes for samples of calc-silicate granulites within the gray-weathering schists of the Littleton Formation. All of the samples are taken from calc-silicate pods within the Gray Schist Member (Dl) except PAM 826 which is from the Feldspathic Schist Member (Dlf).

	GRAY QUARTZ MATRIX			WHITE QUARTZ MATRIX			SMALL ZONED PODS	
	PAY 164	PAM 923Bc	PAM 947M	PAM 947I	PAM 401	PAM 826	PAM 956C	PAM 982C
Quartz	30	46	74	65	45	62	x	x
Plagioclase	42	30	11	14	23	20	x	x
(mol.% An)	(64)	(>70)	(64-70)	(64-70)	(63)	(65-75)	(70)	(66-80)
Garnet	11	9	5	5	11	5	x	x
Diopside		9		10	10	2	x	x
Actinolite		2			1	3	x	
Hornblende	14		9	1				x
Ferrian Zoisite					7			
Pistacite			tr	3		5	x	x
Mg-chlorite	tr							
Sphene	2	2	1	2	2	1	x	x
Rutile						tr		x
Apatite	1	1	tr	tr	tr	1	x	x
Zircon	tr	tr	tr	tr	tr	tr	x	x
Ilmenite						1		
Undiff. Opaques	tr	1	tr	tr	1		x	x

x Indicates that the mineral is present in the rock, but no mode is estimated.

<u>List of Specimens in Table 4a.</u>

PAY 164 - This quartz-rich, garnet-diopside calc-silicate lens is within the gray-weathering schist at its contact with the tonalite (PAY 600). Sample is taken from an east-facing outcrop, 3150 feet (.59 miles) N 89 E of the intersection between Pillsbury Road and Route 119.

PAM 923Bc - Gray, quartz-rich, diopside-actinolite-garnet calc-silicate bed in gray schist on the east slope of Little Watatic Mountain. See PAM 923A for location. This calc-silicate is rimmed by a gray biotite granulite which is seen in the same thin section - see PAM 923Br, Table 5b.

PAM 947M - Outer part of a large, gray, quartzose calc-silicate "football". Sample 947 shows a transition, moving inward in the sample from hornblende (947M) to diopside (947I) as the dominant mafic mineral with a subsequent increase in the amount of pistacite. The "football" is in a large, steep, gray schist exposure on the southwest slope of Mount Watatic, 1270 feet (.24 miles) S 78 W of the fire tower on the main Watatic summit. The outcrop is at 1470 feet elevation.

PAM 947I - Core of the calc-silicate "football" described above. This portion has a white matrix and is rich in garnet, diopside, and pistacite with only minor hornblende. See PAM 947M for location.

PAM 401 - Spectacular meter long, white, sandy, quartz-rich, calc-silicate pod, speckled with pink garnet, pale green diopside and dark green actinolite. In moderately bedded gray-weathering schist with thin quartz granulites. Located on the first ridge north of the main Pratt Mountain summit, just northwest of the saddle at 1735 feet elevation (see also PAM 401R - Table 4b).

PAM 826 - White, sandy, quartz-rich calc-silicate "football" with pink garnet and green diopside and actinolite (similar to PAM 401) in gray-weathering schist. This "football"-bearing outcrop lies in the path of the Midstate Trail on the southern slope of New Ipswich Mountain at 1780 feet elevation.

PAM 956C - Beautiful, zoned calc-silicate "footballs" are confined to a bed in the gray schist. The core of one of these is a fine mesh of orange-pink garnet. The outer part of the pod has a white quartzose matrix with clear reddish euhedral garnets and green diopside (see PAM 956S - Table 3c - for location). No mode is estimated for this sample because of inhomogeneity due to zoning.

PAM 982C -Fist-sized, zoned calc-silicate pod enclosed in gray-weathering schist (PAM 982). The core is a mass of fine pinkish garnet. The outer portion of the pod is a pale gray quartzose diopside-hornblende calc-silicate with reddish euhedral garnets. See PAM 982 - Table 3c - for location.

Table 4b. Estimated modes for samples of biotite-quartz granulites that form thin rims around some of the calc-silicate pods shown in Table 4a from the Littleton Formation.

	PAM 401R	PAM 923Br	PAM 947O	PAM 956R
Quartz	74	60	81	60
Plagioclase	12	27	9	31
(mol.% An)	(18-19)	(>70)	(64-70)	(23)
Biotite	10	5	6	4
Muscovite	1			
Fe-chlorite (Sec.)	tr			1
Garnet	3	4	2	2
Diopside	tr			
Pistacite			tr	
Sphene	tr		tr	
Tourmaline			tr-bg	
Apatite	tr	3	tr	tr
Zircon	tr	tr	tr	1
Ilmenite	tr	1	2	1

bg Indicates blue-green tourmaline.

List of Specimens in Table 4b

PAM 401R - This gray, garnet-bearing, biotite-quartz-plagioclase granulite is sampled from a thin layer, up to 5 cm thick, rimming the large calc-silicate "football" of PAM 401. See PAM 401 - Table 5a for location.

PAM 923Br - Fine-grained, gray, biotite-quartz-plagioclase granulite. This granulite rims the calc-silicate described in PAM 923Bc and is observed in the same thin section. See PAM 923A (Table 4c) for location.

PAM 947O - The outer rim of the calc-silicate described in Table 5a (PAM 947I and PAM 947M) is a fine-grained quartz-biotite granulite with minor calc-silicate minerals present, including garnet, pistacite and sphene.

PAM 956R - Rimming the calc-silicate pods of PAM 956C is a thin layer of fine, gray biotite-garnet-quartz granulite. See PAM 956S (Table 4c) for location.

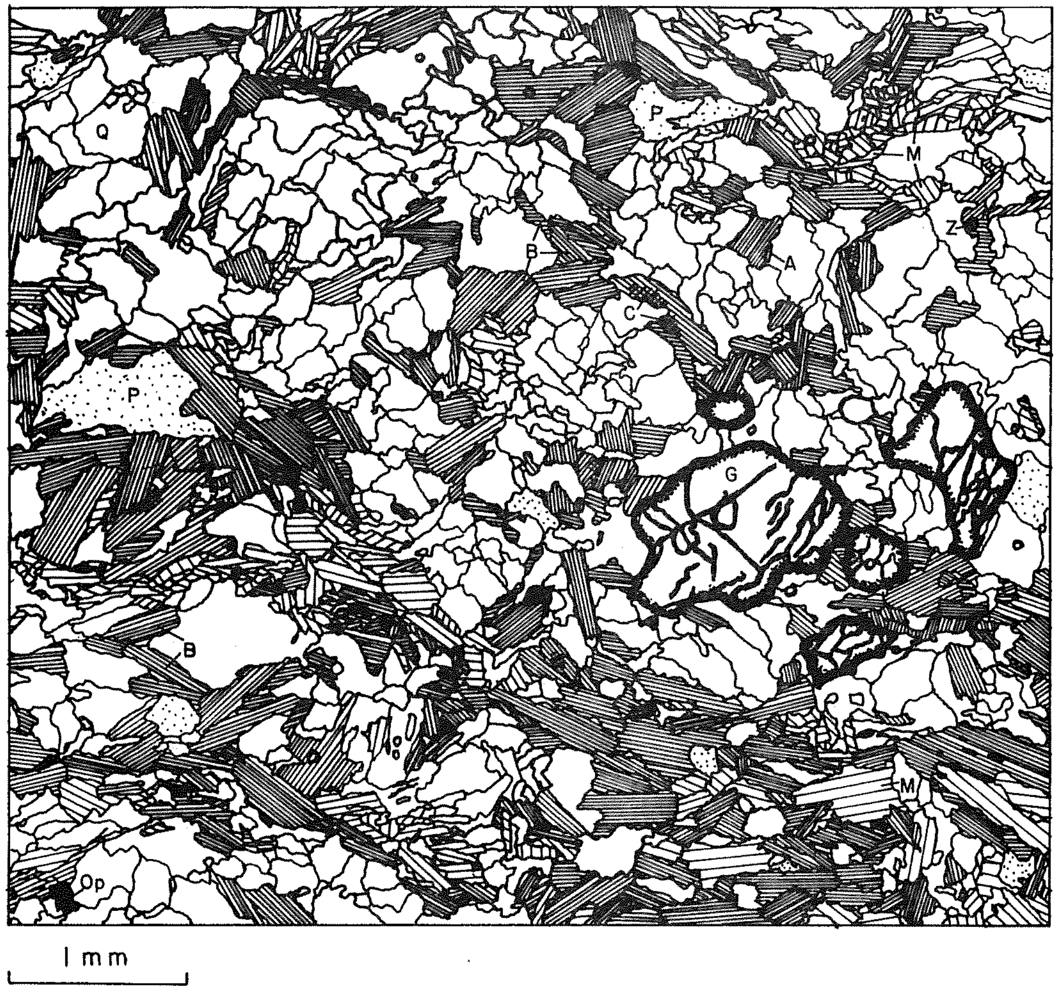


Figure 10. Sketch of a typical thin section of the Gray Schist Member of the Littleton (D1), sample PAY 556. Q = quartz (unpatterned), P = plagioclase (stippled), B = biotite (heavy-lined), M = muscovite (light-lined), C = chlorite (cross-hatched), A = apatite, Z = zircon, G = garnet (unpatterned, high relief), Op = opaque minerals - undifferentiated (black).

Equant quartz and feldspar make up 85% of these granulites. Plagioclase is not necessarily calcic, but ranges from An 18 - An 70. Biotite grains are small and elongate, generally 0.5 mm long, and brown to red-brown. Minor secondary muscovite and Fe-rich chlorite are present locally replacing biotite. Fine, rounded garnet grains, up to 1 mm in diameter, are common in all of these granulites. Diopside, pistacite, and sphene, in trace amounts, if present, are generally more abundant near the contact with the calc-silicate. Green tourmaline is present in PAM 9470.

Two main calc-silicate types can be differentiated based mainly on their appearance in the field. The two are gradational toward one another.

The first type has a coarse, white, sandy quartz matrix dotted with red garnets and green diopside, actinolite, and epidote. These distinctive calc-silicates occur in elongate pods, up to a meter long, along the ridge crest of Pratt Mountain (see PAM 401 - Table 4a).

The second type looks at first like a gray, massive quartzite, but is rich in calc-silicate minerals, including garnet, diopside, hornblende, actinolite, and epidote. A few of the larger gray calc-silicate "footballs" are gradational to the white calc-silicate at their cores. The pod sampled at locality PAM 947 shows this gradation nicely (see Table 4a). PAM 947M is from the outer gray portion of the pod and PAM 947I is from the white core of the pod. The estimated mode from the granulite rimming the pod, PAM 9470, is given in Table 4b. Differences between the outer and inner portions of the calc-silicate pod are dramatic. The white inner calc-silicate has abundant garnet, diopside, and epidote with very little hornblende. As the pod grades outward to gray calc-silicate, diopside is not present, epidote is present only in trace amounts, and hornblende increases in abundance. Garnet is in both types of calc-silicates in equal amounts. Unfortunately, the mineralogical differences noted in PAM 947 between the two types of calc-silicates are not seen consistently in pods in the rest of the area (Table 4a). The pods at PAM 956 and PAM 982 show some of this gradation on a smaller scale. PAM 401 and PAM 826 (see Feldspathic Schist Member) are mostly white and PAM 923Bc and PAM 164 are gray.

Feldspathic Schist Member. The gray-weathering schist labelled Dlf on Plate 1, west of the fault, is separated from the Gray Schist Member (Dl) by a belt of rusty schist. It tends to be more feldspathic and less well bedded than Dl. Much of the area shown as Dlf is characterized by poor exposure so that correlation is based on structural interpretation and geometrical constraints as well as on general lithic character. On the top of New Ipswich Mountain (see PAM 818 - Table 5), the schist is very monotonous and poorly bedded, with few granulite layers and rare calc-silicates. On Binney Hill (PAM 229 - Table 5), the gray schist contains interbedded schist and granulite.

Table 5. Estimated modes for samples examined from the Feldspathic Schist Member of the Littleton Formation.

	PAM 16	PAM 666	PAM 229	PAM 818
Quartz	43	39	48	79
Plagioclase	14	13	29	11
(mol.% An)			(13-19)	(23)
K-feldspar	3*			
Biotite	15	24	12	7
Muscovite (Prim.)	12	10	5	2
Muscovite (Sec.)	4	11		
Fe-chlorite (Sec.)	4		tr	
Sillimanite		tr		
Garnet	2		3	tr
Tourmaline			2-gb	
Sphene	tr			
Apatite	1	tr	tr	tr
Zircon	tr	1	1	1
Ilmenite	2	1	tr	tr
Graphite		1		

* K-feldspar with the properties of sanidine - confined to a vein.
gb Indicates the presence of green and brown tourmaline.

<u>List of Specimens in Table 5</u>

PAM 16 - Gray-weathering, feldspathic, muscovite-rich schist. Some of the feldspar, isolated in a vein, has the optical properties of sanidine with low relief and $2V_X = 15°$. The outcrop sampled is on the south end of Mount Hunger, at elevation 1380 feet, along the Midstate Trail, 1230 feet (.23 miles) S 11 W of the summit.

PAM 666 - Brownish-gray-weathering, coarse-grained feldspar-biotite-muscovite schist with coarse ellipsoidal quartz-feldspar knots parallel to foliation. This rock is taken from a small flat outcrop located 580 feet (.11 miles) S 85 W of the Mount Hunger summit.

PAM 229 - Coarse-grained, blotchy, gray-weathering, garnet-biotite schist with elongate quartz-feldspar lenses. Outcrop sampled is located 360 feet (.07 miles) west of the southern summit of Binney Hill.

PAM 818 - Very quartzose, gray-weathering, garnet-biotite granulite interbedded with coarse muscovite schist and including gray calc-silicate "footballs". This sample is taken from one of several large outcrops on the slope of New Ipswich Mountain, due east of the summit at 1660 feet elevation.

It is a very feldspathic schist with coarse mica and segregated lenses of quartz and feldspar. This feldspathic schist, which has obviously undergone some partial melting and subsequent recrystallization, is similar to the rock described by Greene (1970) as the Souhegan Member of the Littleton. The character of the gray schist on Fisher Hill is very similar to that on Binney Hill. It includes both well bedded and the "Souhegan-type" rock. On Mount Hunger (see PAM 16 and PAM 666 - Table 5), closer to the tonalite, the gray schist is dominated by the "Souhegan-type" gneissic schist with quartz-feldspar lenses. In this area, the schists also display a strong mylonitic foliation.

In the field, these feldspathic schists have a gneissic look with segregated layers rich in mica separated by thin layers or lenses of quartz and feldspar. Thin section study (Table 5) of the minerals reveals that the micas and feldspar, have a coarse recrystallized look (Figure 11). This recrystallization, however, has taken place prior to development of the predominant foliation. The mineral and rock textures suggest that partial melting has taken place relatively early in the deformational history of these rocks, possibly related to intrusion of the tonalite. In one sample (PAM 16), K-feldspar in the highly disordered form, sanidine, is present in a thin monomineralic vein that appears to be post-metamorphic. The sanidine has extremely low relief, pseudo-grid-twinning, $2V_X = 15$, and a distinct $r > v$.

Quartz-plagioclase layers and biotite-muscovite layers make up most of the rock, Secondary muscovite and Fe-rich chlorite are present locally, as are relict sillimanite, garnet, tourmaline, and sphene, Accessory minerals include the usual apatite, zircon, ilmenite, and graphite (Table 5).

Quartz is elongate, strongly recrystallized, and in places, highly strained. It occurs in aggregate lenses with coarsely recrystallized plagioclase. The plagioclase, An 13 - An 23 where measurable, is commonly slightly altered by secondary sericite.

Biotite occurs in elongate, brick-red to brown grains. Two types of secondary muscovite are present: coarse muscovite which may have recrystallized during partial melting and very fine, matted-together grains of muscovite which replace the earlier coarse muscovite, biotite, and feldspar. An example of this, similar to that shown in Figure 9 can be seen in sample PAM 666, where folded needles of relict sillimanite are preserved within coarse muscovite grains that are, in turn, rimmed by fine, felt-like muscovite. Garnet is commonly present in round, slightly embayed grains up to 3 mm in diameter. In sample PAM 16, it is rimmed by Fe-rich chlorite.

Contacts

Because these gray-weathering schists of the Littleton Formation are interpreted as the youngest rocks in the area, only their basal

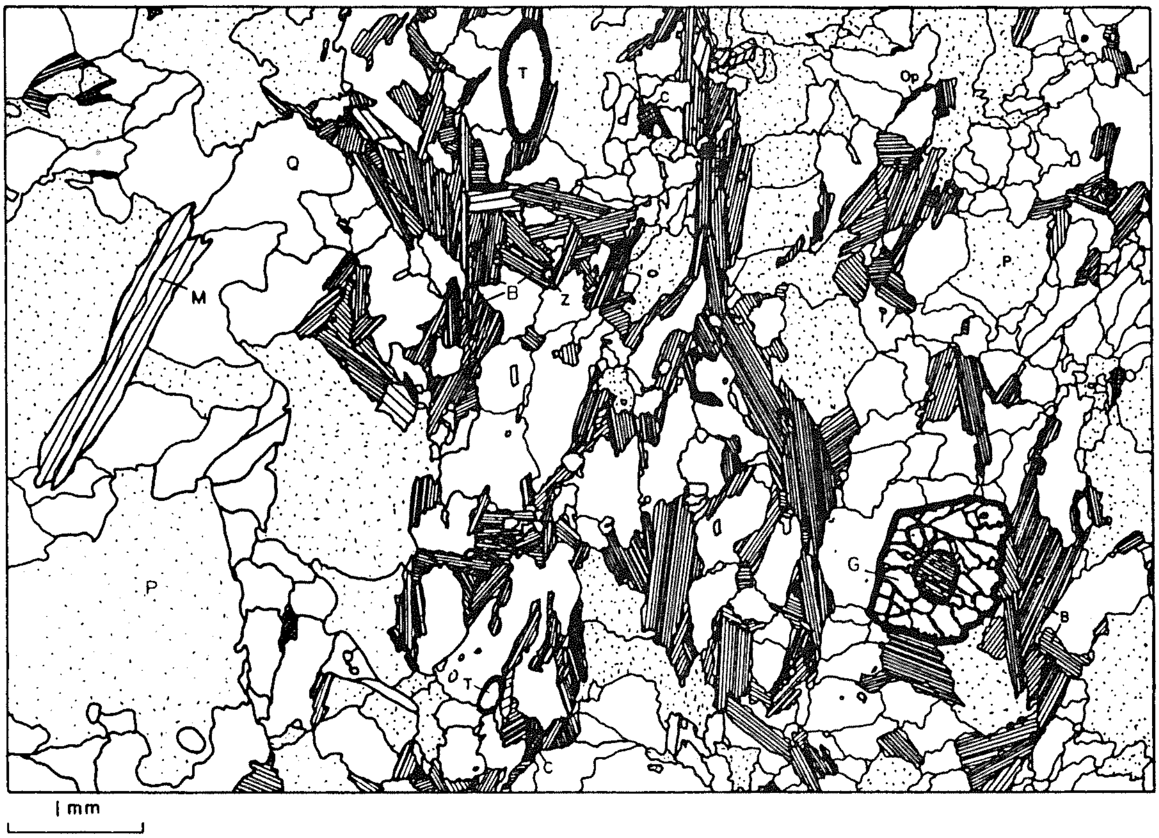


Figure 11. Sketch of a typical thin section of the Feldspathic Schist Member of the Littleton Formation - sample PAM 229. Note the coarse secondary muscovite and the differentiated layering. Q = quartz (unpatterned), P = plagioclase (stippled), B = biotite (heavy-lined), M = muscovite (light-lined), C = chlorite (cross-hatched), G = garnet (unpatterned, high relief), T = tourmaline (unpatterned, high relief), Z = zircon, A = apatite, Op = undifferentiated opaque minerals (black).

contact is exposed. The nature of this contact with both the Gray Granulite Member and the Sulfidic Schist Member of the Paxton Formation was discussed above in connection with these units.

Good graded bedding is not found within the gray schist near enough to its contact with the Paxton Formation to establish a reliable topping direction for the unit as a whole. One locality on the west slope of Pratt Mountain, discussed in a later section on bedding, displays beautiful graded beds in the gray schist topping away from the rusty-weathering schist of the Paxton Formation. Although the graded beds are close to the contact, the location of the contact here was not determined accurately enough to make this an absolutely reliable topping direction.

In general, the gray-weathering schist may take on a slightly brownish-weathering character and may be slightly better bedded near its basal contact. The nature of the contact between the stratified country rock in general and the tonalite is discussed in the section on intrusive rocks,

Derivation

The Littleton Formation is one of several formations, including the Seboomook Formation of Maine, the Gile Mountain Formation of Vermont, and several others, described by Boucot (1970) as part of the most widespread sedimentary unit in the northern Appalachians. These early Devonian flysch-like sediments blanket the Silurian section in this region (Pankiwskyj *et al.*, 1976). The major source for these sediments is thought to have been from the northeast (Hall *et al.*, 1976).

The well bedded gray-weathering schists mapped in the Ashburnham Ashby area as part of the Littleton Formation could be characterized as part of this extensive flysch blanket. A flysch sequence comprises interbedded marine sandstone and shale, generally deposited by turbidity currents. This type of deposit is suggestive of a fairly rapidly uplifting landmass, which is the source of abundant detritus. These Devonian flysch sequences may represent the more distal deposits of a westward advancing submarine fan. The common occurrence of tourmaline in these rocks requires the presence of boron, which is compatible with a marine environment of deposition. The calc-silicates may indicate either periods of limited detrital deposition over a small area or the formation of post-depositional carbonate concretions in the more sandy layers. Because the calc-silicate pods are very quartz-rich and commonly granular to gritty, the second, post-depositional model is appealing.

Thickness

Because the gray schists of the Littleton Formation represent the youngest unit in the stratigraphic section, the top is not exposed and therefore the true thickness cannot be obtained. A minimum true thickness can be obtained from the map or cross sections (Plates 1 and 2) where the mapped thickness in the area is the greatest. As is discussed in the section on thickness of the Sulfidic Schist Member of the Paxton Formation, a doubled thickness is assumed for each belt of schist. This is based on the interpretation of the repeated gray and rusty belts as large scale, early, nappe stage isoclinal folds. The minimum true thickness for the Gray Schist Member (Dl) is measured as 120 - 150 feet. For the Feldspathic Schist Member (Dlf), the minimum true thickness is 100 feet.

INTRUSIVE IGNEOUS ROCKS

Fitchburg Plutonic Complex - Tonalite Member

The Fitchburg Complex (Figure 3) was initially described by Emerson (1917) as a series of granitic sheets which intrude strata in the core of an open syncline. Near its southern end, the open synclinal nature of the complex has been substantiated by reconnaissance work of Grew (1970 - Worcester area), Hepburn (1976 - Sterling quadrangle), Tucker (1976 - Wachusett Mountain area), and Tucker and Robinson (1976-77 - central Massachusetts) (refer to Zen et al., 1983). Mapping in the northern portion of the complex (Peter Robinson - personal communication) suggested that the syncline may be overturned to the east. The plutons intrude Silurian - Devonian strata, metamorphosed to sillimanite - muscovite grade. On the east margin of the complex, the metamorphic grade drops off dramatically away from the pluton. The metamorphic gradient is much more subtle along the west margin of the complex.

Lithically, the complex is quite diverse. Emerson (1917) differentiated between a leucocratic, medium-grained muscovite, biotite granite and a dark-gray, medium-grained, biotite granodiorite, though this is not reflected on his map. Further mapping by Hepburn (1976), Peper (1976), and Tucker (1976) and geochemical and petrologic characterization by Maczuga (1981), have shown that the complex should be divided into three major units: 1) Moderately to well foliated, dark-gray, fine- to medium-grained, biotite granodiorite-tonalite gneiss. This structurally lowest member occurs along the east and west margins of the complex, 2) Gray, fine- to medium-grained, biotite, muscovite granite - granodiorite. This is moderately to strongly foliated and occurs structurally above the tonalite member. 3) Massive to weakly foliated leucocratic, medium- to coarse-grained biotite, muscovite granite. Structurally the highest member, this granite occupies the core of the syncline and cross cuts the other two members. Its poorly foliated nature suggests a late-tectonic time of emplacement (Maczuga, 1981). This unfoliated granite member, described by Emerson (1917) as a granite, uncontaminated by country rock, passes through the town of Fitchburg, for which the complex is named. Several quarrying operations at Rollstone Hill in Fitchburg are described by Dale (1923). Point-counted modes of the granodiorite-tonalite gneiss from Maczuga (1981) and estimated modes from this study plot in the tonalite field on the composition plot after Streckeisen (1973) in Figure 12.

Dark, well foliated, biotite, granodiorite - tonalite (Dfgt on Plate 1) is the only member of the complex that was examined in this study. It occurs in the eastern portion of the Ashburnham-Ashby area mainly in the Ashby quadrangle (Plate 1). It is referred to as tonalite in this manuscript. The tonalite occurs as a semi-concordant sheet which intruded into and was subsequently deformed and metamorphosed with Silurian - Devonian stratified country rock. Compared to the schists, the tonalite is relatively easy to differentiate in the field, which made mapping easier in complex areas.

Lithology. The typical tonalite of the Fitchburg complex in the Ashburnham-Ashby area is a strongly foliated, dark-gray, fine- to medium-grained biotite tonalite gneiss. Outcrops of tonalite are slabby, typically with gray-brown, rounded-weathering surfaces. Several small ridges and hills such as Whittemore Hill and Jones Hill are held up by large flat outcrops of this relatively resistant unit. Up close, the rock has a salt and pepper appearance with abundant, fine, black biotite, gray feldspar, and quartz. Despite its strongly foliated nature, it has a somewhat granular texture. Also typical, are fine clots of biotite, randomly distributed throughout the tonalite to give it a mottled look.

Excellent exposures of typical tonalite can be seen in the "Heartbreak Corners" area northeast of Marble Pond, on Jones and Whittemore Hills, and in several roadcuts along Route 119 in the Ashby quadrangle. In the south, on Jewell Hill, the tonalite is a bit coarser-grained, with a higher percentage of quartz and feldspar. Tonalite exposed to the west of West and Ashburnham Roads is also somewhat coarser-grained than the typical tonalite. Here, it incorporates larger round phenocrysts of gray or white feldspar, which give it a "popcorn-like" appearance. Locally these phenocrysts are elongate parallel to foliation due to shearing associated with the formation of mylonites. This shearing is noted as well in rocks to the north of Mount Hunger. Discussion of this shearing follows in the section on structural geology.

The major constituents of the tonalite (Tables 6a and 6b) are biotite, plagioclase, and quartz. Potassium feldspar (K-feldspar) is present in small amounts but is commonly difficult to pick out in thin section without staining. Other phases present in the tonalite include muscovite, chlorite, garnet, apatite, zircon, sphene, allanite, pistacite, rutile, ilmenite, pyrite, pyrrhotite, magnetite, and covellite. Goethite is present as a secondary weathering product after the sulfides. Biotite forms a strong foliation that is penetrative enough to be generally apparent in thin section (Figure 13). A few

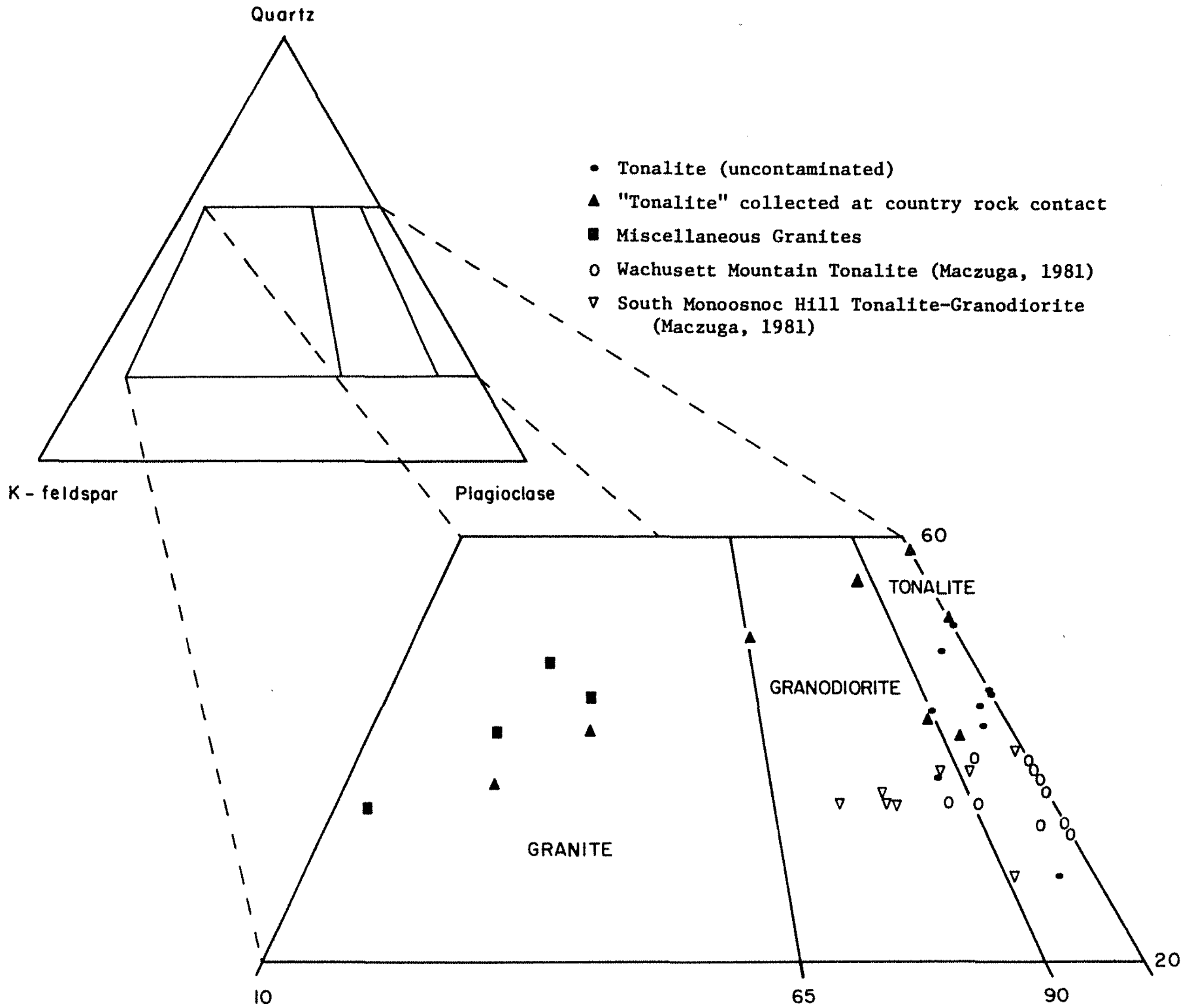


Figure 12. Plot of modal quartz, plagioclase, and K-feldspar, normalized to 100%. Plot is modified after Streckeisen (1973). Samples shown from the Ashburnham-Ashby area represent estimated modes of common tonalite (Table 7a), tonalite-granodiorite (Table 7b), and miscellaneous granites (Table 8). Plots of tonalite and granodiorite samples from Maczuga (1981) are based on point-counted modes.

Table 6a. Estimated modes from samples of typical biotite tonalite from the Tonalite Member of the Fitchburg Plutonic Complex.

	PAM 4	PAY 102	PAM 507	PAY 521	PAY 528	PAY 530	PAY 537D	PAY 770	PAY 961F
Quartz	30	23	30	33	37	19	40	32	32
Plagioclase	36	34	35	40	44	46	40	30	42
(mol.% An)	(48)	(36)	(26.5)	(27)	(26)	(26.5)	(30)	(30)	(24)
Orthoclase		5		1		2	2		
Microcline			4						2
Myrmekite			1			tr			
Biotite	24	25	22	20	14	28	11	30	20
Muscovite				1		2	1	2	tr
Sericite			1		tr	2			
Fe-chlorite (Sec.)	1	5	tr	1	tr	tr	1	tr	tr
Sphene	5						tr		
Allanite	tr	1	1	1	1	tr	tr	tr	tr
Rutile			tr				tr	tr	tr
Apatite	2	3	3	1	2	1	2	4	2
Zircon	tr	1	1	1	1	tr	2	1	tr
Ilmenite	2		tr			tr	1	1	2
Magnetite							tr	tr	
Goethite (Sec.)							tr		tr
Pyrite							tr		
Pyrrhotite							tr		
Covellite							tr		
Undiff. Opaques	tr	3	2	1	1	tr			
Pl/(Pl + Ksp)	100.0	87.1	90.3	97.3	100.0	95.8	95.9	100.0	96.3
Qz/(Qz + Fsp)	45.5	37.1	43.6	44.0	45.3	28.0	49.2	51.6	42.1

List of Specimens in Table 6a.

PAM 4 - Dark gray, medium-grained, well foliated, biotite tonalite. The sample is taken from a large heavily jointed outcrop which extends east from Rindge Turnpike 300 feet (.06 miles) north of the intersection with Old Marble Road.

PAY 102 - Dark gray, well foliated, fine-grained, biotite tonalite-granodiorite with small knots of feldspar and biotite. The sample is collected from a low, north - south trending, slabby outcrop of tightly folded tonalite, east of Rindge Turnpike, 800 feet (.15 miles) N 23 W of the interseciton with Wagg Road.

PAM 507 - Medium-grained, light gray, biotite tonalite. This moderate sized broken west-facing outcrop is located 320 feet N 85 E of the roadcut at PAM 4 (described above).

PAY 521 - Dark gray, fine- to medium-grained, well foliated, biotite tonalite. This sample is taken from a small, slabby outcrop on the north side of Route 119, 600 feet (.11 miles) west of the intersection with Flint Street. The outcrop is just above and to the west of the small stream shown crossing Route 119.

PAY 528 - Dark gray, medium-grained, well foliated and slightly sheared, feldspathic, biotite tonalite. This large, somewhat hidden, cliff outcrop is on the south side of Route 119, 1700 feet (.32 miles) west of the entersection with West Road.

PAY 530 - Strongly foliated and mylonitized, thinly laminated, dark gray, feldspathic, biotite tonalite. This outcrop is located on the north side of Route 119, 230 feet (.045 miles) east of Watatic Pond.

PAY 537D - Dark gray, medium-grained, moderately to well foliated biotite tonalite. The sample is taken from the upper eastern part of an extensive outcrop located in the woods, 800 feet (.15 miles) S 70 E of the intersection of Old Ashby Road and Rindge Turnpike.

PAy 770 - Dark gray, fine-grained, biotite tonalite. The outcrop is mostly pegmatite with remnants of good tonalite. it is located 3500 feet (.66 miles) S 33 E of the radio tower on Byfield Road, to the west of an old northerly-trending carriage road at 1340 feet elevation.

PAY 961F - Fine-grained, well foliated, biotite tonalite. The sample is taken from large, slabby outcrop faces on the west end of Jones Hill at 1140 feet elevation, 400 feet (.075 miles) N 55 E of the concave east bend in Jewett Hill Road.

Table 6b. Estimated modes from samples of tonalite-granodiorite taken from the Tonalite Member of the Fitchburg Plutonic Complex, generally near its contact with country rock.

	PAM 5	PAY 91T	PAY 537L	PAY 568	PAM 590	PAY 600	PAY 691	PAY 897
Quartz	35	30	33	32	39	39	44	34
Plagioclase	20	15	44	22	27	36	28	41
(mol.% An)	(26)	(23)	(29)	(31)	(23)	(47)	(23)	(23)
Orthoclase		36	4					
Microcline	29				4		15	5
Myrmekite	tr	1					1	2
Biotite	12	13	14	36	20	19	8	12
Muscovite	tr		1				1	
Sericite (Sec.)		tr						2
Fe-chlorite (Sec.)	tr	1	tr	tr	tr	2	tr	tr
Garnet						1		
Sphene	tr			5		1	tr	
Allanite	tr	1	tr	1	2	1		1
Pistacite				1				
Rutile	tr			tr				tr
Apatite	2	2	2	3	4	tr	2	2
Zircon	1	tr	1	tr	1	tr	1	tr
Ilmenite	1		1	tr		1	tr	1
Goethite (Sec.)				tr				tr
Pyrite								tr
Covellite				tr				
Undiff. Opaques	tr	1	tr		3	tr	tr	
Pl/(Pl + Ksp)	40.8	29.1	92.4	100.0	87.1	100.0	65.1	88.7
Qz/(Qz + Fsp)	41.6	36.6	41.2	58.8	55.7	52.1	50.7	42.6

List of Specimens in Table 6b.

PAM 5 - Medium-grained, dark gray, well foliated, biotite granodiorite-granite with coarse stretched-out quartz-feldspar knots. Sample is collected within the tonalite, near its contact with schist, from a moderate-sized outcrop, just south of Marble Road and 275 feet (.05 miles) due east of the Marble Road - Rindge Turnpike intersection.

PAY 91T - Medium-grained, dark gray, feldspathic, biotite granodiorite-granite within tonalite, right at the schist - tonalite contact. This sample is collected from same outcrop as PAY 91S, about 50 feet west of the schist sample locality (see Table 3a for location). The tonalite in this outcrop becomes increasingly feldspathic and more heavily intruded by pegmatites toward the schist contact.

PAY 537L - Light gray, medium- to coarse-grained, moderately foliated, feldspathic, biotite tonalite. The sample is taken from the base of the outcrop described for PAY 537D, just above the contact with schist.

PAY 568 - Dark gray, fine-grained, well foliated, biotite tonalite. The contact with schist is exposed in this moderate-sized, north-northeast-facing outcrop on a small knob, 1430 feet (.27 miles) S 35 W of the previously described outcrop at station PAY 528. Near the contact, the tonalite contains coarse red garnets up to 1 cm in diameter) and "swirled-in" pieces of schist.

P AM 590 - Dark gray, fine-grained, biotite tonalite-granodiorite with coarse rounded feldspar knots stretched out parallel to a strong mylonitic foliation. The contact with schist is just above. This low cliff outcrop is below the Midstate Trail at 1260 feet elevation north of Mount Hunger and 2530 feet (.48 miles) S 33 E of the intersection of Holt Road with Route 101.

PAY 600 - Dark gray, fine-grained, well foliated, biotite tonalite. The tonalite - schist contact is exposed in this outcrop, which follows a low ridge at 1200 feet elevation, just north of an old logging road and 2000 feet (.38 miles) N 53 W of the intersection between Route 119 and Flint Street.

PAY 691 - Dark gray, medium-grained, biotite granite-granodiorite with coarse biotite and feldspar knots. Sample is taken from a small outcrop, 3000 feet (.57 miles) S 33 E of the radio tower on Byfield Road.

PAM 897 - Light gray, well foliated, feldspathic, biotite tonalite-granodiorite. This flat outcrop lies just below the schist contact, northwest of Mount Hunger, 2250 feet, (.43 miles) S 22 E of the intersection of Holt Road with Route 101.

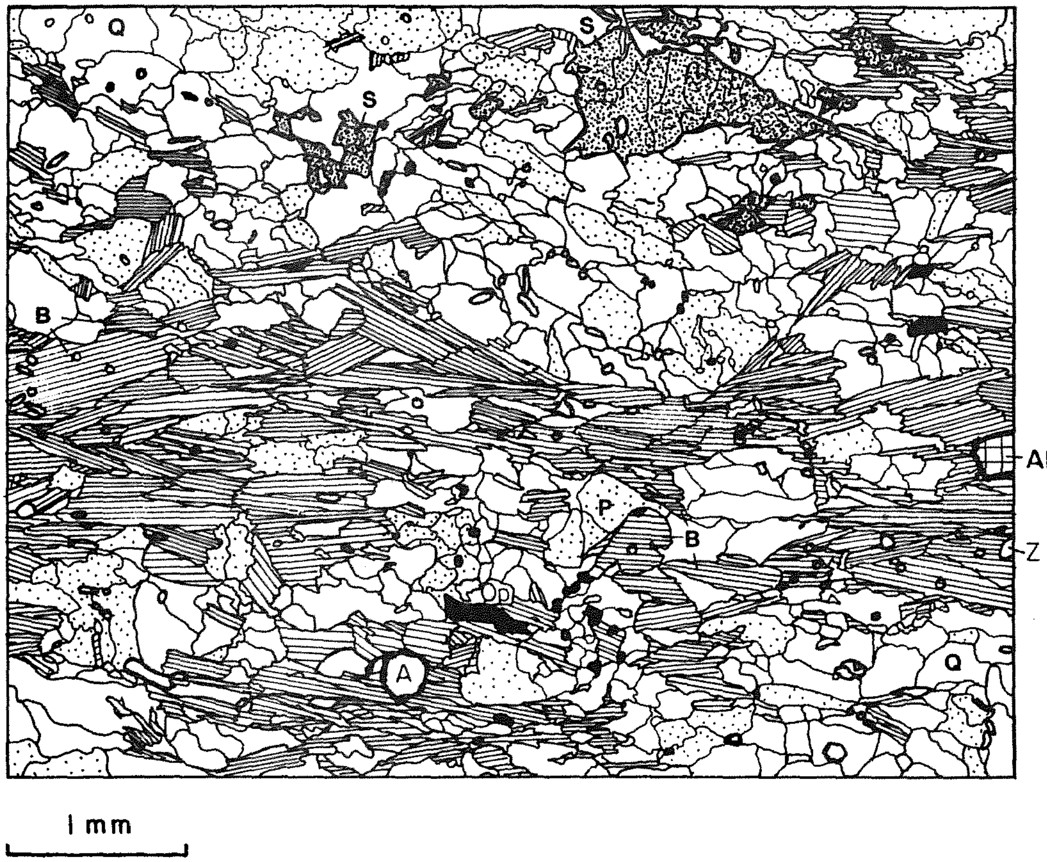


Figure 13. Sketch of a typical tonalite in thin section, from sample PAY 568. B = biotite (heavy-lined), P = plagioclase (stippled), Q = quartz (unpatterned), S = sphene (heavy-stippled), A = apatite (unpatterned, high relief), Al = Allanite (cross-hatched), Z = zircon, Op = undifferentiated opaque minerals (black).

samples show a fine gneissic interlayering of dark, platy biotite-rich layers and lighter, more granular quartz-feldspar-rich layers. The more granular minerals are commonly elongate recrystallized lenses parallel to foliation. A strongly differentiated layering is not present in the tonalite so that minor structural features are not easily observed in outcrop.

The mineralogy of the tonalite throughout the area is quite consistent (Table 6a). Biotite is elongate, generally 0.7 - 2.2 mm long, and strongly pleochroic, with X = pale yellow or tan and Z = Y = brick red-brown. The red-brown color (as opposed to green-brown) of biotite generally indicates a high Ti^{+4} content with respect to Fe^{+3}/Fe^{+2} (Hayama, 1959). This, however, is not a straightforward correlation. Maczuga (1981) found that green biotites analyzed from tonalites on the west margin of the Fitchburg complex at Wachusett Mountain, and red-brown biotites in tonalites from the east margin of the complex at South Monoosnoc Hill, have essentially the same Ti^{+4} content. He attributes the color difference to differences in Fe^{+3}/Fe^{+2}. Shearer (1983) has found that metamorphic recrystallization in the presence of different oxides, depending on their state of oxidation, has an effect on the color of biotites in the Hardwick pluton (see Figure 3). Red-brown biotites recrystallized in the presence of ilmenite are red-brown, however, red-brown biotites recrystallized in the presence of magnetite are green.

In most samples examined from the Ashburnham-Ashby area, biotite has been replaced to some degree by Fe-rich chlorite. Primary muscovite, present as a minor phase in a few samples, generally occurs as small thin grains, intimately intergrown with biotite, or as inclusions in feldspar or quartz. Slightly more common secondary muscovite has two main habits. Coarse muscovite grains replace biotite and commonly cross cut foliation. Fine, felt-like masses of muscovite or sericite occur as alteration products of feldspar. This is much like the relationship shown in Figure 9 in a sample of gray schist.

Plagioclase ranges in size from approximately 0.12 - 2.0 mm with an average grain size of 0.3 - 0.9 mm. A few anomalous grains are up to 3.5 mm in diameter. Polysynthetic albite twinning is nearly universal, accompanied in some grains by carlsbad or pericline twins. Plagioclase compositions determined using the Michel - Levy maximum extinction angle method, and in some cases substantiated by carlsbad - albite determinations (using the chart in Kerr, 1959 - p. 261), range from An 23 to An 48 with an average composition around An 27. In general, the refractive index overlaps with quartz and the 2V is close to 90 degrees. Minor sericitization of the plagioclase helps to differentiate it from quartz in modal estimates.

Quartz, abundant in all of the tonalites, is slightly strained and recrystallized. It is most commonly dispersed throughout the rock, although it may form recrystallized aggregates. Much of the strain in the rock is taken up along quartz - feldspar grain boundaries which are sometimes characterized by crenulated interfaces and reduced grain size.

K-feldspar may be more abundant than is indicated by the modes in Table 6a. In slides that have abundant and evenly distributed biotite and Na-rich plagioclase, relative refractive index and other optical properties are not sufficient to differentiate all K-feldspar without staining. Where present, the K-feldspar, either orthoclase or microcline with weak grid twinning, has a lower refractive index and generally smaller $2V_X$ than plagioclase. Symplectic intergrowths of quartz and K-feldspar occur along the boundaries between these two minerals.

Apatite occurs as hexagonal stubby prisms or fine needles with high relief and low birefringence. It is very abundant and may be up to 1 mm in diameter, although it averages 0.1 mm in diameter. Tiny zircons, averaging 0.05 - 0.12 mm in diameter, occur as round grains, commonly lodged along the cleavage cracks in biotite, surrounded by pleochroic haloes. In some of the samples examined, sphene occurs as beautiful, coarse grains (1 - 2 mm in diameter intimately associated with ilmenite. In general, it occurs as a fine-grained (0.1 - 0.16 mm) accessory mineral. Rutile, a second Ti-bearing accessory is not common. It occurs as deep-red or yellow-brown, nearly opaque, round to needlelike grains included in biotite, ilmenite, or quartz.

Allanite differs in various rocks from red-orange to pale yellow or almost colorless. It occurs as stubby rectangles or irregular elongate grains, which produce dark pleochroic haloes in biotite, similar to those surrounding zircon. Zoned grains are generally euhedral with dark cores and lighter rims. Some grains, especially those that are zoned, are rimmed by pistacite.

Ilmenite is the main opaque mineral and occurs as fairly coarse interstitial grains, commonly associated with sphene, or as dark, needle-like inclusions, lying along the cleavage planes in biotite. Minor amounts of magnetite, pyrrhotite, pyrite altering to an Fe-O-OH (goethite-like) phase, and covellite are locally present. Pyrite and pyrrhotite deposited as insoluble residues subparallel to foliation, generally within biotite-rich layers, have been mostly replaced by a goethite-like phase. This occurs in rocks with a strong metamorphic fabric and may be evidence of mobilization of material to form a solution cleavage.

The abundance of red biotite, ilmenite, and other Ti-bearing accessories such as sphene and rutile indicates that the tonalite may be relatively Ti-rich. The strongly foliated texture, presence of recrystallized metamorphic quartz, and the presence of oriented ilmenite within the biotite indicate that the tonalite probably underwent extensive recrystallization during regional metamorphism in this area.

The character of the tonalite appears to differ with proximity to the country rock contacts. Table 6b gives the modes and descriptions for several samples collected within the tonalite, at or near its contact with the country rock. Although neither abundant nor common, garnet is present in the tonalite near the contact and is not present elsewhere. The highly embayed nature and reduced grain size of the garnets in sample PAM 600 give it the appearance of being out of equilibrium with the rock. Although the thin section obtained for sample PAY 568 does not contain any garnet, the specimen has large (1 cm in diameter) garnets on its surface. At this locality, the contact is exposed in the outcrop and bits of schist appear to have been partially melted and swirled around within the tonalite. This provides field evidence for contamination of the tonalite by melting of the country rock at the contact. Near the contact, the tonalite also seems to show an increase in the amount of K-feldspar and a decrease in the amount of biotite. This can be seen on the plot in Figure 14 of biotite plus chlorite against K-feldspar and muscovite. Here, most of the contact tonalites have more K-feldspar and less biotite than most of the "normal" tonalites. This can be seen in the field as a decrease in color index and intensity of foliation in the tonalite with increasing proximity to the country rock. A similar trend can be observed on the diagram after Streckeisen (1973) of Figure 12, which plots relative amounts of plagioclase/(plagioclase + K-feldspar). The contact rocks tend toward granodiorite rather than tonalite. Figure 15 shows that, although there is this general increase in K-feldspar to total feldspar, the anorthite (An) content does not seem to be affected. The probable reasons for this general trend toward lighter, K-feldspar-enriched rocks include contamination by slight melting of the country rock and mixing with the syn- or post-intrusive pegmatites that characterize the contact area.

Contact relations. In the Wachusett Mountain area to the south, the tonalite gneiss member is described by Maczuga (1981) as a sill-like body, however, in this area (Tucker, 1976) and in the Ashburnham-Ashby area the tonalite actually forms a semi-concordant sheet. The shape of the pluton roughly parallels the fabric of the country rock, but in places it cross cuts the stratigraphy. Poor outcrop does not permit exposure of any triple point of contacts, however, over a short distance the same tonalite contact can be seen in contact with both gray- and rusty-weathering schist. An example of this is the contact exposed south of the intersection of Marble and Byfield Roads (Plate 1). The tonalite here is in contact with gray schist. A little northeast on Route 119 near Flint Road, what appears to be the same tonalite is in contact with extremely rusty-weathering, sulfidic schist.

There is little or no evidence of contact metamorphism of the country rock due to intrusion of the tonalite. Part of this may be due to the extensive intrusion of pegmatite into the country rock in

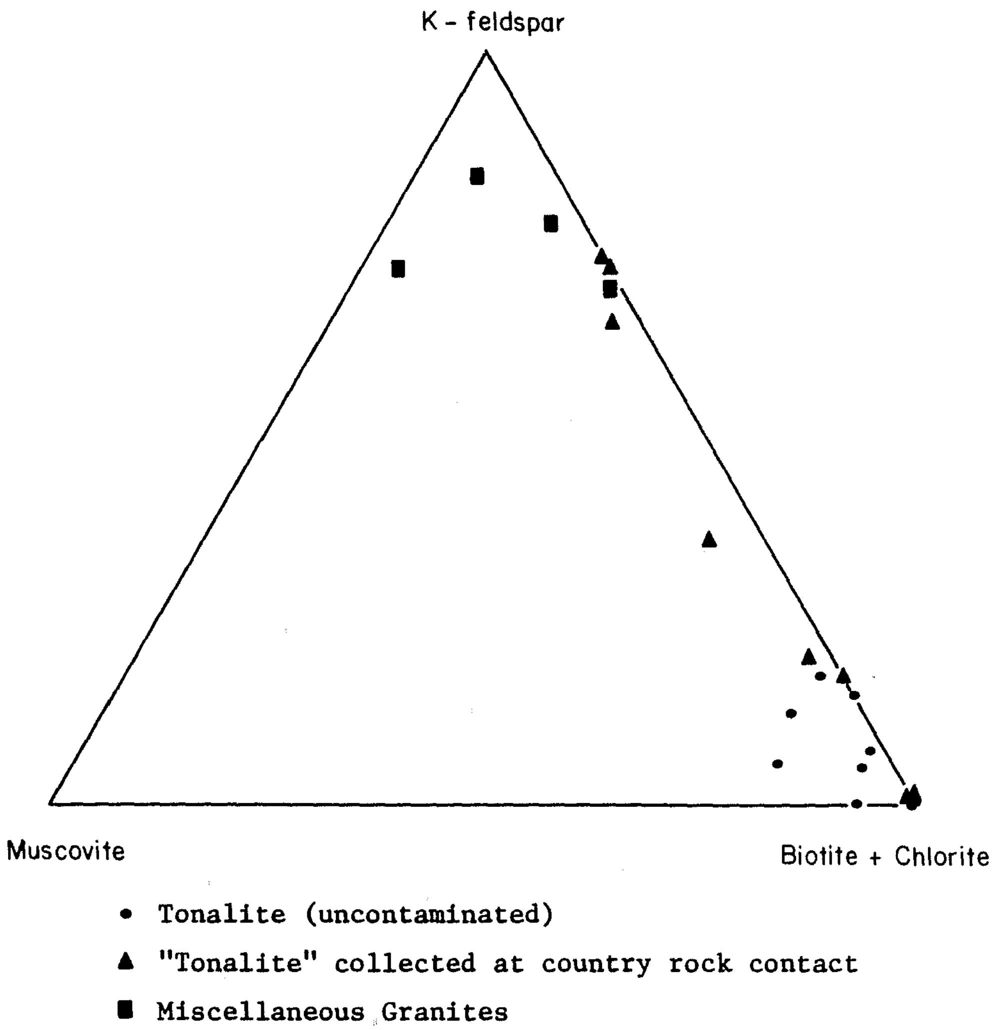
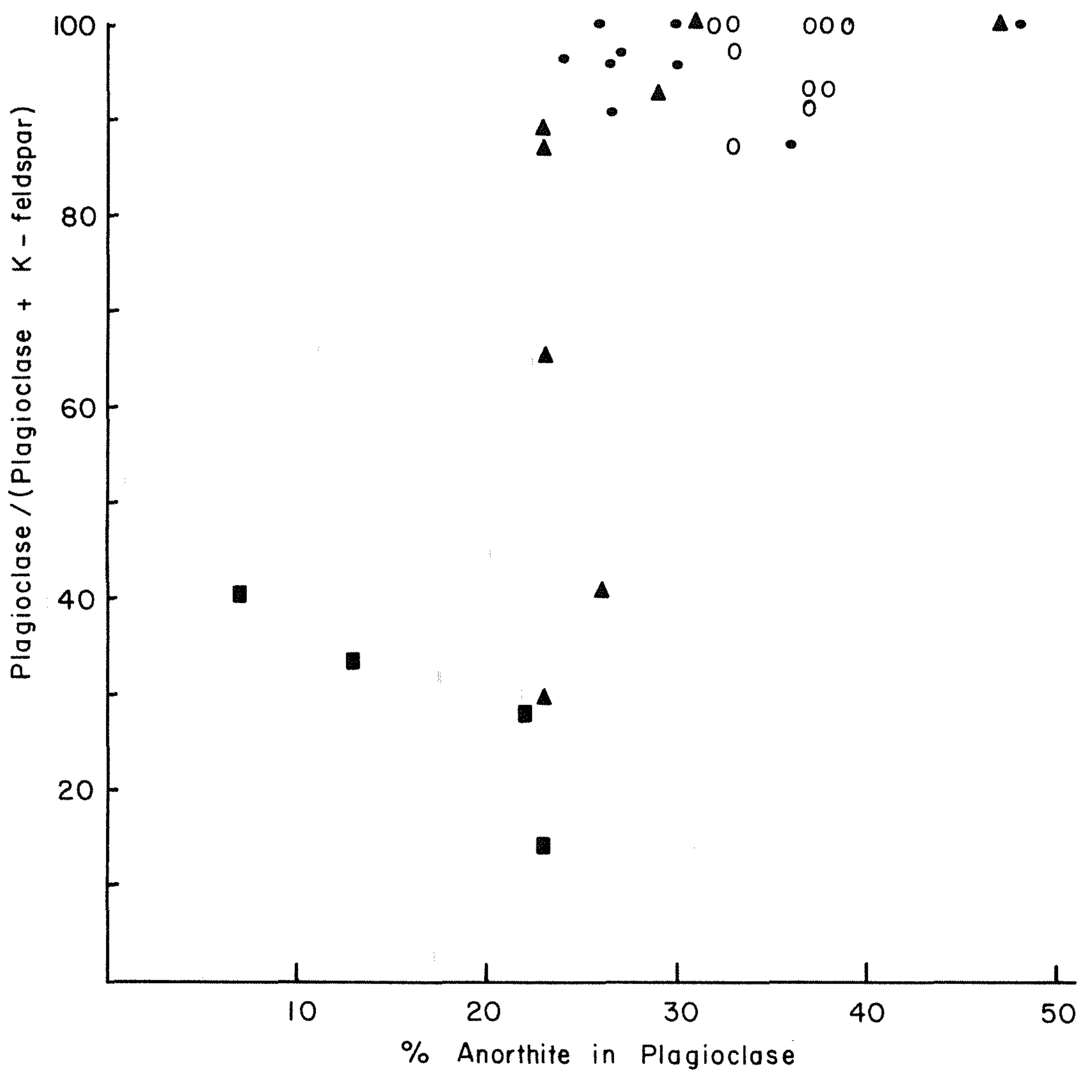


Figure 14. Plot of the potassium-bearing phases: muscovite, K-feldspar, and biotite (+ chlorite), normalized to the sum of all four. The plot is based on estimated modes.



- • Tonalite (uncontaminated)
- ▲ "Tonalite" collected at country rock contact
- ■ Miscellaneous Granites
- O Wachusett Mountain Tonalite (Maczuga, 1981)
- ∇ South Monoosnoc Hill Tonalite-Granodiorite (Maczuga, 1981)

Figure 15. Plot of plagioclase to total feldspar against Anorthite (An) content for intrusive rocks in the Ashburnham-Ashby area, based on estimated modes. Plots of samples from the foliated granodiorite of Maczuga (1981) are based on point-counted modes.

the vicinity of the tonalite and to recrystallization during regional metamorphism.

Thickness. The thickness of the tonalite varies dramatically within the area of study. A thin sheet on the order of 30 feet thick is traceable for a distance of hundreds of feet in the area northeast of Rindge Turnpike and northwest of Wilker Road. In general, the tonalite is approximately 150 - 200 feet thick, however, in some areas, such as in the vicinity of Jones Hill, it appears thicker, possibly due to folding.

Derivation. Maczuga (1981) suggests a possible petrologic model for the Fitchburg plutonic complex, based on petrographic and geochemical data from parts of the complex examined south of this study area. He finds that the complex does not fit well into the I- (igneous) and S- (sedimentary) type granitoid classification developed by Chappell and White (1974). In this classification, S-type granitoids, produced by partial melting of material exposed to a weathering cycle (sedimentary source) can be differentiated from I-type granitoids, formed from partial melting of an igneous source on the basis of chemical and mineralogical differences. The rocks examined by Maczuga (1981) from the Fitchburg complex appear to be gradational between the two types. On the basis of field, petrographic and chemical evidence, Maczuga (1981 - p. 120) concludes that "the granodiorite gneiss and the granite gneiss were generated by partial melting of some remote crustal rock source, probably continental crust in an Acadian subduction zone". The granodiorite gneiss referred to by Maczuga (1981) is similar to the tonalite of this study. Both gneisses appear to be non-minimum partial melts of similar sources, but with less melting required to attain the granodiorite gneiss composition. The third member of the complex, the muscovite - biotite granite, may then be a later minimum melt of the same source, or, it might have formed as an in situ melt product during the peak of Acadian regional metamorphism. A minimum melt - restite segregation mechanism (White and Chappell, 1977) is suggested by Maczuga (1981) to explain local variations within the granodiorite gneiss - tonalite member that are noted by Tucker (1978), Maczuga (1981), and in this study.

Miscellaneous Granites and Pegmatites

The eastern portion of the Ashburnham-Ashby area is characterized by omnipresent outcrops of rather nondescript granite and pegmatite which surround bits of country rock. At first one might map this area as granite with scattered inclusions of country rock as Emerson (1917) did when he described this area as being underlain by Hubbardston Granite with random inclusions of Paxton Quartz Schist and Brimfield Schist. Because one of the main goals of this study was to describe the deformation of the stratified rocks in the area, these granites and pegmatites were essentially ignored in favor of the stratified country rock. A few samples of these granites were collected and estimated modes and descriptions are given in Table 7. The samples fall well within the granite field as seen by the classification diagram (after

Streckeisen, 1973) in Figure 12.

Granites in the area from which sample PAM 14 is collected may be strongly affected by late faulting and brittle deformation in this area. As shown in Table 7, the biotites in the granite are completely replaced by retrograde green chlorite.

The area north of Route 119 and east of Pillsbury Road (called "Gypsy Hill" by the author and her field assistant after the gypsy moth summer of 1981), from which sample PAY 168A is taken, is characterized by huge outcrops of insidious granite and pegmatite which almost totally mask the true country rock. Sample PAY 168A is taken from a ridge of essentially unfoliated muscovite - biotite granite near the main tonalite - schist contact.

The western half of the area, west of the central fault, is not so extensively intruded by granite and pegmatite. Samples PAM 288G and PAM 933 are taken from a light-colored, muscovite, biotite granite that follows, more or less, the contact between gray- and rusty-weathering schists on the south and west sides of Mount Watatic. This granite was intruded late enough in the deformational history of the area to have retained some of its primary igneous foliation, in the form of oriented feldspar phenocrysts, that cross cuts the metamorphic foliation of the country rocks.

Pegmatites were intruded throughout the deformational history of the area. Some of the earliest pegmatites display a coarse metamorphic foliation, whereas later pegmatites are essentially undeformed. Tourmaline veins are commonly associated with the intruding pegmatites and fine black tourmaline coats many of the joint surfaces created by these pegmatites and associated quartz veins.

Particularly spectacular pegmatites are along the east slope of New Ipswich Mountain. Single crystals of quartz and feldspar, up to 6 - 8 inches (15 - 20 cm) in diameter, have been observed in these weakly deformed pegmatites and coarse muscovite plates were used extensively by local inhabitants as woodstove "windows".

Table 7. Estimated modes of samples of weakly- to non-foliated, light-colored granites.

	PAM 14	PAY 168A	PAM 288	PAM 933
Quartz	33	28	39	42
Plagioclase	13	8	19	15
(mol.% An)	(22)	(23)	(7)	(13)
Orthoclase	33	46		
Microcline			29	30
Myrmekite	tr	7		2
Biotite	tr	4	2	2
Muscovite (Prim.)		6	9	7
Muscovite (Sec.)	1		tr	
Fe-chlorite (Sec.)	14		tr	tr
Garnet			1	
Sphene	1			
Allanite	1			
Pistacite	2			
Rutile	tr			1
Apatite	1	1	1	1
Zircon	tr	tr	tr	tr
Ilmenite	tr	tr		
Undiff. Opaques	1	tr		
Pl/(Pl + Ksp)	27.7	14.1	40.1	33.3
Qz/(Qz + Fsp)	41.6	34.3	44.9	48.1

List of Specimens in Table 7.

PAM 14 - Light tan, weakly foliated, pink feldspar granite. Biotite is totally replaced by chlorite. This large outcrop is located at the base of the east slope of Mount Hunger (1280 feet elevation) 750 feet (.14 miles) N 26 W of the north end of Crosby Road.

PAY 168A - Light gray, weakly foliated, medium-grained, muscovite-biotite granite. The sample is taken from an outcrop located 2300 feet (.43 miles) N 42 W of the intersection of Route 119 with Flint Street which is at the north end of a long northeast-trending ridge upheld by the granite.

PAM 288G - White, fine- to coarse-grained, muscovite-biotite granite porphyry with primary foliation. Sample is taken from the large open outcrop on top of the west peak of Mount Watatic below the fire tower at 1830 feet elevation.

PAM 933 - Light gray, medium- to fine-grained, weakly foliated muscovite-biotite granite porphyry intruded along the schist contact. Sample is taken from one of several large broken outcrops just west of the Midstate Trail at 1450 feet elevation, south of the summit of Mount Watatic and north of Route 119.

PAY 736 - Medium- to coarse-grained, unfoliated, biotite-muscovite granite and aplite with chilled margin. Intruded along the contact between tonalite and schist on the east slope of Jewell Hill. Sample is taken from an outcrop at 1185 feet elevation, N 55 E of the summit of Jewell Hill. This sample is not listed in Table 7 due to its inhomogeneity.

CORRELATION AND AGE OF ROCKS

General Statement

Map units in the Ashburnham-Ashby area are assigned names based on correlation with the Silurian - Devonian stratigraphy defined in central Massachusetts (Figure 16, 17) and particularly in the Wachusett Mountain area (Tucker, 1976, 1978). The stratigraphic sequences described in central Massachusetts and in central and southern New Hampshire are defined on the basis of correlations with the stratigraphy described in northwest Maine. There is a significant problem for correlation of the Ashburnham-Ashby area, because of different interpretations of similar rocks in the Wachusett Mountain area to the south and the Peterborough area (E. Duke, in preparation) to the north. This centers on, but is not limited to, the gray-weathering schists which were assigned to the Lower Devonian Littleton Formation at Wachusett Mountain, and the Lower Silurian lower part of the Rangeley Formation, or possibly older units, in Peterborough. Detailed description of the rocks observed in the Ashburnham-Ashby area will aid in reaching a resolution of these two conflicting interpretations.

A brief discussion of the depositional history of these rocks will aid in understanding the correlations suggested. The Silurian - Devonian sedimentary rocks found east of the Bronson Hill anticlinorium in the Merrimack synclinorium (Figure 2) were deposited in the Merrimack - Fredericton trough (Robinson and Hall, 1980). Sedimentation into this trough from the west during the Silurian was primarily due to degradation of the North American continent following the Taconian Orogeny. Throughout the Silurian, this western source was eroded and the relief reduced so that its input into the Merrimack trough became less significant. Toward the end of the Silurian and early in the Devonian, uplift to the east of the trough became an increasingly important source of sediment (Hall et al., 1976).

A fairly well defined stratigraphy has been described in Maine on the basis of well preserved sedimentary structures and local fossils. In northwest Maine, in the Rangeley - Kennebago Lake area (see Figure 2 for location of Rangeley, Maine), Moench and Boudette (1970) have described a continuous sedimentary sequence from Late Ordovician to Early Devonian along the northwest limb of the Merrimack Synclinorium. This stratigraphic sequence and the ages of the rocks described in it are shown in Figures 16 and 17. Pankiwskyj et al. (1976) and Osberg (1980) have tentatively correlated a similar stratigraphy across the synclinorium to the southeast. These correlations are shown in Figure 17.

In New Hampshire, the stratigraphy of the Bronson Hill Anticlinorium (Figures 16 and 17) was initially described by Billings (1956) on the basis of mapping in the vicinity of Littleton, New Hampshire where there is good stratigraphic and paleontologic control. The quartzites and quartz-pebble conglomerates of the Clough Quartzite are dated as late Llandovery (Boucot and Thompson, 1958, 1963). The age of the overlying Fitch Formation, initially given as Middle Silurian by Billings and Cleaves (1934) has since been revised by Boucot (1968. and Berry and Boucot (1970) as Ludlovian and more recently by Harris et al. (1983) as late Ludlovian to early Pridolian. The Littleton Formation, which overlies the Fitch, has most recently been dated by Boucot and Arndt (1960) as Lower Devonian (Emsian) and equivalent to the lower Onandaga of New York State.

Further east in the Merrimack synclinorium of New Hampshire Billings (1956) described most of the schists as various members of the Devonian Littleton Formation. Lithologic and stratigraphic similarities to the sequence near Rangeley, Maine noted in recent mapping by Hatch et al. (1983) resulted in subdivision of these rocks into the Silurian and Devonian units shown in Figures 16 and 17. As can be seen in Figure 17, the Silurian section thickens from the Bronson Hill anticlinorium to the Merrimack synclinorium across a tectonic hinge that appears to extend the length of the sedimentary basin.

In this thick Silurian sequence deposited in the Merrimack - Fredericton trough the following rock units have been described in Maine and New Hampshire. The basal Silurian Rangeley Formation in Maine consists of varied clastic sediments ranging from coarse conglomerates to shale. The presence of quartz-rich conglomerates and the interpreted Late Landoverian age of the Rangeley Formation in Maine (Moench and Boudette, 1970; Hatch et al., 1983) suggest that it may correlate with the Clough Quartzite (Figures 16 and 17). In New Hampshire, the Rangeley Formation described by Hatch et al. (1983) is a quartz-rich, locally gritty, and generally poorly bedded schist. The upper member has a distinctive, red-weathering character. The Rangeley Formation is overlain by sharply interlayered quartzites and pelites of the Perry Mountain Formation. The Smalls Falls Formation, a distinctive, extremely rusty-weathering sulfidic shale or schist interbedded with quartzite, overlies the Perry Mountain (Figures 16 and 17). In central New Hampshire, the Francestown Formation is an extremely rusty-weathering calc-silicate rock that appears to be a facies of the Smalls Falls Formation. Similar rocks have been described in the Fitch Formation in western New Hampshire. Locally in New Hampshire, rocks in the Smalls Falls are described as pelitic Francestown (see Figure 16 in the Peterborough column). The widespread presence of these sulfide-bearing sediments suggests that euxinic conditions may have prevailed in the Merrimack trough in the Middle Silurian. Overlying the Smalls Falls Formation, calcareous siltstones and sandstones characterize the Madrid Formation in northwest Maine. This is correlated with the Warner Formation in central New Hampshire (Hatch et al., 1983) (see Figures 16 and 17). The Madrid - Warner rocks, interpreted to be upper Silurian (Osberg et al., 1968) are lithically similar and may be equivalent to the upper part of the Fitch Formation in western New Hampshire.

Stratigraphic Correlation Chart - Merrimack Synclinorium

Period	Western New Hampshire (Billings, 1956), West Central Massachusetts (Robinson, 1963)	Rangeley, Maine (Moench and Boudette, 1970)	E./S. Central New Hampshire (Hatch, Moench, and Lyons, 1983)	Peterborough, New Hampshire (Duke, in progress)	Ashburnham-Ashby area (This study)	East Central Massachusetts (Field, 1975; Robinson and Tucker, 1976; Tucker, 1976, 1977)
DEVONIAN	Littleton Formation	Seboomook Formation	Littleton Formation	Littleton Formation	Littleton Formation	Littleton Formation
SILURIAN	Fitch Formation	Madrid Formation	Warner Formation	Warner Formation	Paxton Formation Granulite Member	rusty schist (Spss); Paxton Formation biotite granulite (Sp)
		Smalls Falls Formation	Francestown Formation; Smalls Falls Fm.	calcareous Francestown Fm.; pelitic Frances- town = Smalls Falls	Paxton Formation Sulfidic Schist Member	Paxton white schist (Spsq) = Smalls Falls; Paxton rusty quartzite (Spqr)
		Perry Mountain Formation	Perry Mountain Formation	Perry Mountain Formation		
	Clough Quartzite	Rangeley Formation C B A	Rangeley Formation Upper Lower	Rangeley Formation Upper Lower		
U. ORD.		Greenvale Cove Fm.; Quimby Formation				
M. ORD.	Partridge Formation; Ammonoosuc Volcanics	Dixville Formation				Partridge Formation; Ammonoosuc Volcanics

Figure 16. Stratigraphic correlation chart showing the generalized stratigraphic columns for rocks mapped in the Merrimack synclinorium from Maine to Massachusetts.

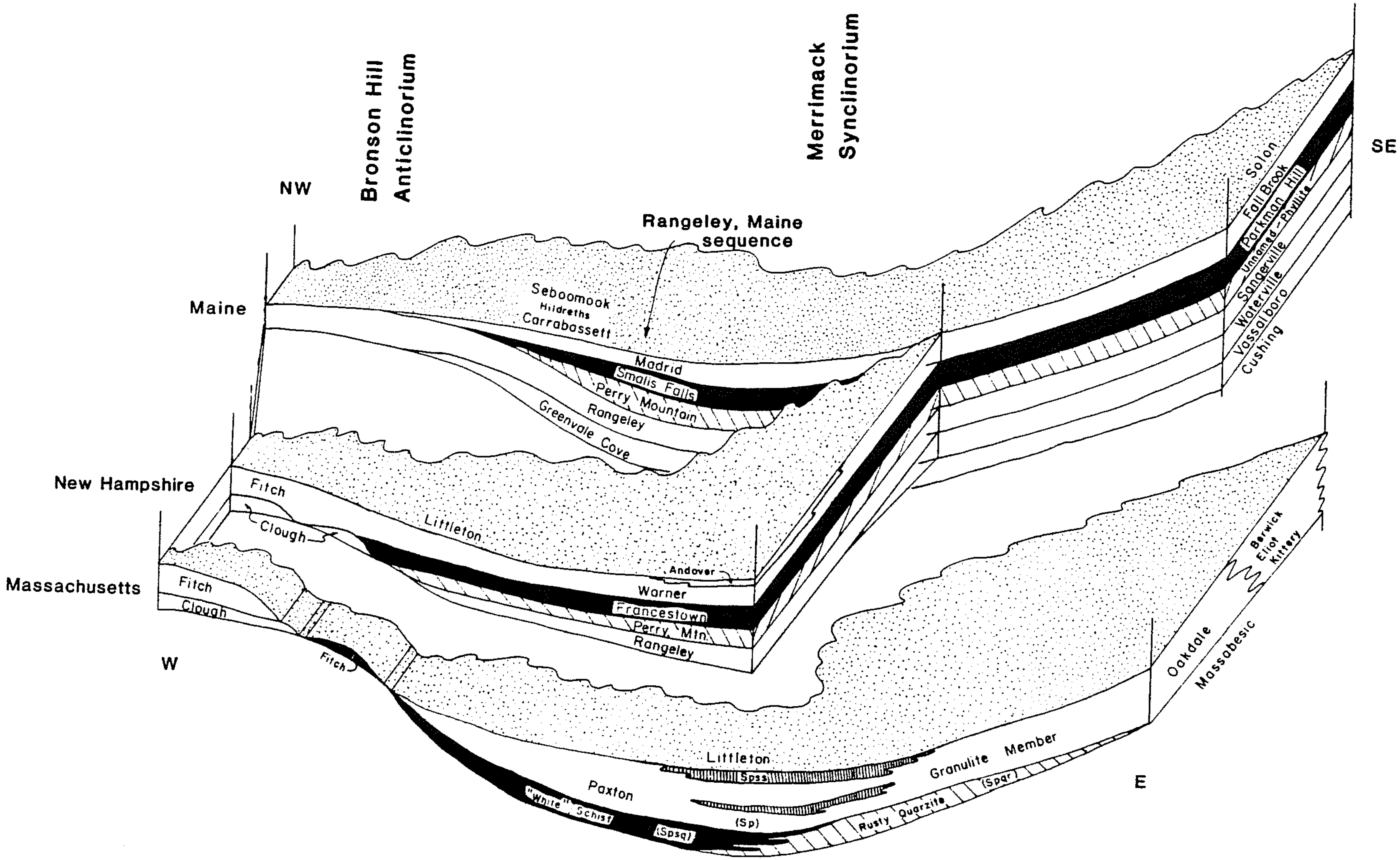


Figure 17. Generalized correlation diagram showing the stratigraphy described in the Merrimack synclinorium for Massachusetts (Robinson et al., 1982b), New Hampshire (Billings, 1956; Hatch et al., 1983), and northwest (Moench and Boudette, 1970) and south-central (Osberg, 1980) Maine with suggested correlations shown between the different regions. Most of the units shown are Silurian. The Perry Mountain Formation and its suggested correlatives are shown with a wide-ruled pattern, the Smalls Falls and equivalents have a solid pattern, and other rusty schists in central Massachusetts are narrow-ruled. The dotted surfaces represent the base of the Devonian section.

In central Massachusetts, stronger metamorphism and deformation have made it more difficult to observe primary sedimentary features although they still exist in some areas. Thus stratigraphic successions are more difficult to define, although correlations with the sequence in Maine were suggested by Field (1975). Field (1975) and Robinson et al. (1982b) correlate the extremely rusty-weathering, sulfidic, magnesian "white" schist of the Paxton Formation (Spsq on the Massachusetts state map - Zen et al, 1983 - see also Figure 3) with the Smalls Falls Formation (Figures 16 and 17). As in New Hampshire, this may be the pelitic facies of the calcareous Fitch Formation in the Bronson Hill anticlinorium to the west. The Smalls Falls-equivalent rocks are overlain by a thick sequence of gray biotite granulites and calc-silicate rocks of the Paxton Formation that Field (1975) correlated with Madrid Formation in northwestern Maine (Figures 16 and 17).

Further east in central Massachusetts, reconnaissance mapping in the Gardner, Wachusett Mountain, and Paxton quadrangles (Robinson and Tucker, 1976; Tucker, 1976) showed a sulfidic, micaceous quartzite (Spqr) underlying the gray granulite of the Paxton Formation. Robinson (1981) suggests a lithic and stratigraphic similarity between this rusty quartzite and the unnamed phyllite of Osberg (1980) which has tentatively been correlated with the Perry Mountain Formation of northwest Maine (Osberg, 1980) (Figure 17). In parts of central Massachusetts (Field, 1975; Tucker, 1977) the biotite granulite of the Paxton Formation contains interbeds and lenses of extremely rusty-weathering, sulfidic schist (Spss) (Robinson, 1979; Zen et al., 1983).

East of the Fitchburg plutons, the biotite-quartz granulites mapped as Paxton Formation have been correlated by Emerson (1917) with the Oakdale Quartzite (Figure 17). The Oakdale Quartzite has been correlated to the north and east with the various members of the Merrimack Group, which has been subdivided by Katz (1917) into the Kittery, Eliot, and Berwick Formations in southeast Maine. Katz (1917) and Hussey (1968) suggest that the Oakdale Quartzite may be the same as the Kittery Formation. On the state map of Massachusetts (Zen et al., 1983), the Oakdale is shown to correlate with the Eliot and Berwick Formations. Billings (1956) and Osberg (1980) suggest that correlation of the Eliot and Berwick Formations in New Hampshire with the Vassalboro and Waterville Formations in south-central Maine (Figure 17) might be reasonable. Lyons et al. (1982) suggest that the Merrimack Group is separated from the Merrimack synclinorium (renamed the Kearsarge Central Maine synclinorium) by the Massabesic anticlinorium (Figure 2) and propose a late Ordovician or late Precambrian age for deposition of these sediments. In general, differences between these rock types are slight and in some cases may be attributed to differences in metamorphic grade.

In the early Devonian, an extensive blanket of flysch from a significant eastern source covered over much of the Silurian section in the northern Appalachians (Pankiwskyj et al., 1976). This is represented by the Carrabasset and Seboomook Formations in northwest Maine, the Solon

Formation in south - central Maine, and the Littleton Formation in New Hampshire and Massachusetts (Figure 17). The basal contact of these rocks is generally gradational (for instance, between the Solon and Fall Brook Formation) (Pankiwskyj et al., 1976). In New Hampshire, a rusty-weathering schist referred to as the Andover Formation, occurs locally at the top of the Warner Formation (Figure 16). This may be correlative with the rusty-weathering schist (Spss) that occurs locally at the top (?) of the Paxton Formation beneath the gray-weathering schists of the Littleton Formation in central Massachusetts.

Paxton Formation

The Gray Granulite Member of the Paxton Formation in the Ashburnham-Ashby area is lithically similar to the purplish-gray biotite granulites (Sp) characteristic of the Paxton Formation to the south in central Massachusetts (Field, 1975; Tucker, 1976; Robinson and Tucker, 1976; and Tucker, 1977) and to the Warner Formation (Hatch et al., 1983) and Madrid Formation (Moench and Boudette, 1970) mapped to the north in New Hampshire and Maine. In general, the granulite in the Ashburnham-Ashby area tends to be richer in calc-silicate beds than that typically observed in the Wachusett Mountain area to the south. Further, the transition from biotite granulite upward into more calc-silicate-rich granulite noted in this study is the reverse of what is typical of the Warner (New Hampshire) and Madrid (Maine) Formations (Figure 16) (Osberg et al., 1968). Nevertheless, strong lithic similarities support the stratigraphic correlations suggested by Field (1975) and Robinson (1981) between the Paxton and Warner (Madrid) Formations.

The Granulite Member also bears some resemblance to the Fitch Formation of the Bronson Hill anticlinorium. This would be expected if the correlation suggested by Moench (Moench and Boudette, 1970) between the Madrid - Warner rocks and the Fitch Formation is correct. Similarities between the Gray Granulite Member of the Paxton Formation and the Fitch Formation include the calcareous nature of the rock, and the presence of the muscovite-cored quartz-feldspar "lumps". Similar lumps have been observed by P. Chamberlain (personal communication) in the Fitch Formation of the Lovewell Mountain quadrangle, New Hampshire.

The areal extent of the Gray Granulite Member of the Paxton Formation in this area is limited and its occurrence in an isoclinal fold provides exposure only of its upper (?) contact with gray-weathering schist. On the state map of Massachusetts (Zen et al., 1983), within the Paxton Formation, the biotite granulite (Sp) is shown to overlie the sulfidic "white" schist - quartzite (Spsq) southwest of this area in stratigraphic zone C of Robinson (1979 - see Figure 3). Further east in Massachusetts in zone D (Robinson, 1979) the same granulite appears to overlie a rusty-weathering quartzite (Spqr) (Figures 16 and 17). Unfortunately, Spsq and Spqr cannot be connected on the ground surface in Massachusetts so that their relationship to each other is uncertain. A fairly thick, rusty-weathering, sulfidic schist unit (Spss) is locally at the top of the Paxton Formation (Robinson, 1979).

The Sulfidic Schist Member of the Paxton Formation in the Ashburnham-Ashby area includes numerous rock types and bears resemblance in places to each of the three rusty-weathering units in the Paxton Formation (Spsq, Spqr, Spss) described above. The stratigraphic position of the Sulfidic Schist Member with respect to the Gray Granulite Member is unknown, because they are not in contact with each each other. The Sulfidic Schist Member of the Paxton Formation in this area is lithically similar in part to the Smalls Falls-type rock described as pelitic Francestown by E. Duke in the Peterborough quadrangle, New Hampshire (Figure 16). These rusty-weathering schists are probably pelitic equivalents of the more quartz-rich calcareous granulites and schists of the Francestown Formation described further to the north and west in New Hampshire (Figure 16).

Similarities between the rusty-weathering quartzites, quartzose granulites, and calc-silicates on Emerson Hill and the east slope of New Ipswich Mountain in this area, and the rusty quartzite (Spqr) of the Wachusett Mountain area have been suggested by Robinson (personal communication) even though they have a different setting. The Emerson Hill and New Ipswich Mountain quartzites are only in contact with gray-weathering schist of the Littleton Formation whereas Spqr is in contact only with gray biotite granulite of the Paxton Formation. On a field trip in May, 1983, E. Duke, N. Hatch, and P. Thompson noted a strong resemblance between these same rocks on the east slope of New Ipswich Mountain and the red-weathering, quartz-rich rocks mapped as Upper Rangeley in central and southern New Hampshire.

Littleton Formation

The rocks mapped as Littleton Formation in the Ashburnham-Ashby area are gray-weathering aluminous schists and granulites. They are clean, thinly interbedded schist and quartz granulite, locally with good graded bedding, or feldspar-rich schist, commonly with a gneissic texture and little or no trace of bedding. Locally, the gray schist contains calc-silicate "footballs" which range from 10 cm to 1 meter in length. These gray-weathering schists are very similar to those mapped as Littleton in the Wachusett Mountain area (Tucker, 1976) and Gardner (Robinson and Tucker, 1976) quadrangle.

The pattern of interlayered gray-weathering schists of the Littleton Formation and granulites and rusty-weathering schists of the Paxton Formation mapped by Tucker (1976, 1978) on Wachusett Mountain is shown on his cross section in Figure 18. The unit Sp in this cross section contains both rusty-weathering schist (dash-dot pattern) and biotite granulite (stippled pattern). Tucker places all of the gray-weathering schists in the Littleton Formation (Dl) and interprets the repetitions as isoclinal folds. A similar type of lithic sequence is

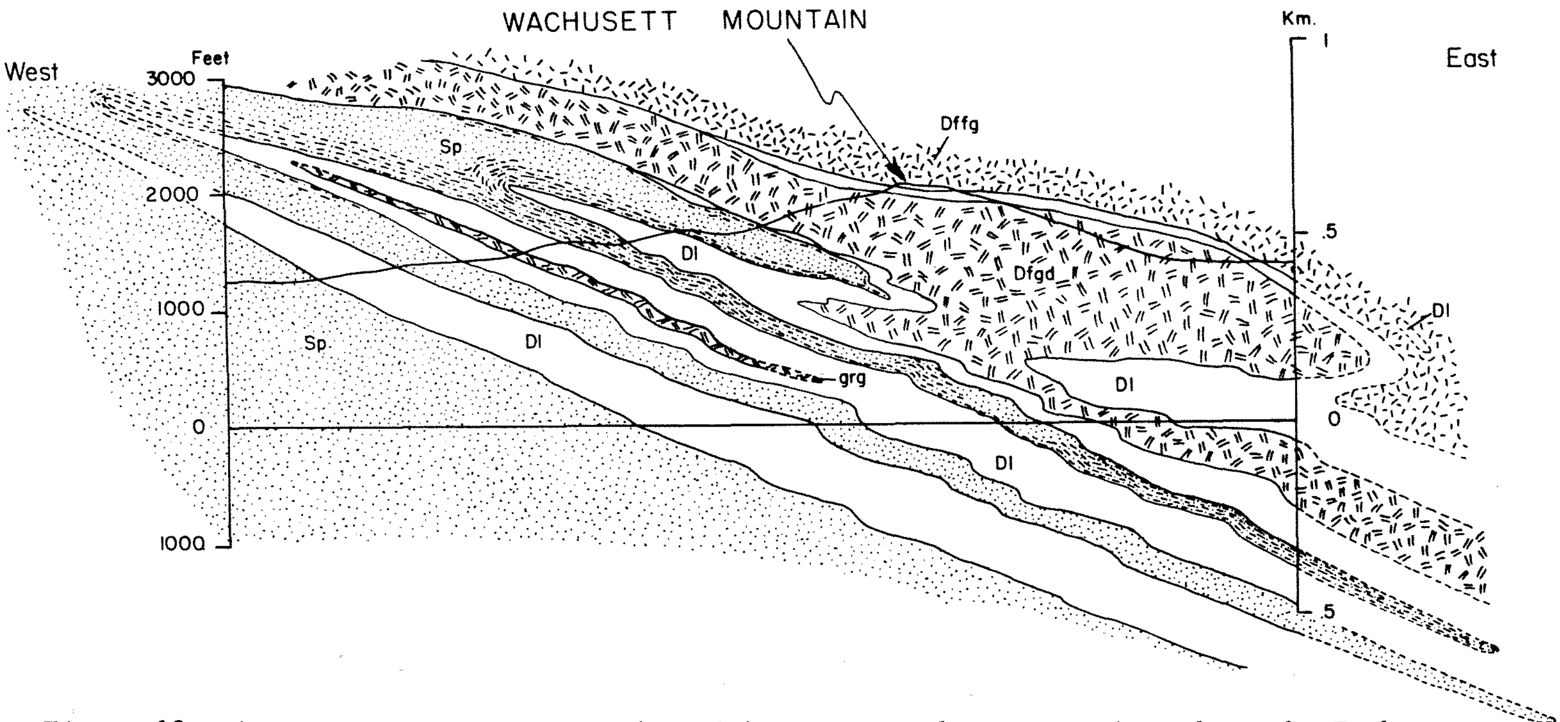


Figure 18. An east - west cross section with no vertical exaggeration, drawn by Tucker (unpublished) across Wachusett Mountain showing the mapped and interpreted geology and style of deformation along strike to the south from the Ashburnham-Ashby area. Sp represents various rocks within the Paxton Formation. The stippled pattern within the Paxton is granulite and the dashed pattern is rusty schist. The distribution on the cross section represents the actual mapped distribution of these lithologies within the Paxton. Dl (unpatterned) is the Littleton Formation. Dfgd is the foliated granodiorite gneiss and Dffg is the foliated granite, both of the Fitchburg Plutonic complex. grg is a granite unaffiliated with the complex.

observed in the Ashburnham-Ashby area. This is the basis for correlating the gray-weathering schists in the Ashburnham-Ashby area with the Devonian Littleton Formation.

Alternative interpretations have been suggested by E. Duke (personal communication) on the basis of observations made to the north in New Hampshire. In accordance with Billings (1956), Greene (1970) described all of the stratified rocks in the Peterborough quadrangle as members of the Littleton Formation. Duke has produced a much more detailed preliminary map and reinterpreted the stratigraphy to include a fairly thick Silurian section (Figure 16) based on correlations with Maine (Nielson, 1981; Hatch et al., 1983). Greene's (1970) Warner, Francestown, and Crotched Mountain Members of the Littleton Formation are now the Silurian Warner, Francestown, and Perry Mountain Formations respectively (Figure 16). Red-rusty-weathering quartz granofels with minor pelite has been mapped as the Upper Member of the Rangeley Formation and much of the gray-weathering schist assigned by Greene to the Souhegan Member of the Littleton Formation is now included in the Lower Member of the Rangeley Formation (Figure 16). These are very similar to some of the gray-weathering schists assigned to the Littleton Formation in the Ashburnham-Ashby area. In particular, the gray-weathering, moderately bedded, calc-silicate-bearing schists upholding the Pratt Mountain ridge are similar to the Lower Rangeley rocks to the north. Furthermore, Duke suggests that the monotonous, gray-weathering schists with very small calc-silicate "footballs" observed on the top of New Ipswich Mountain are similar to rocks observed near Franklin Falls, New Hampshire, which Lyons has interpreted to be either Upper Ordovician or at the base of the Silurian.

The major question concerning the schists mapped as Littleton in this study area is whether they are all in the Littleton, none of them are in the Littleton, or some of them are in the Littleton. Alternatives are that the rocks belong in the Rangeley Formation, the Perry Mountain Formation, or in the unit exposed at Franklin Falls.

General Correlation Problems and Suggestions

The pertinent sequence of rock layers is well exposed on Pratt and New Ipswich Mountains (see Plate 1 and Plate 2 - cross section A - A'), making it a good place to study the stratigraphic problems. Further detailed mapping here and to the north would greatly improve understanding of the stratigraphy. Three stratigraphic interpretations are suggested here by the sequence mapped on these mountains. The first is the interpretation put forth by this manuscript, consistent with stratigraphic interpretations in central Massachusetts. The second and third interpretations are more consistent with the current mapping in the Peterborough quadrangle.

In the first interpretation (Figure 19a) all of the gray-weathering schist is mapped as westward-closing, nappe stage isoclinal synclines

Ideal Stratigraphic Sequences

Central Massachusetts (a)

Littleton Formation	Dl - Dlf
Paxton Formation	Sp - Sps

New Hampshire (b) and (c)

Littleton Formation	Dl
Warner Formation	Sw
Unnamed gray schist (local)	
Smalls Falls Formation	Ssf
Perry Mtn. Formation	Spm
U. Rangeley Formation	Sru
L. Rangeley Formation	Srl
"Franklin Falls"	OSf

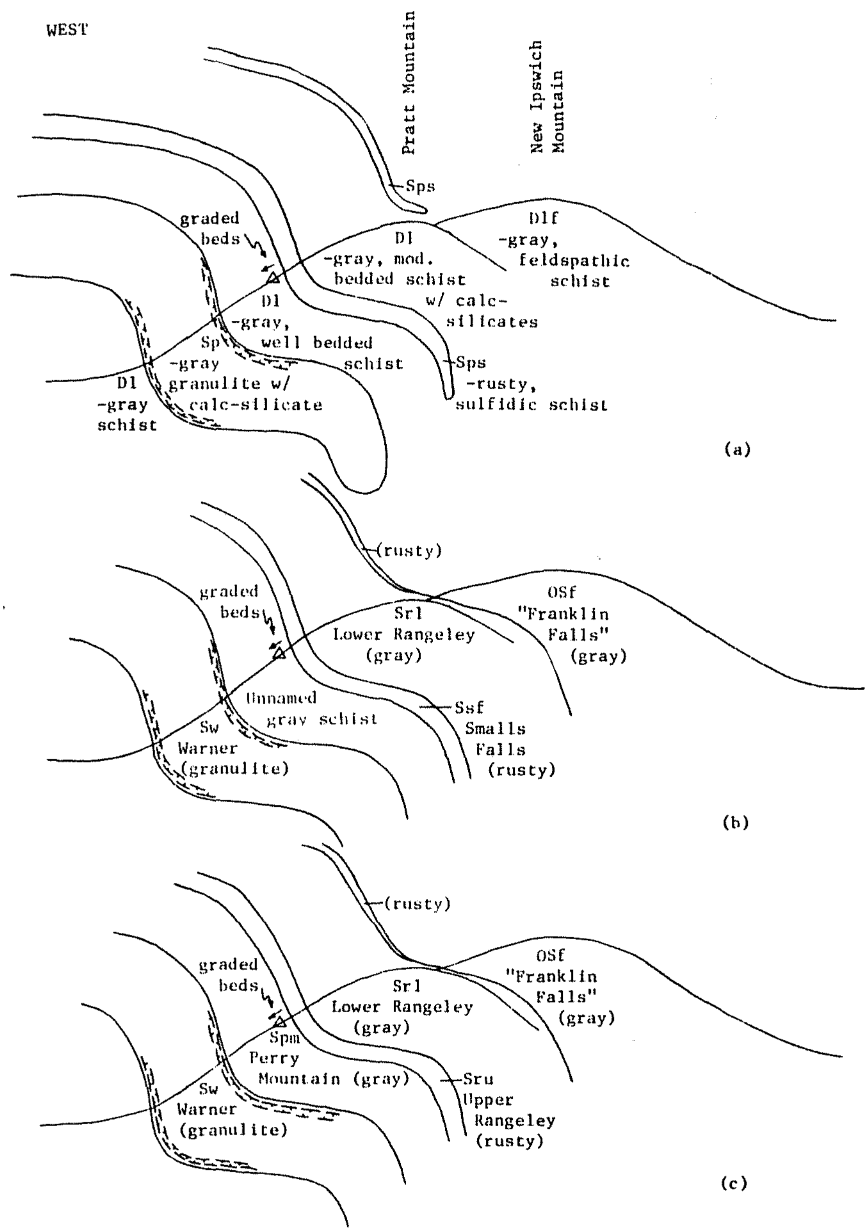


Figure 19. Schematic diagram showing three possible stratigraphic interpretations of the rocks observed on Pratt and New Ipswich Mountains. The brief rock descriptions given in (a) are the same for (b) and (c). The columns on the left show the ideal stratigraphy for (a) Massachusetts and (b) and (c) New Hampshire. The first interpretation (a) is based on correlations with Wachusett Mountain, Massachusetts. Interpretations (b) and (c) are two alternative models based on correlations with the work of E. Duke (in progress) in the Peterborough area, New Hampshire.

of Littleton Formation separated by thin eastward-closing isoclinal anticlines of the various members of the Paxton Formation. A graded bedding locality in the gray-weathering schist unit that lies east of the Gray Granulite Member and west of the Sulfidic Schist Member of the Paxton Formation on the west slope of the mountain (Figure 19a) is topping westward, away from the Sulfidic Schist. Younging of the gray-weathering schist away from the rusty-weathering, sulfidic schist is consistent with all three interpretations. Cross section A - A' (Plate 2) and Figure 19a show the stratigraphic and structural character of this interpretation and its similarity to Tucker's interpretation of Wachusett Mountain shown in Figure 18.

The second and third interpretations call for upside-down, westward-younging sequences that are not repeated. The uppermost, monotonous gray-weathering schists on top of New Ipswich Mountain (Figure 19b and c) are possibly interpreted as very lowest Silurian (or Ordovician) rocks, similar to those observed at Franklin Falls, at the base of the section. This grades westward into the calc-silicate-bearing, moderately bedded, gray-weathering schists of the Lower Rangeley Formation (Figure 19b, 19c) which uphold the Pratt Mountain ridge. West of the Lower Rangeley - type rocks on the mountain (Figure 19b and c) a direct correlation with the "typical" New Hampshire stratigraphy is not possible. The next unit is a thin, but continuous layer of very rusty rocks that bear a strong resemblance in places to the Smalls Falls Formation (Figure 19b). If this is indeed the Smalls Falls, then the red-weathering Upper Rangeley and gray-weathering, well bedded Perry Mountain Formations are missing here. The next unit to the west is a thin layer of well bedded, gray-weathering schist containing the graded bedding locality mentioned above. This gray-weathering schist may correlate with a gray-weathering schist noted locally at the contact between the Francestown and Warner Formations by P. J. Thompson (personal communication) in the Mount Monadnock quadrangle (Figure 19b), At the west base of the mountain, in contact with this gray-weathering schist is the Gray Granulite Member of the Paxton Formation correlated here with the Warner Formation in New Hampshire (Figure 16). A detail of the Warner here is that it grades from more calcareous rocks near the contacts (the stratigraphic base in this interpretation) into more biotite-rich granulites away from the contact. Such a sequence is typical of the Warner Formation in New Hampshire and the Madrid Formation in Maine (Osberg et al., 1968).

A slight modification of this interpretation (Figure 19c) would be to assign the rusty-weathering schist which lies west of the Lower Rangeley type rocks to the Upper Member of the Rangeley Formation (Figure 19c). The thin, well bedded gray-weathering schist structurally west of this might then be Perry Mountain Formation and the Francestown or Smalls Falls would be missing from this section.

Further mapping is needed to verify one of these interpretations or another alternative. The correlation of the Gray Granulite Member of the Paxton Formation at the base of the mountain with the Warner Formation is not really in question and the correlation between the thin rusty-weathering Sulfidic Schist Member of the Paxton Formation with the Smalls Falls Formation is also probable, at least on the west slope of the mountain. The biggest difference in the alternatives of Figure 19 is in the interpretation of the gray-weathering schists. The abundance of calc-silicates near contacts in the Gray Granulite Member of the Paxton Formation may indicate this part of the unit is the base, not the top, and hence that the adjacent gray schist is not Littleton. A second argument in favor of this is that the schists mapped as Littleton in New Hampshire do not commonly contain calc-silicate pods. The gray-weathering schist observed along the Pratt Mountain ridge contains abundant calc-silicate pods. Contrary to this P. Robinson (personal communication) has observed calc-silicates in the Littleton Formation in Massachusetts and also found them to be abundant in the Littleton of southwestern New Hampshire in close proximity to contacts of the Warner and Fitch Formations (observations on a regional field trip, July, 1983). Further mapping with these ideas in mind may produce a reasonable solution for correlation of the rocks in the Ashburnham-Ashby area with those to the north and to the south.

STRUCTURAL GEOLOGY

INTRODUCTION

The map pattern observed in the Ashburnham-Ashby area is a product of five major phases of ductile deformation during the Acadian Orogeny and one phase of brittle deformation, including major faulting, during Mesozoic rifting. The complex relations between the many phases of folding were determined through detailed structural analysis in areas of good bedrock outcrop, where the structural fabric has been well preserved and the intersections of features formed during different phases were evident. The information obtained from these detailed analyses, combined with the map pattern obtained in areas of good bedrock control, was used to construct the map pattern in areas where bedrock outcrops are scarce or nonexistent. The tendency of the tonalite to form outcrops and its distinctive appearance in the field compared to the schists made it easier to map out the detailed pattern observed on the east side of the fault (Plate 1). The tonalite on the east side of the fault appears to control the structural behavior of the rocks in its vicinity. The stiffer nature of the tonalite with respect to the schists seems to have prevented the later stages of folding from severely deforming the rocks so that the earlier fabrics are well preserved and dominate the map pattern. On the west side of the fault, the predominance of schist seems to have allowed the rocks to react easily to all or most of the deformation that has been imposed upon them. This apparent effect is enhanced by the increase in intensity of dome stage folds westward. Thus, the map pattern and structural style of these rocks is wildly confusing. Excellent exposures on the top of Mount Watatic and in the vicinity of Pratt and New Ipswich Mountains as well as on some other hills have helped to decipher the structural history revealed by these rocks.

The structural history of the rocks in the Ashburnham-Ashby area can be related to the sequence of regional deformation described in some detail by Robinson (1963, 1979) for central Massachusetts. Within the Merrimack Synclinorium in Massachusetts, this deformation has been attributed to three main stages of movement during the Acadian Orogeny.

The earliest stage of deformation, the nappe stage, involved extreme westward overfolding of Ordovician to Early Devonian strata in the form of tight recumbent folds or nappes (Figure 20a). Detailed studies in the vicinity of the Bronson Hill anticlinorium (Thompson et al., 1968) have shown that the nappes higher in the stratigraphic pile have drawn on successively higher grade metamorphic rocks, presumably from deeper or at least hotter positions within the Merrimack synclinorium. Further to the east in central Massachusetts, in the Ware (Field, 1975) and Barre (Tucker, 1977) areas, in particular, repetitions of thin belts of Ordovician - Lower Devonian strata have been interpreted as isoclinal folds formed during this regional nappe stage. Unfortunately only a few hinges of nappe stage folds have been observed. In the Ashburnham-Ashby area, the first phase of deformation, defined mainly by the repetitions of belts of rusty- and gray-weathering rocks of the Paxton and Littleton Formations, respectively, is thought to correspond to the nappe stage elsewhere in central Massachusetts.

The next stage of Acadian deformation in central Massachusetts, the backfolding stage, involved large scale refolding of the nappes, transporting them back toward the east (Figure 20b). Extreme transport associated with this phase produced a strong east - west trending mineral lineation that is a dominant fabric in eastern central Massachusetts. Mylonitization, probably just subsequent to the peak of metamorphism, followed or was associated with the late stages of backfolding. The second and third phases of folding in the Ashburnham Ashby area are thought to correspond to the backfolding stage. These produced the predominant foliation, an intense east-west trending mineral lineation, and locally, mylonite zones parallel to the foliation. Further west, this east-west fabric is strongly overprinted and all but obliterated in the vicinity of the Bronson Hill anticlinorium by the later deformation of the dome stage.

The third or dome stage of regional deformation caused the plastic flow and uplift of the basement gneisses that form the cores of the gneiss domes of the Bronson Hill anticlinorium (Thompson et al., 1968) (Figure 20c). Structural features produced during the dome stage generally have a north - northeasterly trend. Phase four in the Ashburnham-Ashby area is probably coeval with the dome stage.

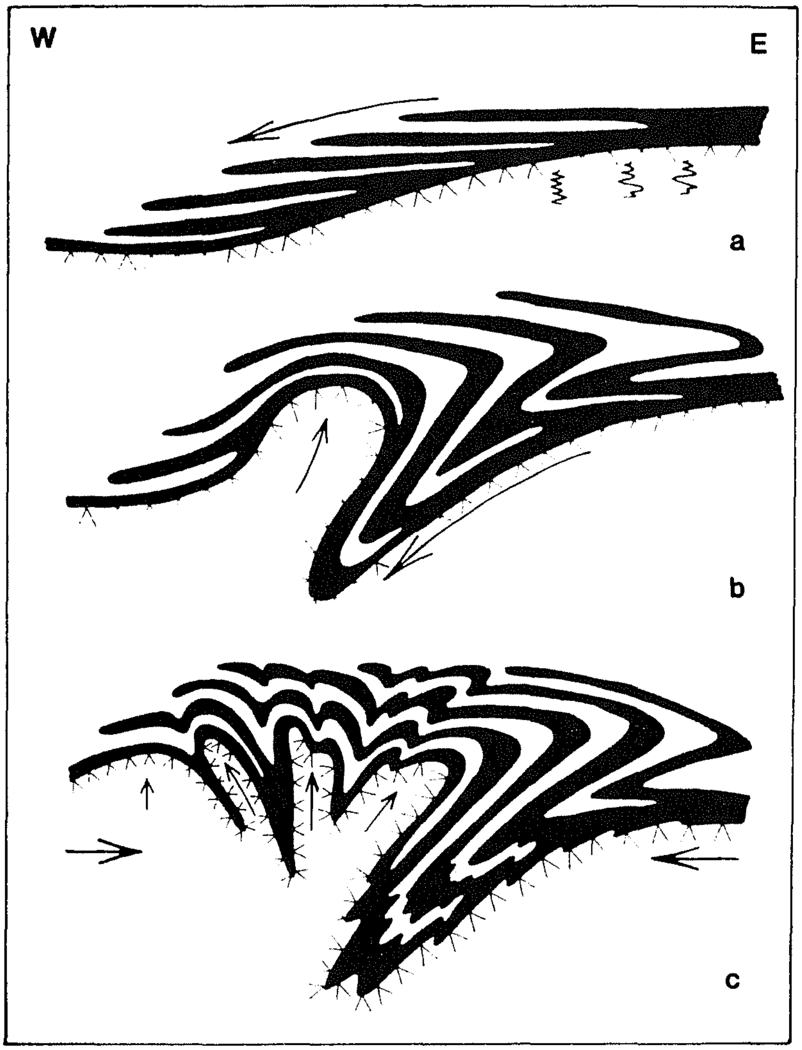


Figure 20. Schematic sections showing the three major stages of deformation that affected the rocks in central Massachusetts during the Acadian Orogeny (adapted from Hall and Robinson, 1982). a. Nappe stage. b. Backfold stage. c. Dome stage.

The last gasps of the Acadian Orogeny produced open upright, generally northerly-trending folds that gently deform the dome stage fabric. The Gardner anticline, west of this study area is a large scale example of these gentle late warps. In the Ashburnham-Ashby area, these are represented by the open folds of phase five.

Opening of the present-day Atlantic Ocean began with Mesozoic rifting that left fault-bounded basins filled wiih Mesozoic sediments and volcanics along the eastern margin of North America. The Connecticut Valley Mesozoic basins are half-grabens formed at this time by down-dropping along an eastern border fault. Diabase dikes, faults, and extensive joint sets observed through New England are a product of this Mesozoic extension. The major fault that cuts the Ashburnham-Ashby area and the accompanying shearing, silicification, jointing and formation of coarse quartz and tourmaline veins are interpreted to be post-metamorphic and probably Mesozoic.

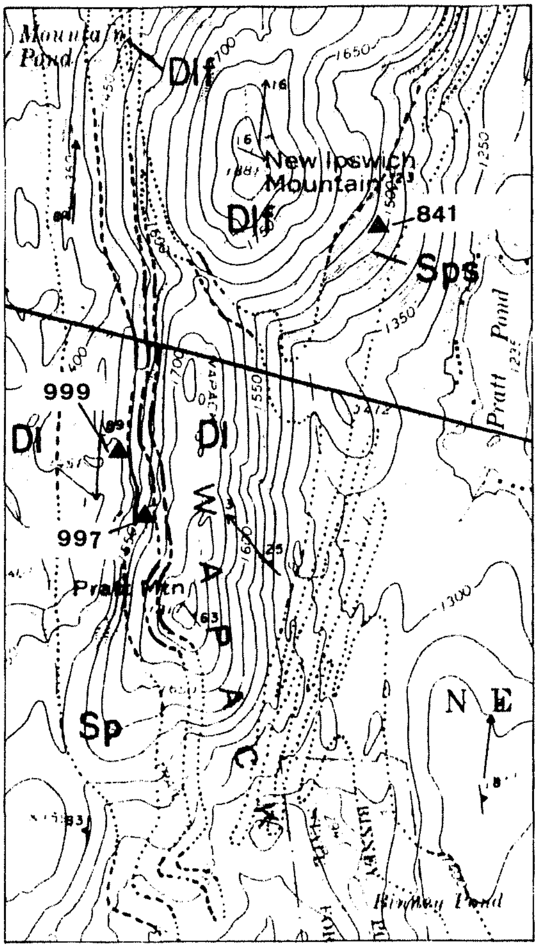
MINOR STRUCTURAL FEATURES

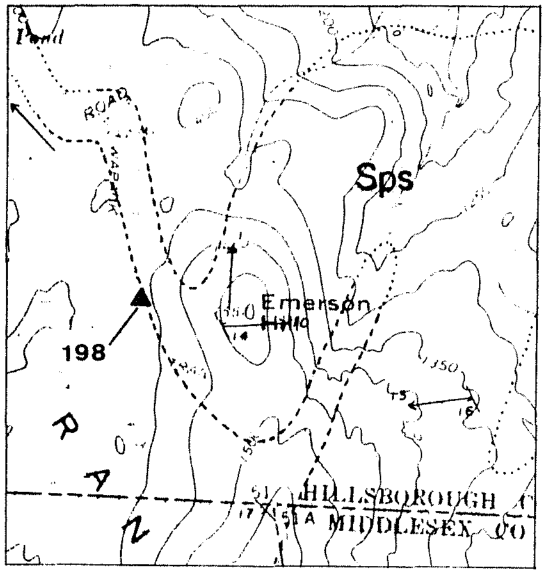
Bedding

In general, contacts between different stratified rocks can be thought of as bedding surfaces. On the outcrop scale, bedding is consistently well preserved in the Gray Granulite Member of the Paxton Formation and locally throughout the schist units in the area. In the Gray Granulite Member, it is generally recognized by interlayers of fine biotite and calc-silicate granulite. Bedding thickness ranges from 2 to 10 cm. Graded bedding is not common in this unit, however, the samples of "lump" rock collected at PAM 999 (Figure 21) have a graded matrix with coarse gritty granulite above a sharp contact, grading into a fine biotite rich granulite. The size of the lumps also decreases upward, which indicates that they may have originated from a feature present in the primary sediment. If the lumps are purely a metamorphic feature, the opposite size trend would be expected due to the increased reaction surface available in a finer-grained sediment. Unfortunately, the graded samples were collected far from any contacts and those showing the best grading are from a slightly moved block, not usable for stratigraphic interpretaion.

In the schists, bedding is represented by interlayered fine quartz-feldspar-rich granulite and muscovite-biotite-rich schist. Beds are as thin as 5 mm and rarely thicker than 10 cm. Through much of the area, bedding has been obliterated by partial melting, intrusion of pegmatitic material, or by a strong later deformational fabric. In a few locations, as shown on Figure 21, graded bedding is fairly well preserved. Measured bedding orientations are shown on Plate 4 and on the equal area projections of Figure 29.

One graded bedding locality (PAM 997 - Figure 21) on the west slope of Pratt Mountain at the east edge of the thin belt of gray schist east





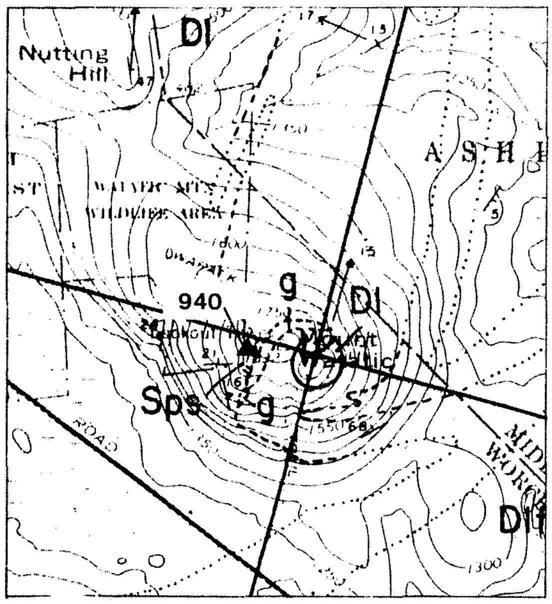


Figure 21. Map segments from Plate 1 showing the location of some of the more notable graded bedding localities in the study area. The triangles mark the outcrop locations and the station number for each is given.

of the Gray Granulite and near the Sulfidic Schist contact has unequivocal west-topping beds. At this locality there are at least three sets of beds that grade from slightly gritty gray quartz granulite at the base into a fine muscovite-biotite schist. These indicate that the gray schist may be younger than the rusty, however, the outcrops are widely spaced enough so that local isoclinal folding, reversing this relationship, cannot be completely ruled out. Clean graded beds are exposed in the rusty calc-silicate quartzites at locality PAM 841 (Figure 21). The beds here are tightly folded so that a single consistent top direction is not observed. West of Emerson Hill, an outcrop in which the gray - rusty schist contact is exposed (PAM 198 Figure 21) displays equivocal graded bedding that suggesis an older age for the gray schist. Distinctive graded beds can also be found on the southwest slope of Mount Watatic (PAM 940 - Figure 21), however these beds can be traced through several isoclinal folds so that the direction of tops for the unit is indeterminable.

Foliation

The predominant foliation in the area is a strong schistosity formed by a preferred orientation of micas developed parallel to second phase axial planes during the backfolding stage of regional deformation. This foliation is subparallel to bedding and strongly affects the tonalite as well as the stratified rocks. The tonalite appears to cross cut nappe stage axial surfaces (see cross section D - D', Plate 2 and the eastern part of Plate 1 near Route 119) and is pervaded by the second phase foliation. This foliation, in turn, is folded by the east - west trending third phase folds. East of the fault the foliation is the predominant planar feature, bedding is not commonly observed, and late fabrics are only locally prevalent. The foliation has a consistent northerly strike and a gentle west dip as shown on Plate 4 and on the equal area plots for subareas 2A, 2B, 6A, 6B, and 7 in Figure 29.

On the west side of the fault the foliation is prevalent in the schists, but not strongly developed in the quartz granulite interbeds in the schists of the Littleton Formation, in the granulites and quartzites of the Sulfidic Schist Member, nor in the Gray Granulite Member of the Paxton Formation. This is a function of the predominance of granular minerals over platy minerals. Extensive intrusion and partial melting in some areas may also have obliterated the primary foliation. In these areas, the foliation observed may be developed at the time of formation of migmatites following the second phase folding. In many places, folding and cleavage development related to later phases of folding (generally the fourth and fifth) have reoriented the main foliation. This is particularly the case on the west side of the Stodge Meadow Pond Fault. Foliations plotted on the map (Plate 4) and on the equal area nets for subareas west of the fault (Figure 29) show a scatter rather than the fairly consistent trend observed east of the fault.

It is also probable that in places the observed foliation was formed during the third phase of folding. Because phase two and three folds have nearly parallel axial planes, distinguishing between second or third phase foliations is only possible in the hinge areas of folds related to these phases.

Mylonitic Zones

Strong mylonitic foliation is locally developed. This foliation is considered to be a ductile structural feature unrelated to later Mesozoic faulting. The localities where these mylonitic rocks have been observed are mainly in the Ashby quadrangle, and many of them happen to lie in the vicinity of the late Stodge Meadow Pond Fault. Examples of outcrops that contain mylonitic foliation and have been extensively sheared can be found at localities PAY 361 and PAM 590 (see Plate 3). The mylonitic rocks display extreme grain size reduction (0.1 - 1 mm) or mineral elongation parallel to a strong preferred orientation (Figure 22). Lenses or augen of coarser feldspar and quartz are elongate parallel to the sheared fabric. The mylonitic foliation closely parallels the attitude of the predominant foliation in the area. An intense linear fabric is associated with the mylonites and is commonly expressed as smeared-out mineral grains on the mylonitic foliation surfaces. This lineation essentially parallels the strong regional east - west trending mineral lineation. A plot of poles to planes of mylonitic foliation in the area is shown in Figure 23. The significance and timing of development of this mylonitic fabric will be discussed below.

Cleavage

Strong crenulation cleavages are locally developed in the schists in the area, mainly as a response to fourth and fifth and rarely third phase deformation. In a few places, a related fracture cleavage is weakly developed in the more quartz-rich, less micaceous rocks. The cleavage is best developed in the hinge regions of folds, parallel to the axial surfaces. The crenulation cleavage folds the dominant foliation in the rock, in most cases strongly reorienting the elongate minerals. This is evident from both hand specimen and thin section inspection. Muscovite, graphite, and sillimanite, oriented parallel to an earlier foliaiion, have been strongly reoriented by folds related to a crenulation cleavage as shown in Figure 24. A goethite-like Fe-oxide is typically present replacing Fe-sulfides which have been left as an insoluble residue that commonly cuts through the hinge regions of these folds parallel to their axial surfaces (Figure 24). This may be evidence of differential solution along cleavage planes during folding.

In general, crenulation cleavage is related to fourth phase axial surfaces and is best developed in hinge regions of large folds. These fourth phase crenulations are commonly coarser than the fifth

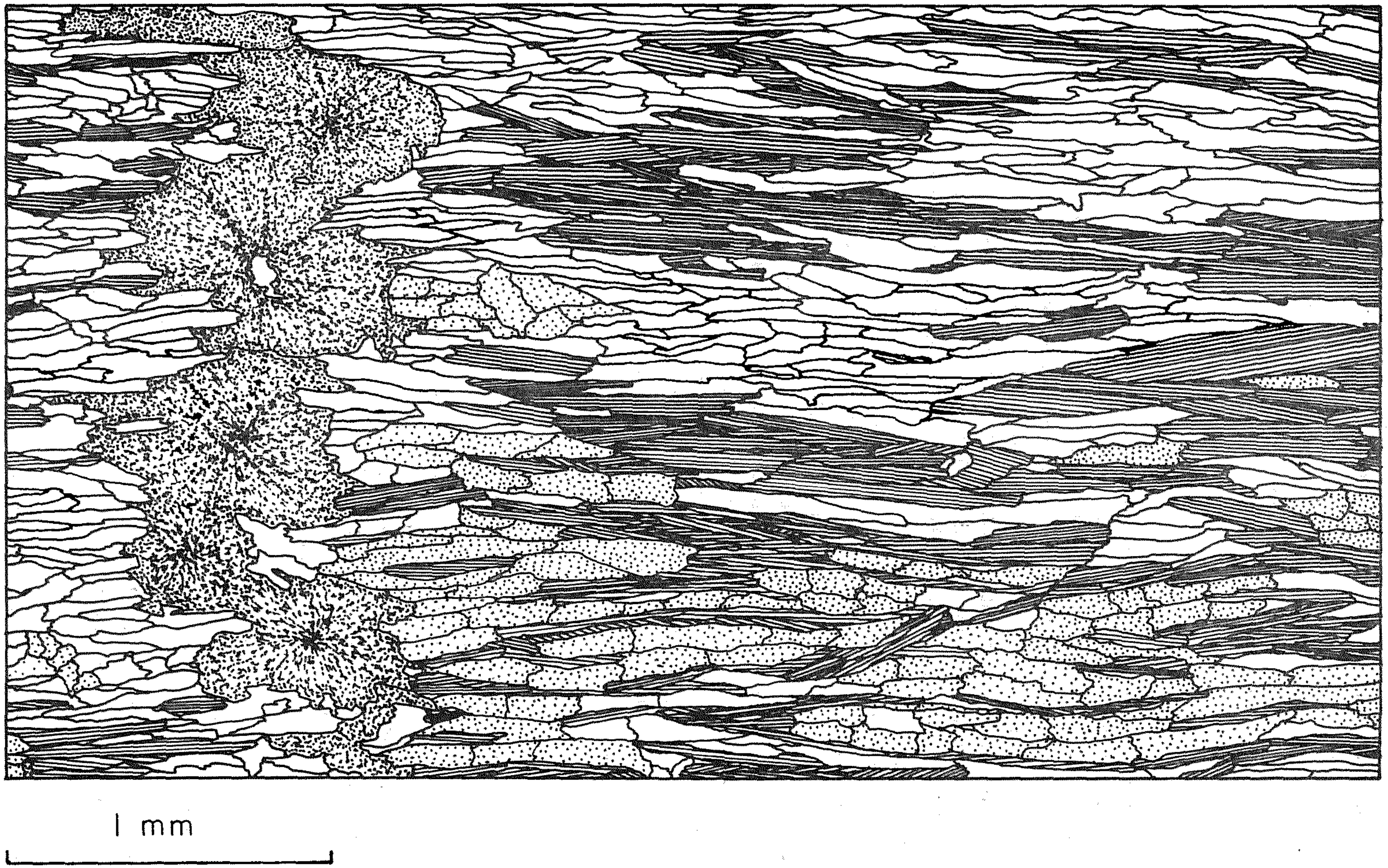


Figure 22. Drawing of a portion of a thin section from sample PAY 361B showing attenuated mineral grains due to shearing. A late chlorite vein cuts across the sheared fabric. Many of the grains in this rock have undergone extreme grain size reduction. Chlorite = heavily stippled radiating grains, Biotite = narrow ruled, Muscovite = light stipple, Quartz and Feldspar = unpatterned.

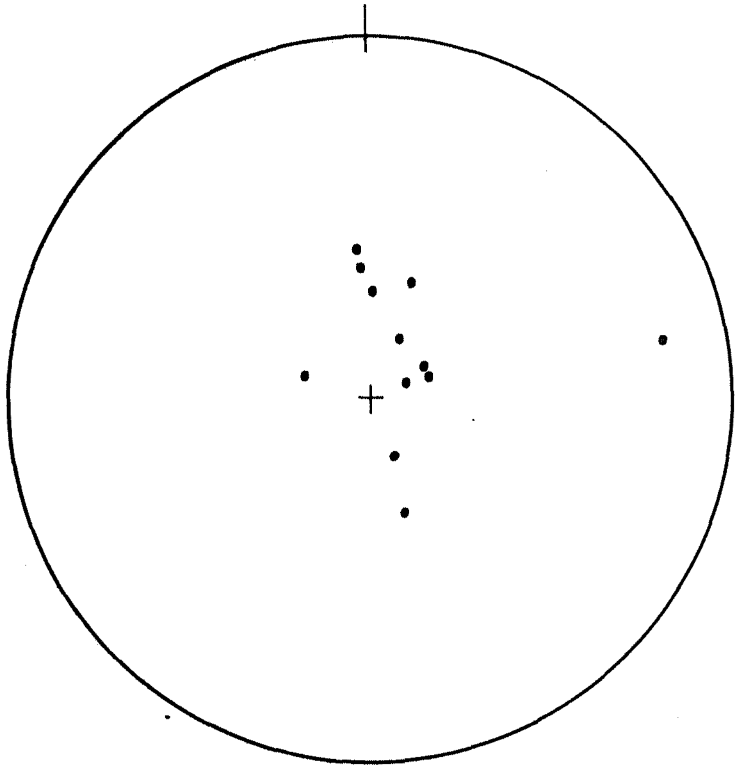
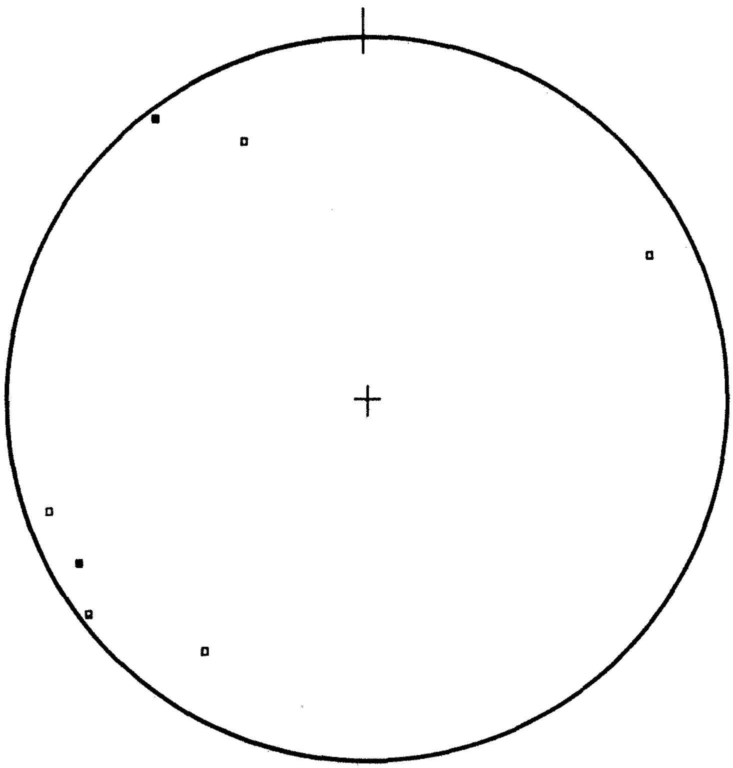


Figure 23. a. Equal area projection of poles to mylonitic foliation (solid circles). Measurements are taken over the entire area.

n = 12



b. Equal area projection of the trends of lineations formed by boudinage, parallel to boudin neck lines. Includes all measurements taken in the Ashburnham-Ashby area. Open symbols represent data collected west of the fault. Closed symbols represent data collected east of the fault.

□ n = 5
■ n = 2

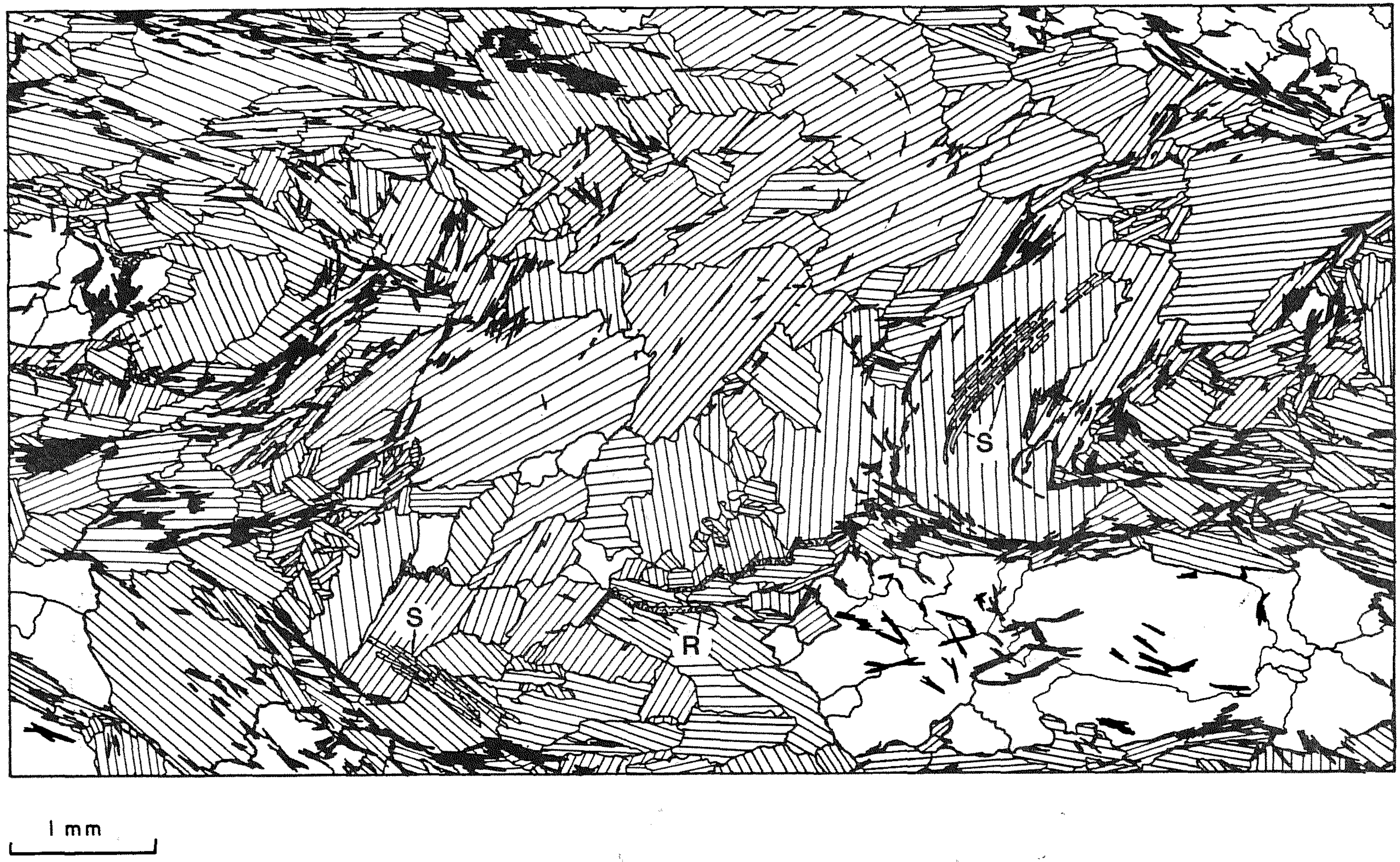


Figure 24. Thin section sketch of portion of sample PAM 373A in the Sulfidic Schist Member of the Paxton Formation east of Emerson Hill. A fourth phase crenulation cleavage is strongly developed as small tight folds, accompanied by an insoluble residue (R - heavy stipple pattern) formed by solution cleavage. Graphite (solid black) and relict sillimanite (S) needles are folded by the crenulation cleavage. The elongate lenses of recrystallized quartz (unpatterned) are also folded, but this is not shown here. The ruled pattern shown for the muscovite grains roughly approximates the cleavage traces of the grains. This coarse secondary muscovite appears to mimic the folded pattern of the mineral(s) it replaces, but is probably formed after the folding.

phase cleavage, which is developed only locally in the hinges of small upright chevron folds. Larger scale folds related to the fourth phase tend to retain a chevron shape, whereas larger fifth phase folds are generally open folds with gently curved hinge regions.

Crenulation cleavage is better developed in the rocks to the west of the fault zone than in those to the east. This appears to be due to a regional increase in intensity of dome stage folds westward, but may be affected by the abundance of tonalite east of the fault. The tonalite appears to have reacted strongly to the earlier phases of folding while it was still hot and relatively ductile, however upon cooling during the later stages of folding it may have behaved more competently than the schists due to its higher percentage of granular minerals versus the platy minerals that predominate in the schists. Axial plane orientations shown on Plate 4 generally represent crenulation cleavage attitudes. These measured crenulation cleavage and axial plane attitudes are also represented on the equal area projections of planar data (Figure 29) discussed below.

Lineations

Lineations observed in the area are of two main types: mineral lineations and lineations formed by the intersection of two planar fabrics. The mineral lineations are formed by the parallel orientation of elongate minerals including micas, sillimanite, and stretched quartz (quartz rods) and feldspar grains. Locally tourmaline crystals are oriented to form a weak linear fabric. The most prevalent mineral lineation in this area plunges gently toward the west and is best developed east of the fault zone (Plate 5) where later fabrics have not significantly masked its presence. West of the fault, this mineral lineation is well developed, but has more competition from later northerly-trending lineations. These late lineations are generally formed by the intersections of fourth or fifth phase cleavage with bedding or foliation. Mineral alignment, especially of micas, parallel in this direction is common. The mineral lineations observed in the area appear to be parallel to the axes of folds formed in the same phase, General lineation trends are shown on Plate 5 and on equal area nets in Figure 29.

Minor Folds

Minor folds are abundant throughout the area ranging in amplitude from millimeters to meters and commonly in intersecting patterns with folds of other phases. Map-scale minor folds are evident from the map pattern (Plate 1). Many of the inferred fold hinges on the map have been located on the basis of detailed examination and interpretation of outcrop scale minor folds. Minor folds can also be seen at the scale of a thin section. In Figure 25 sillimanite, micas, and elongate, recrystallized quartz grains are folded into fine crenulation folds, probably related to phase five. The coarse garnet grains, in this case,

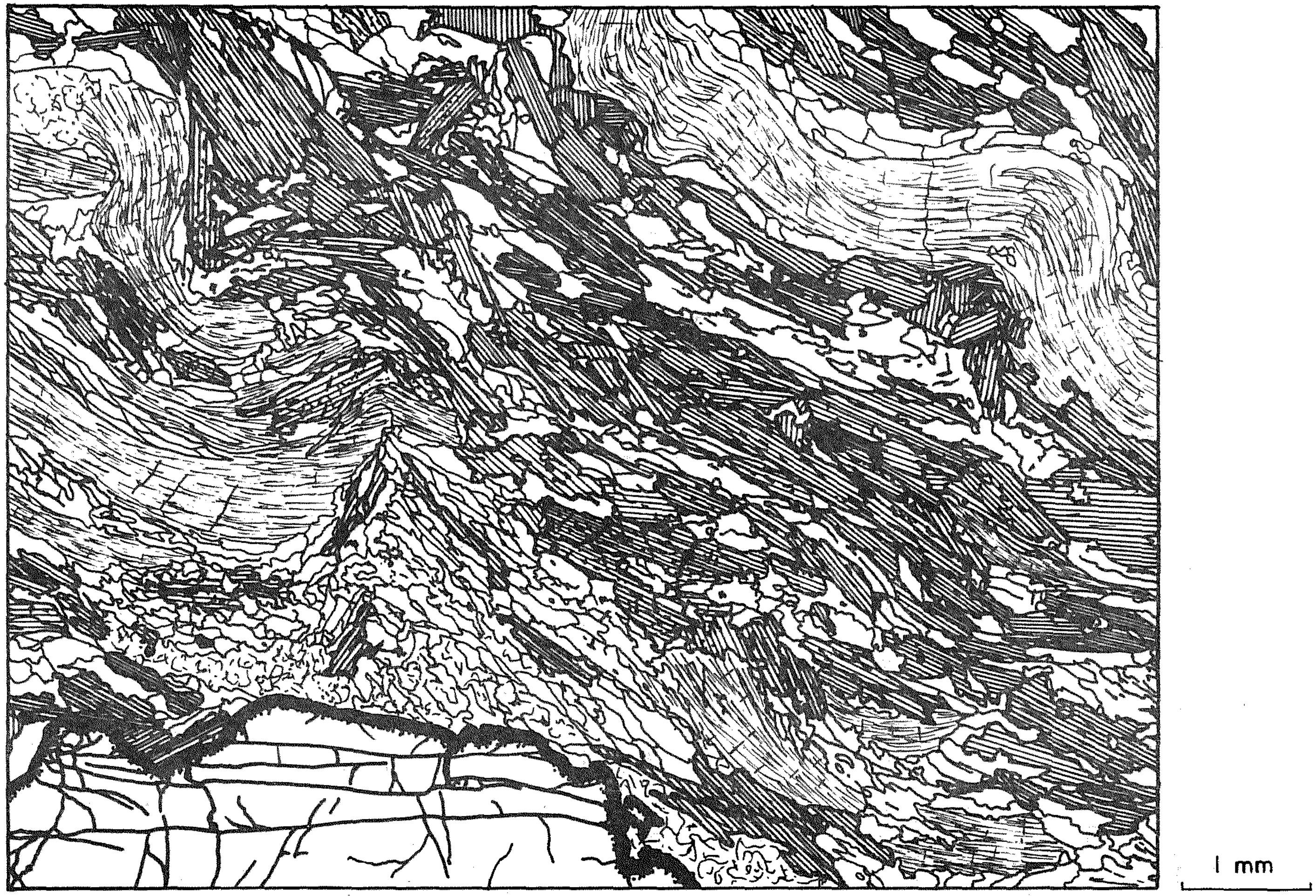


Figure 25. Thin section sketch of a portion of sample PAY 680 showing microscopic late minor folds in gray schist. Here grains are folded around a coarse garnet (high relief grain at bottom left of sketch) and cleavage is weakly developed. Quartz = unpatterned, Feldspar = squiggly-lined pattern, Biotite and Muscovite = ruled pattern, Sillimanite = fine irregular lines with some cross hatches, Opaques = black.

appear to form the nucleus of the folds. The crenulation cleavage here is not so well developed as it is in the sample shown in Figure 24.

Minor folds related to phases one and two are rarely observed in outcrop. Particular examples will be discussed in a later section.

Outcrop and map scale minor folds related to phase three are abundant throughout the area especially east of the fault. These are generally east - west trending isoclinal folds with axial planes essentially parallel to the foliation that they fold and fold axes plunging nearly down the dip of the axial plane. It is commonly difficult to tell the rotation sense of these folds in outcrop. The typical style of phase-three minor folds is shown in Figure 26a.

Minor folds related to phase four have a fairly consistent west over east rotation sense, a gentle north plunge, and a moderate to gentle west-dipping axial surface. Folds of this phase are not common in the tonalite, but are abundant in schist outcrops. The folds tend to have limbs that are at a high angle to one another with axial planar crenulation cleavage concentrated along their short limbs (Figure 26b).

On a small scale, phase five minor folds are either small chevron-like folds related to a local crenulation cleavage or gentle warps in foliation (Figure 26c). The axial planes of these folds tend to be steeply to moderately dipping. The rotation sense varies and is commonly indistinct. On a larger scale, these folds are almost always gentle warps in the earlier planar fabrics. Typical minor folds of the fifth phase are shown schematically in Figure 26c.

Boudinage

Small boudins are fairly common throughout the schists in this area, generally in the quartzose granulite beds or calc-silicates. The boudins produce gentle warping of the layering and in places the trend of boudin neck lines roughly parallels the trend of fifth phase fold axes. Those boudin neck-line lineations measured are shown on the equal area net of Figure 23b.

Faults Joints and Post-metamorphic Veins

Brittle structural features were not measured systematically throughout this area. Those features measured are shown on the equal area projections of Figure 27. In general, the highest concentration of brittle features was found near the major fault that cuts the area. Since most of the bedrock exposure near this fault is on its east side, most of the data is from this narrow zone. The orientation data collected west of and further from the fault are scarce and show a lot of scatter. Figure 27a shows poles to individual fault planes, the measured trend of slickensides, and where possible, the calculated direction of sigma 2. A fairly good cluster is apparent (see outlined

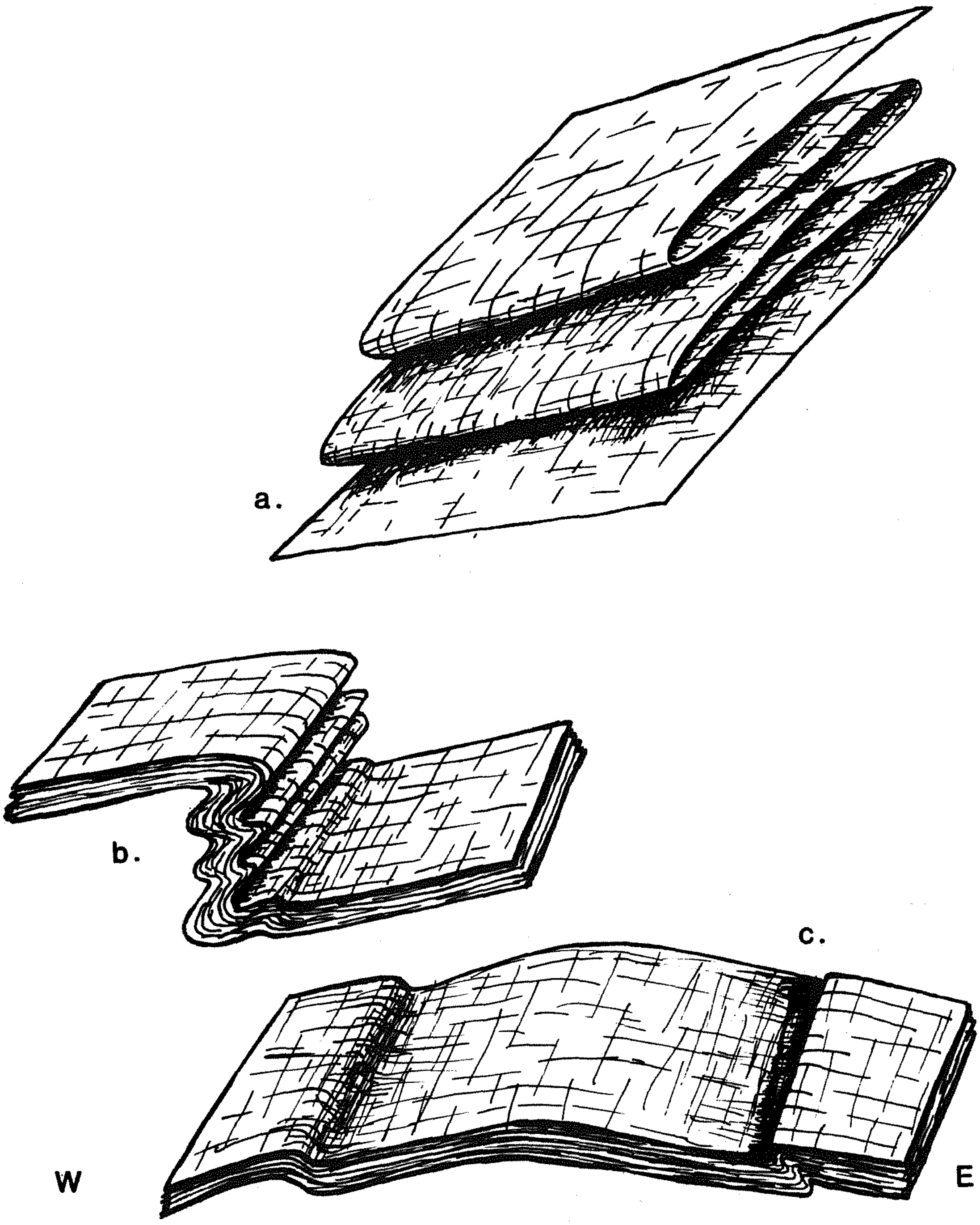
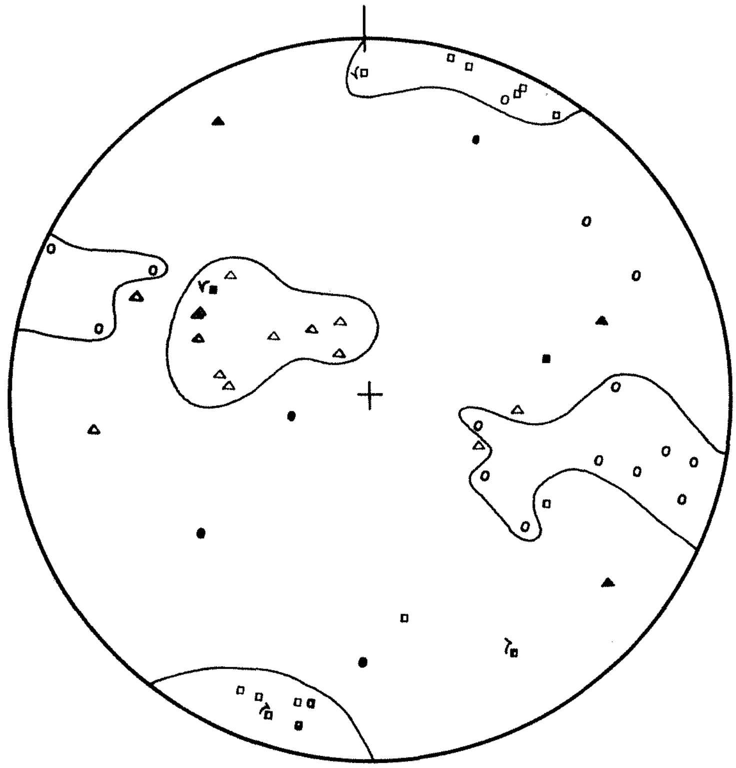
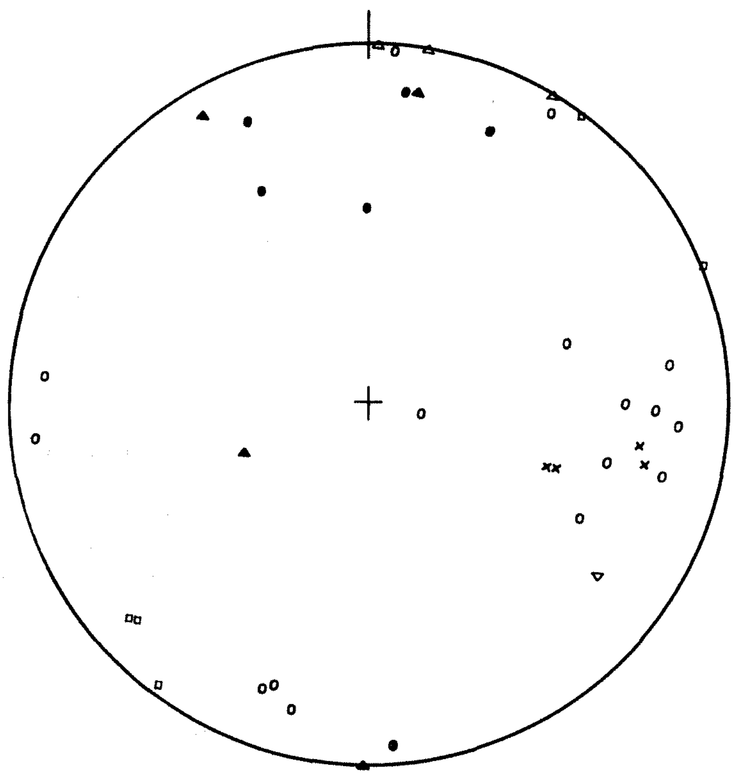


Figure 26. Schematic drawings of the typical character of minor folds in the Ashburnham-Ashby area. Directions shown are approximate. a. Phase three minor folds. b. Phase four minor folds. c. Phase five minor folds.

Figure 27. Equal area projections of brittle structural features measured in the Ashburnham-Ashby area. Open symbols represent data collected east of the fault. Closed symbols represent data collected west of the fault. a. Fault data. O = poles to measured faults (n = 19), △ = trends of slickenslides (n = 17), □ = trend of sigma 2 (n = 17) (calculated). Rotation sense is shown on sigma 2 where known. Outlined areas show clusters of faults, slickensides, and sigma 2 measured east of the fault.





b. Other brittle data (all planar). x = poles to the planes of major shear zones related to the fault (n = 4), O = poles to joint surfaces (n = 22), △ = poles to tourmaline-covered joint surfaces (n = 7), ▽ = pole to a coarse vuggy quartz vein (n = 1), □ = poles to thin quartz veins (n = 5).

data) for normal faults with a north - northeast trend and a horizontal sigma 2 (Note: The normal rotation sense observed is shown for some sigma 2 values in Figure 27a). Other scattered faults show a considerable oblique slip component, however lack of data makes any further comment regarding these faults impossible.

Joint sets, shear zones, and veins measured near the major fault have attitudes similar to measured minor faults Figure 27b). Joints and veins measured west of the fault show a general west - northwest trend (Figure 27b). Many of the joints represented here are actually rock walls coated with quartz and tourmaline. Most commonly the tourmaline is very fine and looks like a coat of flat black paint, however, locally, coarse crystals, up to 1 cm in diameter may be found along the thicker veins. Although all of these features are definitely late- or post-metamorphic, they are not necessarily all Mesozoic.

DISTRIBUTION AND ORIENTATION OF MINOR STRUCTURAL FEATURES

The nature of deformation in the area makes division of the map into homogeneous structural domains impossible, however, it is possible to subdivide the area into subareas of similar structural character. Differences between some of the subareas are very subtle and some have the characteristic in common of total chaos of the structural fabric. In part, the boundaries of the subareas were determined by the distribution of areas of bedrock outcrop. The subarea divisions are shown in Figure 28 with representative structural symbols. The structural data for each subarea are presented in equal area nets in Figure 29.

Bedding

Poles to bedding, presented with the planar data in Figure 29, show it to be roughly parallel to foliation throughout much of the area Bedding is not so commonly observed in the schists and granulites east of the fault as it is west of the fault. Bedding is well developed in the Gray Granulite Member of the Paxton Formation which dominates subarea 12C. In a few of the subareas (8A, 10 - 12), the spread of poles to bedding is greater than the spread of poles to foliation. This may indicate that in these areas bedding and foliation were initially not so closely parallel, or in other words, the data was collected in the vicinity of a fold hinge that formed at the time of foliation development. Alternatively, the folds associated with the formation of foliation may not initially have been tight isoclinal folds but later deformation may have locally brought bedding and foliation close to parallel.

Foliation

East of the fault the attitude of the dominant foliation is

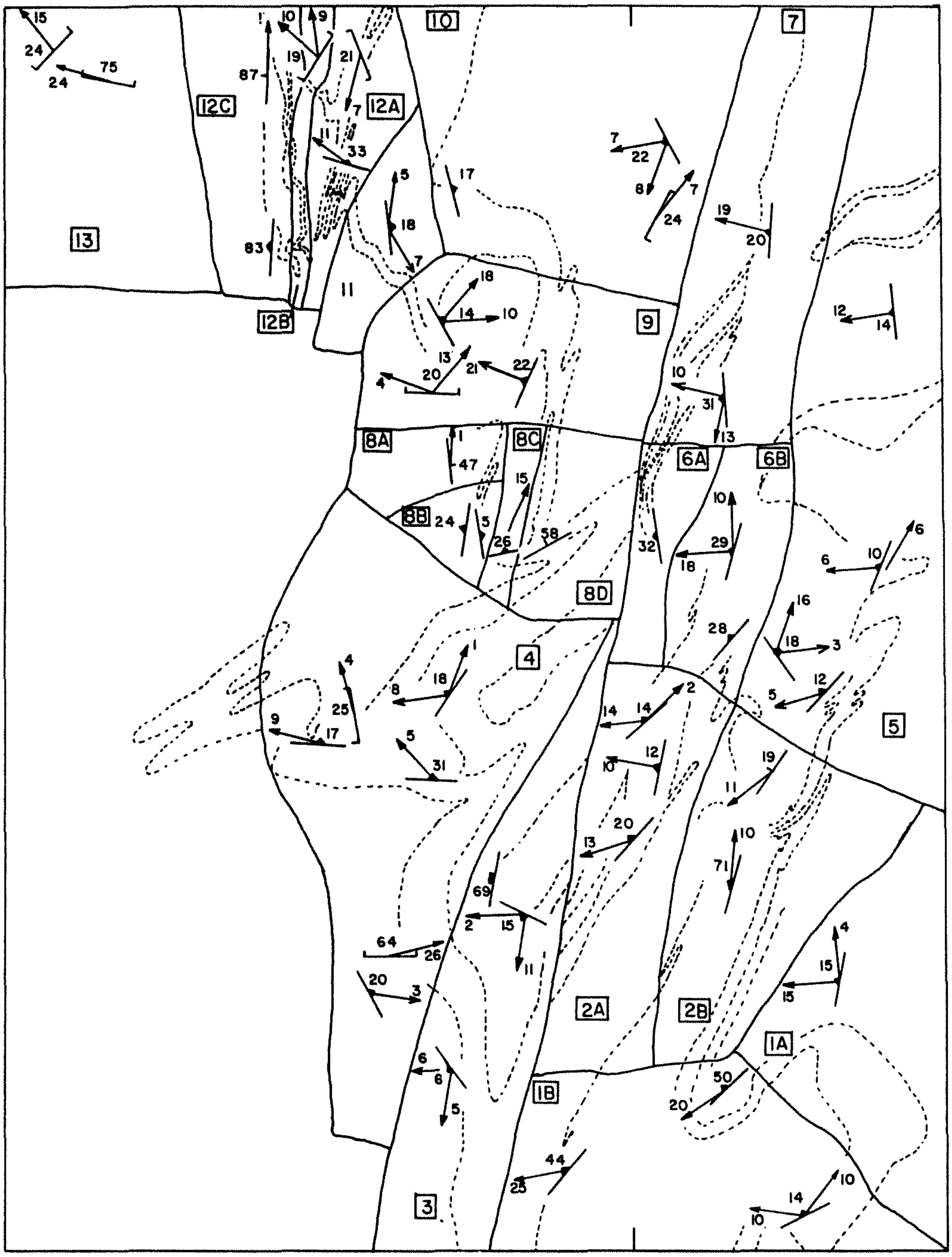


Figure 28. Outline map of the Ashburnham-Ashby area showing the distribution, location, and areal extent of the structural subareas. Geologic contacts are shown by dashed lines. Representative structural symbols are given for each subarea. - Bedding, -Foliation, - Axial plane cleavage, - Mineral lineation, - Fold axis.

Figure 29. Equal area projections of planar and linear features measured for each of the subareas shown in Figure 28. For each subarea, the poles to planar features are shown in the upper net and the attitudes of linear features are shown in the lower net. The symbols used and the number of structural features presented in the nets are shown below.

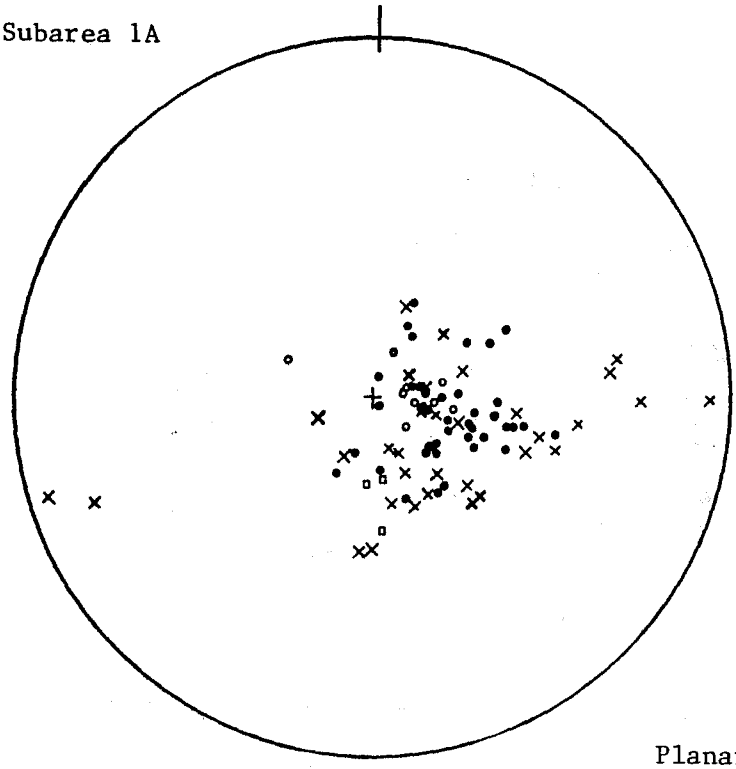
Number of Planar Features

	Phase 3			Phase 4		Phase 5	
Subarea	Bedding	Foliation	Axial Plane	Cleavage	Axial Plane	Cleavage	Axial Plane
	x	●	○	■	□	▲	△
1A	35	43	9		3		
1B	16	48	1		3		
2A	6	190			10		
2B	4	111	1		15		
3	14	108	1		22		
4	52	103	1		9		
5	3	141			2		
6A	23	78	6		18		
6B	13	94			7		
7	18	103	1		5		
8A	27	19		2	9	1	9
8B	11	45			11		
8C	6	50	1		9		
8D	16	32			8		
9	50	84	1		10		
10	22	39			14		
11	40	45	1		11	4	2
12A	24	29			12		
12B	41	38	1		6		
12C	44	66		1	3		
13		10	3	1	6		

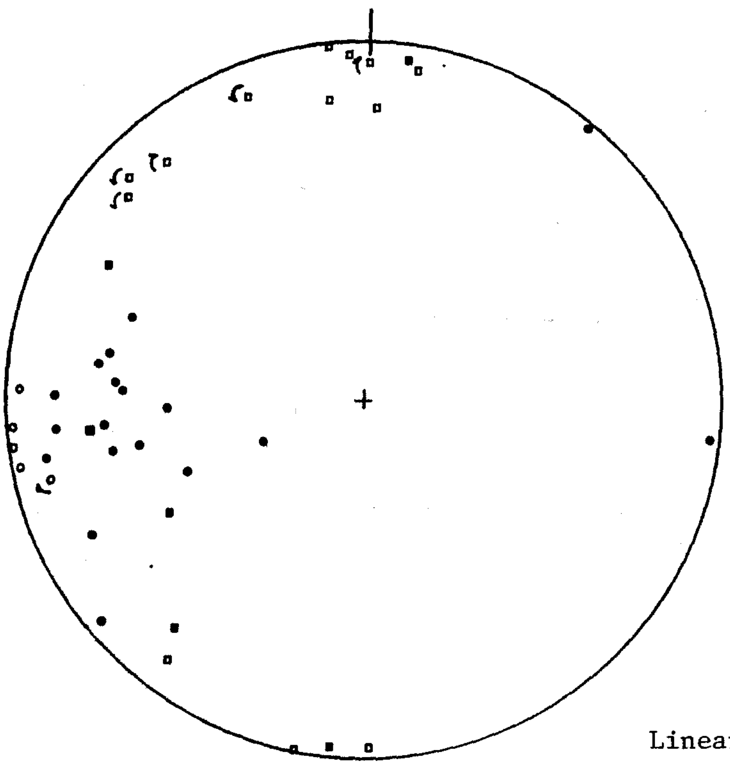
Number of Linear Features

	Phase 3		Phase 4		Phase 5	
Subarea	Mineral Lineation ●	Fold Axis ○	Mineral Lineation ■	Fold Axis □	Mineral Lineation ▲	Fold Axis △
1A	18	5	6	13		
1B	11	2	3	1		
2A	80	9	12	14		
2B	26		6	9	3	3
3	14		18	23		
4	29	3	16	19		
5	52	6	3	6	1	3
6A	27	6	6	9		
6B	30	7	11	7	2	1
7	53	9	3	3		
8A	4		1	9	3	10
8B	25			19	1	
8C	23	2	2	7	1	2
8D	5			6		
9	30		2	12		
10	9	1	6	16	5	2
11	16		3	9	3	10
12A	15	1	1	5		
12B	7	4	16	11		
12C	8		58	8		
13	6			12		

Subarea 1A

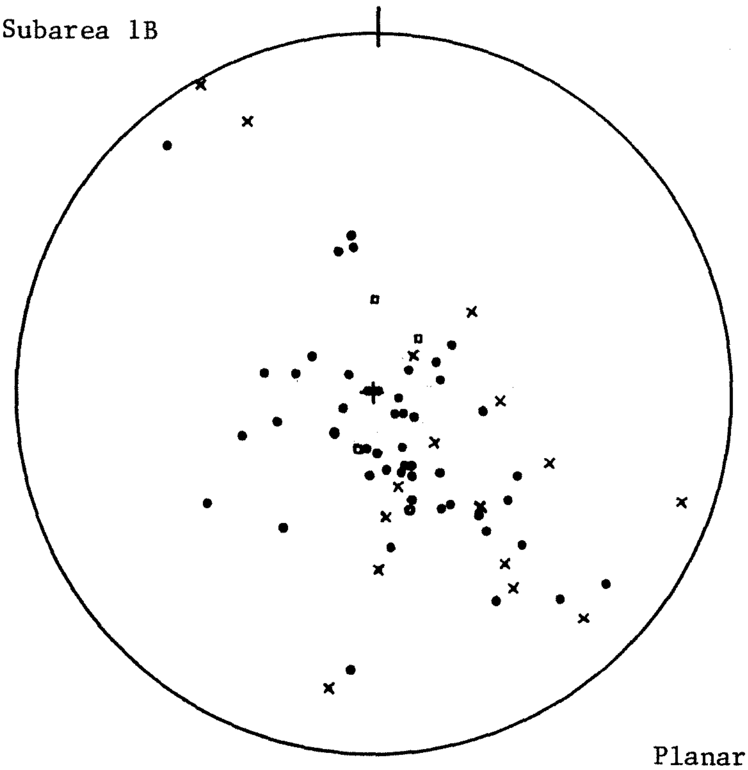


Planar

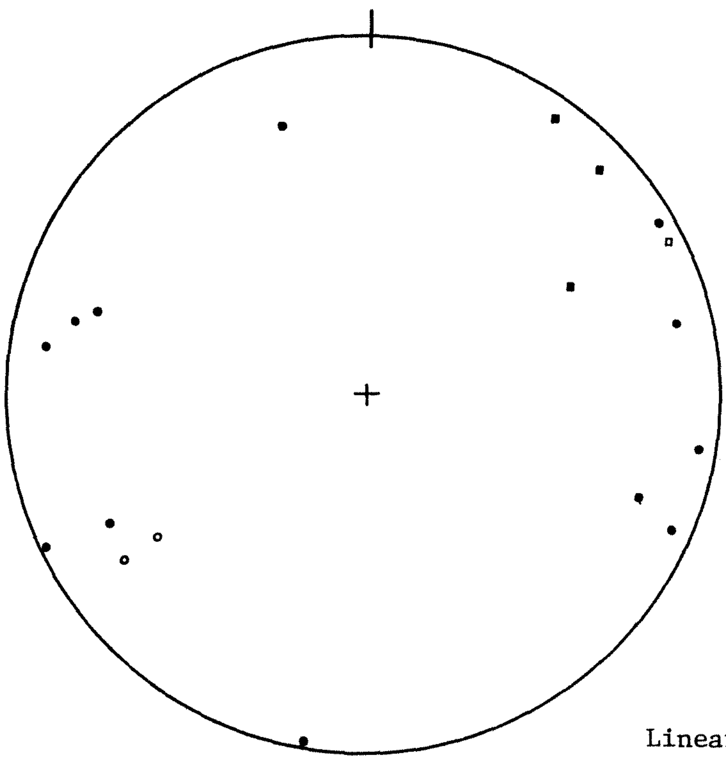


Linear

Subarea 1B

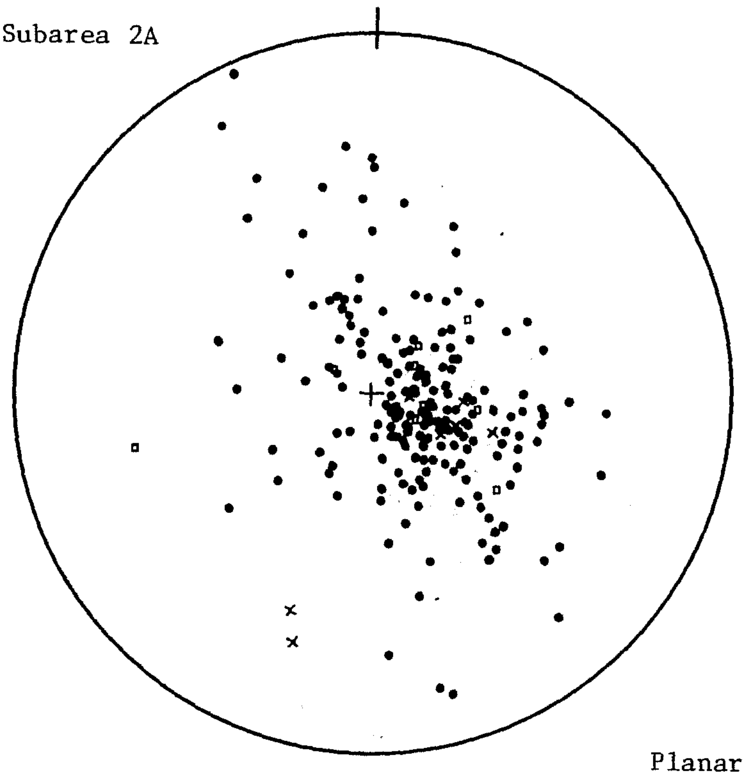


Planar

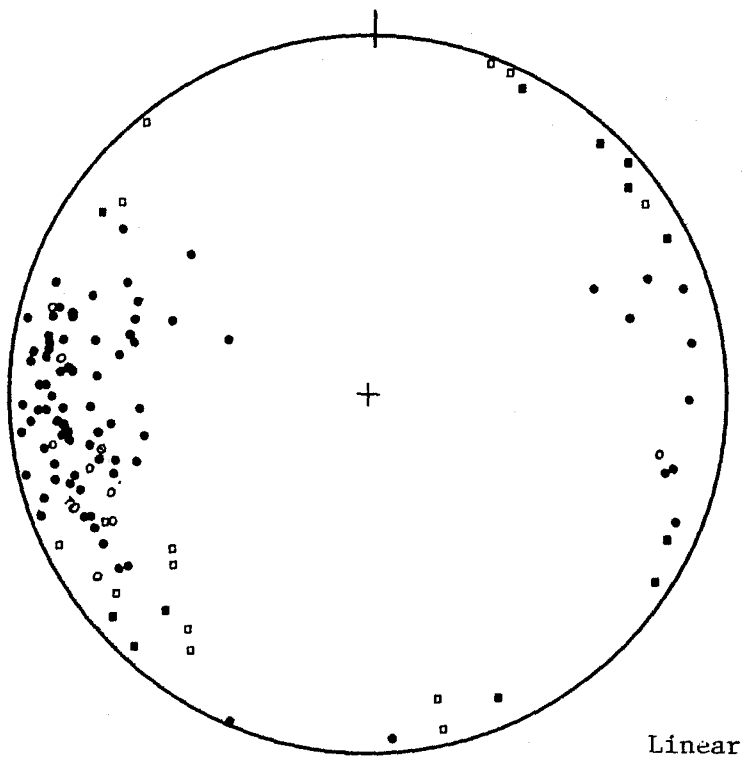


Linear

Subarea 2A

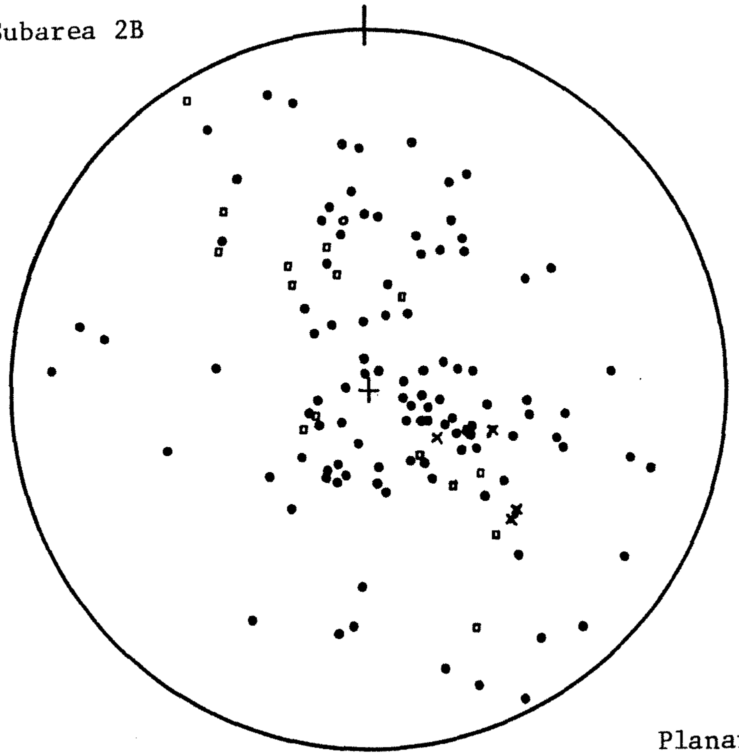


Planar

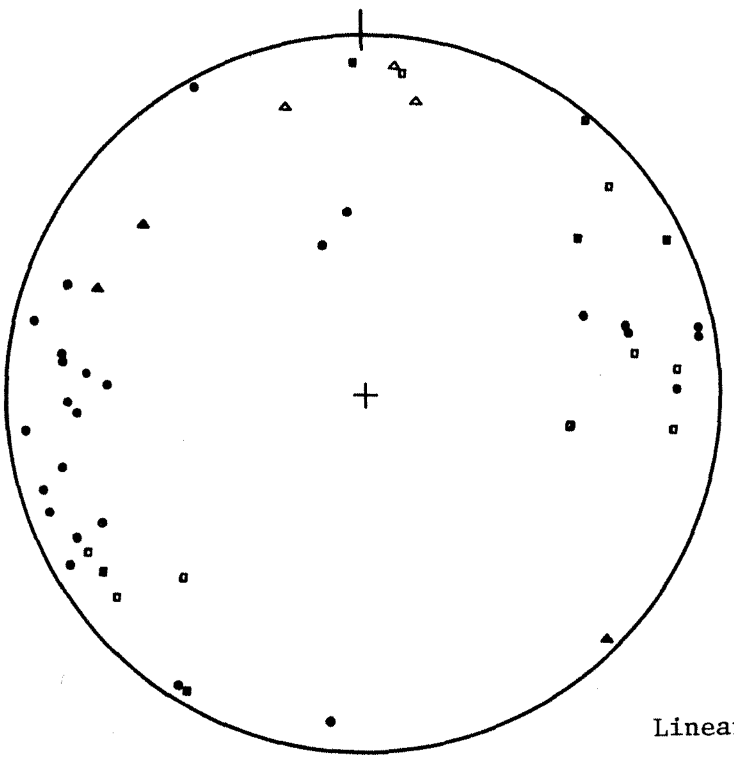


Linear

Subarea 2B

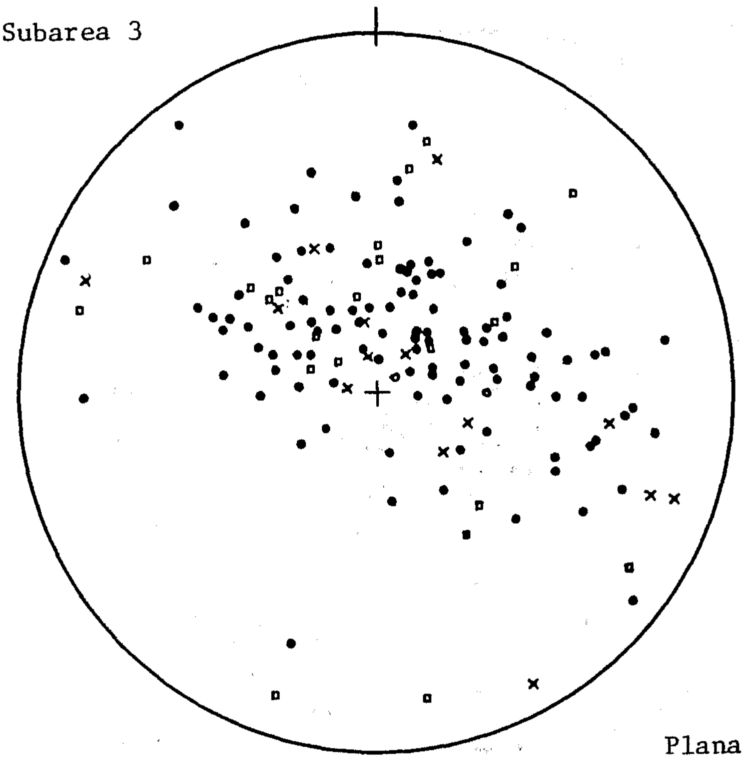


Planar

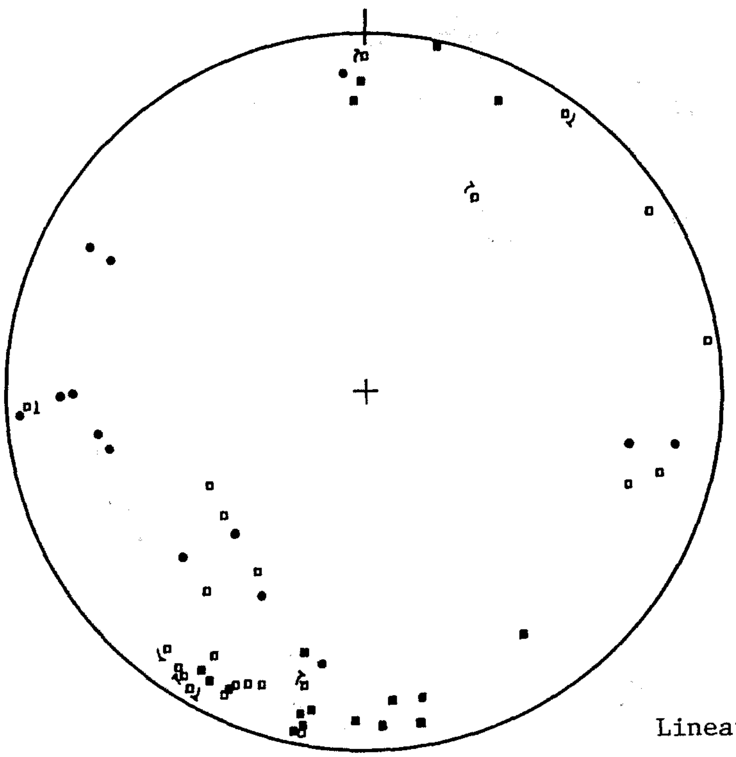


Linear

Subarea 3

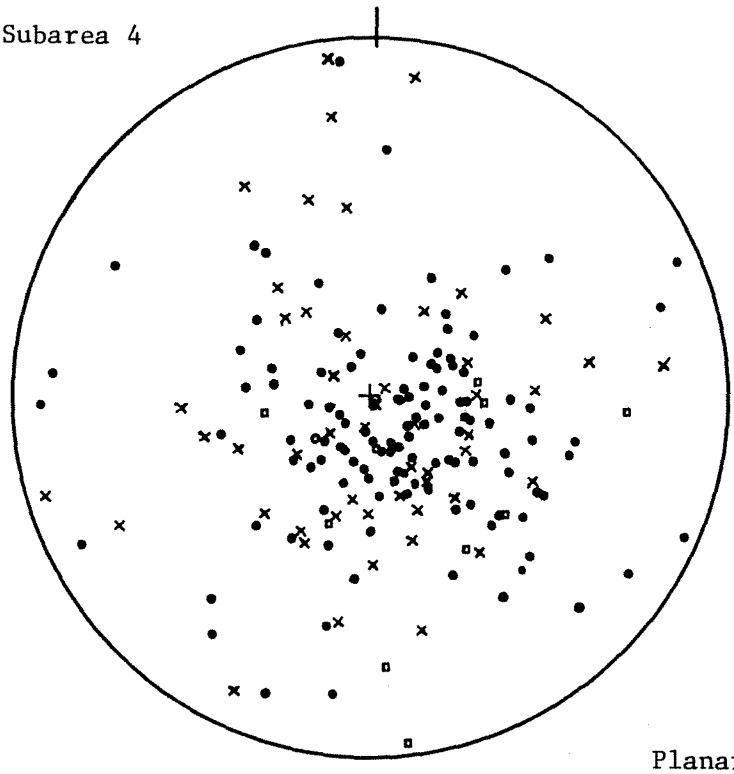


Planar

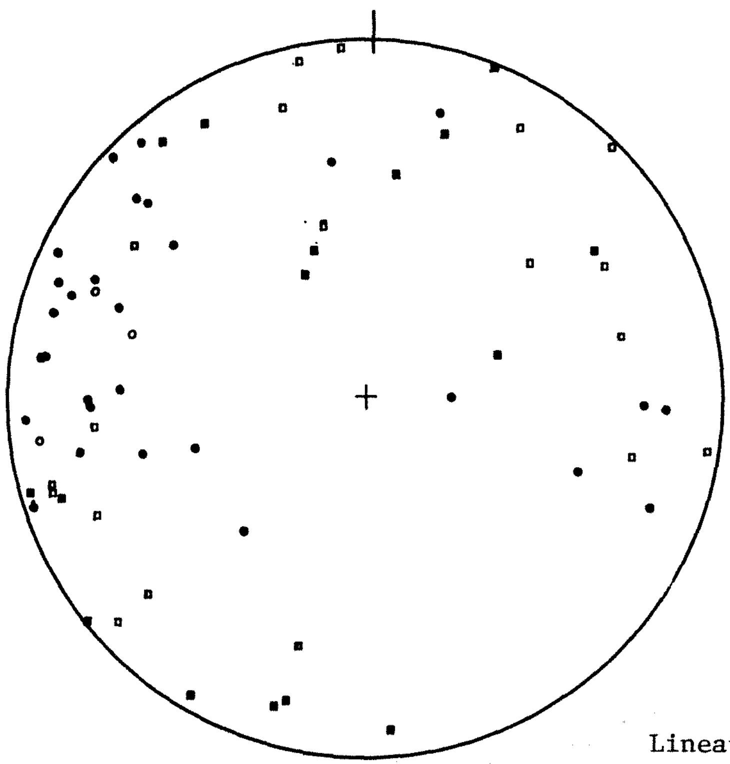


Linear

Subarea 4

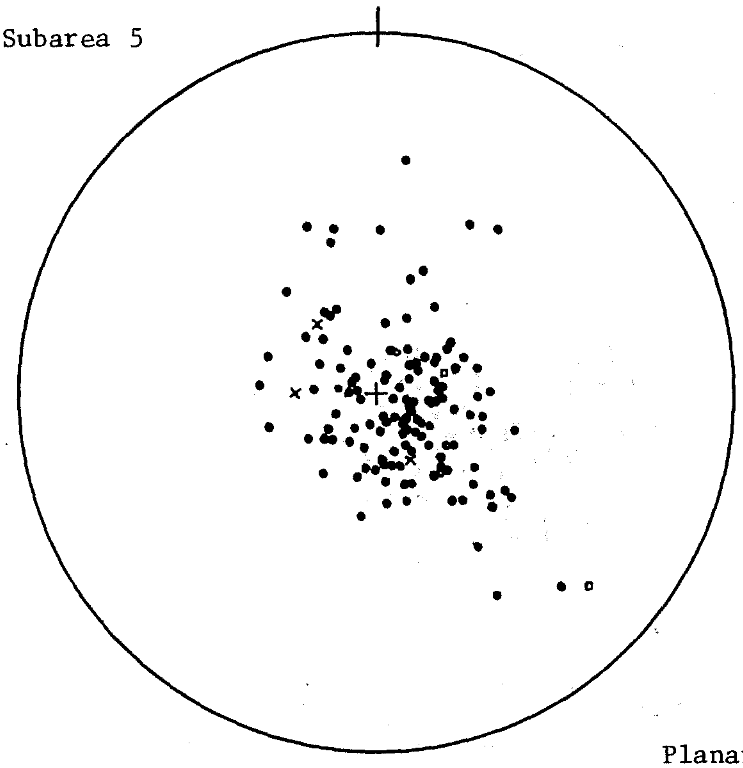


Planar

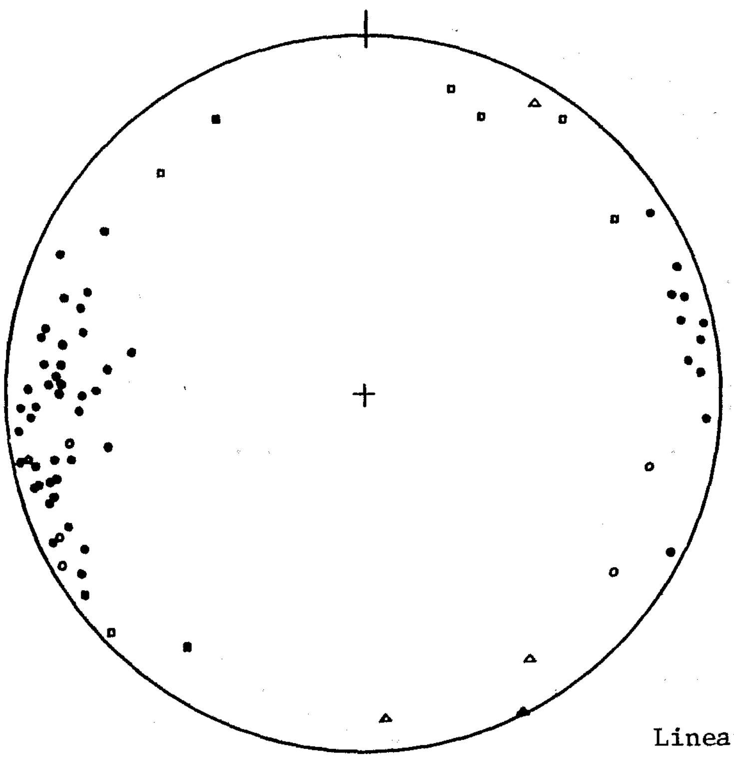


Linear

Subarea 5

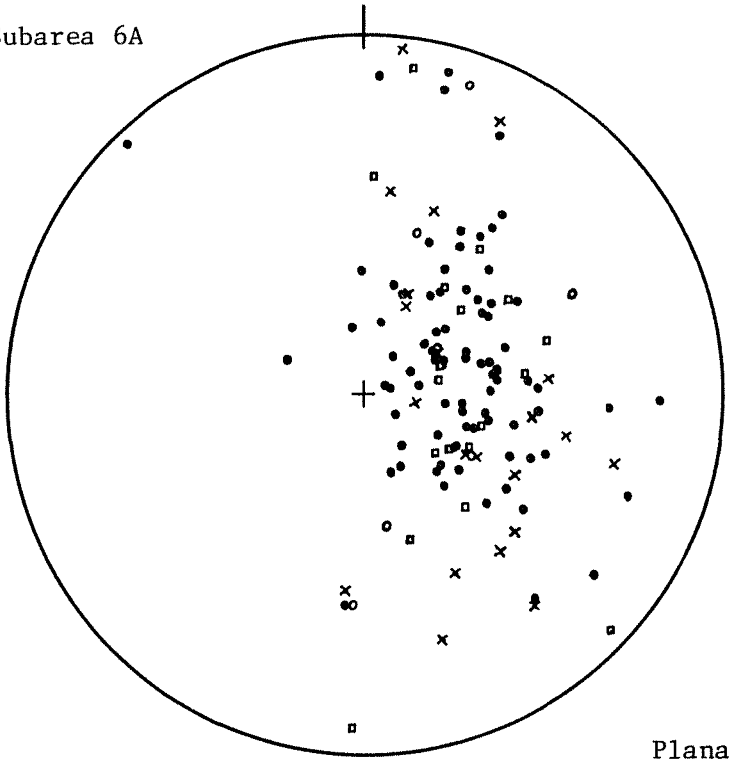


Planar

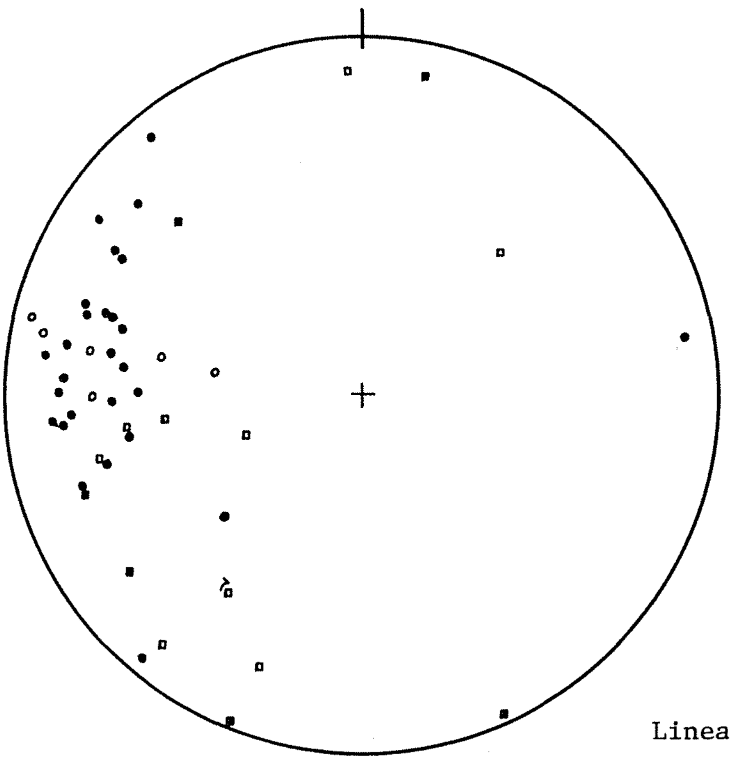


Linear

Subarea 6A

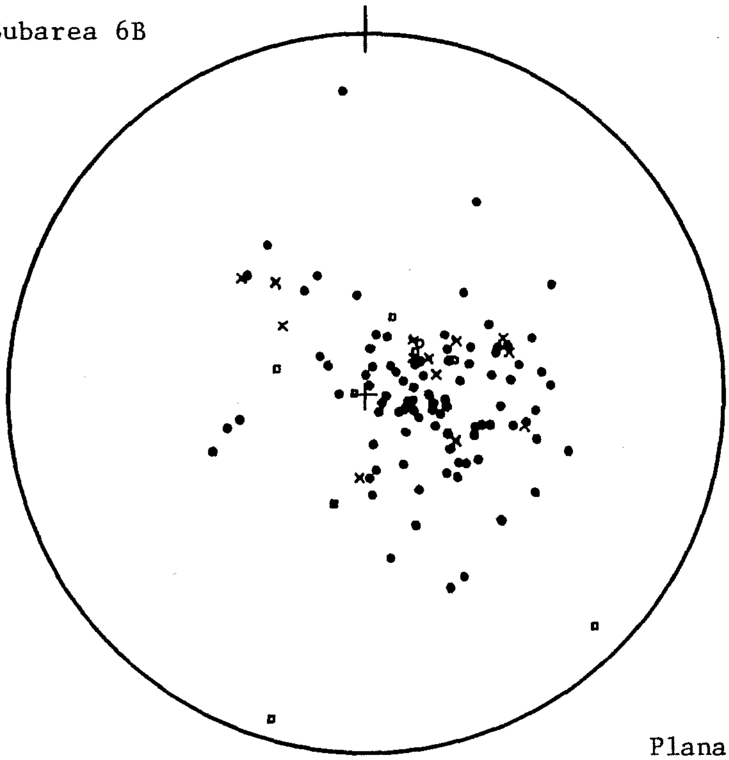


Planar

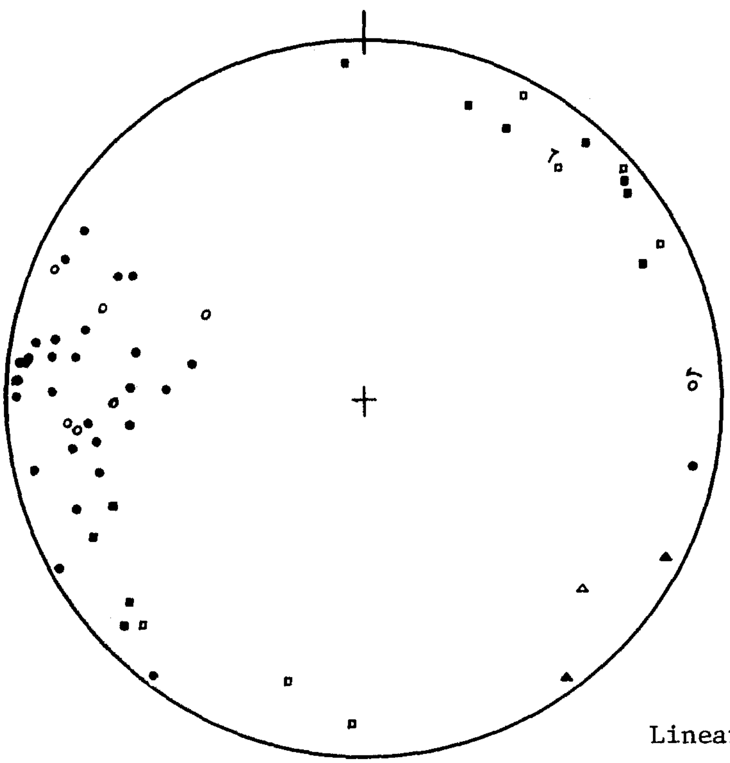


Linear

Subarea 6B

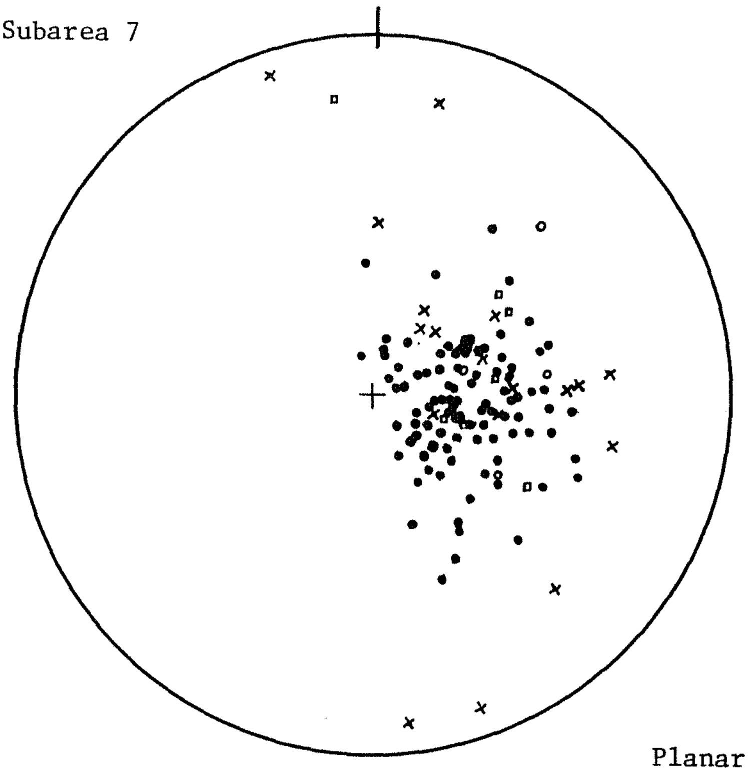


Planar

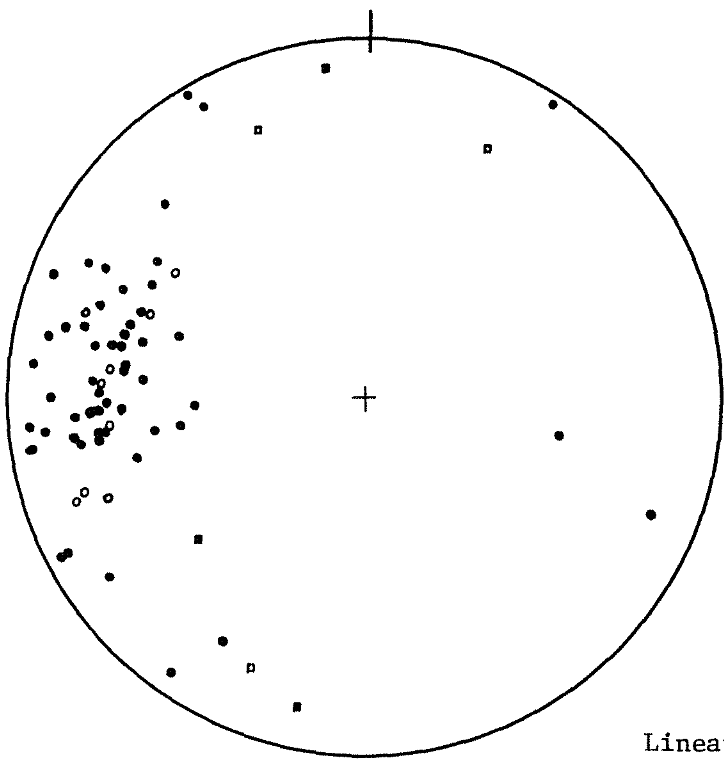


Linear

Subarea 7

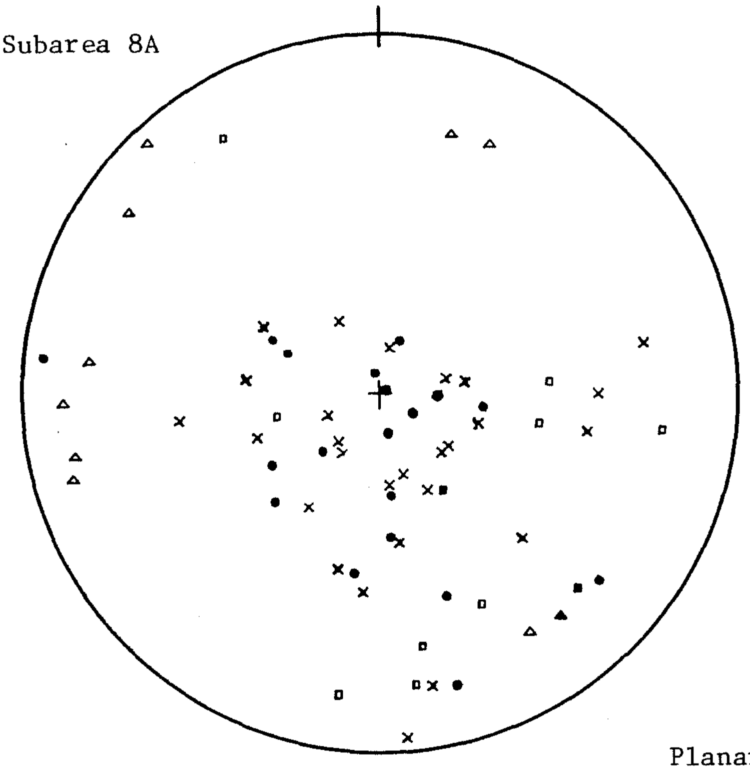


Planar

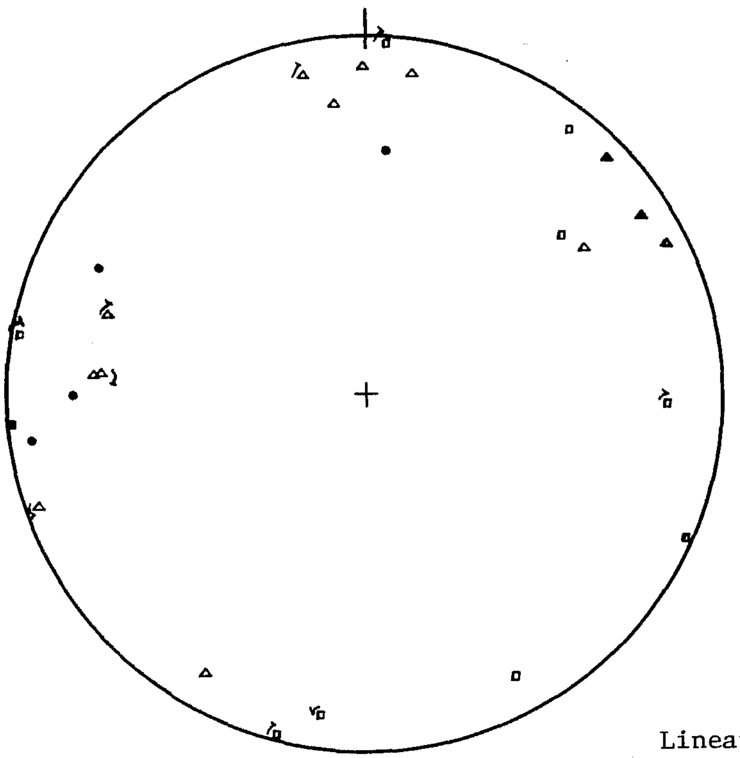


Linear

Subarea 8A

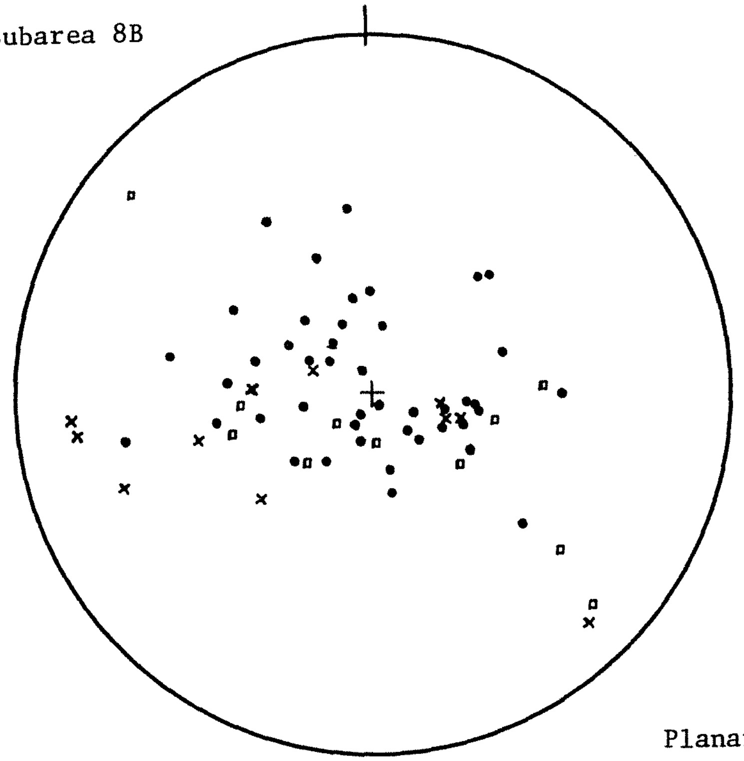


Planar

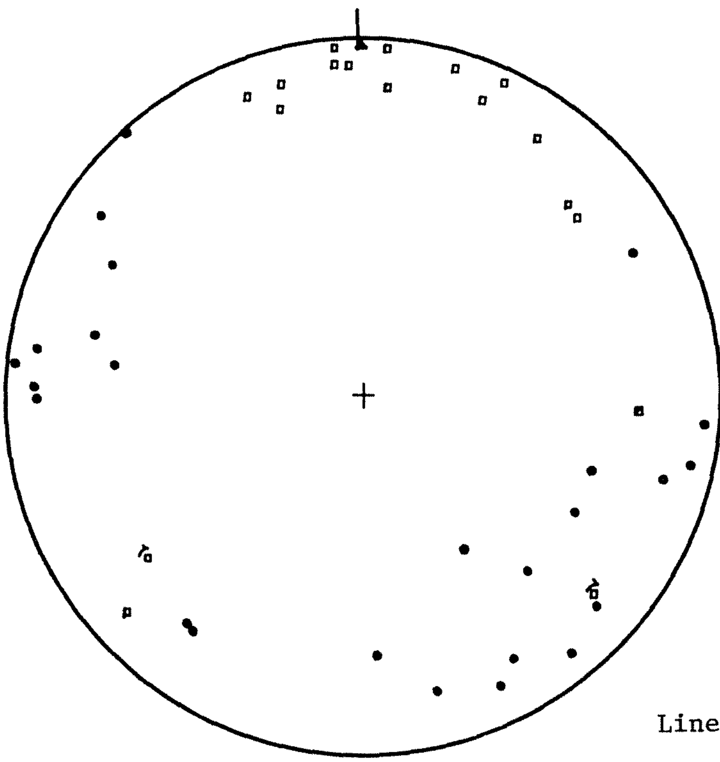


Linear

Subarea 8B

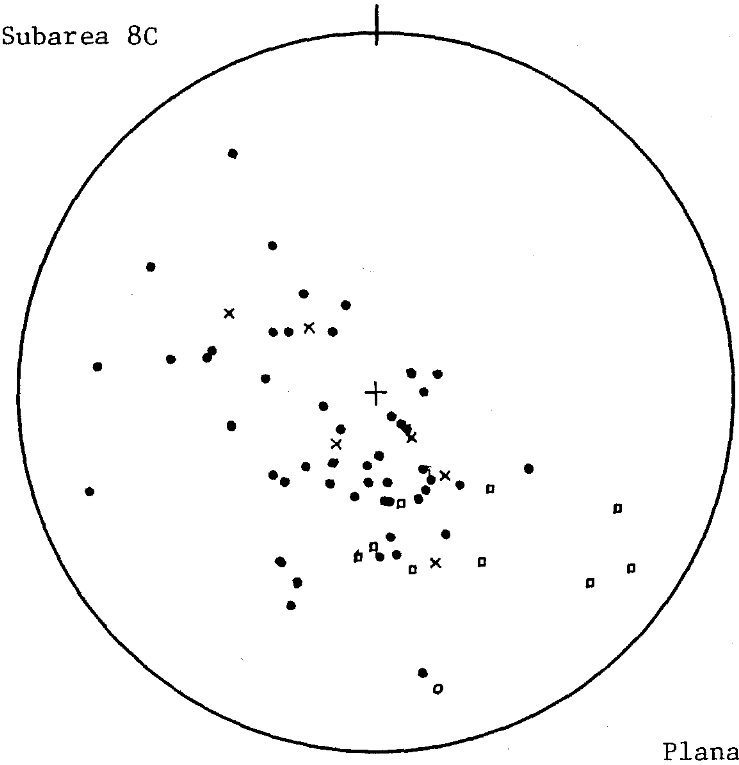


Planar

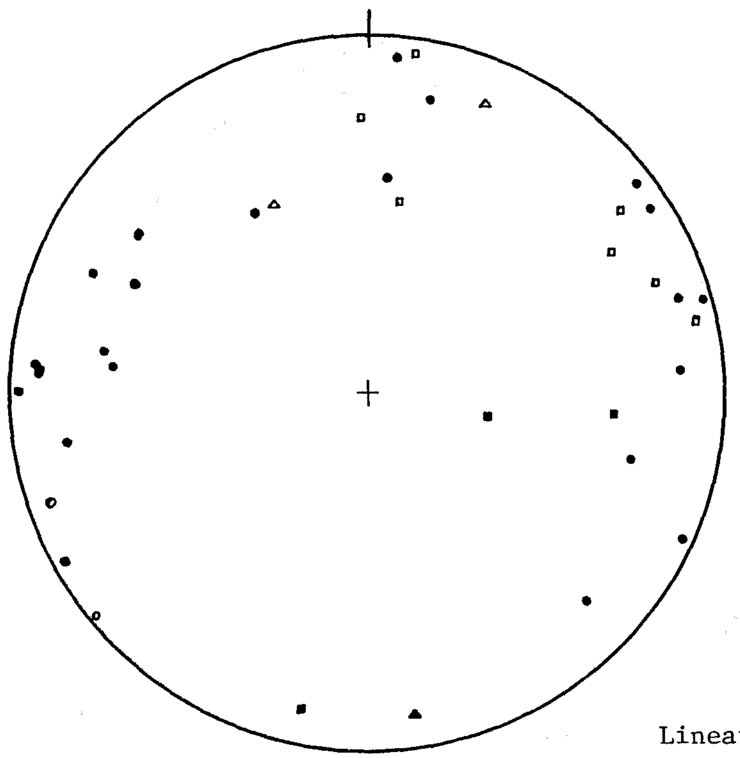


Linear

Subarea 8C

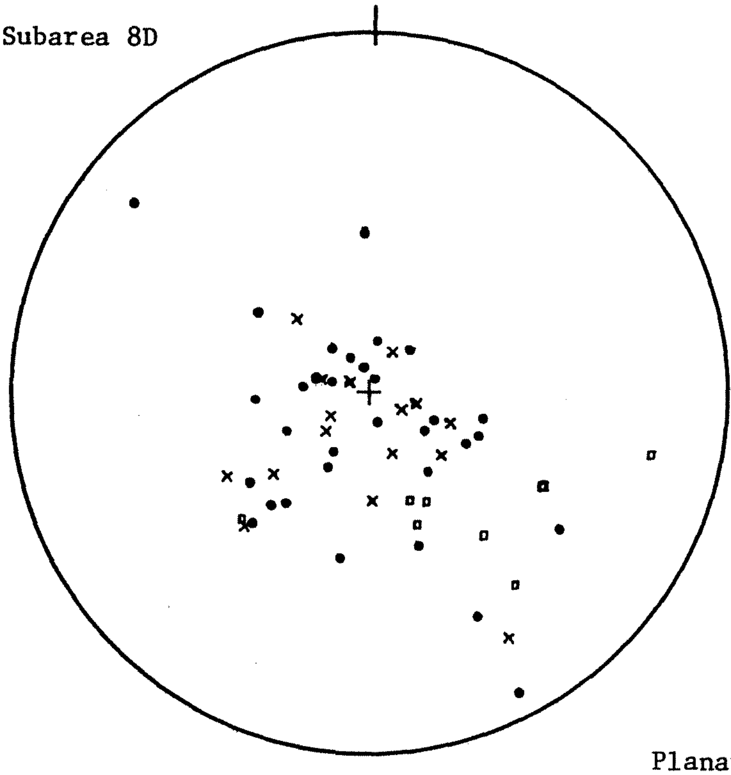


Planar

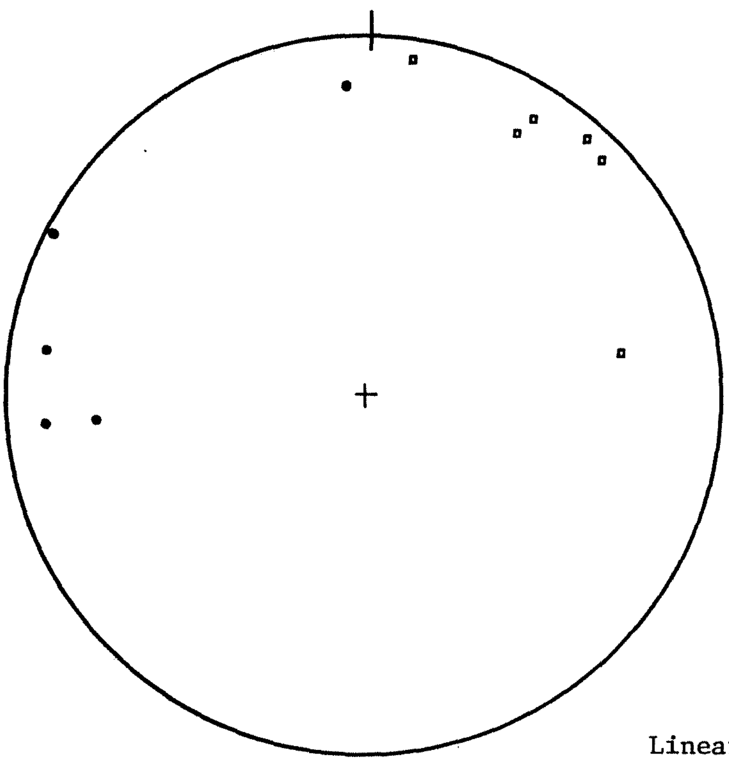


Linear

Subarea 8D

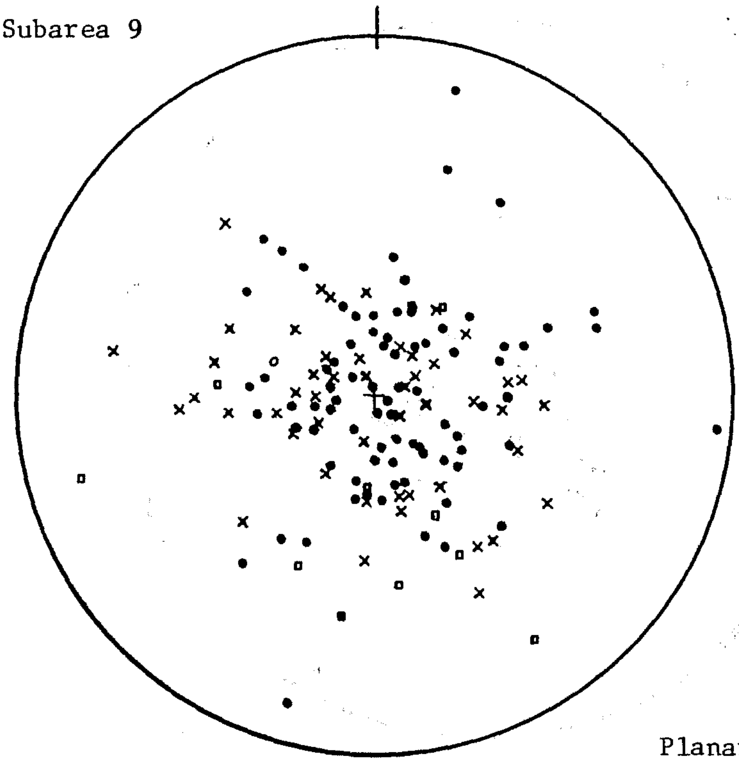


Planar

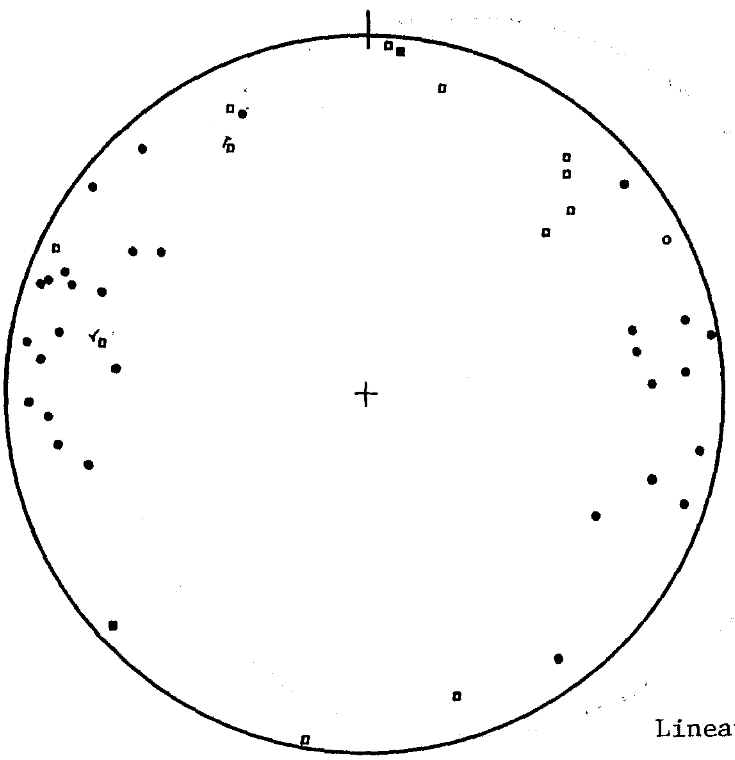


Linear

Subarea 9

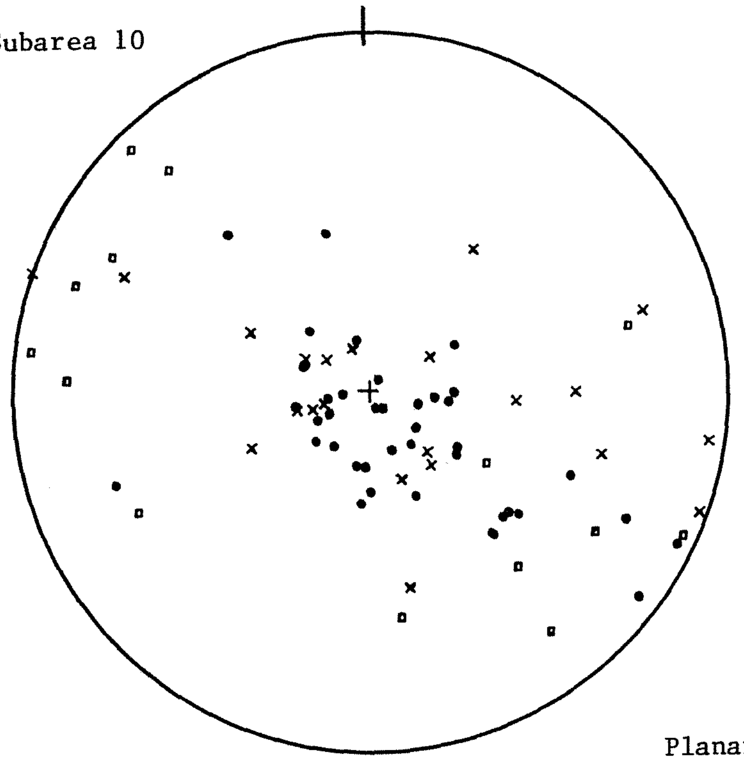


Planar

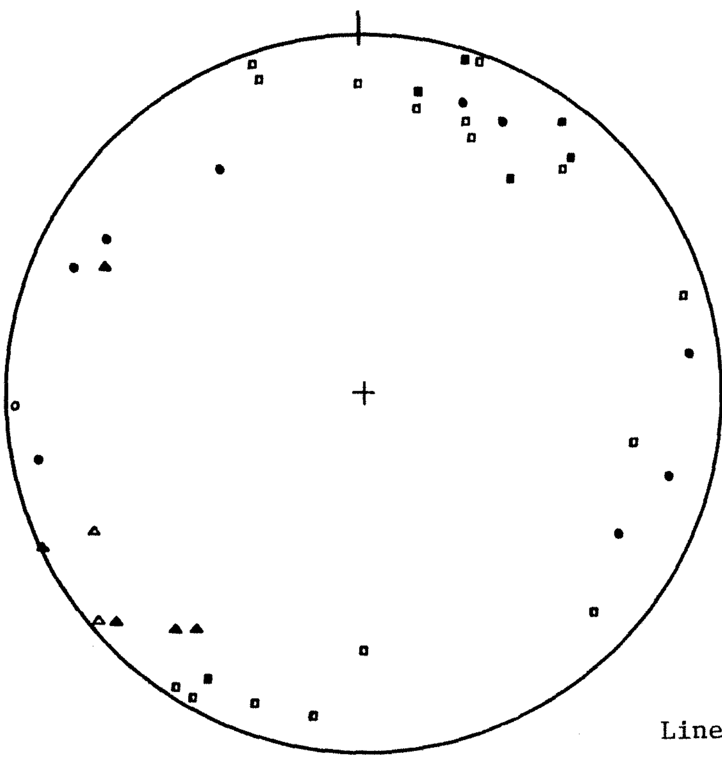


Linear

Subarea 10

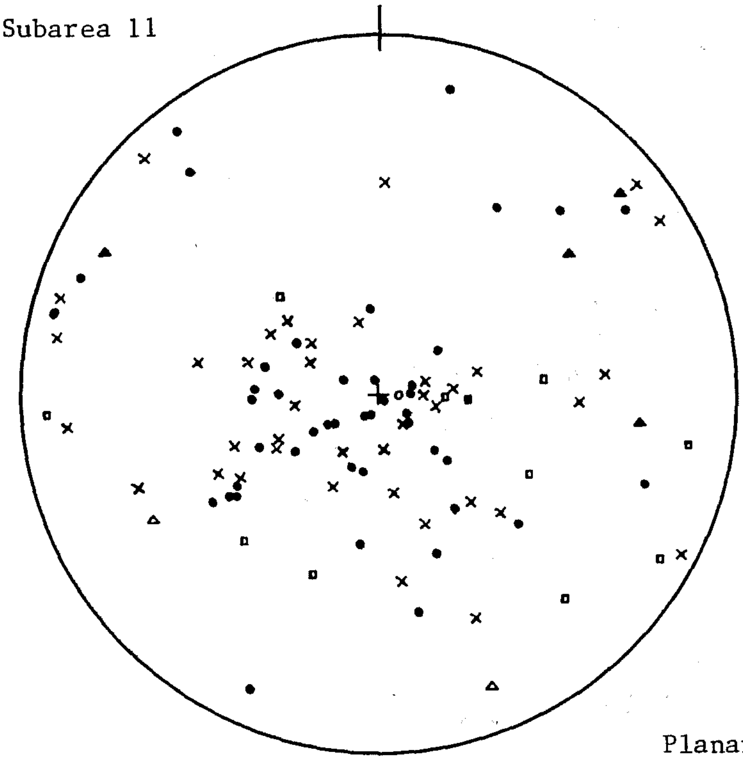


Planar

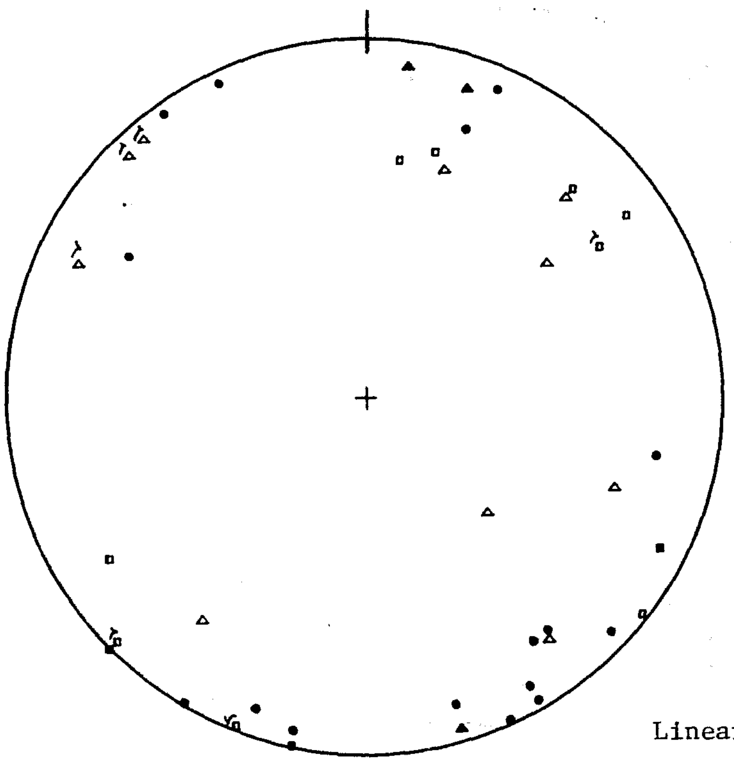


Linear

Subarea 11

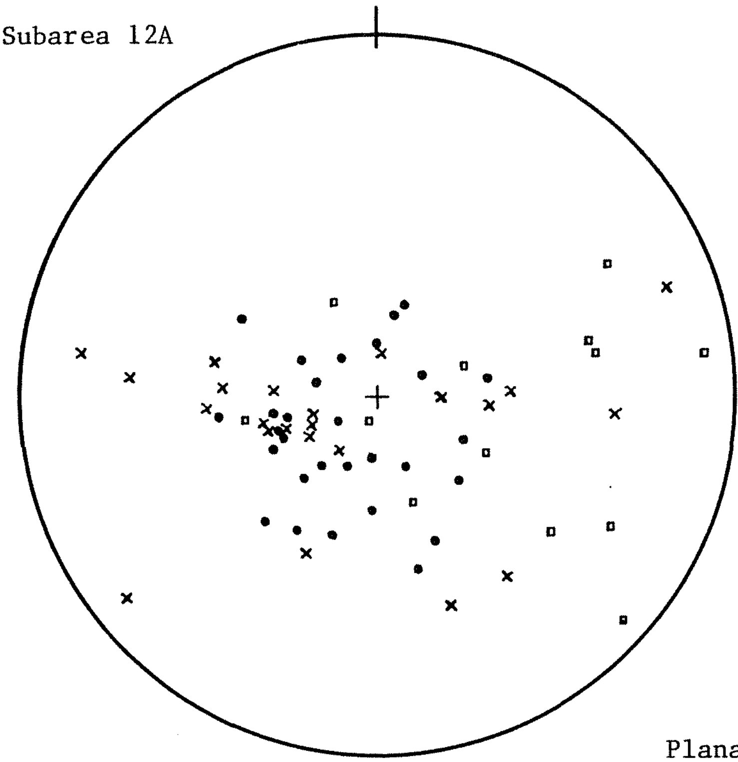


Planar

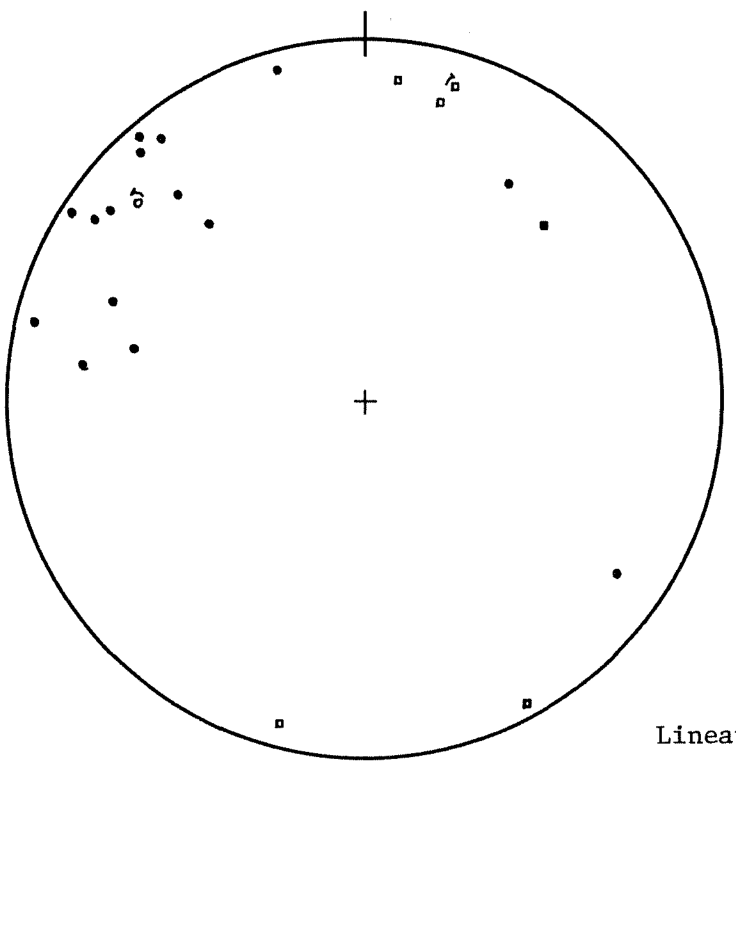


Linear

Subarea 12A

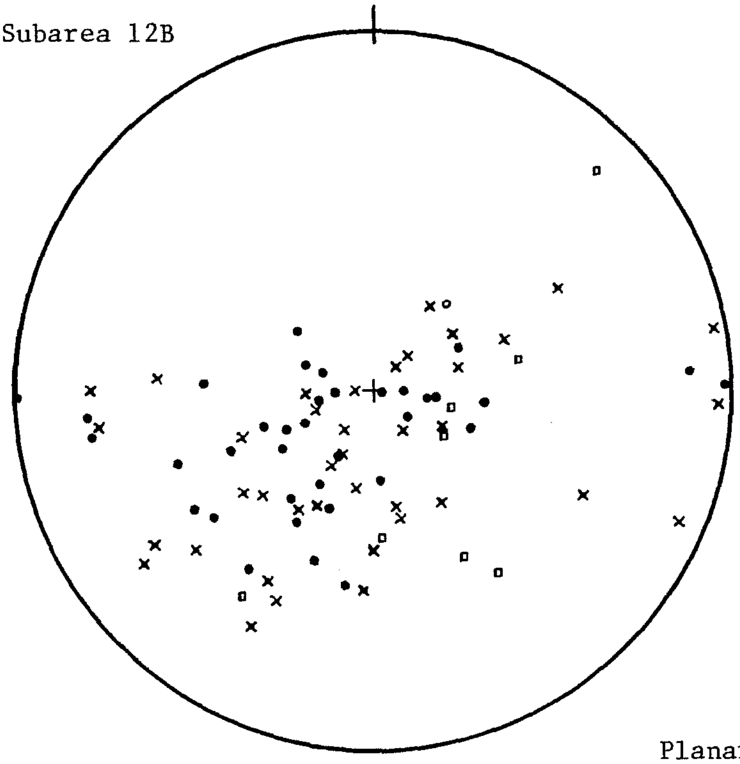


Planar

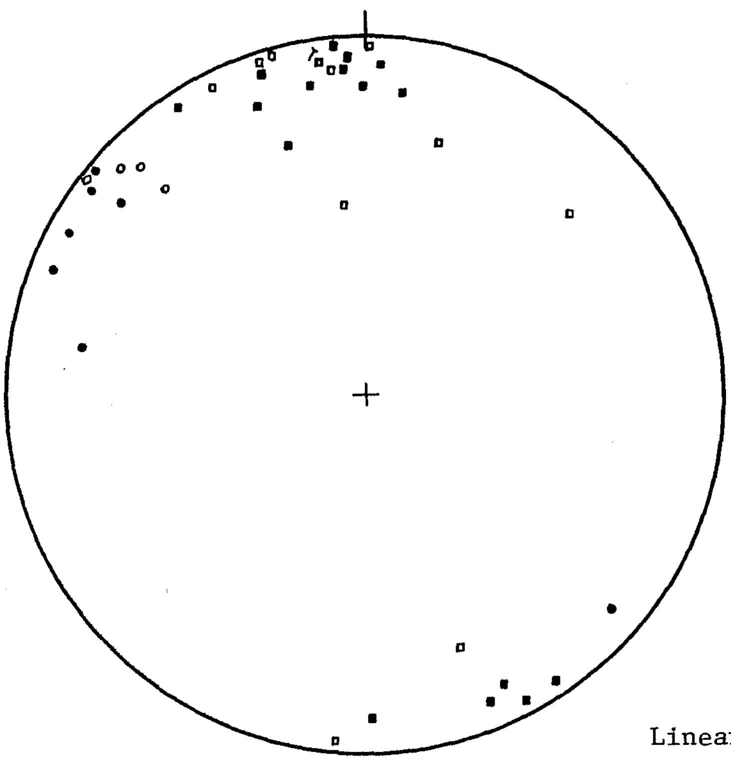


Linear

Subarea 12B

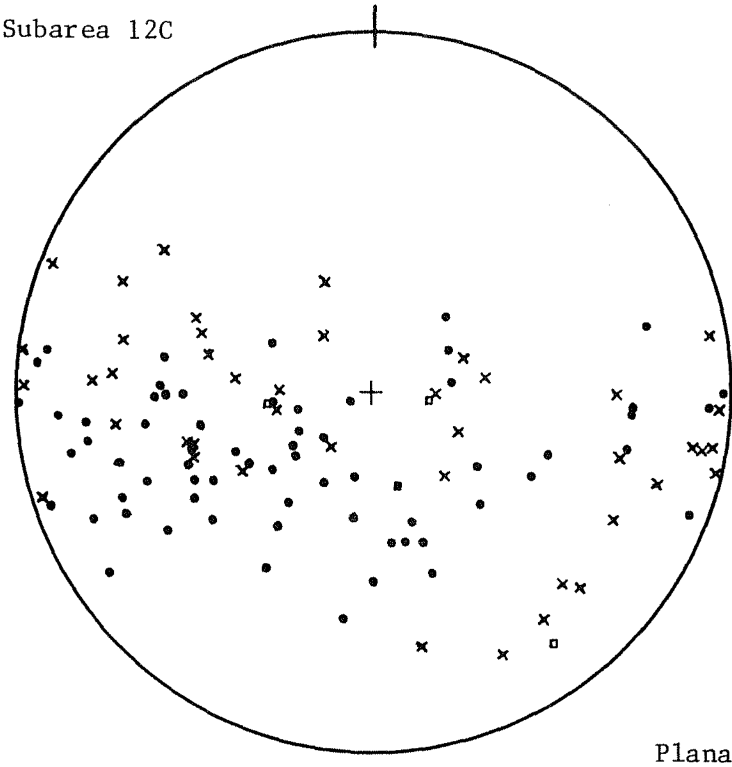


Planar

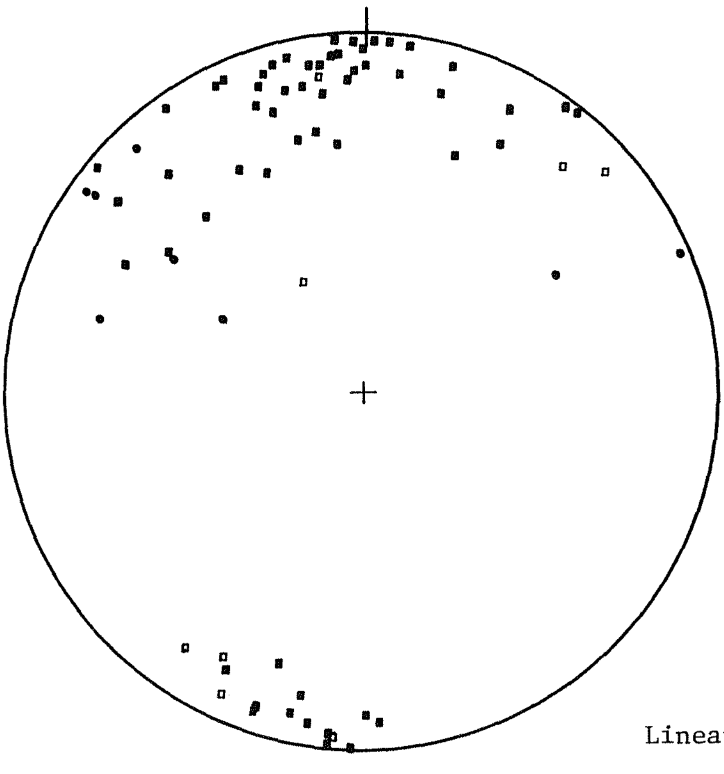


Linear

Subarea 12C

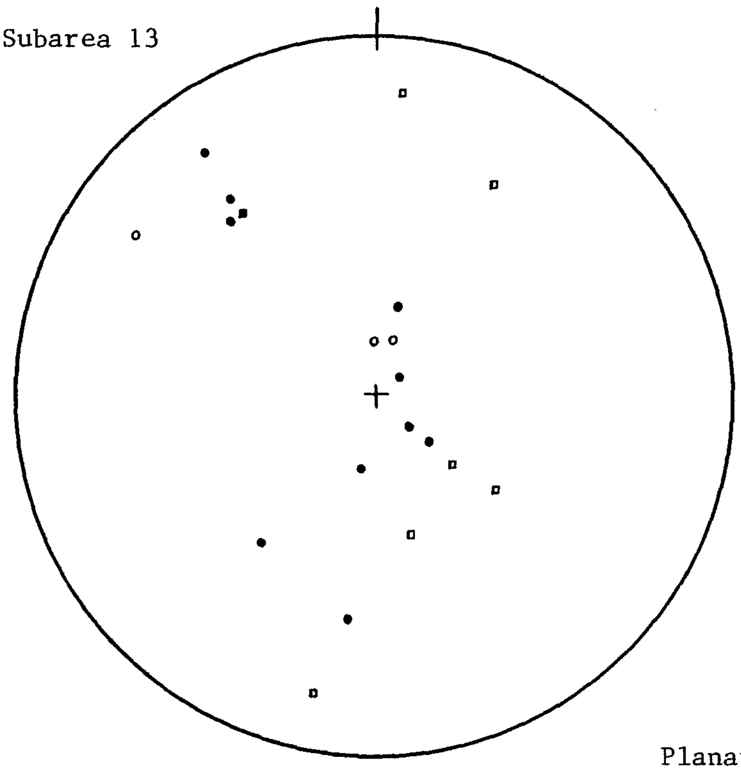


Planar

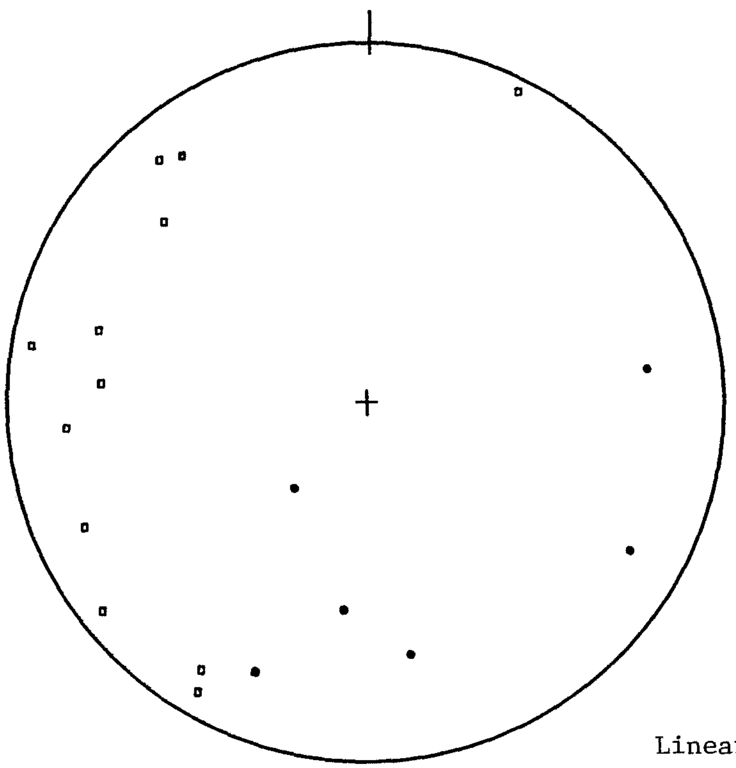


Linear

Subarea 13



Planar



Linear

fairly consistent, with a northerly trend and gentle west dip (Figure 28, 29). This differs from the attitudes observed along strike to the south on the west margin of the Fitchburg Plutonic complex where the average dip of foliation is toward the east. West of the fault, the general foliation is very gently dipping, but there is less consistency in orientation than is observed east of the fault. This variability in attitude can be generally attributed to later folding. This is especially evident on the equal area projections for subareas 3, 9, 10, and 12 (Figure 29). Subarea 4 is one which is characterized by lack of consistency in foliation attitude. This can be seen easily on Plate 4 and in Figures 28 and 29. The intersection of several phases of folding of relatively equal dominance in this area results in the random looking foliation pattern in the equal area net plot.

Cleavage

A pervasive cleavage is not evident throughout this area. Crenulation cleavage is developed locally in the hinge regions of fourth and fifth phase folds and may be pervasive within a relatively small area. In general, cleavage developed by fourth phase deformation is moderately west dipping. It is common in schist outcrops on Pratt and New Ipswich Mountains and on Mount Watatic. The fifth phase cleavage is generally more upright than that developed during the fourth phase.

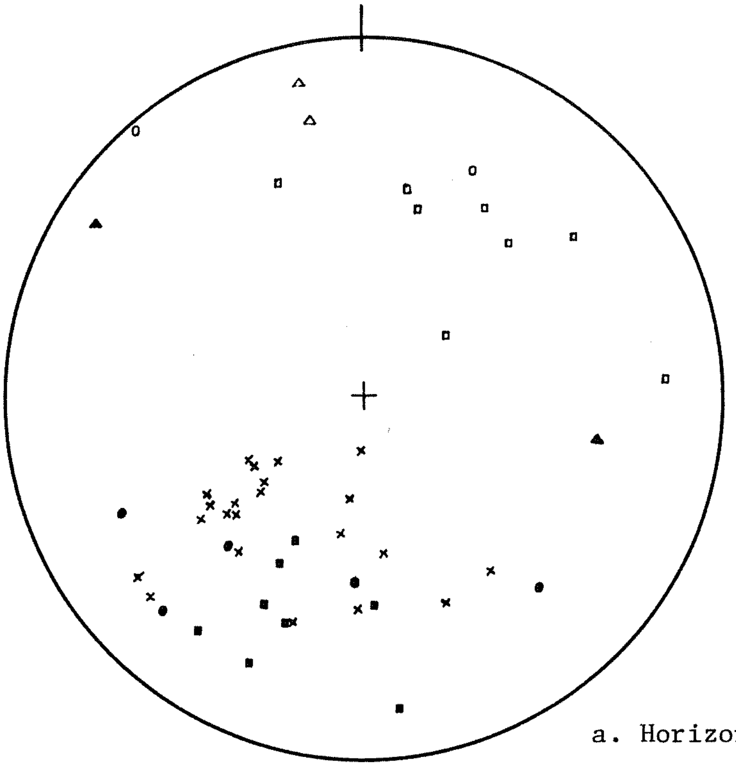
Linear Structural Features

As previously mentioned, a strong east - west mineral lineation is well developed throughout this area, East of the fault this linear fabric is the dominant and nearly exclusive lineation present, especially in the vicinity of the tonalite. Where the schists predominate, as in subarea 1A, a second lineation trending north - northwest is also fairly well developed in association with fourth-phase folds (Figure 29). West of the fault, the trend of linear fabric is more varied. In subarea 3, well developed fifth-phase folds are accompanied by a strong south - southeast directed linear fabric (Figure 29). Orientations of lineations observed on Mount Watatic (subarea 8) are produced by the intersection of third, fourth, and fifth phase folds. A third-phase east - west trend, a fourth-phase north - northwest trend, and a fifth-phase north - northeast trend are evident on the equal area nets for this subarea in Figure 29, although all three are not commonly seen together. The manner of interaction of these three phases has in part been determined through detailed structural analysis of the east peak of Mount Watatic. The data for this analysis is presented in Figure 30 and on Plate 6 and discussed below. This information will be used in the following detailed discussion of the various phases. Further north, the trend of the third-phase-related mineral lineation (east - west) is actually trending more toward the northwest. East of Pratt and New Ipswich Mountains, a north - northeast trending fifth phase lineation is also well developed. To the

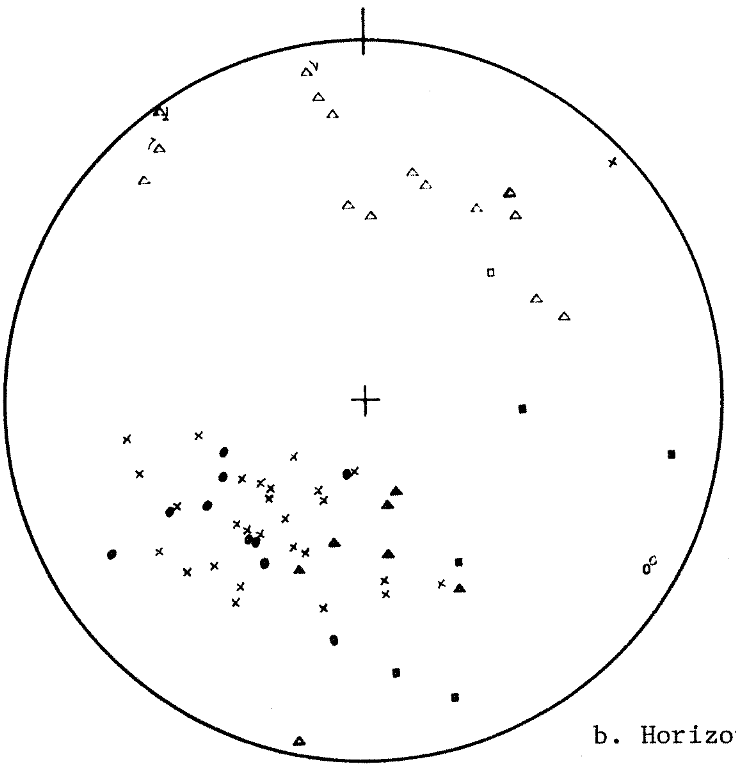
Figure 30. Equal area projections of structural data measured on the east peak of Mount Watatic (see Plate 6). Data collected from the horizontal surface (plan view) in Plate 6 is keyed to grids on the right side of the plate and plotted on the equal area nets in this figure. The symbols used for the nets, and the number of measurements presented are given below.

Symbols used and number of structural measurements presented in Figure 30.

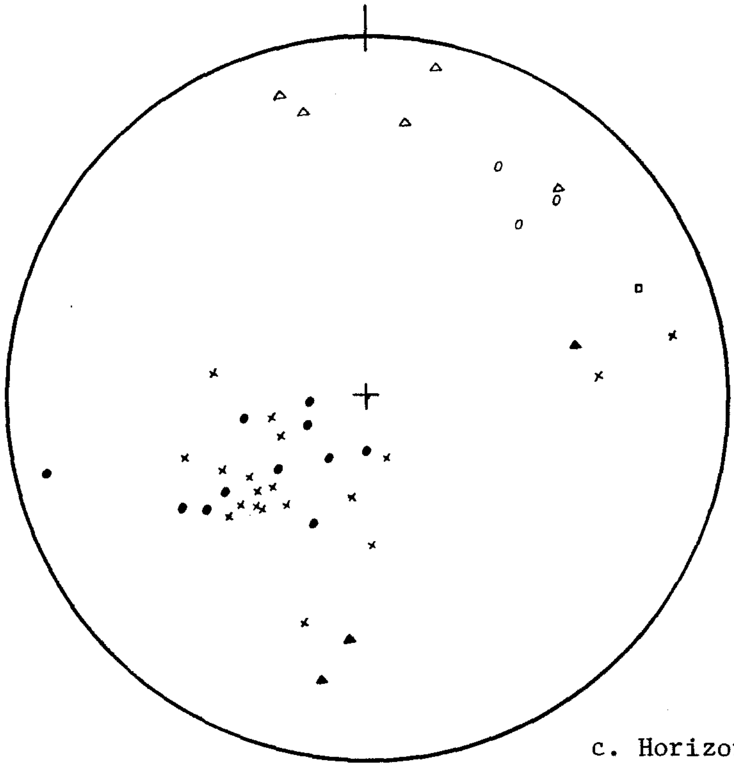
Net		a.	b.	c.	d.	e.	f.	g.	h.	i.	j.
Bedding	×	22	28	19	24	5	9	15	2	14	-
Phase 3 - Planar	●	5	10	11	43	29	18	38	4	4	-
Phase 3 - Linear	○	2	2	3	1	5	4	13	-	13	-
Phase 4 - Planar	■	8	5	-	20	7	2	4	5	6	-
Phase 4 - Linear	□	8	1	1	15	6	4	11	2	7	-
Phase 5 - Planar	▲	2	6	3	7	2	-	3	4	1	-
Phase 5 - Linear	△	2	16	5	8	10	6	15	-	13	-
Pegmatite veins	×	-	-	-	-	-	-	-	-	-	6
Tourmaline veins	●	-	-	-	-	-	-	-	-	-	3



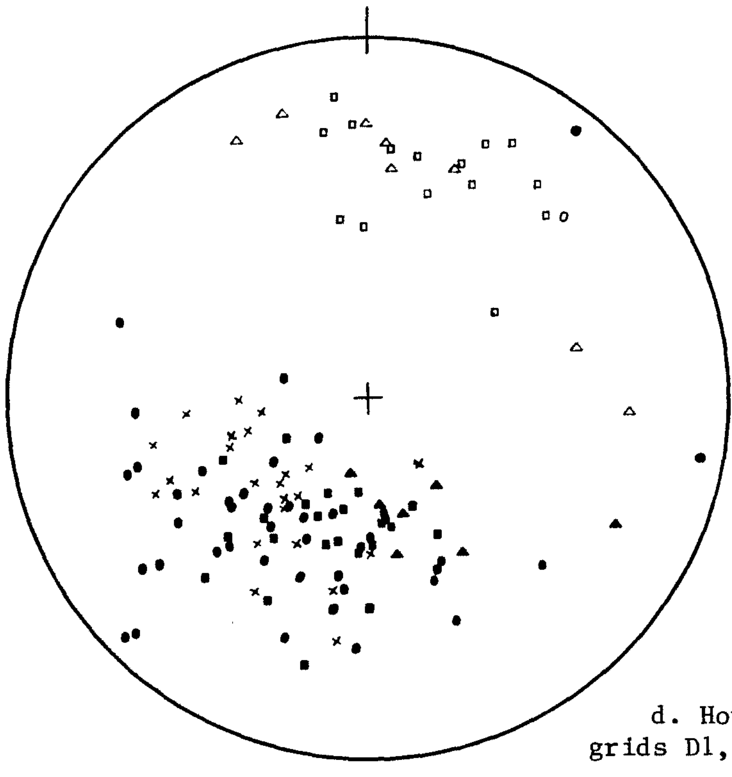
a. Horizontal grids A1, A2.



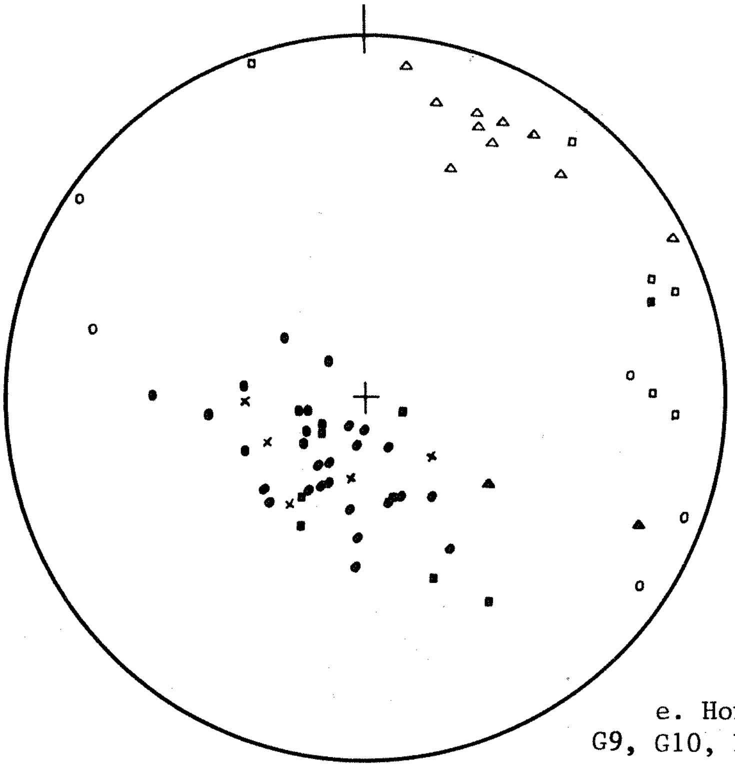
b. Horizontal grids B1, B2, B3.



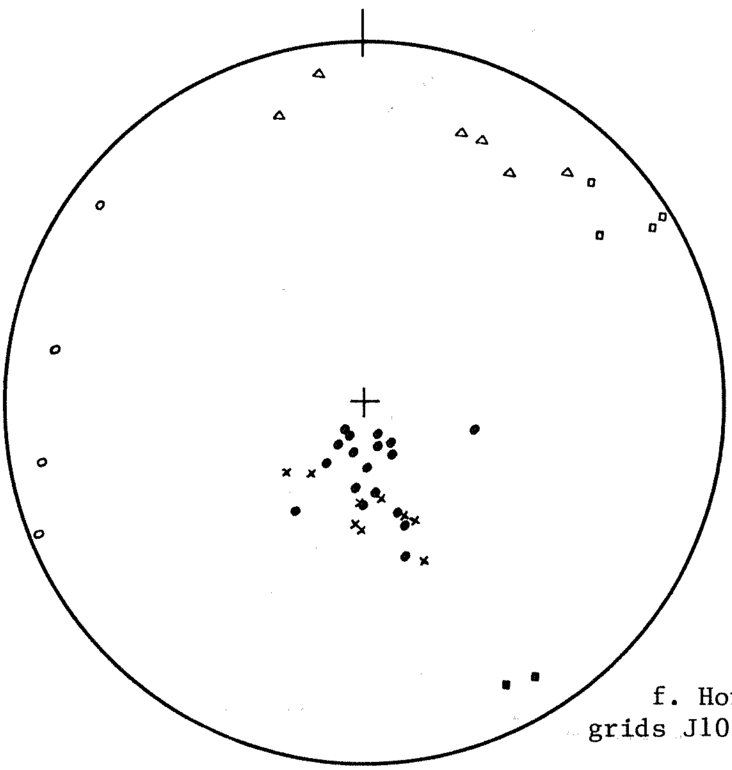
c. Horizontal grids C1, C2, C3.



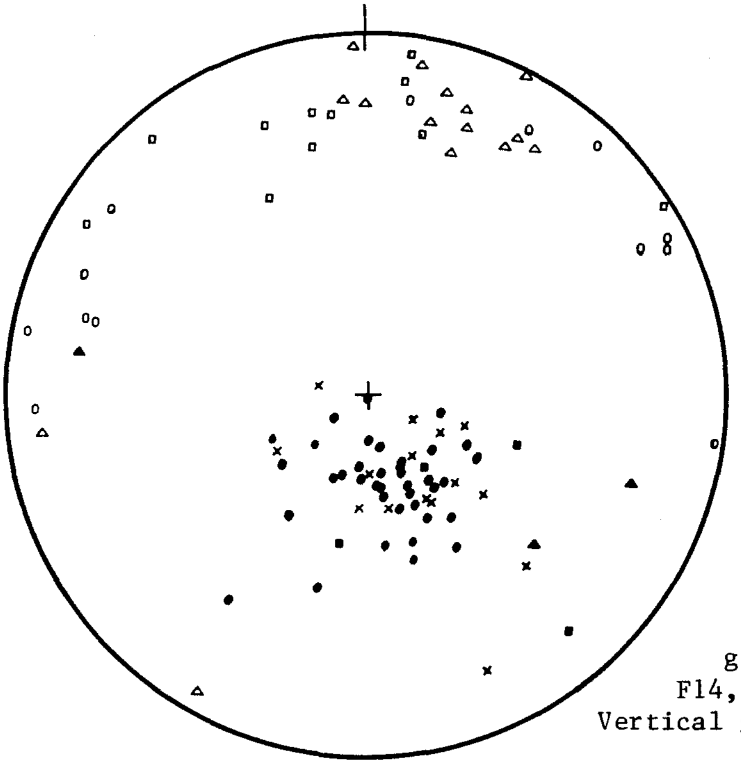
d. Horizontal grids D1, D3, D4, D5, D6.



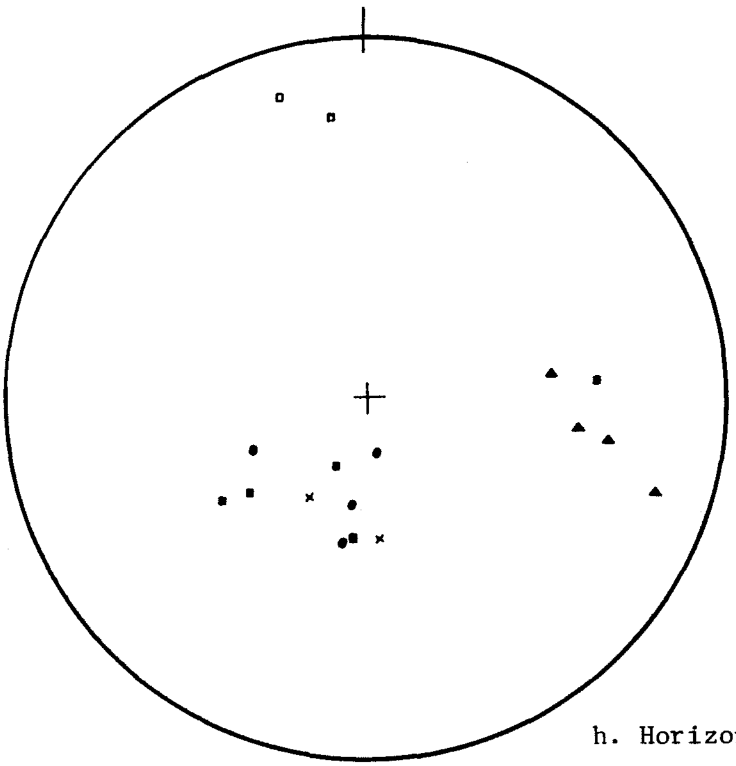
e. Horizontal grids
G9, G10, H9, H10, H11, I9, I10.



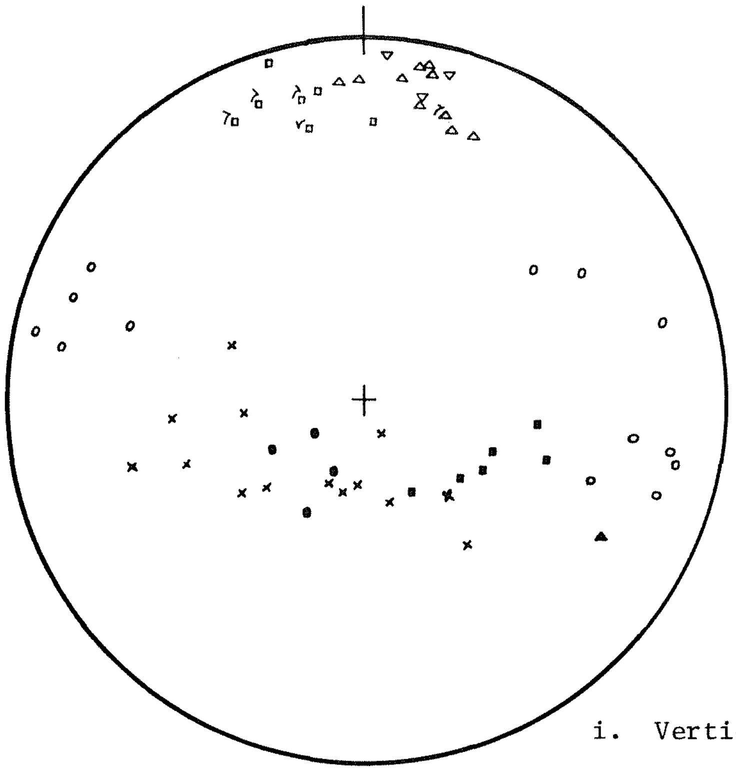
f. Horizontal
grids J10, K9, K10.



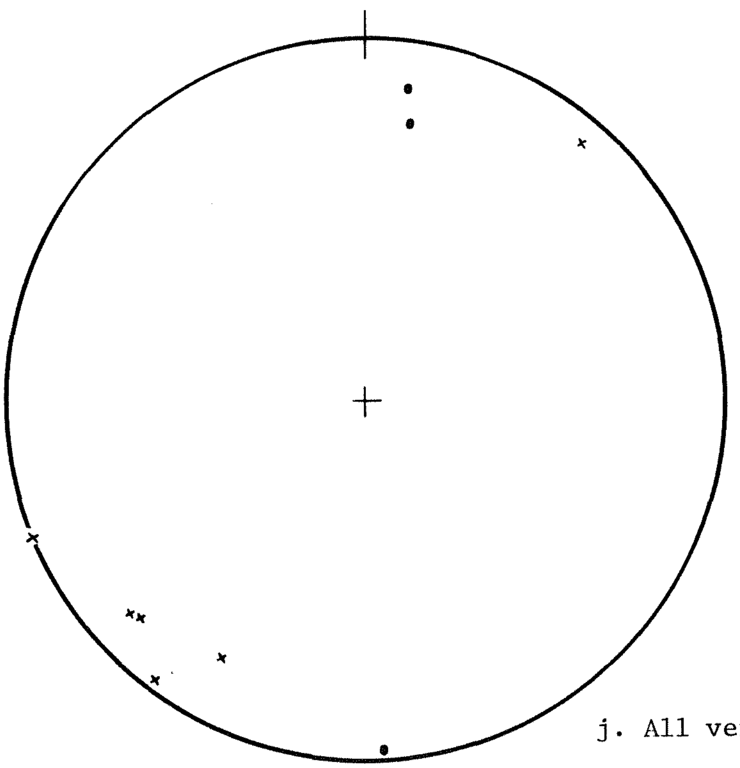
g. Horizontal grids F13, F14, F15, F16, F17, G17, Vertical grid F67.



h. Horizontal grid H17.



i. Vertical grids 1 - 4.



j. All veins.

west and on the ridge itself, a very strong north - south lineation is predominant, especially in the Gray Granulite Member of the Paxton. A shift in dominance can be observed from the third phase northwest mineral lineation in subarea 12A to the fourth phase north - south intersection lineation in subarea 12C. Subarea 12B is a zone of transition where both lineations are fairly strong (Figure 12C).

The significance of the linear patterns observed will be discussed in the section on detailed interpretation of structural features. Plate 5 shows the distribution of linear features for the entire area and gives a feel for the different patterns present.

East Peak of Mount Watatic - A Structural Study

A detailed structural study of the east peak of Mount Watatic, a large bedrock exposure of intricately folded gray- and rusty-weathering schists, provided much insight into the type of interference between the later phases of folding in the Ashburnham-Ashby area. Several drawings of parts of the outcrop are shown on Plate 6. They were drawn to scale by placing a five-foot square grid over chosen areas. Planar and linear structural features measured in the grid areas shown on the equal area projections in Figure 30.

A south-facing vertical joint face, drawn at a scale of 1 inch = 1 foot, is shown as vertical grids 1 - 4 along the top of Plate 6. This shows several third phase isoclinal folds folded by fourth phase folds with moderately west-dipping axial surfaces or gently warped by upright fifth phase folds. The map view (Plate 6) of the relatively horizontal area south of this vertical face was drawn at 1 inch = 5 feet. On the right-hand side of Plate 6, a gridded reduced version keys it to the equal area nets of Figure 30. The map view shows the gentle folding of fourth phase folds by fifth phase folds. From west to east the trace of the fourth phase fabric goes through a gentle north-plunging fifth phase syncline. This is the map-scale syncline that forms the heart-shaped pattern on the peak. The location of vertical grid F67 (lower left-hand corner of Plate 6) is shown on the map view. Planar and linear structural features plotted on equal area nets in Figure 30 show the change in attitude of the planar fabric and the strength of the late northerly trending linear fabrics.

DETAILED INTERPRETATION OF STRUCTURAL FEATURES

Features Formed During Earliest Recumbent Folding

Minor folds and other small scale features. Very few of these were observed and none can be absolutely associated with nappe-stage deformation, In terms of minor folds, the best evidence for this very early phase of folding is in an outcrop (Figure 31) 800 feet due west of the summit of "Gypsy Hill", the irregularly-shaped hill just to the east of Pillsbury Road. This outcrop of well bedded gray schist shows possible evidence for three phases of folding. The final and most

Figure 31. Sketch of an outcrop at station PAY 143 looking west. The outcrop shows the interference of possibly three phases of folding. The third phase folds are crenulations with gently west-dipping axial surfaces that appear subhorizontal in this view. Possible first and second phase folds are numbered. See text for explanation.

pervasive set of folds in the outcrop has the character and attitude of the third phase folds described throughout the area. The two folds labelled '2' on Figure 31 may share the same axial surface. If this is true, they fold the axial surface of the folds labelled '1' and are in turn refolded by the predominant third phase folds. No axial plane foliation nor lineation associated with this early fold was observed.

Map scale evidence. Map scale evidence for nappe-stage axial surfaces is based on the stratigraphic interpretation that the alternating belts of Paxton Formation and Littleton Formation represent repetitions by folding of the same stratigraphic sequence. This would imply that each belt of rock mapped as Silurian Paxton Formation was probably deposited at roughly the same time as the others, but in different parts of the sedimentary basin. These rocks, overlain by gray schists of the Littleton Formation, were then transported into the Ashburnham-Ashby area by large scale nappes. By this interpretation a nappe stage axial surface lies at the center of each distinct belt of rocks mapped in this area. Rocks mapped as Paxton Formation form the cores of anticlines and rocks mapped as Littleton Formation form the cores of synclines.

The exposed Granulite Member of the Paxton Formation in the northwestern part of the area (Plate 1 and Plate 2 - cross section A - A') is interpreted to lie in a north-plunging isoclinal structural syncline that may represent a nappe stage stratigraphic anticline closing to the east. If so, it is the only map-scale closure of the first phase exposed in this area.

This interpretation of a repeated Silurian - Devonian stratigraphy in large scale nappes is also favored by Field (1975) in the Ware area, by Tucker (1977) in the Barre area, and by Tucker (1978) in the Wachusett Mountain area, all in central Massachusetts (Figure 1). These nappes are part of the same system of nappes described by Robinson (1967) and Thompson et al. (1968) in the Bronson Hill anticlinorium. Some workers mapping further south in central Massachusetts and in north-central Connecticut (Peper, 1974; Seiders, 1974; Peper and Pease, 1975) do not believe in stratigraphic repetition by folding within the Merrimack syhclinorium and suggest instead that the stratigraphic sequence east of the Monson gneiss is a west-dipping homoclinal sequence faulted against the Bronson Hill anticlinorium.

Features Formed Early in Regional Backfolding - Phase Two Deformation

Minor folds and foliation. The predominant foliation observed in the Ashburnham-Ashby area appears to have developed during phase two deformation parallel to the axial surfaces of folds produced at this time. The general attitude of the planar fabric in the area can be characterized by the attitude of the foliation which is nearly horizontal or dipping gently west. The foliation is defined in both the stratified rocks and in the tonalite by parallel alignment of platy minerals, predominantly micas, and by some flattening of the more granular minerals such as quartz and feldspar. This foliation is folded by the east - west trending third-phase folds, but is parallel to the axial surfaces of second-phase folds, where they can be distinguished. This relationship can be seen in the outcrop sketched in Figure 31. Unfortunately, minor folds produced during the second phase are rarely observed or are masked by third phase deformation.

Lineations. Lineations developed during second phase folding have been mostly destroyed by the very strong east - west trending lineation and intense shearing that accompanied third-phase folding. Weak northwest-trending lineations developed in the vicinity of map-scale second-phase fold hinges, especially in the tonalite east of the fault, may represent second phase lineations.

Map scale evidence. The best evidence for second phase folding is in the map of the schist - tonalite contact in areas of excellent bedrock exposure, in particular in the area south of Route 119 and north of Whitney Road. Third phase lineations in this area have a consistent west - southwest plunge, however, foliation attitudes and the positions of fold hinges (A and B on Figure 32) with respect to topography make it impossible for the folds to have a trend parallel to the mineral lineation, and suggest the folds trend northwest. This trend has been used, in general, to project folds of this phase onto the cross sections of Plate 2. Axial surfaces of major phase-two folds are labelled on the cross sections. A perspective on these folds can be seen in the structural relief diagram of Figure 33.

Figure 34 is a map showing the traces of axial surfaces of major second and third phase folds. The predominance of the second phase folds on the east side of the fault may be due to the association of this phase with intrusion of the tonalite discussed below. Thickening of the tonalite toward the north in the eastern portion of the area is interpreted here as doubling due to second phase folding, but may be partly a function of poor exposure.

West of the fault, most of the major second phase folds shown are based on structural interpretation in areas of poor bedrock exposure. In order to piece together the known geology in areas of good exposure into a comprehensive map pattern, a phase prior to the third phase folds is necessary. Since this phase is observed to the east of the fault, its presence is assumed west of the fault. One good second phase hinge has been mapped west of the fault on the small knob south of Fisher Hill.

Intrusion of the tonalite. Several lines of evidence from both map scale and outcrop scale observations in this area suggest that intrusion of the tonalite took place during the second phase of folding. As can be seen from the map pattern and on cross sections, the tonalite crosscuts stratigraphy and the interpreted nappe stage

Figure 32. Poriton of the geologic map of the Ashburnham-Ashby area (from Plate 1). Specific hinge localities mentioned in the text are labelled. The tonalite is shaded black, the country rock is unshaded.

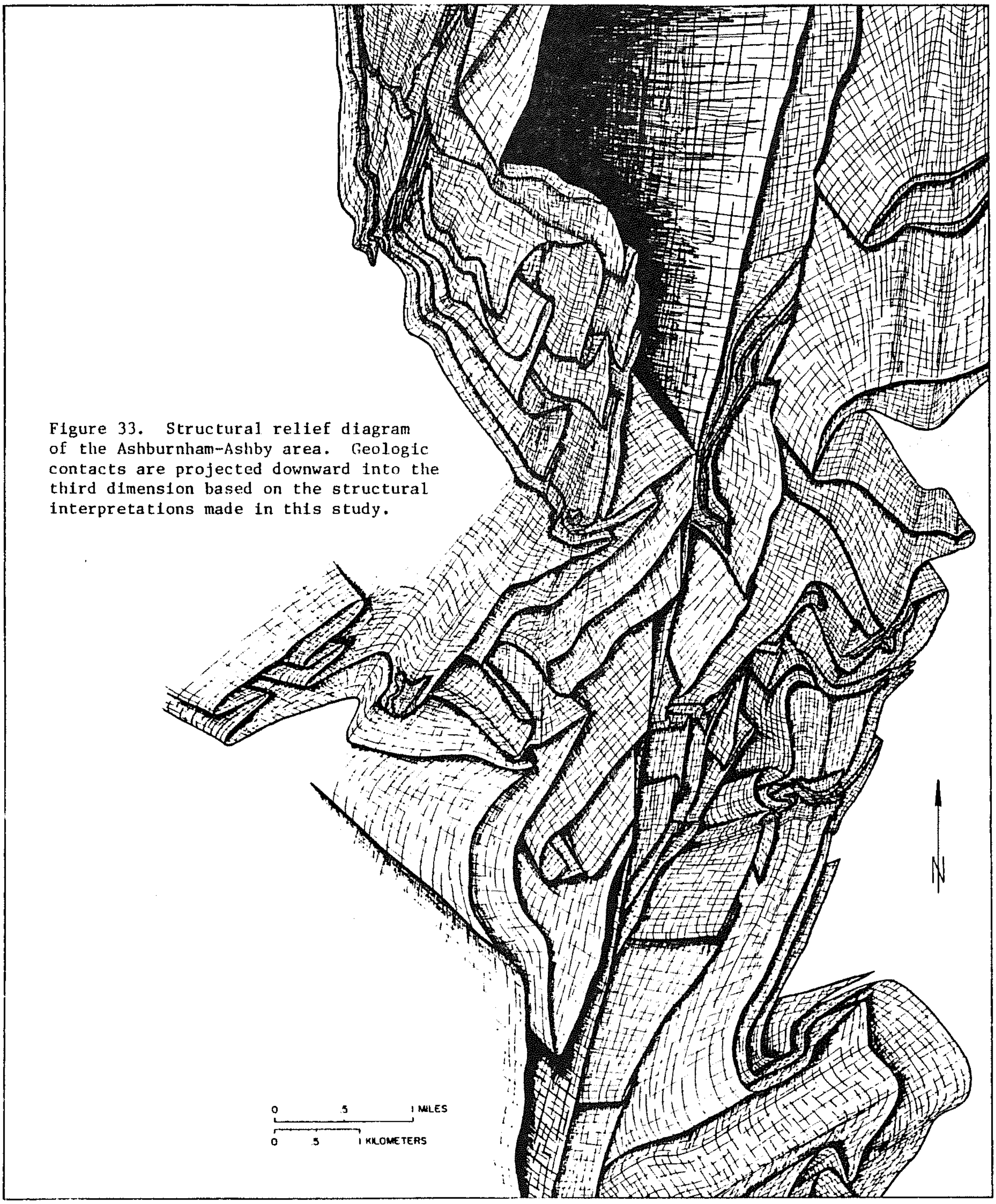


Figure 33. Structural relief diagram of the Ashburnham-Ashby area. Geologic contacts are projected downward into the third dimension based on the structural interpretations made in this study.

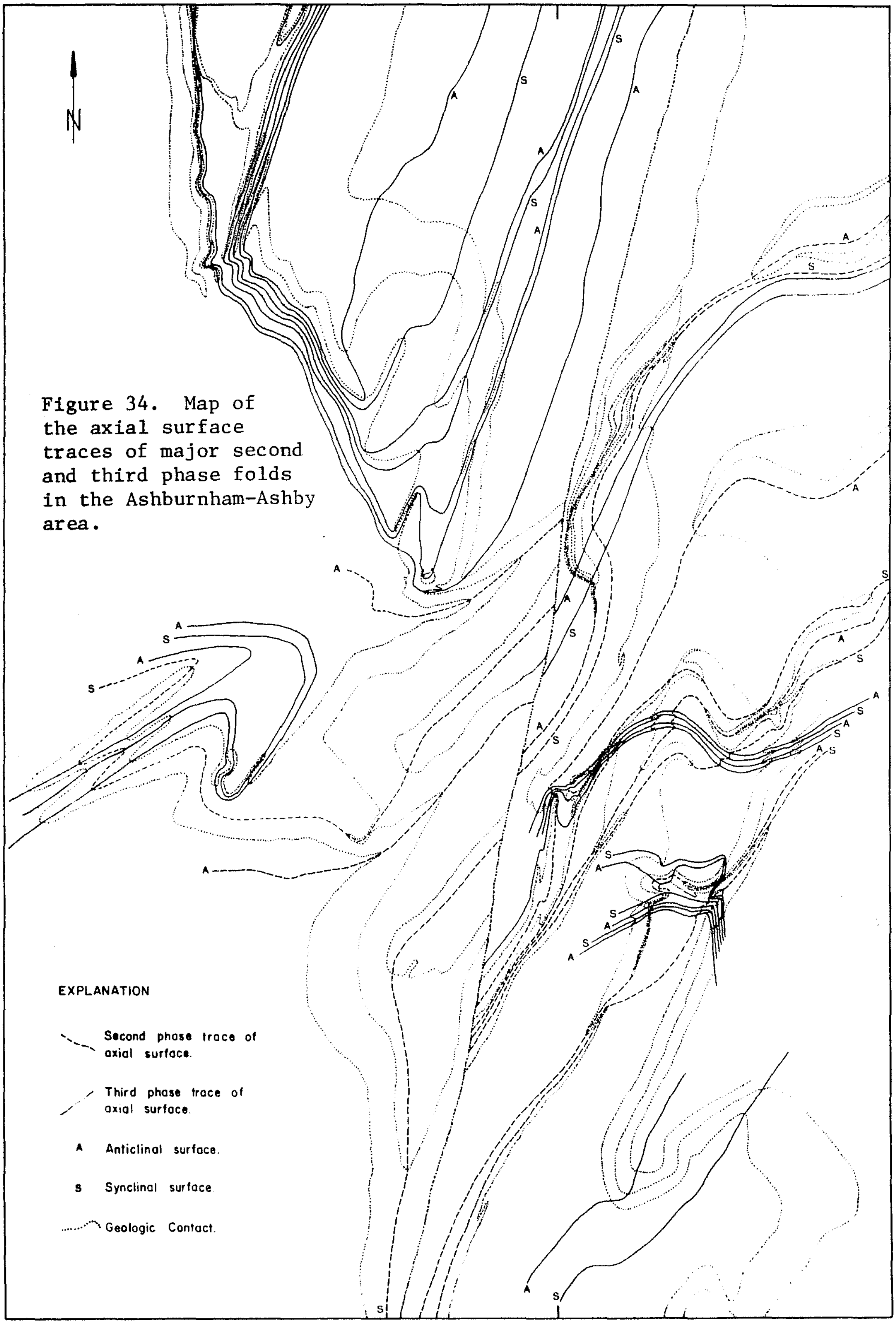


Figure 34. Map of the axial surface traces of major second and third phase folds in the Ashburnham-Ashby area.

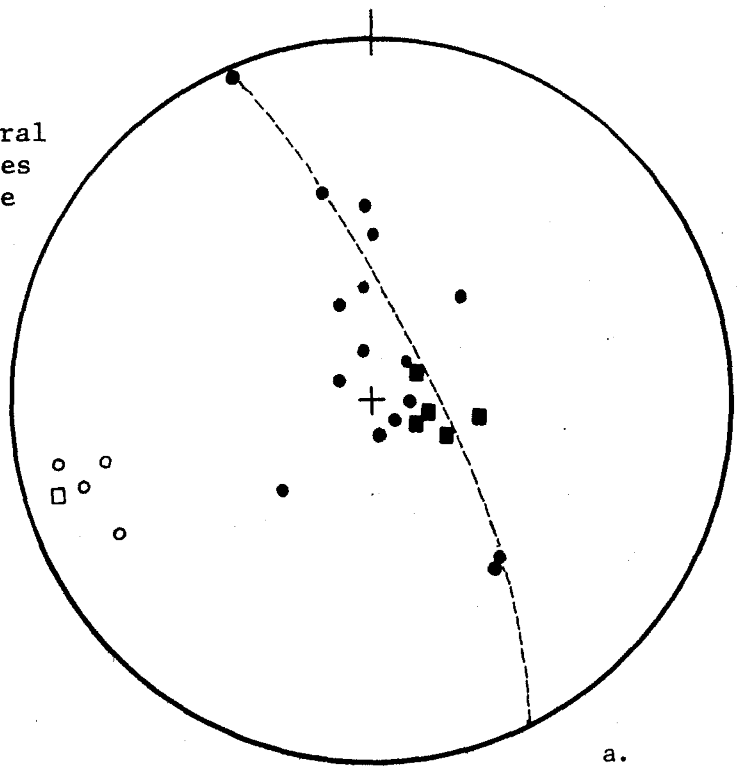
axial surfaces at the center of each stratigraphic belt of rock. This, of course, suggests post-nappe-stage emplacement. The prominent foliation in the area and the folds associated with it are strongly developed in the tonalite. These folds and foliation are folded by the well developed east-west trending folds of the third phase. On the west slope of "Gypsy Hill" in the vicinity of Pillsbury Road, a thin isoclinal fold (labelled C on Figure 32) of rusty- and gray-weathering schists is cross cut by a thin arm of the tonalite. The schists and tonalite have subsequently been deformed together by folds of the third phase. This evidence suggests a very specific time of intrusion of the tonalite. Prior to intrusion, the second phase had begun to fold the stratified rock, however, the main folding and foliation development related to this phase occurred during or after the time of tonalite intrusion.

Features Formed Late in Regional Backfolding - Phase Three Deformation

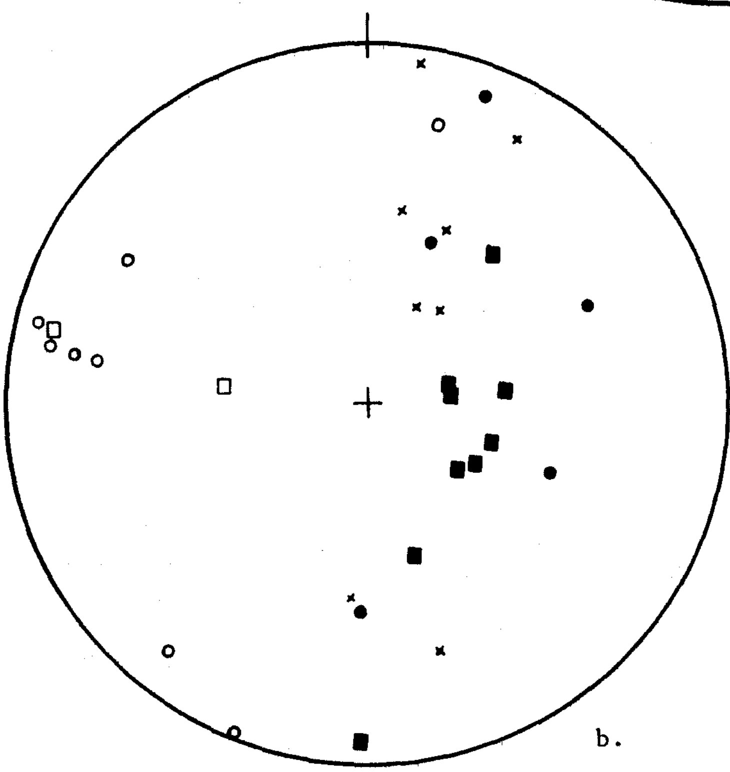
Minor folds and foliation. Minor folds related to the third phase of folding are abundant and generally well developed, ranging in amplitude from centimeters to meters. A foliation is locally developed in the hinge regions of these folds, and in the schistose rocks it may have the character of a crenulation cleavage. Overall, the predominant foliation in the rock is folded by the third phase folds but is not overcome by any planar fabric related to the folds. Third phase folds have relatively horizontal axial surfaces throughout the area. They are generally isoclinal (as shown in the vertical grids of Plate 6) but may be relatively open with a crenulation-like axial plane foliation (see Figure 31). The folds are commonly reclined. Although the isoclinal character and attenuated limbs of these folds makes determination of rotation sense difficult, they generally tend to have a north over south sense of movement. This rotation sense is evident on cross sections D - D' and E - E' of Plate 2.

The attitude and affects of the third phase folds can be seen from the structural data plotted on the equal area nets of Figure 35 which was collected at two outcrops located east of the fault. Figure 35a is an equal area projection of structural data from an outcrop of tonalite folded by an outcrop-scale third phase fold. The fold axes are strongly clustered in a direction just south of west and plunge down the dip of the axial plane. The predominant foliation shows a spread due to folding by these third phase folds. A similar structural character can be seen in the data plotted in Figure 35b collected from the outcrop pictured in Figure 31 (in the vicinity of C on Figure 32). Here the third phase fold axes and associated lineations plunge slightly north of west. Axial plane measurements show a cluster indicating a north northeast strike and gentle west dip. The bedding and predominant foliation are, once again, spread due to third phase folding.

Figure 35. Equal area projections of structural data from two localities in the Ashby quadrangle showing the local effects of third phase folding. × Pole to bedding, ● Pole to foliation, ■ Pole to third phase axial plane, ○ Third phase mineral lineation, □ Third phase fold axis. a. Data collected from a third phase fold in the tonalite at station PAY 497 (see locality D of Figure 32).



a.



b.

Dashed line (above) represents the great circle distribution of poles to foliation. b. Data collected from the outcrop pictured in Figure 31 (near locality C of Figure 32).

West of the fault the character of the third phase folds is best shown by the detailed structural analysis made of the east peak of Mount Watatic. The tight refolded isoclinal folds of the third phase are most easily seen on the vertical grids 1 - 4 and on vertical face F67 of Plate 6. The linear fabric associated with these folds, shown on the equal area nets of Figure 30, especially nets 7 and 9, generally trends slightly north of west with a shallow plunge down the dip of flat axial surfaces. In this area, the strength of later fabrics makes it difficult to distinguish the third phase axial planar fabric from the predominant (second phase) foliation.

Lineations. A very strong, generally east - west trending lineation is developed throughout the area parallel to the fold axes of third-phase folds. This lineation is represented by parallel alignment of sillimanite, micas, or elongate quartz and feldspar grains. In places the mineral grains are extremely attenuated. The lineation is best developed east of the fault. West of the fault, later phases interfere with it locally.

The trend of the lineation varies somewhat through the area. In the southern and eastern portions (Figures 28, 29) it plunges west or slightly south of west. In the northern and western portions of the area, it rotates toward the northwest (compare Figure 35 a and b).

It appears that this lineation may represent the direction of movement of the backfold stage. In this area extreme transport, suggested by the intensity of the lineation and its association with shearing fabrics and mylonitization, may have rotated the axes of the third phase folds into a direction parallel to the transport direction.

Formation of mylonites. Thin mylonites and a mylonitic foliation are developed in some areas with an attitude nearly parallel to the predominant foliation. Associated with this mylonitic fabric is the strong east - west lineation characteristic of third phase folds. The mylonitization may have occured during the time of most rapid transport of third phase folds, possibly due to local shearing of the short limbs of the folds. Since the mylonitic foliation mimics the second phase foliation but appears to have formed at the time of third phase deformation, it is suggested that the second phase represents early movement of the backfold stage and that the third phase folds formed during the time of most active backfolding. Where sillimanite is still preserved, it is elongate parallel to the third phase mineral lineation. Because sillimanite is a characteristic mineral of the peak metamorphic assemblage in the area, its orientation suggests that it formed before or during the time of maximum backfolding and peak metamorphism.

Map scale evidence. The traces of axial surfaces of third phase folds are shown as solid lines in Figure 34. Large scale third-phase folds are common throughout the area. The "Heartbreak Corners" area, in the vicinity of Marble and Byfield roads, is dominated by tight map-scale third-phase folds (see gently west plunging folds in Figure 33). Abundant bedrock exposure, mapped in the autumn under a diminished vegetative cover, allowed quite accurate mapping of this complex stack of third-phase folds. The large third-phase fold mapped on Jewell Hill is, unfortunately, separated from the rest of the field area by wide expanses of poor bedrock outcrop so that its relationship to the rest of the map area is incompletely understood.

West of the fault third-phase folds are generally tight refolded isoclinal folds. On Mount Watatic, a third-phase syncline is downwarped by a fifth phase syncline to produce the heart-shaped pattern on the east peak. This style is reflected in the style of minor features mapped on the east peak. In this exposure (Plate 6) numerous recumbent, west-plunging third-phase isoclinal folds are refolded by more upright northerly-plunging fourth and fifth phase folds.

The map-scale third phase folds evident in the gray - rusty schist contacts northwest of Mount Watatic plunge northwest, As can be seen in the structural relief diagram of Figure 33 later folding of these third phase axial surfaces forces the hinges back up out of the ground east of the Pratt Mountain ridge. This concentration of southeast-plunging third phase fold hinges in an area of poor outcrop east of Pratt Mountain was drawn here as a necessity of structural interpretation between areas of good exposure.

On the south side of Little Watatic Mountain, axial surfaces of third-phase folds dip down the slope of the topography, greatly complicating mapping even in this area of excellent exposure. Map-scale third phase folds appear to be refolded by a large-scale fourth phase fold (Figure 33). The nature of the structural fabric in this area appears chaotic, as can be seen on Plates 4 and 5 and on the equal area projections of Figure 29, subarea 4.

Features Formed During Regional Dome Stage - Phase Four Deformation

Minor folds and foliation. The minor folds of this phase have gently to moderately west-dipping axial surfaces, northerly-trending axes, and high angle limbs. The rotation sense of these folds is characteristically west over east. This rotation sense persists throughout this study area and has been observed to the south by P. Robinson (personal communication) most notably at Church Rock in the Gardner quadrangle. The character of these folds is shown on Plate 6, especially on vertical grids 1 and 2 and in the western part of the plan view. On the related equal area projections (Figure 30), the trend of fold axes is variable due to late folding, but is generally north. The planar fabric produced by the fourth phase is a crenulation cleavage developed parallel to the axial surfaces of fourth-phase folds. The cleavage is generally restricted to hinge areas of these folds. It is locally pervasive, in the hinge regions of map scale folds. This is true on the southwest slope of Mount Watatic. A fairly flat west-dipping crenulation cleavage is pervasive in this area on the short limb of a major fourth phase fold.

Folds related to the fourth phase are most abundant in the northwest part of the study area (Figures 28, 29), however they are also well represented in the vicinity of Little Watatic Mountain and Mount Hunger (Figure 29, subareas 3 and 4). Phase four deformation is weak east of the fault zone and the crenulation-like deformational features associated with this phase appear to be particularly sparse in the vicinity of the tonalite.

Lineations. The linear fabric associated with this phase is mainly produced by the intersection of the fourth phase crenulation cleavage with earlier surfaces, but parallel alignment of mineral grains is present in areas of well developed lineation, generally in hinge regions. In a few subareas in Figure 28 including 3, 8B, 10, 12B, and 12C, most of which are in hinge regions of map-scale fourth phase folds, fourth phase minor folds and lineations are very well developed. The trends of these lineations vary from slightly north-northwest to northeast due both to irregularites created by earlier folding and to refolding by the gentler phase-five folds.

Map scale evidence. Several map-scale folds of the fourth phase occur in the northwest portion of the map. The traces of their axial surfaces are shown on Figure 36. On a large scale these asymmetric folds with high angle limbs have deformation concentrated at the hinges or along short limbs. The folds with traces running through Mount Watatic and Little Watatic Mountain are characterized by strong development of cleavage and minor folds along the short limb. In this case, although the enveloping surface of the short limb is near vertical, this attitude is rarely seen due to reorientation along the short limb by crenulation cleavage and related small scale folds in the schists. In contrast, the entire Pratt - New Ipswich Mountain ridge is underlain by a large scale fourth-phase fold in which the nearly vertical attitude of the short limb is well preserved. This is due in part to the presence of the Gray Granulite Member of the Paxton Formation at the west base of the mountains. This unit reacts more stiffly to the imposed deformation than do the surrounding schists. In a traverse eastward from the west base of the mountain, the predominant planar fabric, either bedding or foliation, can be observed to change drastically from near vertical to near horizontal. This can be seen on the south side of Pratt Mountain in the granulite and near the ridge summit in the schists, which respond to the competent presence of the granulite. With distance from the granulite, the schist reflects the crenulation cleavage more strongly. The presence of this major fold on Pratt and New Ipswich Mountains is signalled not only by the attitude change described, but also by the abundance of fourth-phase minor folds in the area.

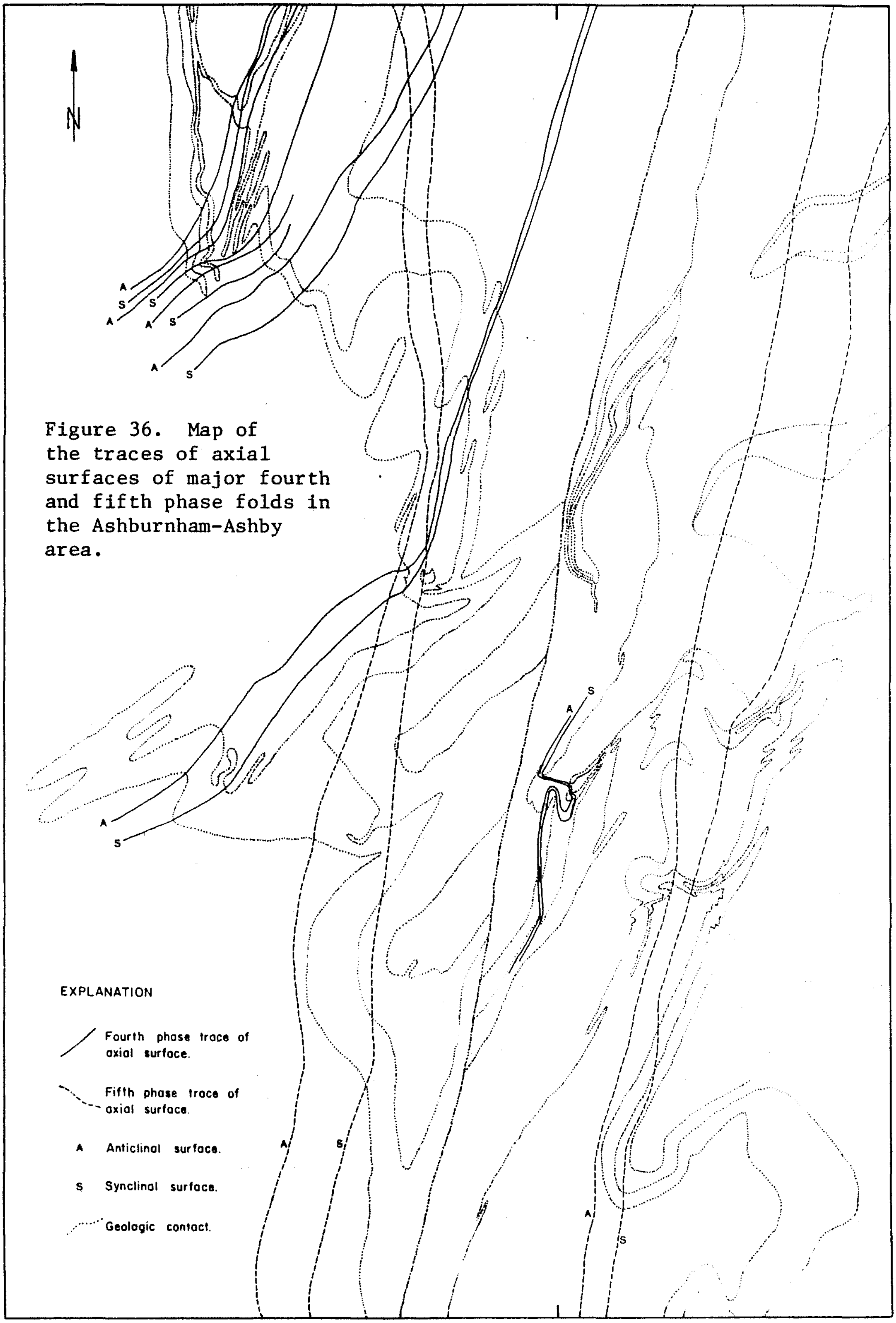


Figure 36. Map of the traces of axial surfaces of major fourth and fifth phase folds in the Ashburnham-Ashby area.

Phase Five Deformation - Late Warping

Minor folds and cleavage. Minor folds related to this phase are fairly pervasive open upright folds with a gentle northerly plunge. On a small scale, fifth-phase folds range from gentle warps in the earlier fabric to chevron-like folds, both with relatively steeply dipping axial surfaces. Unlike the fourth-phase folds, these do not have a consistent rotation sense over the area.

Typical open folds of this phase are shown folding the earlier fabric in the vertical grids of Plate 6. On a larger scale, on the plan view of Plate 6, folding of the fourth phase axial surfaces by these gentle open folds can be traced from west to east across the map. This is a reflection of the map-scale fifth-phase syncline that interferes with a map-scale third-phase syncline to form the heart-shaped pattern on the east peak of Mount Watatic. The north - south trend of these folds throughout the area is shown on the equal area projections of Figures 29 and 30.

A crenulation cleavage is locally developed in the hinge regions of some of the minor folds, commonly the more asymmetric ones. It generally strikes north and has a steep dip. The neck-lines of boudins in the vicinity of these folds (see Plate 6) are roughly parallel to the trend of the axes. The relationship between these structures, however, is uncertain.

Lineations. Lineations developed during this phase are formed by the intersections of the fifth phase crenulation cleavage with the earlier planar fabrics. These lineations, in general, represent the trends of fold axes of this phase. Weak mineral alignment occurs in some places parallel to the fold axes.

Map scale evidence. Map-scale folds of this phase are gentle open folds that produce subtle changes in attitudes of contacts. Two pairs of folds are represented in Figure 36. West of the fault, the main evidence for the anticline - syncline pair shown is the gentle change in attitude of the planar structural fabric on Mount Watatic (see Figure 33) that cannot be attributed to an earlier phase. On the southwest slope of the mountain, the anticline is shown by a change of average dip from gently west to gently east along a west to east traverse. On the top of the mountain, the syncline interferes with a tight third phase fold to produce the heart-shaped pattern observed on the east peak (Plate 6) and the change in dip of foliation across this synclinal axial plane can be observed on the south face of the mountain (Figure 33).

East of the fault, gentle fifth-phase folds deform the second phase axial surface indicated by A and B in Figure 32 and have a major effect on the pattern of contacts in this vicinity and in the cross sections B - B' and C - C' on Plate 2.

Evidence for Large Scale Post Metamorphic Faulting.

The north - northeast trending fault referred to here as the Stodge Meadow Pond Fault was located in the area based on several lines of evidence, including differences in rock types and different structural styles on either side of the proposed fault. Rocks on the east side of the fault, predominantly tonalite intruding schists, have been affected mainly by the second and third phase folds, whereas the rocks west of the fault, predominantly schists, have been strongly deformed by the later phases as well. The direction and amount of displacement on the fault cannot yet be determined with any certainty.

Shearing and silicification. The first evidence for the existence of a major fault was the discovery of large outcrops containing rocks that had been extremely sheared and silicified, presumably due to fault movement. Several of these outcrops form a linear trend in the vicinity of Mount Hunger, probably along the main zone of faulting. The effects of the shearing decrease with distance away from the fault. A suite of thin sections from rocks collected close to and within the fault zone display nicely the progressive change in style of deformation with an increase in the effect of shearing. In the least deformed rock in this suite, the country rock, in this case, tonalite, can still be identified. The original mineral grains have been extremely attenuated with a strong preferred orientation. The micas have a large length to width ratio (see Figure 23) and the quartz and feldspar are elongate and highly strained. A few grains have undergone mechanical grain size reduction. Less deformed quartz and epidote veins cut across the shearing fabric. In the more deformed specimens, the population of elongate minerals, mainly mica and feldspar, has been diminished by extreme shearing and silification. The remaining quartz grains have been reduced in size by grinding and are extremely strained. In the most deformed specimens, most of the rock is very fine-grained and viewed in thin section, has the pinpoint extinction character of chert. Only a few elongate grain fragments remain scattered throughout the ground mass.

Minor faults, joint sets, and veins. The minor faults and joints observed in the vicinity of the Stodge Meadow Pond Fault have a fairly consistent northeast strike and steep west dip (Figure 27). Where the rotation sense on these minor faults was observed, they were normal. It is possible, but not necessary, that the attitude and sense of these minor structures reflect the major structure. The number of minor faults and joints in the country rock increases dramatically in intensity near the fault, allowing much deeper rock weathering in this vicinity. This makes fresh samples of these rocks difficult to obtain and is probably one of the reasons that the major lowland in the area, containing most of the lakes, is a valley parallel to the trend of the fault.

Silicification associated with the faulting has strongly affected the rocks in the vicinity of the fault, in some places making identification of the country rock almost impossible. Milky white vuggy quartz veins with pink or yellow blotchy stains, commonly up to a foot thick, are also abundant in the vicinity of the fault. These are undeformed and tend to follow joint surfaces.

Other Post-Metamorphic Brittle Features

Joints. Joints were observed throughout the area, but were not systematically measured. Their character has been discussed above and some of their attitudes are shown in Figure 27. The predominant set measured east of the fault strikes north - northeast, roughly parallel to the fault, and dips steeply to the west. Joint intensity increases dramatically toward the proposed fault and the data set is biased by being mostly measured near it.

Most joint measurements collected west of the fault zone are from outcrops in the Mount Watatic area that are not directly proximal to the fault. They are nearly vertical and strike west - northwest. This west - northwest set is approximately perpendicular to the northeast set observed east of the fault. This may indicate the presence of more than one set of late stress conditions, one associated with formation of the major fault, the other of unknown affiliations. A more deliberate and quantitative study of the brittle features here would be necessary to make any kind of stress interpretations.

OVERVIEW OF THE ASHBURNHAM-ASHBY AREA IN THE STRUCTURAL GEOLOGY OF CENTRAL MASSACHUSETTS

Fitting the geology mapped in the Ashburnham-Ashby area into a coherent pattern with the rest of the geology mapped in central Massachusetts is complicated by a lack of detailed mapping in the surrounding area. The geology of the adjacent quadrangles as well as of the western portion of the Ashburnham quadrangle and the eastern portion of the Ashby quadrangle has been interpreted on the basis of reconnaissance mapping (Field and Robinson, 1976: Robinson and Tucker, 1976; Robinson, 1962-78; Stoddard, 1977: D'Onfro, 1974; Tucker, 1976: Peper and Wilson, 1978; Maczuga, 1981) for the Bedrock Geologic Map of Massachusetts (Zen et al., 1983). To the south, the Wachusett Mountain area (Tucker, 1976), and to the southwest, the Barre area (Tucker, 1977) and the Ware area (Field, 1975) have been mapped in more detail. Robinson (1979) presents a synthesis and description of the general geology of this region.

West of the Ashburnham-Ashby area, the Gardner anticline (Figure 37), exposing the Granulite Member of the Paxton Formation (Sp), is a late foliation arch that gently deforms dome stage and older structural fabrics observed in the vicinity and is probably synchronous with phase-

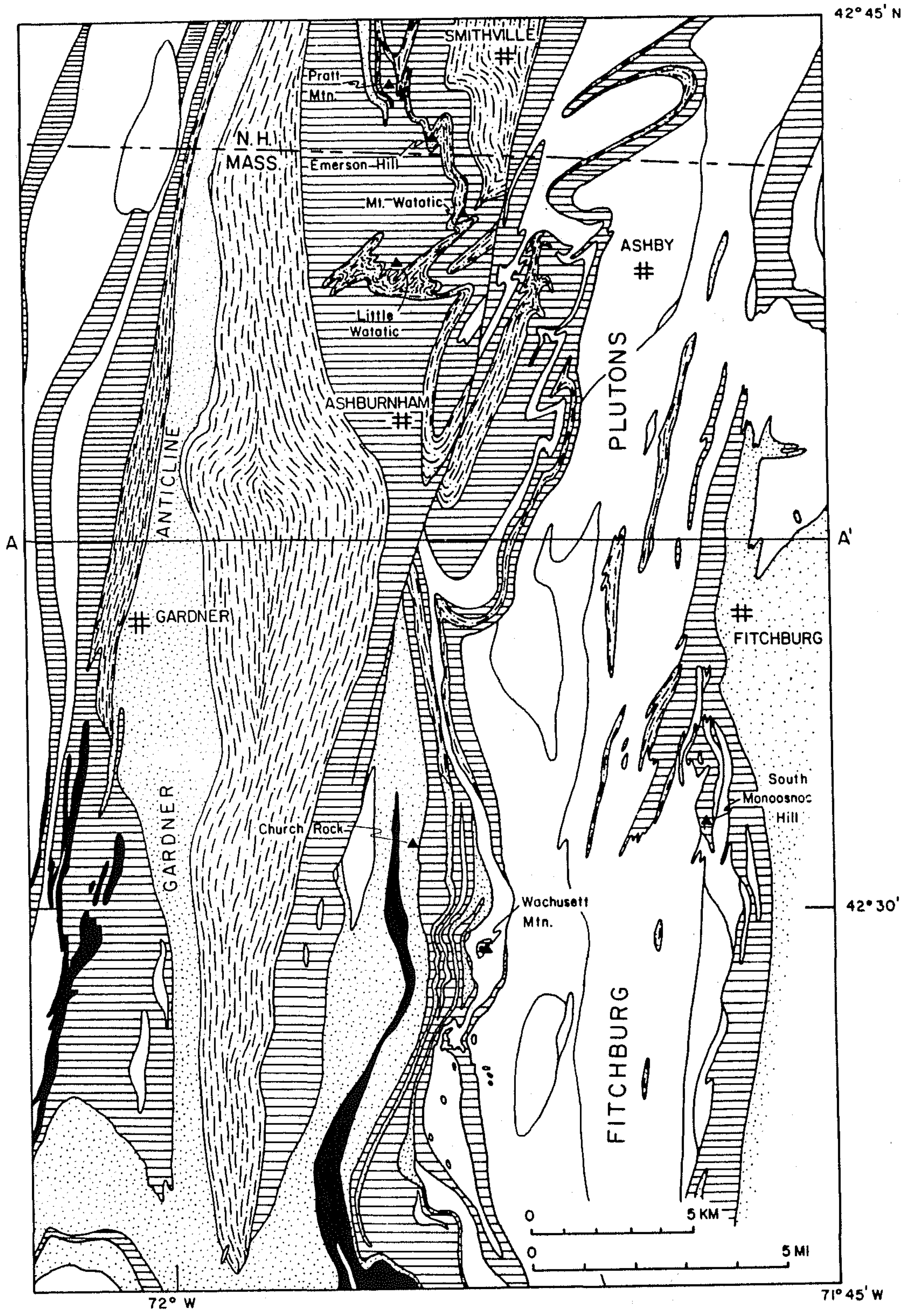
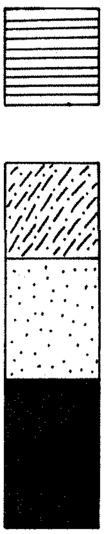

42°45' N
SMITHVILLE
Pratt Mtn.
N.H.
MASS.
Emerson Hill
Mt. Watatic
ASHBY
Little Watatic
PLUTONS
ASHBURNHAM
ANTICLINE
A
A'
GARDNER
FITCHBURG
South Monoosnoc Hill
GARDNER
Church Rock
Wachusett Mtn.
42°30' N
FITCHBURG
0
5 KM
0
5 MI
72° W
71°45' W

Figure 37. Geologic map of part of north-central Massachusetts showing one possible structural correlation between the Wachusett Mountain and Ashburnham-Ashby areas. This interpretation requires minor offset along the Stodge Meadow Pond Fault and correlates the tonalite in the Ashburnham-Ashby area with the tonalite on Wachusett Mountain. Cross section A - A' is shown in Figure 38.

Explanation for Figures 37 - 40.

Only Silurian - Devonian stratified rocks are patterned.



Lower Devonian — Littleton Formation, gray schist.

Silurian — Paxton Formation, sulfidic schist where mapped separately.

Paxton Formation, Granulite Member, includes extensive sulfidic schist.

Paxton Formation, White Schist Member (Spsq), sulfidic cordierite schist (west of the Gardner Anticline); Quartzite - Rusty Schist Member (Spqr) (east of the Gardner Anticline).

five folds in the Ashburnham-Ashby area. The tight backfolded nappe-stage isoclinal anticlines and synclines of Ordovician Partridge and Devonian Littleton Formations form long narrow belts that pass through the Ware (Field, 1975) and Barre (Tucker, 1977) areas west of the Gardner anticline. The Silurian Paxton Formation is fairly extensive in the eastern part of these areas, but to the west, the Silurian in this region has been interpreted as very thin or absent. These nappes of Ordovician - Devonian rocks are interpreted by Robinson (1979) to flop over the Gardner anticline and appear to the east as tight, complexly deformed isoclinal anticlines of Silurian Paxton Formation and isoclinal synclines of Littleton Formation. The Silurian apparently thickens dramatically eastward across a tectonic hinge, similar to that described in Maine (Moench and Boudette, 1970). The Ordovician Partridge in the roots of the anticlinal nappes does not extend eastward far enough to be exposed on the ground on the east side of the Gardner arch. The Granulite Member exposed at the center of the anticline is flanked by rusty-weathering sulfidic schist also mapped as Paxton Formation (Spss). On the west side, this belt of rusty schist is relatively thin and pinches out to the south, On the east side this belt is very thick and extends well into the Ashburnham quadrangle. Its relationship to the rusty schists mapped in this study area is, however, not well known. To the south, the belt of rusty-weathering schist east of the Gardner anticline appears to pinch out or be faulted out (Figure 37). The Gardner anticline acts as a broad foliation arch with regional dips toward the east on the east flank. At the latitude of Wachusett Mountain this dip remains relatively consistent all the way to the center of the Fitchburg Plutonic Complex, which lies in a late syncline. In the eastern portions of the Ashburnham-Ashby area, the average dip is gently to the west. This indicates the presence of a broad gentle syncline between this area and the Gardner anticline that does not exist directly along strike to the south. The closest equivalent might be the Wachusett syncline (Robinson, 1979).

To the south, the phase of folding comparable to the fourth phase of this study has been called the "Church Rock" phase by Robinson (personal communication) after a spectacular outcrop of the Granulite Member of the Paxton Formation at Church Rock in the Gardner quadrangle, characterized by late north - northeast trending folds with relatively flat axial surfaces and a west over east rotation sense. This west over east rotation sense is consistent to the north of Church Rock in the Ashburnham-Ashby area as well as to the south. Robinson (personal communication, 1981) suggests that these folds are folded over the Gardner anticline and correspond to phase 2B of Tucker (1977). In the northern portions of the Barre area and in the southeastern part of the Templeton quadrangle (Robinson, 1979 - Figure 5-11) these folds have the same west over east rotation sense and may be on the same limb of a major dome stage fold that has been folded over the Gardner anticline. Lineations associated with this phase are also deformed by this late warping across the Gardner anticline (Robinson, 1979 - Figure 5-7). East of the Gardner arch, "Church Rock" or dome stage linear fabric plunges gently north northeast. The east - west lineation, so strong in the

Ashburnham-Ashby area and along strike to the south dies out westward toward the Bronson Hill anticlinorium where more northerly trending fabrics produced by dome stage deformation are most strongly developed (Robinson, 1979, 1982b), obliterating earlier linear fabrics. In the Ashburnham-Ashby and Wachusett Mountain areas the dome stage deformation was less significant and the strong earlier east - west fabric apparently created by regional backfolding is well preserved.

In correlating the Ashburnham-Ashby area with areas to the south, several specific problems must be addressed. First, a structural model is needed to account for the west dip of foliation in the eastern part of the Ashburnham-Ashby area as compared to its east dip near Wachusett Mountain to the south. A second problem is the one of making structural connections between the Gray Granulite Member of the Paxton Formation in the northwest corner of this study area with any of the other areas of Paxton biotite granulite shown in central Massachusetts. No physical connection has yet been found between these areas and two possibilities are suggested. The Ashburnham granulite might connect north through the Peterborough quadrangle to a northern extension of the biotite granulite belt in the center of the Gardner anticline (See Figure 37) which has been observed as far north as New Hampshire (1.3 miles north of the border). Alternatively, it might connect in the air to the belt of biotite granulite exposed directly south of Ashburnham, with its northernmost outcrop on Route 2 due east of Gardner (see Figure 37). This belt is interpreted as an early southeast-plunging recumbent anticline, with a doubled belt of Paxton Formation rusty quartzite (Spqr) along its axial surface. The hinge dives beneath the Fitchburg plutons and reappears on its southeast end (beyond the limits of Figure 37). This hinge may come down to the ground again to the north of Ashburnham as the isoclinal anticline of Paxton Gray Granulite exposed on the west side of Pratt Mountain.

Although the rocks mapped in the Ashburnham-Ashby area are very similar to those mapped to the south in the vicinity of Wachusett Mountain, there are problems in correlating the units mapped within the the Paxton Formation. The rusty quartzites described in the Ashburnham-Ashby area are similar lithologically to the Paxton rusty quartzite (Spqr) mapped to the south, however Spqr in the type area is separated from the gray schists of the Littleton Formation by the Paxton biotite granulites. In Ashburnham, the rusty quartzite is not in contact with the Gray Granulite Member of the Paxton and is in contact with the gray schists of the Littleton Formation. A second stratigraphic difference is the relationship between the gray granulite and rusty schist in the two areas. As shown on Figure 18 the Paxton Formation (Sp) in the Wachusett Mountain area is mapped in several separate belts interpreted as isoclinal anticlines, each of which has a slightly different lithic character. The upper belt contains interbedded rusty-weathering schist and biotite granulite, the middle belt is predominently rusty schist with only minor granulite, and the lower belts consist entirely of biotite granulite. In contrast, the Gray Granulite Member of the Paxton Formation in Ashburnham is separated from any rusty-weathering schist by a belt of gray-weathering schist. It is possible that the Gray Granulite Member of the Paxton in Ashburnham correlates with the lower belts of Paxton biotite granulite (Sp) on Wachusett Mountain (Figure 18) and that the Sulfidic Schist Member in the Ashburnham-Ashby area correlates with the middle Sp belt on Wachusett Mountain. No correlative for the upper Sp belt on Wachusett Mountain is observed in this study area. Tucker's (1976, 1978) interpretation that each belt of Paxton Formation is a large scale anticlinal nappe separating younger belts of gray-weathering schist of the Littleton Formation is adopted in this study to make the map of Plate 1 and for the correlations suggested in Figures 37 - 40.

A final problem to be dealt with in making these correlations is the question of the regional extent and displacement of the post-metamorphic Stodge Meadow Pond Fault mapped in the Ashburnham-Ashby area. Robinson (1962-78) has observed zones of silicification and outcrops of cataclasite similar to those mapped in the Ashburnham-Ashby area along strike to the south suggesting a southward extension (Figures 37 and 39). E. Duke (personal communication) has seen similar shear zones and evidence of faulting in the Peterborough quadrangle to the north. These faults or shear zones appear to connect to late faults mapped by Aleinikoff (1978) in the Milford quadrangle, New Hampshire suggesting that the fault mapped in this area may have regional extent.

Two alternative structural interpretations are suggested in Figures 37 - 40, The first interpretation (Figures 37 and 38) requires only minor displacement along the fault and a north-trending dome stage or "Church Rock" phase fold to account for the change in the dip from south to north. The second interpretation (Figures 39 and 40) requires major displacement along the fault so that west-dipping rocks on the east side of the Wachusett syncline are faulted up against rocks still dipping east off the Gardner anticline. The first alternative suggests that the tonalite in the Ashburnham-Ashby area is the same belt of tonalite as that mapped on Wachusett Mountain. The second somewhat more radical alternative implies that the Ashburnham-Ashby tonalite is actually similar in position to the tonalite on the east margin of the Wachusett syncline. This tonalite has been characterized by Maczuga (1981) at South Monoosnoc Hill.

These suggested alternatives represent a beginning in the understanding of the stratigraphic and structural correlation problems in this area. More detailed mapping is still necessary in these areas to make more exact regional interpretations. No attempt has been made here to make a structural correlation to the north where the work of Edward Duke is still in progress. The general style of structural deformation and the overall structural fabrics of the Ashburnham-Ashby area appear to be similar to those observed in the eastern part of the Peterborough quadrangle to the north. Unfortunately, differences in stratigraphic interpretation at this time make structural and

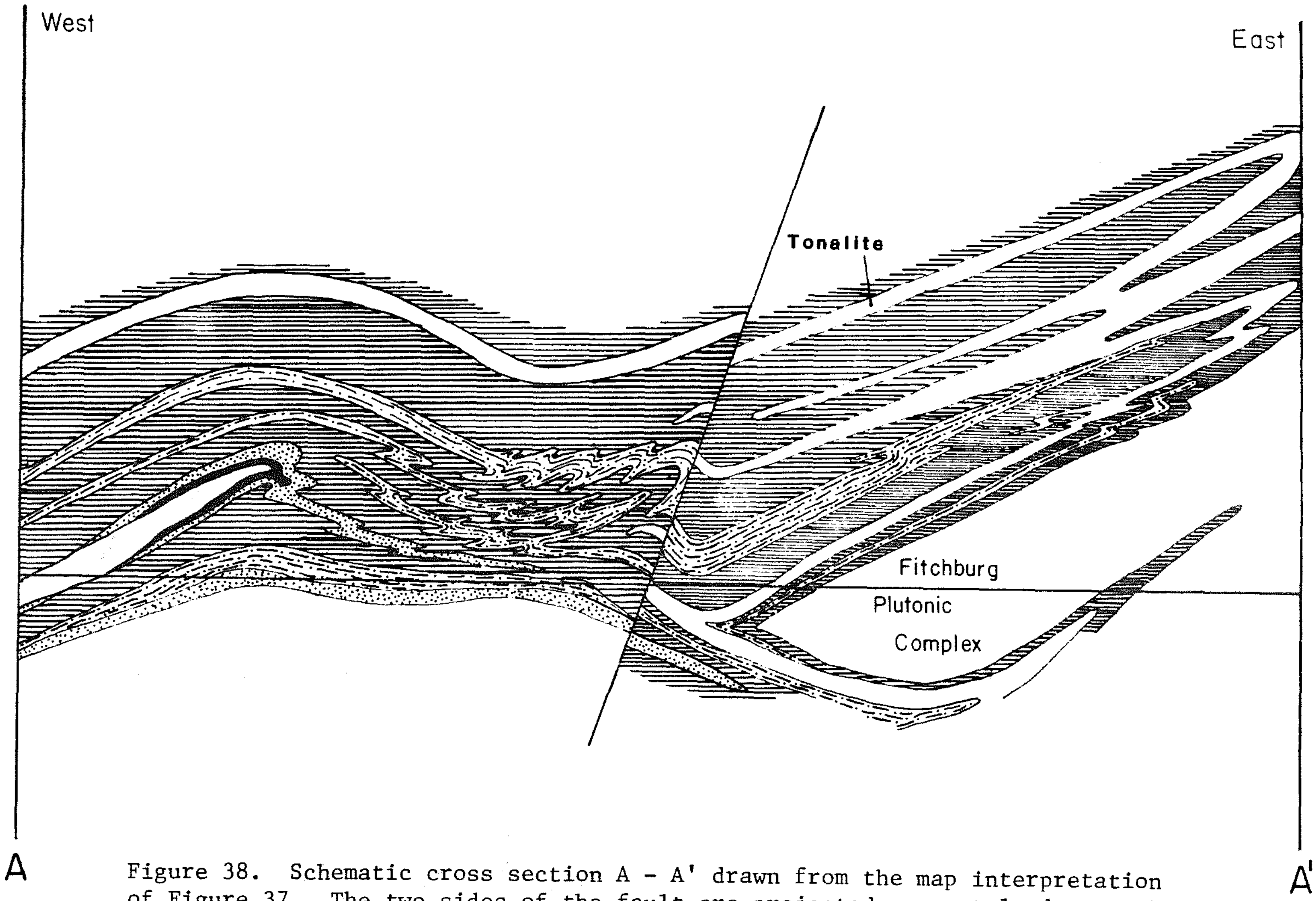


Figure 38. Schematic cross section A - A' drawn from the map interpretation of Figure 37. The two sides of the fault are projected separately due to the unknown amount and direction of displacement on the fault. The area labelled 'Fitchburg Plutonic Complex' includes both foliated and unfoliated members of the complex. See Figure 37 for explanation of the units.

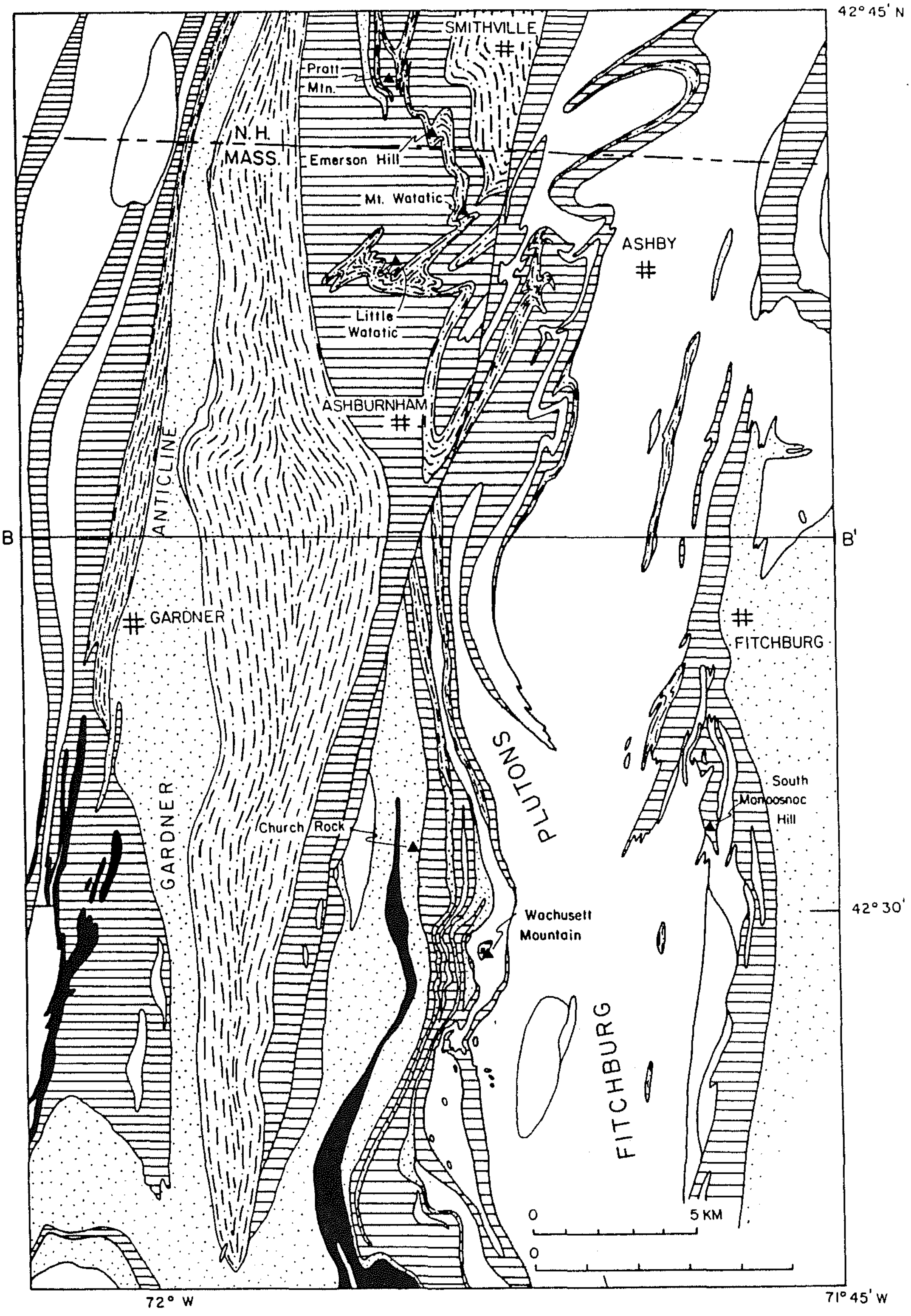


Figure 39. Geologic map of part of north-central Massachusetts showing one possible structural correlation between Ashburnham-Ashby and the area to the south. This interpretation requires major offset along the Stodge Meadow Pond Fault and correlates the tonalite in this study area with that on the east side of the Fitchburg Plutonic complex including that studied by Maczuga (1981) at South Monoosnoc Hill. Cross section B - B' is shown in Figure 40. See Figure 37 for an explanation of the units.

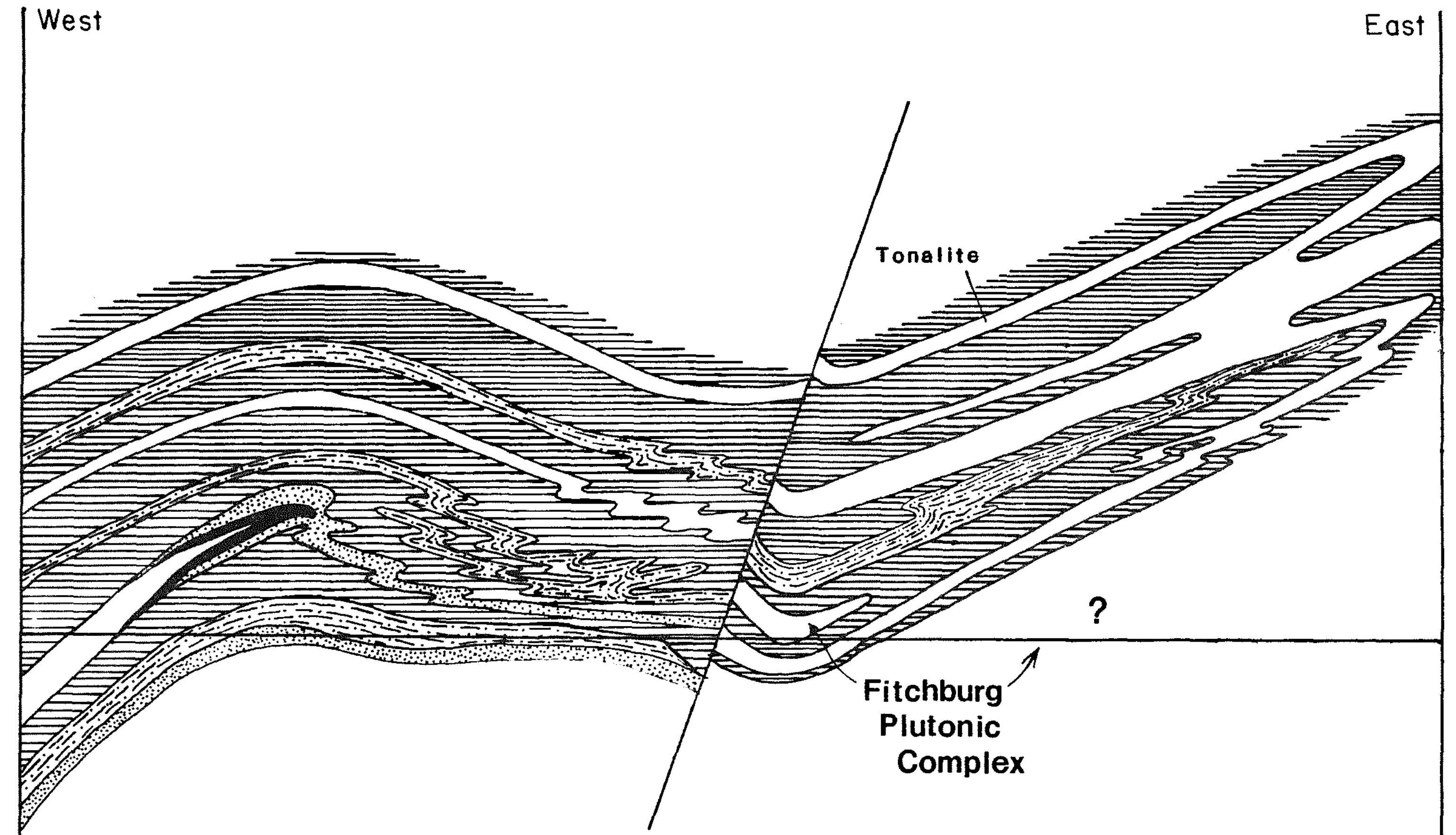


Figure 40. Schematic cross section B - B' drawn from the map interpretation of Figure 39. This interpretation requires major offset on the Stodge Meadow Pond Fault, but the amount and direction are not known. For this reason the two sides of the fault are projected separately. The granites at the core of the Wachusett syncline are very thin in this section and disappear to the north. The area labelled ' Fitchburg Plutonic Complex' includes both foliated and unfoliated members of the complex. See Figure 37 for explanation of the units.

stratigraphic correlations difficult.

METAMORPHISM

General Statement

The Ashburnham-Ashby area is predominantly underlain by pelitic schists which have been intruded by the Tonalite Member of the Fitchburg plutonic complex near which contact metamorphic effects appear to have been minimal. The effects of Acadian regional metamorphism on the pelitic rocks, on the calc-silicates, and on the tonalite in the area will be examined here.

The Ashburnham-Ashby area was shown by Thompson and Norton (1968) to lie in the sillimanite - K-feldspar zone, however more recent metamorphic maps of central Massachusetts (Robinson, 1979: Tracy and Robinson, 1980; and Robinson et al., 1982a), the metamorphic map of southwestern New Hampshire (Chamberlain and Lyons, 1983), and the present study all show it to lie mainly in the sillimanite-muscovite zone (Zone III) below the stability limit of K-feldspar in pelitic schists (Figure 41). The changes in the aluminum-silicate polymorphs that have taken place with time across central New England have been used to trace the metamorphic history. A fossil triple-point isobar described by Thompson and Norton (1968) cuts generally north - south across central Massachusetts and New Hampshire. They suggest that although sillimanite appears to have been the final equilibrium polymorph over much of this region, it was preceded by kyanite to the west and by andalusite to the east of the isobar. East of the isobar, pseudomorphs of sillimanite after andalusite (named "andalumps" by Peter Robinson) are common. Although kyanite and sillimanite are both found west of the isobar, examples of sillimanite replacing kyanite are rarely observed (Tracy and Robinson, 1980; Robinson et al., 1982a). Thompson and Norton (1968) suggest that the isobar may be present due to greater overburden to the west just prior to peak thermal metamorphism.

Tracy and Robinson (1980) describe one continuous metamorphism with local differences in the timing of peak metamorphic temperatures and pressures. The thermal metamorphic peak is thought to have occurred during the dome stage deformation in the Bronson Hill anticlinorium and during the backfold stage in the Merrimack synclinorium (Robinson et al., 1982a). In the Bronson Hill anticlinorium the peak metamorphic pressure coincided with the thermal peak. This was probably the time when overburden was the greatest in the anticlinorium due to piling up of nappes. Later deformation in the Bronson Hill anticlinorium produced uplift and pushed much of the overburden away, possibly toward the Merrimack synclinorium. The peak metamorphic pressure in the synclinorium occurred in the late stages of deformation, during the dome stage and apparently much later than the thermal peak. Robinson and Tracy (1980) also show pressure - temperature trajectories for rocks in different parts of central Massachusetts. These paths help to explain the distrubution of the different aluminum-silicate polymorphs. Finally,

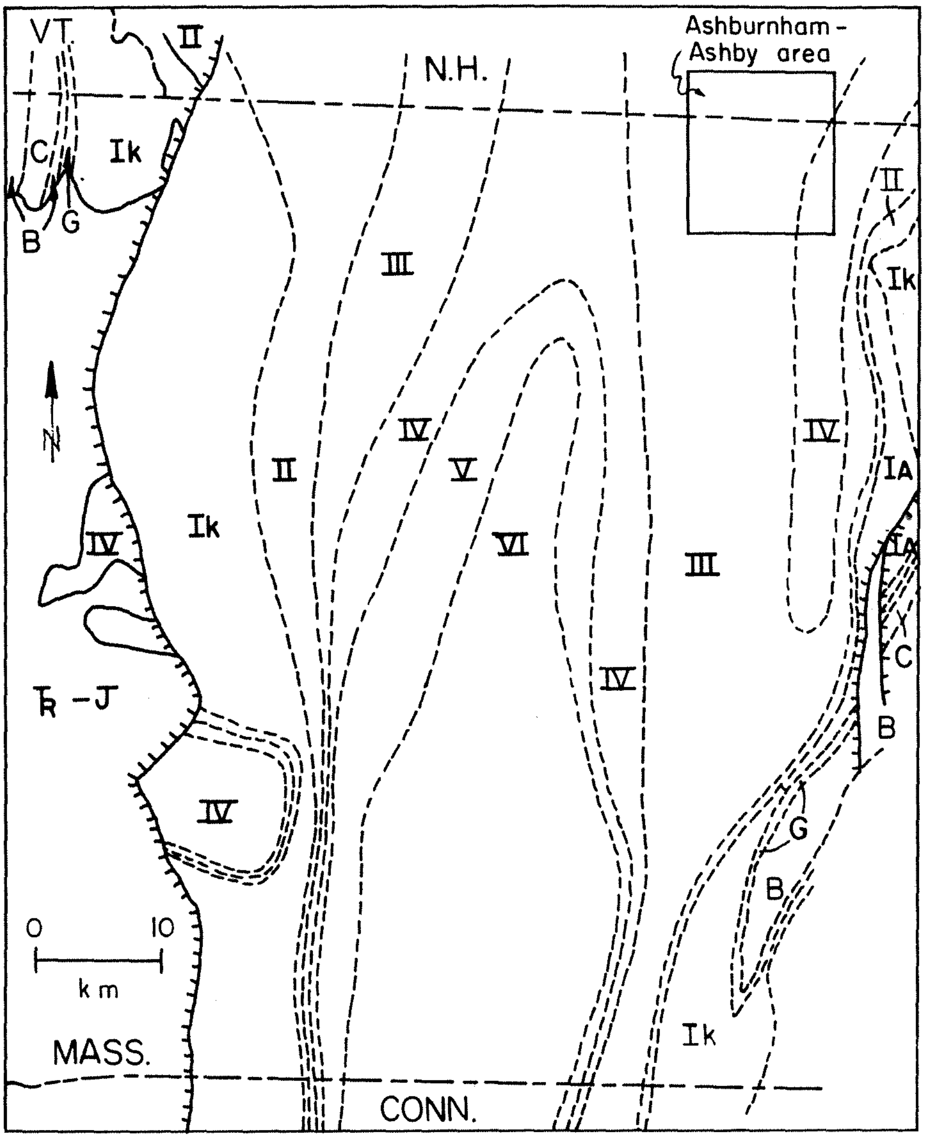


Figure 41. Metamorphic map of central Massachusetts. Metamorphic zones based on mineral assemblages in pelitic schists are: C - chlorite; B - biotite; G - garnet; I_K - kyanite-staurolite; I_A - andalusite-staurolite; II - sillimanite-staurolite; III - sillimanite - muscovite; IV - sillimanite-muscovite-orthoclase; V - sillimanite-orthoclase; VI - sillimanite-orthoclase-garnet-cordierite. The Ashburnham-Ashby area is outlined. (From Robinson et al., 1982a)

Robinson et al. (1982a) and Hollocher (1981) describe several areas of post-Acadian retrograde metmorphism.

Chamberlain and Lyons (1983) describe the changes in metamorphic assemblages, particularly in the aluminum-silicate minerals in New Hampshire, as due to three metamorphic stages. This sequence bears some resemblance to the four stage metamorphic history described by Holdaway et al. (1982) in Maine. The first stage (M1) took place at relatively low pressure and produced andalusite. The second stage (M2) occurred at the peak of metamorphism and produced assemblages from sillimanite - muscovite to cordierite - K-feldspar. M2 appears to have wiped out most of the evidence for earlier prograde metamorphism, except the widespread sillimanite pseudomorphs after andalusite. A third phase (M3) consisted of local retrogression of garnet and biotite to chlorite and extensive replacement of aluminous minerals in pelitic schists by secondary muscovite. The metamorphic sequence described by Chamberlain and Lyons (1983) is similar to that observed in the pelitic schists in the Ashburnham-Ashby area.

Assemblages in Pelitic Schists

Retrograde muscovite is ubiquitous in pelitic schists of the area. Locally however, peak prograde metamorphic minerals are still well preserved and the characteristic assemblage is quartz-muscovite-biotite-sillimanite-garnet-plagioclase. Chemical compositions have not been determined for these minerals. Biotite is generally abundant and appears to be moderately Fe-rich except in the most sulfide-rich schists where it is pale-orange and probably Mg-rich. Muscovite is present in nearly all the schists although much of it is secondary. Sillimanite is generally replaced by muscovite, even in the areas that appear to have undergone the least retrogression. It is observed in thin section as fine needles preserved at the centers of coarser muscovite, quartz, or garnet grains. The former presence of sillimanite is also evident in outcrop as coarse knotty lumps or "boot-grabbers" on the rock surface. Andalusite has not been observed in this area, but there are some elongate lumps which appear to be former sillimanite pseudomorphs after andalusite that have been totally replaced by muscovite. These lumps are similar to but not so distinctive nor well preserved as the "andalumps" observed in the Mount Monadnock area or elsewhere in Massachusetts. Coarse sillimanite is well preserved in one sample of extremely sulfide-rich schist (PAY 473A). Red garnet is locally abundant and is probably almandine-rich. Plagioclase is less abundant than quartz, but is generally present. A typical pelitic schist assemblage plotted on an AFM projection would be similar to the plot of Figure 42, without the cordierite.

Exceptions to the "typical" schist assemblages in this area, of particular interest include: 1) the magnesian, sulfidic Smalls Falls-type schists typified by sample PAY 473A and 2) sample. PAM 7A of cordierite-bearing gray schist.

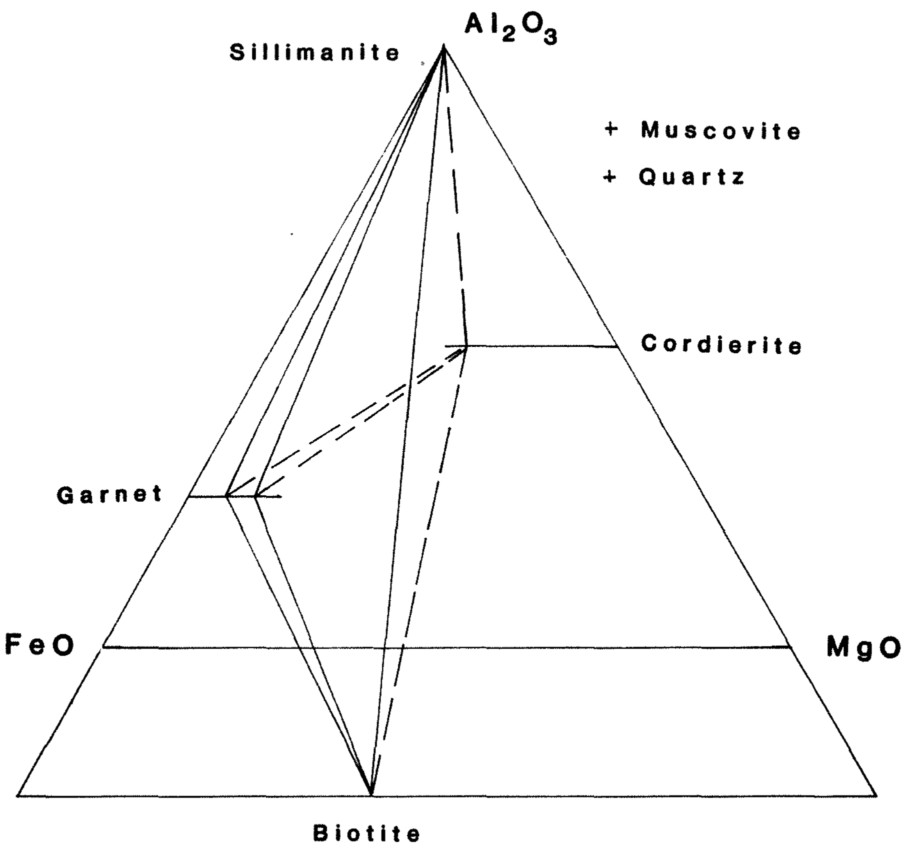


Figure 42. Projection from muscovite onto the Al_2O_3 - FeO - MgO plane showing the "typical" pelitic schist assemblages observed in the Ashburnham-Ashby area (solid tie lines). The dashed tie lines together with the solid lines show the assemblage observed in sample PAM 7A.

The mineral assemblage observed in the extremely sulfidic Smalls Falls-type rock of sample PAY 473A (see Table 2a) includes Mg-biotite + sillimanite + muscovite + quartz + plagioclase + rutile + graphite + pyrite. This rock is similar to rocks described by Robinson et al. (1982a) in the Smalls Falls-type unit "Spsq" ("Spw" of Field, 1975 and Robinson et al., 1982b) in central Massachusetts. The rutile in PAY 473A and in the samples examined by Robinson et al. (1982a, 1982b) indicates a very low activity of FeO consistent with Mg-rich silicate compositions, In rocks with a lower Mg/(Mg + Fe) ratio in the silicates, ilmenite would form as the stable Ti-bearing phase (Figure 43) (Robinson et al., 1982a). Robinson (personal communication) considers rutile to be a "guide fossil" of the magnesian schists of the Smalls Falls Formation. Pale orange biotites also indicate a fairly Mg-rich bulk composition. A qualitative comparison of PAY 473A to rocks in the same unit collected from zones four, five, and six (see Figure 41) in central Massachusetts is shown in Figure 44. The comparison is made on the basis of biotite color and on the mineral assemblages observed. Pyrite in the original sediments has been replaced by pyrrhotite as the coexisting Fe-sulfide in these Smalls Falls-type rocks with increasing metamorphic grade in all but the most Mg-rich rocks (Figure 43, 44). Figure 43 shows the potential coexisting phases in the high grade, K-feldspar-bearing Smalls Falls-type schists in central Massachusetts. At lower grades, represented by the muscovite sillimanite-bearing schists from this area, the field of biotites coexisting with pyrite might be expanded in the direction of the arrow in Figure 43. This could explain the presence of pyrite rather than pyrrhotite in PAY 473A.

The gray schist sample collected at locality PAM 7 contains an interesting assemblage of quartz-muscovite-biotite-garnet-cordierite-ilmenite (see Table 3a). Although sillimanite needles are present in the centers of some garnet grains and beryl is found in a thin quartz-rich layer, neither mineral is part of the coexisting assemblage described above. The presence of beryl in the adjacent layer suggests that there may be significant BeO in the assemblage.

Preliminary electron microprobe analyses of garnet and cordierite from this assemblage (Table 8) show both cordierite and garnet to be relatively Fe-rich and garnet also to have a significant Mn-component compared to the typical values observed for these minerals in the pelitic schists of central Massachusetts. In fact, some of the garnet analyses in Table 8 are among the most Mn-rich known in pelitic schists from central Massachusetts as can be seen by comparison of the garnets plotted in Figure 45 with those shown in Figure 4 of Robinson et al. (1982a). Cordierite analyses are consistently low in total cations (at least partly due to the presence of water in the structure) and give high values for Na_2O (around 2 weight %) (Table 8). The hint of the presence of BeO in the rock suggests a possible substitution of Na^{+} + Be^{+2} for Al^{+3} in the cordierite structure. The microprobe will not detect the presence of beryllium, so that its presence in the cordierite might be responsible in part for the low totals. This substitution is suggested by Cerny and Povandra (1966) to account for the presence of beryllium in a cordierite from Vezna, Western Moravia, CSSR. Experimental synthesis of an Na - Be cordierite by Povandra and Langer (1971) has shown this to be a plausible substitution. Newton (1966) suggests other possible types of substitution to get Be into the cordierite structure, but he favors solid solution between cordierite and beryl which have similar crystal structures.

The Na - Be substitution model of Cerny and Povandra (1966) and Povandra and Langer (1971) allows for five times more beryllium in cordierite than is permitted by solid solution along the cordierite - beryl join. In nature, both mechanisms are probably operative, because Na^{+} does not always balance the Be^{2+} present (Povandra and Cech, 1978). Higher quality microprobe analyses and wet chemical analyses will be necessary to determine whether or not beryllium is indeed present in this cordierite and if it is, to make further speculation on how it got there.

Very few assemblages of coexisting garnet, cordierite, and muscovite in pelitic schists have been reported in the literature, whereas at higher grades garnet and cordierite are commonly observed to coexist in the presence of K-feldspar. In the high grade assemblages the pertinent reaction is sillimanite + biotite + quartz = garnet + cordierite + K-feldspar + H_2O in the system SiO_2-Al_2O_3-FeO-MgO-K_2O-H_2O (KFMASH). This reaction is the so-called "six phase curve" of Holdaway and Lee (1977) with a positive slope that lies entirely above the breakdown of muscovite and is quite sensitive to the activity of H_2O. A related and more pertinent reaction within the field of muscovite is cordierite + garnet + muscovite = sillimanite + biotite + quartz + H_2O, The exact position and slope of this reaction is uncertain and the H_2O on the product side is heavily dependent on the H_2O in the cordierite. A. B. Thompson (1976, Figure 5) suggests this reaction may be stable at about 580°C and 5 kbar in the KFMASH system with biotite + sillimanite + quartz on the high temperature side.

The pelitic schists in the Ashburnham-Ashby area usually contain retrograde muscovite that appears in thin section to have formed in two stages (see Figure 9). The muscovite occurs as coarse grains that cross cut the structural fabric, or as fine-grained layers or lenses with a matte-like or woven texture. The finer-grained muscovite is, in places, observed to replace the coarser muscovite indicating that it formed at a later time. Locally, sillimanite needles remain at the centers of the coarser muscovite grains, giving a hint of the former metamorphic grade. In the highly retrograded areas it is difficult to determine which phases were present in the peak metamorphic assemblage. It is possible that K-feldspar was part of this assemblage and has all reacted with sillimanite and quartz to form muscovite, but no evidence of relict K-feldspar has been found. Chlorite, present in small amounts throughout the area as a retrograde mineral, replaces biotite and/or garnet.

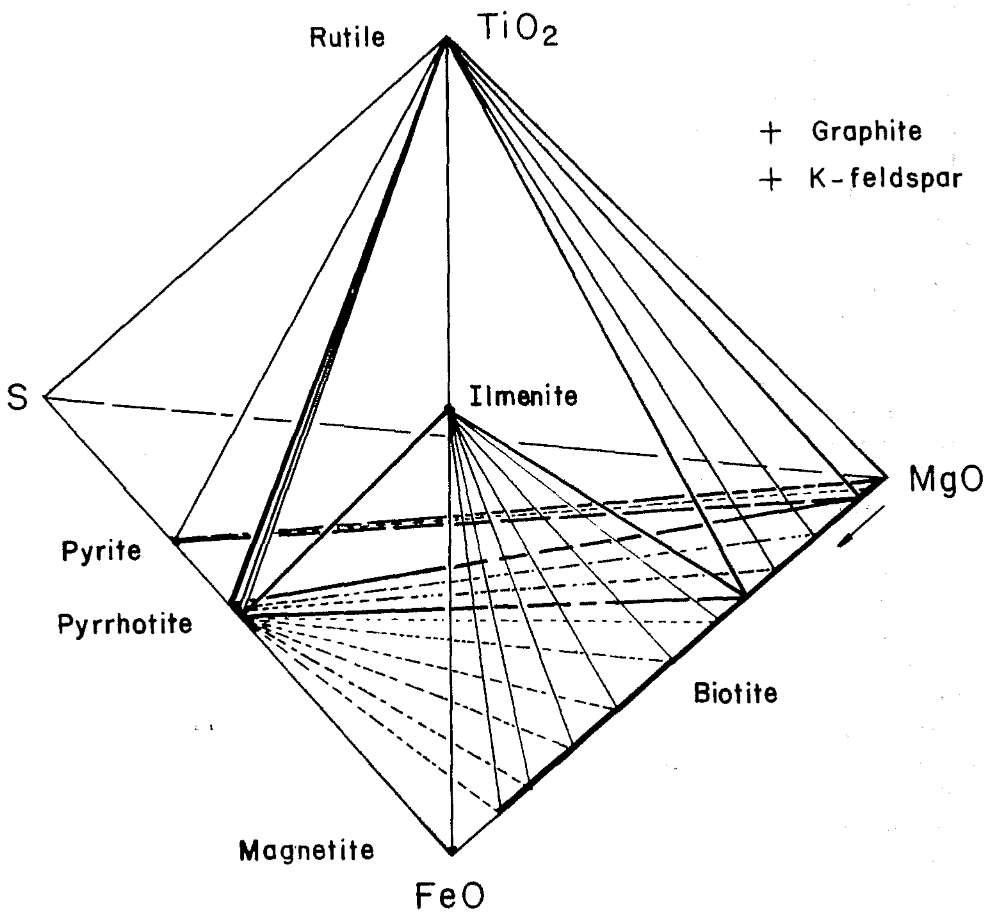


Figure 43. Projection developed by Robinson et al. (1982a) to show the possible assemblages observed in the magnesian Smalls Falls - type rocks in central Massachusetts. MgO is added to the graphite projected plane FeO - S - TiO_2 to show the ferromagnesian minerals. Projections from quartz and K-feldspar facilitate the portrayal of biotite. These projected assemblages at high grades show pyrite to coexist only with Mg-rich biotite and rutile. The arrow indicates that at lower grades the field of biotites coexisting with pyrite would extend toward lower Mg/(Mg + Fe) compositions due to lesser progress of the reaction Pyrite + Fe-biotite + Graphite --→ Pyrrhotite + Mg-richer Biotite + K-feldspar + Sillimanite + $2H_2O$ + $3CO_2$.

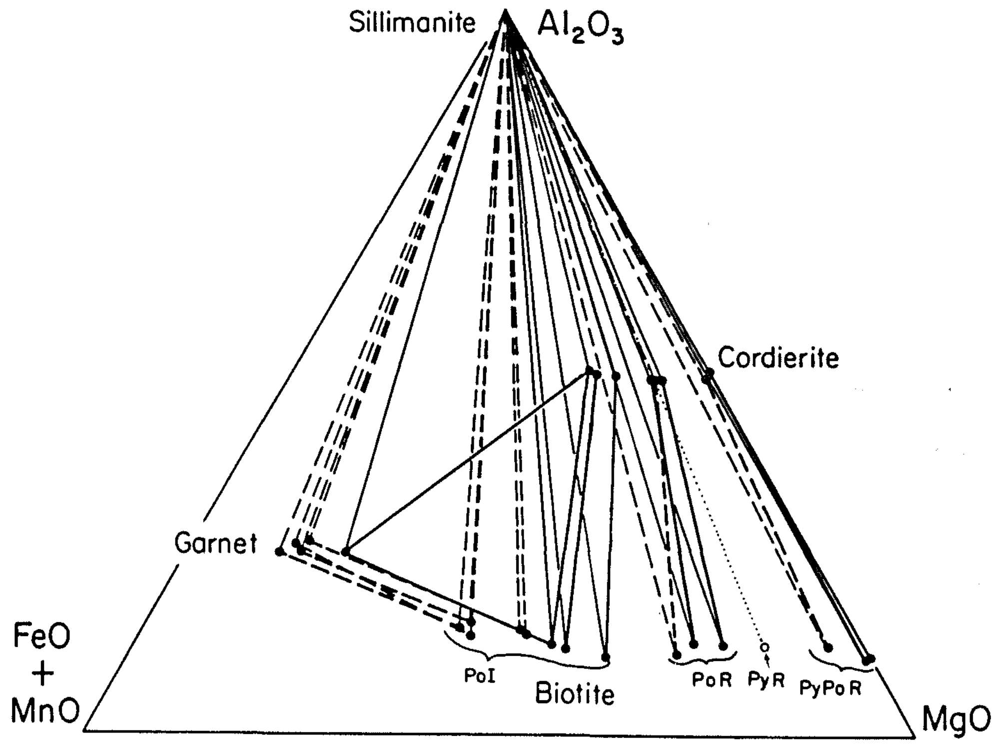


Figure 44. Quartz + K-feldspar projection of sulfidic pelitic schist assemblages from Zones IV and V (dashed tie lines) and Zone VI (solid tie lines), including the estimated position of PAY 473A from the Ashburnham-Ashby area (open circle at biotite connected by dotted tie line to sillimanite). Although this is not a proper projection because PAY 473A coexists with muscovite rather than K-feldspar, it shows the relative composition of this sample to others of similar lithology examined by Robinson et al. (1982a) and shown in this diagram. The MgO/(FeO+MgO+MnO) is roughly estimated on the basis of relative color. (Figure adapted from Robinson et al., 1982a).

Table 8a. Electron microprobe analyses of garnet from sample PAM 7A. Garnet A is in contact with cordierite. The analyses for garnet A are taken from traverses across the grain. Garnet E is an average of several analyses from one relatively homogeneous grain.

Analysis No.	E Avg	A Rim(1)	A Int(2)	A Core(14)
SiO_2	36.74	36.74	36.89	35.60
TiO_2	.02	.04	.03	-
Al_2O_3	18.82	19.78	19.91	20.28
FeO	32.31	35.31	32.39	33.77
MnO	8.33	4.30	6.22	5.44
MgO	1.69	1.90	1.87	2.91
CaO	1.16	2.16	2.66	1.17
Sum	99.07	100.23	99.97	99.17
Structural Formulae				
Si-site				
Si	3.048	3.002	3.010	2.935
Al-site				
Al	1.841	1.906	1.916	1.972
Ti	.002	.003	.002	-
Sum	1.843	1.909	1.918	1.972
M^{+2}-site				
Fe	2.242	2.414	2.212	2.331
Mg	.209	.231	.227	.357
Mn	.586	.298	.430	.380
Ca	.103	.189	.232	.103
Sum	3.140	3.132	3.101	3.171
Total	8.031	8.043	8.029	8.078
Almandine %	71.40	77.08	71.33	73.51
Spessartine %	18.66	9.51	13.87	11.98
Pyrope %	6.66	7.38	7.32	11.26
Grossular %	3.28	6.03	7.48	3.25
Total	100.00	100.00	100.00	100.00
Fe/(Fe+Mg+Mn)	.738	.820	.771	.760
Fe/(Fe+Mg)	.915	.913	.907	.867

Table 8b. Electron microprobe analyses of cordierite from sample PAM 7A. Three methods are used to calculate the structural formulae of the cordierites analyzed. Model (1) assumes that no BeO is present. This leaves vacancies in both the tetrahedral and octahedral (M) sites. A ferric iron correction would only increase the number of vacancies. Model (2) assumes that Be^{+2} fills the vacancies in the tetrahedral sites. Model (3) corrects the total non-channel cations to 11 cations, again using Be^{+2} to fill the vacancies.

	Cordierite A1			Cordierite F2		
Model No.	(1)	(2)	(3)	(1)	(2)	(3)
SiO_2	50.02			48.75		
TiO_2	.01			.03		
Al_2O_3	28.88			30.10		
FeO	9.28			9.75		
MnO	.31			.27		
MgO	7.04			7.27		
CaO	.11			.15		
Na_2O	2.22			1.53		
K_2O	.02			.04		
BeO*	-	1.58	2.65	-	1.33	1.54
Sum	97.89	99.47	100.54	97.89	99.22	99.43
Structural Formulae						
Tetrahedral site						
Si	5.237	5.124	5.050	5.112	5.019	5.004
Al	3.564	3.487	3.437	3.720	3.652	3.642
Be	-	.389	.643	-	.329	.380
Sum	8.801	9.000	9.130	8.832	9.000	9.026
Octahedral site						
Fe	.813	.795	.783	.855	.839	.837
Mn	.027	.027	.027	.024	.024	.023
Mg	1.099	1.075	1.059	1.136	1.115	1.112
Ti	.001	.001	.001	.002	.002	.002
Sum	1.940	1.898	1.870	2.017	1.980	1.974
Channel cations						
Ca	.012	.012	.012	.017	.016	.016
Na	.451	.441	.434	.311	.305	.304
K	.003	.003	.002	.005	.005	.005
Sum	.466	.456	.448	.333	.326	.325
Total	11.207	11.354	11.448	11.182	11.306	11.325
Fe/(Fe+Mg)	.425	.425	.425	.429	.429	.429

*The presence of BeO is not detected by the electron microprobe. The weight percents shown for models (2) and (3) are calculated from the corrections used to determine the structural formulae.

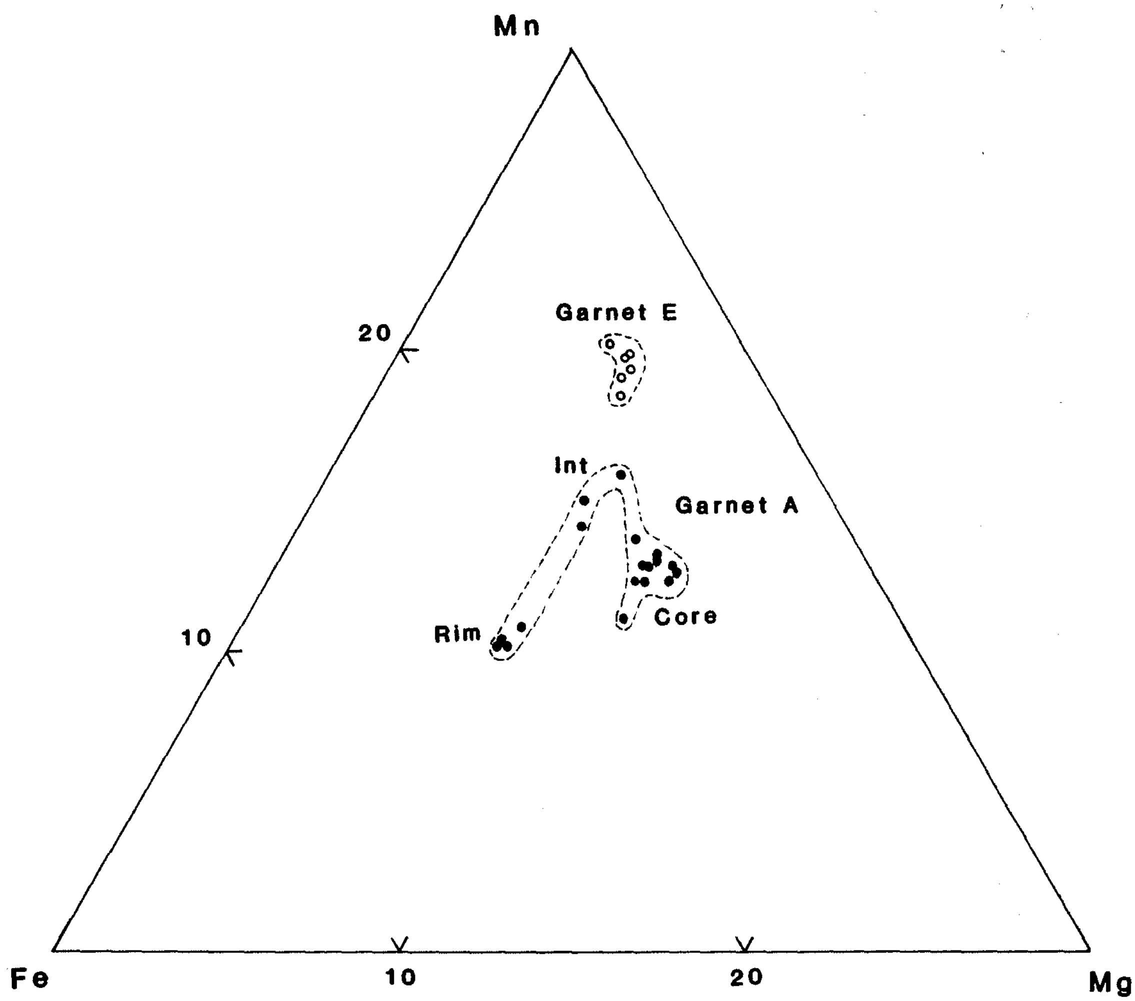


Figure 45. Plot of microprobe analyses of garnets A and E comparing the Fe, Mg, and Mn components. Representatives of these are shown in Table 8a. Garnet E analyses (open circles) are relatively consistent across the grain. The analyses of garnet A (closed circles) are from two perpendicular traverses across the grain. This data is outlined to show the compositional variation from core to rim.

Assemblages in Calc-silicate Rocks

Thin layers, lenses and pods of calc-silicate granulite are present in the pelitic schists and feldspathic granulites in the area. They are very quartz-rich with variable amounts of calcic plagioclase, clinopyroxene, hornblende, actinolite, zoisite, clinozoisite, and garnet (Tables 1, 2c, and 4a). The amphiboles, pyroxene, and garnet generally occur as rounded, poikilitic, embayed grains. Where hornblende and actinolite occur together, the actinolite is generally secondary and has a more fibrous texture than the hornblende. Garnet and hornblende do not generally coexist, although they may be in the same thin section. Zoisite and clinozoisite occur either as discrete grains or as rims around the other calcic minerals. Thompson and Norton (1968, Table 24-1) show that these mineral assemblages in general indicate medium grade metamorphism, roughly equivalent to the staurolite and sillimanite zones in pelitic schists.

The response of specific assemblages in these rocks to changes in metamorphic grade is not yet well understood, but work in progress by R. Durig on similar rocks collected in west-central Massachusetts should aid in understanding them. Representative microprobe analyses from one sample of calc-silicate granulite (PAM 1005C) within the Granulite Member of the Paxton Formation in the area are given in Table 9. The analyses shown are typical analyses of coexisting minerals taken from two main locations on the thin section (locations 4 and 5). The plagioclase analysis shown is actually from a different part of the slide, but is a rough approximation of the typical plagioclase composition.

The data from Table 9 is plotted in the ternary diagrams of Figure 46 using the plotting parameters of Robinson et al. (1981 p 27). Figure 46a, the simplest of these, is similar to a conventional ACF diagram with the added component Na, which takes into account the variation in plagioclase. This shows the four-phase assemblage ferrian zoisite/clinozoisite-hornblende-diopside-plagioclase present in the sample. The core compositions of hornblende are assumed to give representative values for the prograde mineral; the rim compositions are probably retrograde, based on textural similarities between the core hornblendes and the other phases. The occurrence of a five phase assemblsge in an apparent three-component system, is of course due to the amalgamation of components at the three apices, Na and Ca at NC, Fe^{3+} and Al at A, and Fe^{2+} and Mg at FM. Figure 46b pulls apart the NC corner of Figure 46a to show the normative anorthite-albite ratio in the phases involved. Of interest here is that typically in hornblende-plagioclase assemblage the normative anorthite ratio is higher in hornblende than in its coexisting plagioclase (Robinson et al., 1981, Figure 111) whereas in this sample the reverse is true. Figure 46c pulls apart the A corner of Figure 46a to show variations in the $Fe^{3+}/(Fe^{3+} + Al)$ ratio.
This ratio is significantly higher in the hornblende than in the coexisting zoisite and clinozoisite. Figure 46d shows very little difference in Fe/(Fe + Mg) between the hornblende and clinopyroxene. A

Table 9. Representative electron microprobe analyses of the minerals in the calc-silicate sample PAM 1005C.

Hornblende

Analysis No.	4	5(core)	5(int)	5(rim)
SiO_2	44.80	47.70	49.64	50.18
TiO_2	0.68	0.30	0.11	0.08
Al_2O_3	8.77	6.87	4.63	4.22
FeO	18.28	18.52	17.17	16.92
MnO	0.33	0.38	0.35	0.39
MgO	10.37	11.21	12.38	12.64
CaO	12.11	12.11	12.34	12.39
Na_2O	0.78	0.60	0.43	0.36
K_2O	0.74	0.44	0.25	0.19
Sum	96.86	98.13	97.30	97.37
Structural Formulae				
Si-site				
Si	6.727	7.018	7.316	7.374
Al	1.273	0.982	0.684	0.626
Sum	8.000	8.000	8.000	8.000
M-1,-2,-3 sites				
Al	0.280	0.211	0.121	0.106
Ti	0.077	0.034	0.012	0.009
Fe^{3+}	0.537	0.567	0.435	0.424
Mg	2.324	2.459	2.722	2.771
Fe^{2+}	1.759	1.712	1.683	1.658
Mn	0.023	0.017	0.027	0.032
Sum	5.000	5.000	5.000	5.000
M-4 site				
Mn	0.019	0.031	0.018	0.017
Ca	1.949	1.910	1.950	1.953
Na	0.032	0.059	0.032	0.030
Sum	2.000	2.000	2.000	2.000
A-site				
Na	0.111	0.113	0.090	0.073
K	0.143	0.082	0.047	0.036
Sum	0.254	0.195	0.137	0.109
Total	15.254	15.195	15.137	15.109
Fe/(Fe+Mg)	.431	.410	.382	.429

Calcic Pyroxene

Analysis No.	4	5
SiO_2	52.07	52.18
TiO_2	0.14	0.14
Al_2O_3	0.56	0.50
FeO	13.09	12.44
MnO	0.37	0.38
MgO	10.17	10.99
CaO	23.79	23.33
Na_2O	0.11	0.14
Sum	100.30	100.10
Si-site		
Si	1.984	1.982
Al	0.016	0.018
Sum	2.000	2.000
M-1 site		
Al	0.009	0.004
Ti	0.004	0.004
Fe^{3+}	0.007	0.015
Mg	0.578	0.623
Fe^{2+}	0.402	0.354
Sum	1.000	1.000
M-2 site		
Fe^{2+}	0.008	0.027
Mn	0.012	0.012
Ca	0.972	0.950
Na	0.008	0.010
Sum	1.000	0.999
Total	4.000	3.999
Fe/(Fe+Mg)	.415	.372
(Ca+Na)/2	.490	.480

Table 9. (Representative mineral analyses from PAM 1005C, continued).

	Clinozoisite		Ferrian-Zoisite		Plagioclase
Analysis No.	4	5	5		1(avg)
SiO_2	38.89	38.59	38.29	SiO_2	46.56
TiO_2	0.06	0.05	0.04	TiO_2	-
Al_2O_3	28.67	29.09	29.31	Al_2O_3	33.09
Fe_2O_3	6.00	4.99	4.12	FeO	0.02
FeO	-	-	-	CaO	17.16
MnO	0.05	0.10	0.10	Na_2O	1.80
MgO	0.06	0.06	0.07	K_2O	0.03
CaO	24.19	24.06	24.14	Sum	98.66
Sum	97.92	96.94	96.06		

Structural Formulae

Si-site					
Si	3.011	3.007	3.002	T-site	
Al	-	-	-	Si	2.168
Sum	3.011	3.007	3.002	Al	1.817
				Sum	3.985
Al-site					
Al	2.000	2.000	2.000	A-site	
Sum	2.000	2.000	2.000	Fe	0.001
				Ca	0.857
Fe^{3+}-site				Na	0.163
Al	0.618	0.672	0.708	K	0.002
Fe^{3+}	0.350	0.293	0.243	Sum	1.023
Ti	0.003	0.003	0.002		
Mg	0.007	0.007	0.008	Total	5.008
Sum	0.978	0.975	0.961		
				An	83.9
Ca-site				Ab	15.9
Ca	2.008	2.011	2.029	Or	0.2
Mn	0.004	0.005	0.007	Sum	100.0
Sum	2.012	2.016	2.036		
Total	8.001	7.998	7.999		
$Fe^{3+}/(Fe^{3+}+Al)$	.118	.099	.082		

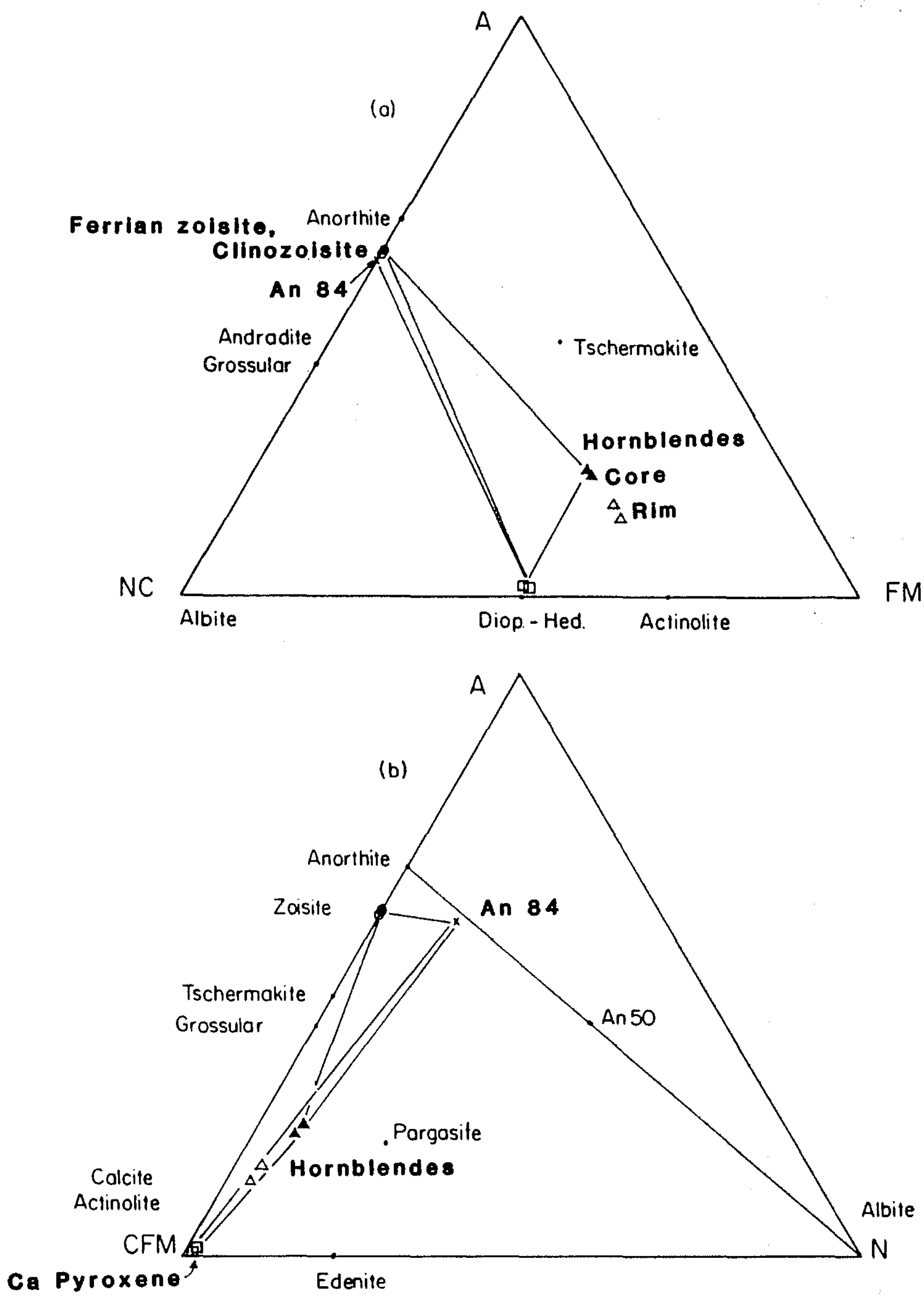


Figure 46. Ternary diagrams showing the variations in the components A, C, F, M, N for the calc-silicate sample PAM 1005C. The data plotted is shown in Table 9. The formulas for the end member components of the ternary diagrams are the following: $A = Al^{3+} + Fe^{3+} + 2Ti^{4+} - Na - K$; $C = Ca^{2+}$; $F = Fe^{2+} + Mn^{2+} - Ti^{4+}$; $M = Mg^{2+}$; $N = 2Na^{+} + 2K^{+}$;

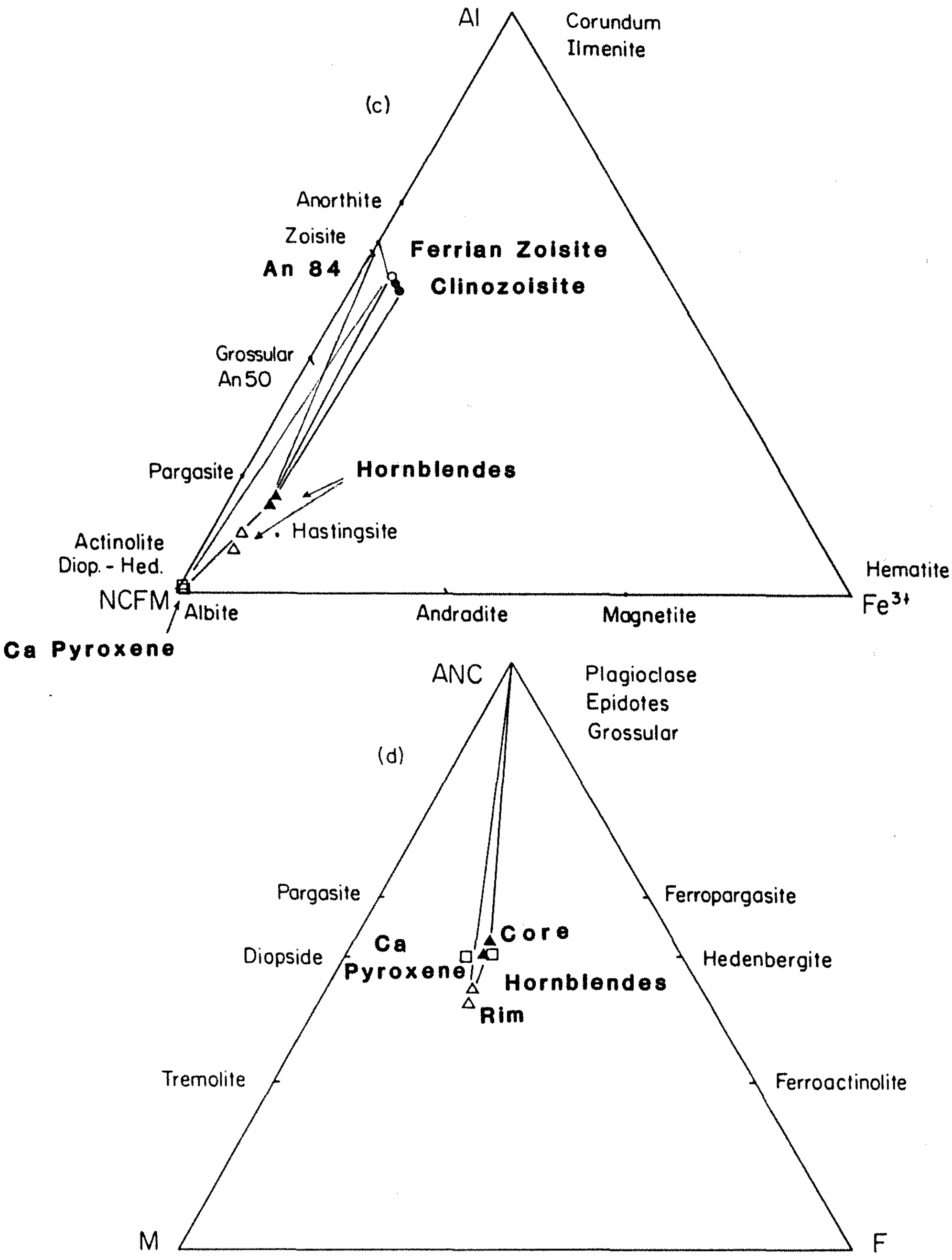


Figure 46 (continued). Al in (c) = $Al^{3+} + 2Ti^{4+}$. Quartz is present in the rock. This method of plotting is adapted from Robinson et al. (1982c - p 27). The symbols used are: x - plagioclase (An 84); closed circle - clinozoisite; open circle - ferrian zoisite; open square - clinopyroxene; closed triangle - hornblende core composition; open triangle - hornblende rim composition. Solid lines are tie lines between coexisting phases.

conclusion of this brief chemographic survey is to suggest that this five phase assemblage can be well characterized in the five component system Al-Fe^{3+}-N-C-FM without appeal to variable Fe - Mg ratios.

Intrusive Rocks

Although the intrusive rocks in this area have undergone the same degree of structural deformation as the surrounding stratified country rocks, their mineral assemblages show relatively little about their metamorphic history. The primary coexisting phases present in the Fitchburg Tonalite include biotite, plagioclase, and quartz. K-feldspar, muscovite, chlorite, sphene, allanite, rutile, apatite, zircon, and opaque minerals are also present in minor amounts (see Table 6). Recrystallization of biotite and quartz due to metamorphism is evident in thin section. Intrusion of the tonalite appears to have caused partial melting of the nearby country rock during peak metamorphism. Migmatites produced in the vicinity of the tonalite contact by partial melting have been subsequently deformed and possess a strong foliation, giving the rocks a gneissic appearance.

Conditions of Metamorphism

The rocks in the Ashburnham-Ashby area have been subjected to medium-grade metamorphism during the Acadian Orogeny, characterized by sillimanite - muscovite - biotite - garnet assemblages in the pelitic schists. Assemblages in the calc-silicate and intrusive rocks are consistent with this. More data is needed to give a good estimate of the metamorphic temperatures and pressures, however preliminary analyses of the garnet - cordierite - biotite - muscovite - sillimanite (?) assemblage in sample PAM 7A suggest conditions of around 625°C and 5.3 kbar, some 100°C cooler and 1 kbar lower pressure than in the center of the metamorphic high near Sturbridge, Massachusetts. The peak of metamorphism appears to have coincided with the second or third phase of deformation described in this study. Sillimanite needles (or relict sillimanite grains) oriented parallel to the third phase lineation or lying in the plane of the predominant foliation give evidence of this relationship.

Evidence for earlier lower pressure andalusite in this area is circumstantial. No unequivocal andalusite pseudomorphs can be demonstrated in this area, however elongate lenses of secondary muscovite which may have previously been andalusite crystals are common. Retrograde formation of muscovite and chlorite occurred late in the deformational history of the area and might even be related to the late Paleozoic Alleghenian deformation that is well known at Worcester and Harvard, Massachusetts some miles to the southeast (Grew, 1976; Thompson and Robinson, 1976). There is some evidence for weak deformation of the secondary muscovite, however, in most cases, it cross cuts the structural fabric of the rock.

The tonalite appears to have intruded the country rock in this area close to the time of peak metamorphism. The added heat from the intrusion may have boosted the metamorphic effects in this area, however the relative effect on the metamorphism is not known.

GEOLOGIC HISTORY

Prior to collision of the Avalon plate with the North American plate during the Devonian Acadian Orogeny, Silurian and Lower Devonian sediments and volcanics were deposited into a basin formed between the two plates which is referred to by Robinson and Hall (1980) as the Merrimack - Fredericton trough. The sediments which included the protoliths of the stratified rocks observed in the Ashburnham-Ashby area were mainly shales and sandstones.

The earliest known deformation of the strata during the Acadian Orogeny was accomplished by large-scale nappes with westward transport from the site of deposition toward the present day Bronson Hill anticlinorium. The nappes of successively higher levels formed from rocks in successively hotter regions of the trough so that higher grade rocks were piled on lower grade rocks creating a reverse metamorphic gradient in the western part of the Bronson Hill anticlinorium (Thompson et al., 1968). As collision continued, the rocks in the vicinity of the Bronson Hill anticlinorium were uplifted, causing eastward backfolding of the pile of nappes toward the Merrimack synclinorium.

This regional backfolding stage was probably the most significant stage in the structural history of the Ashburnham-Ashby area, corresponding to the second and third phases of folding described in this study, to the beginning of intrusion of the Fitchburg Plutonic Complex, and to the peak of regional metamorphism. Shearing associated with transport during the late stages of backfolding produced thin zones of mylonite in the area. Although later strong deformation producing generally upright or overturned northerly-trending folds has affected the area, the imprint of backfolding is still well preserved. The late Paleozoic Alleghenian Orogeny, important further east in New England, may also have had effects in the area, possibly including the widespread retrograde metamorphism. Mesozoic rifting began the opening of the present-day Atlantic Ocean and produced numerous fault-bounded basins that roughly parallel the east coast of North America and are filled with Triassic-Jurassic sediments, volcanics, and intrusives. Associated faults, diabase dikes, veins, and joints can be observed throughout New England. The Stodge Meadow Pond Fault that cuts through the Ashburnham-Ashby area probably formed at this time.

During the Late Pleistocene a continental ice sheet covered the area and its activity molded the landscape. It scraped the bedrock clean over much of the uplands and deposited a thin layer of till over a good portion of the lowlands. The erosion produced by the ice appears to have been controlled to some extent by the structural fabric of the bedrock. Melting and retreat of the ice left kettles, eskers, and other outwash deposits over much of the area. Since the Pleistocene, fluvial and human degradation have slightly modified the landscape.

CONCLUSIONS

The main contribution of this project has been to produce a bedrock map and cross sections of the Ashburnham-Ashby area and to describe in some detail the nature of the rocks and their structural geometry based on field and petrographic observations and on comparison with other areas. In conjunction with this, the following conclusions have been reached: 1) The rocks described in the Ashburnham-Ashby area show strong similarities in lithologic character and stratigraphic position to rocks described by Tucker (1976, 1978) to the south in the Wachusett Mountain area and also to those in the Peterborough, New Hampshire quadrangle to the north (E. Duke, in progress). These rocks are interpreted to be Silurian and Devonian in age. 2) The stratigraphy in the Ashburnham-Ashby area has been correlated with the Silurian Devonian stratigraphic sequence described to the south in central Massachusetts and in particular with the Wachusett Mountain sequence and the assigned stratigraphic names are based on this correlation. Unfortunately, present differences in interpretation make correlation of this stratigraphy with that described to the north uncertain. 3) Five phases of folding during the Acadian Orogeny and later Mesozoic faulting produced the present outcrop pattern and can be reasonably correlated with the stages of regional deformation elsewhere in central Massachusetts. 4) The Tonalite Member of the Fitchburg Plutonic Complex intruded the Silurian - Devonian country rocks during the second phase of folding identified in the area, that corresponds to the early part of the backfold stage of regional deformation. The tonalite was subsequently deformed and metamorphosed along with the adjacent country rocks. 5) Metamorphism accompanying the Acadian Orogeny produced sillimanite - muscovite grade assemblages rather uniformly in the pelitic schists of the area. Preliminary analyses from a garnet - cordierite - muscovite - biotite $\pm$ sillimanite schist in the area suggest metamorphic conditions of approximately 625°C at 5.3 kbars.

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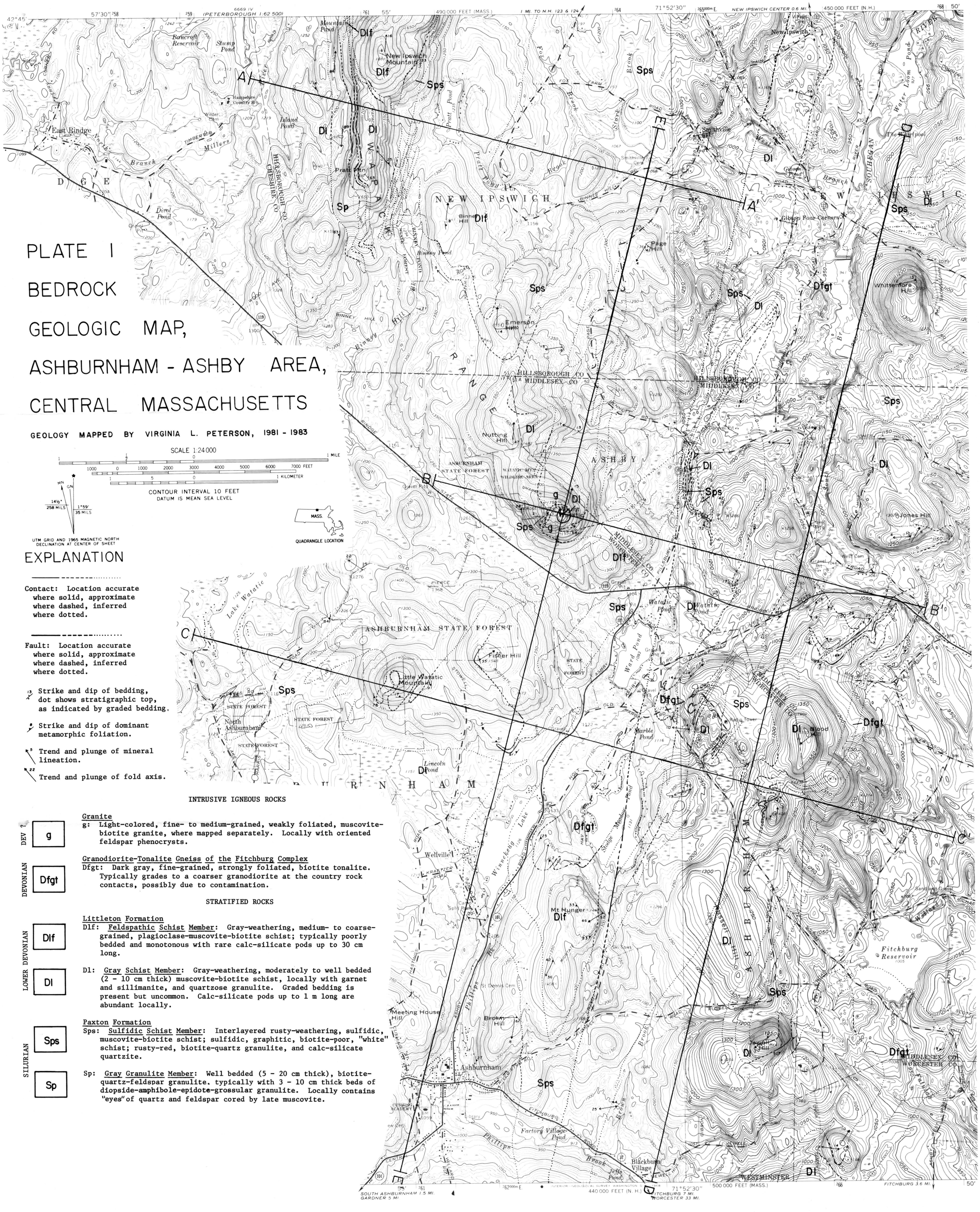


PLATE I

BEDROCK GEOLOGIC MAP, ASHBURNHAM - ASHBY AREA, CENTRAL MASSACHUSETTS

GEOLOGY MAPPED BY VIRGINIA L. PETERSON, 1981 - 1983

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

UTM GRID AND 1965 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

QUADRANGLE LOCATION

EXPLANATION

Contact: Location accurate where solid, approximate where dashed, inferred where dotted.

Fault: Location accurate where solid, approximate where dashed, inferred where dotted.

Strike and dip of bedding, dot shows stratigraphic top, as indicated by graded bedding.

Strike and dip of dominant metamorphic foliation.

Trend and plunge of mineral lineation.

Trend and plunge of fold axis.

INTRUSIVE IGNEOUS ROCKS

DEV ? — g

Granite
g: Light-colored, fine- to medium-grained, weakly foliated, muscovite-biotite granite, where mapped separately. Locally with oriented feldspar phenocrysts.

DEVONIAN — Dfgt

Granodiorite-Tonalite Gneiss of the Fitchburg Complex
Dfgt: Dark gray, fine-grained, strongly foliated, biotite tonalite. Typically grades to a coarser granodiorite at the country rock contacts, possibly due to contamination.

STRATIFIED ROCKS

Littleton Formation

LOWER DEVONIAN — Dlf

Dlf: Feldspathic Schist Member: Gray-weathering, medium- to coarse-grained, plagioclase-muscovite-biotite schist; typically poorly bedded and monotonous with rare calc-silicate pods up to 30 cm long.

LOWER DEVONIAN — Dl

Dl: Gray Schist Member: Gray-weathering, moderately to well bedded (2 - 10 cm thick) muscovite-biotite schist, locally with garnet and sillimanite, and quartzose granulite. Graded bedding is present but uncommon. Calc-silicate pods up to 1 m long are abundant locally.

Paxton Formation

SILURIAN — Sps

Sps: Sulfidic Schist Member: Interlayered rusty-weathering, sulfidic, muscovite-biotite schist; sulfidic, graphitic, biotite-poor, "white" schist; rusty-red, biotite-quartz granulite, and calc-silicate quartzite.

SILURIAN — Sp

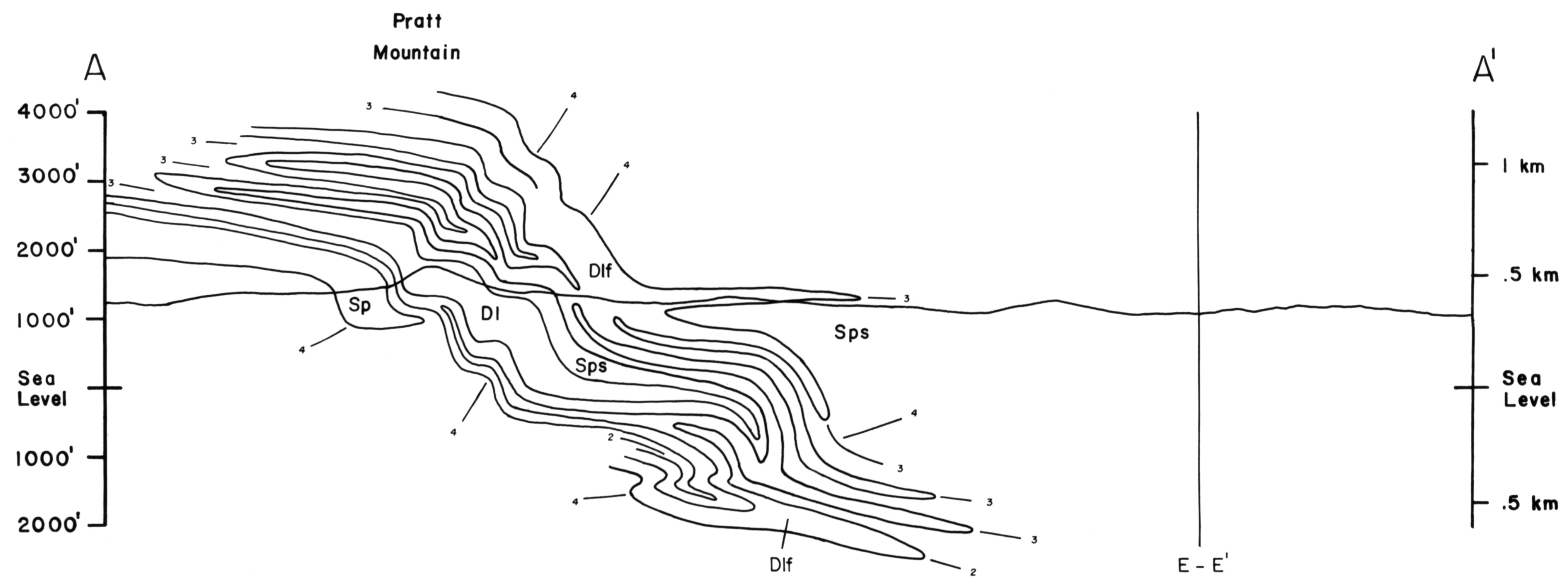
Sp: Gray Granulite Member: Well bedded (5 - 20 cm thick), biotite-quartz-feldspar granulite, typically with 3 - 10 cm thick beds of diopside-amphibole-epidote-grossular granulite. Locally contains "eyes" of quartz and feldspar cored by late muscovite.

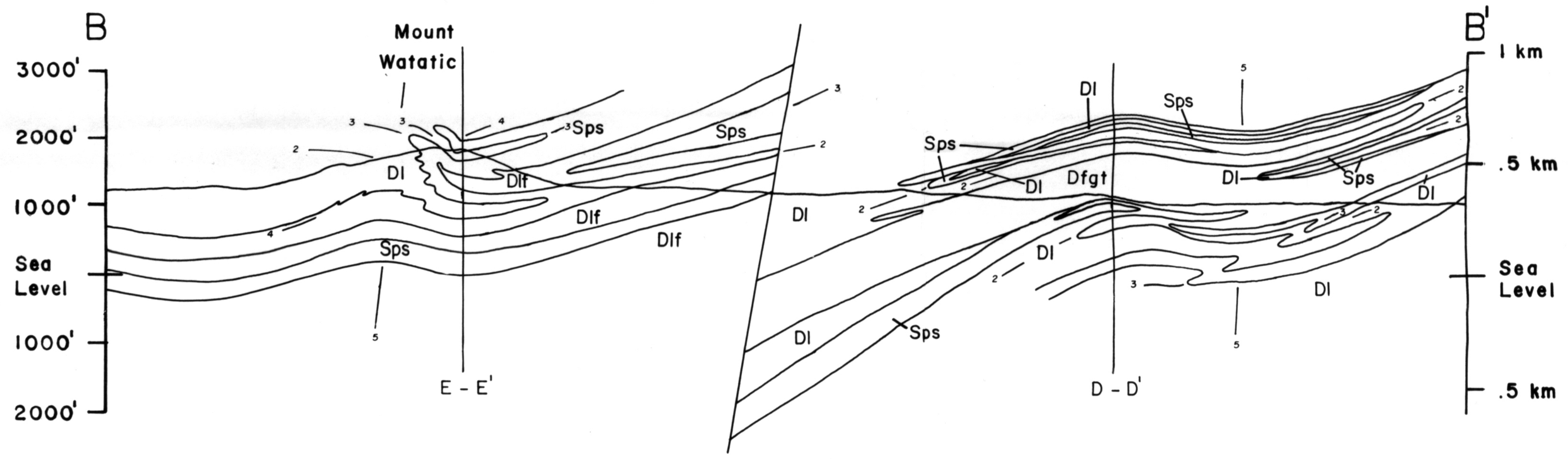
PLATE 2

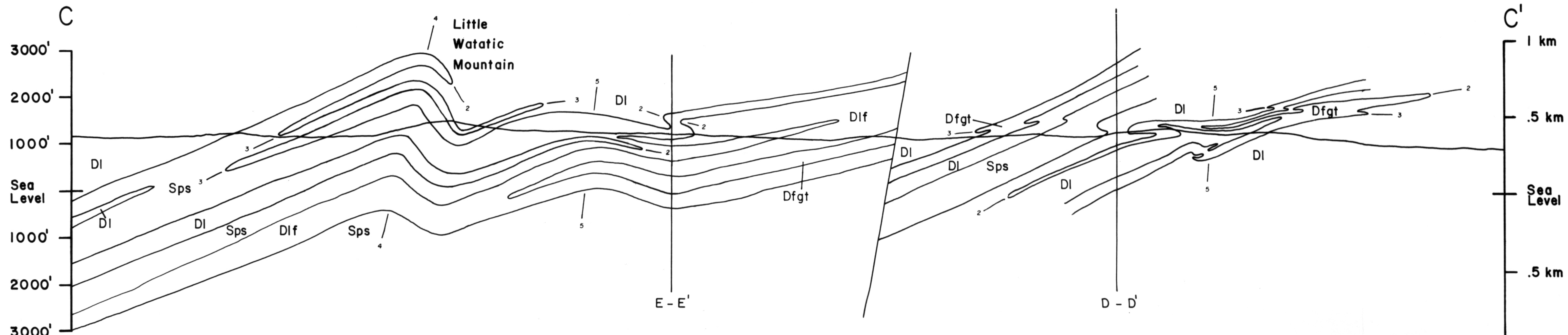
GEOLOGIC CROSS - SECTIONS OF THE ASHBURNHAM - ASHBY AREA

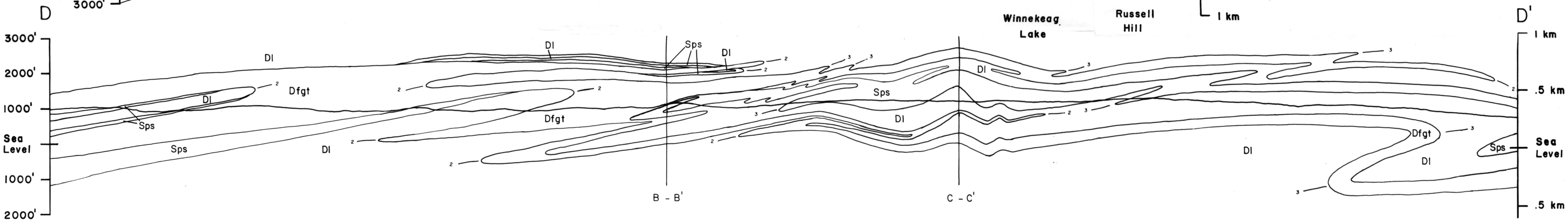
LINES OF CROSS SECTION ARE SHOWN ON GEOLOGIC MAP (PLATE 1).

AXIAL SURFACE SEGMENTS OF FOLDS OF PHASES 2, 3, 4, and 5 ARE REPRESENTED BY NUMBERED LINES.









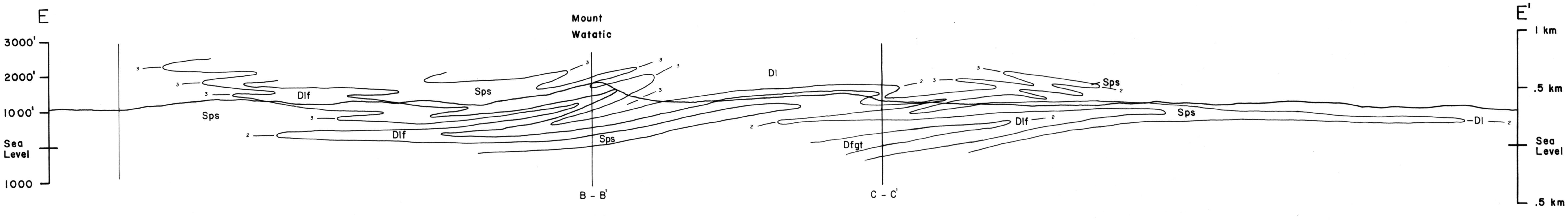
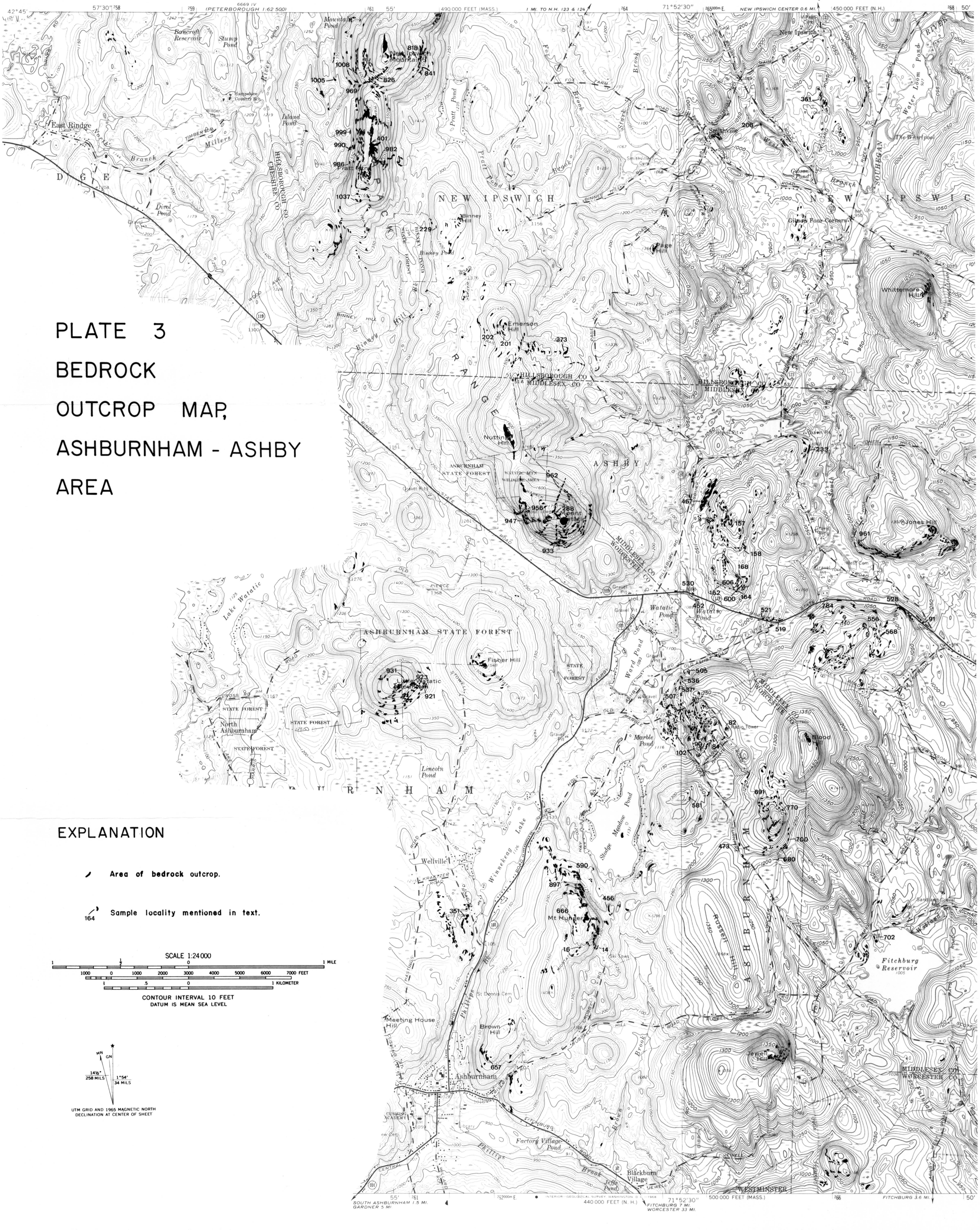


PLATE 3
BEDROCK OUTCROP MAP, ASHBURNHAM - ASHBY AREA



EXPLANATION

Area of bedrock outcrop.

164 Sample locality mentioned in text.

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

UTM GRID AND 1965 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

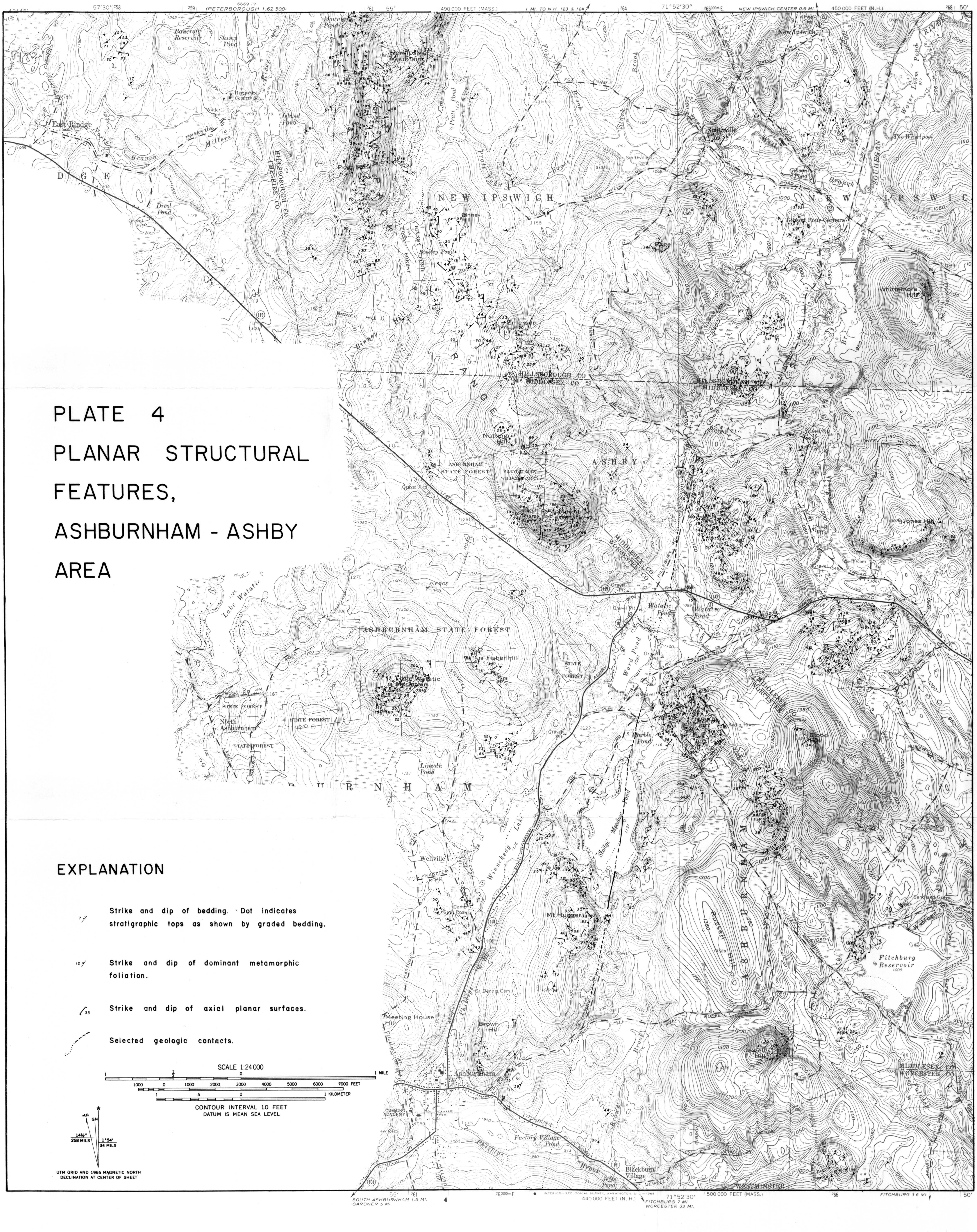


PLATE 4
PLANAR STRUCTURAL FEATURES, ASHBURNHAM - ASHBY AREA
EXPLANATION
Strike and dip of bedding. Dot indicates stratigraphic tops as shown by graded bedding.
Strike and dip of dominant metamorphic foliation.
Strike and dip of axial planar surfaces.
Selected geologic contacts.
SCALE 1:24 000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER
CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL
UTM GRID AND 1965 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET
258 MILS
34 MILS
(PETERBOROUGH 1:62 500)
490 000 FEET (MASS.)
NEW IPSWICH CENTER 0.6 MI.
450 000 FEET (N.H.)
SOUTH ASHBURNHAM 1.5 MI.
GARDNER 5 MI.
440 000 FEET (N.H.)
FITCHBURG 7 MI.
WORCESTER 33 MI.
500 000 FEET (MASS.)
FITCHBURG 3.6 MI.
71°52'30"
East Rindge
New Ipswich
Smithville
NEW IPSWICH
HILLSBOROUGH CO
MIDDLESEX CO
ASHBY
ASHBURNHAM STATE FOREST
Fisher Hill
North Ashburnham
Lincoln Pond
Wellville
Mt Hunger
Meeting House Hill
Brown Hill
Ashburnham
CUSHING ACADEMY
Russell Hill
Fitchburg Reservoir
Blackburn Village
Whittemore Hill
Jones Hill
Watatic Pond
Ward Pond
Marble Pond
WESTMINSTER
MIDDLESEX CO
WORCESTER CO

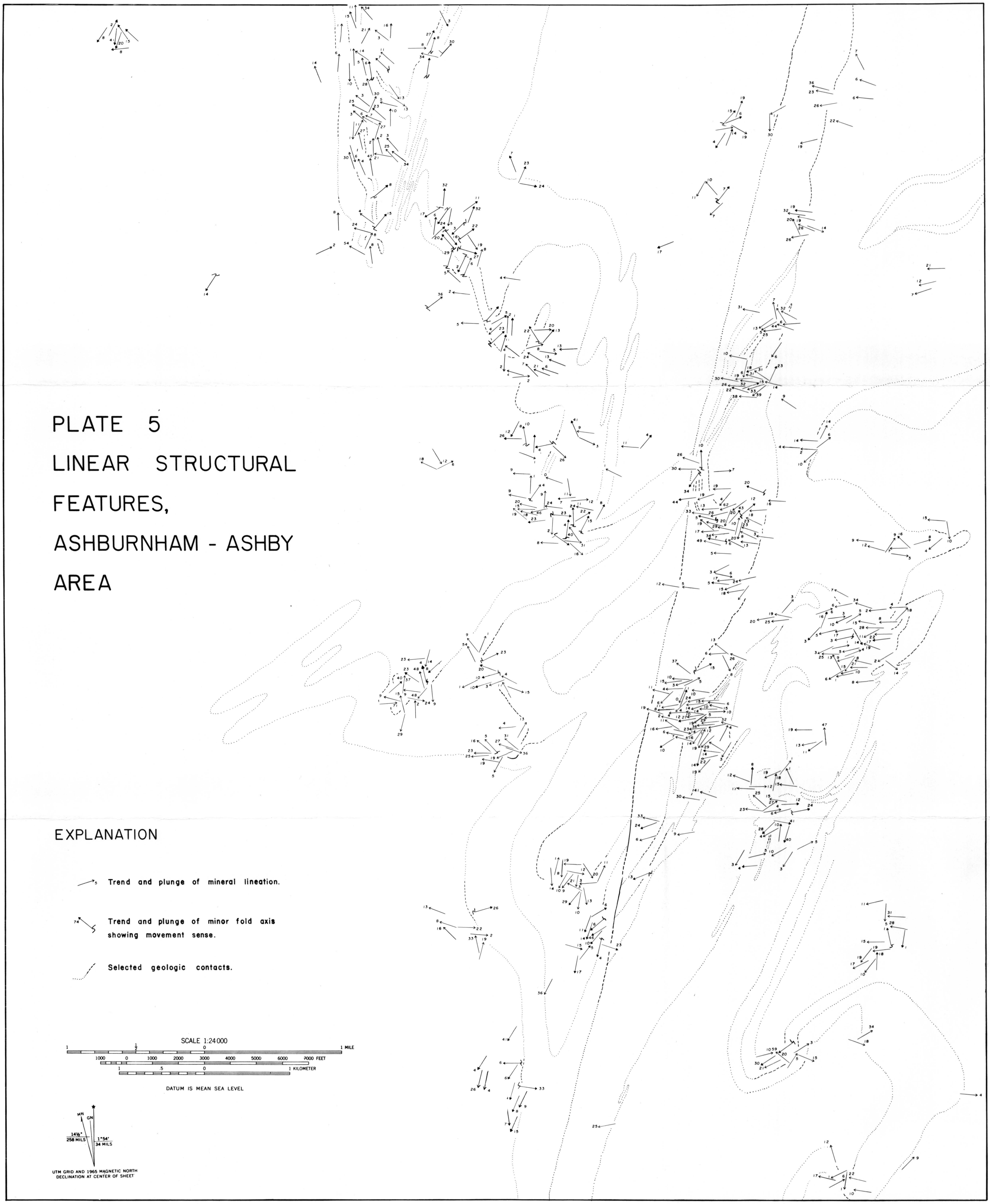


PLATE 5
LINEAR STRUCTURAL FEATURES, ASHBURNHAM - ASHBY AREA
EXPLANATION
Trend and plunge of mineral lineation.
Trend and plunge of minor fold axis showing movement sense.
Selected geologic contacts.
SCALE 1:24 000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER
DATUM IS MEAN SEA LEVEL
MN
GN
14½°
258 MILS
1°54'
34 MILS
UTM GRID AND 1965 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

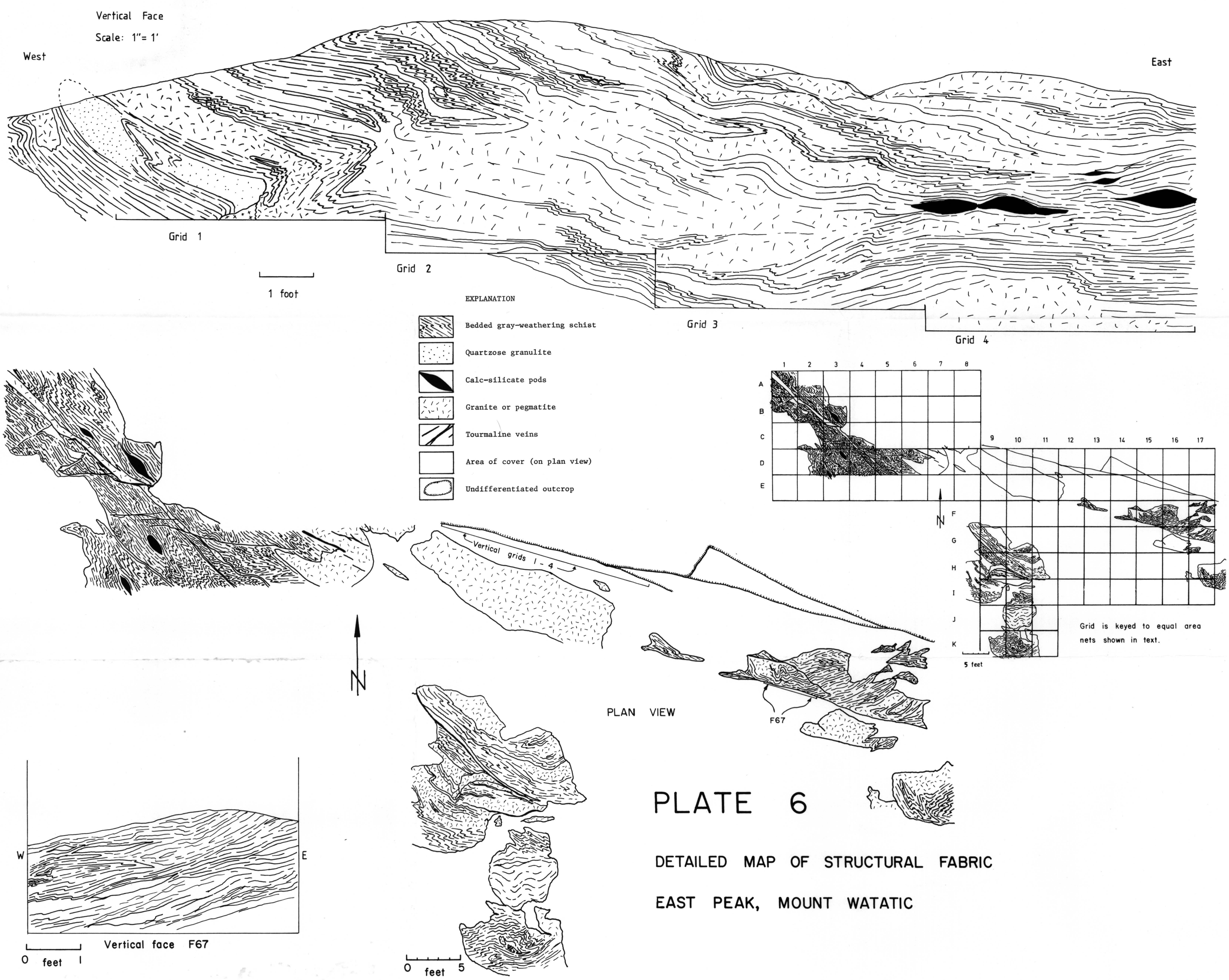


PLATE 6

DETAILED MAP OF STRUCTURAL FABRIC

EAST PEAK, MOUNT WATATIC