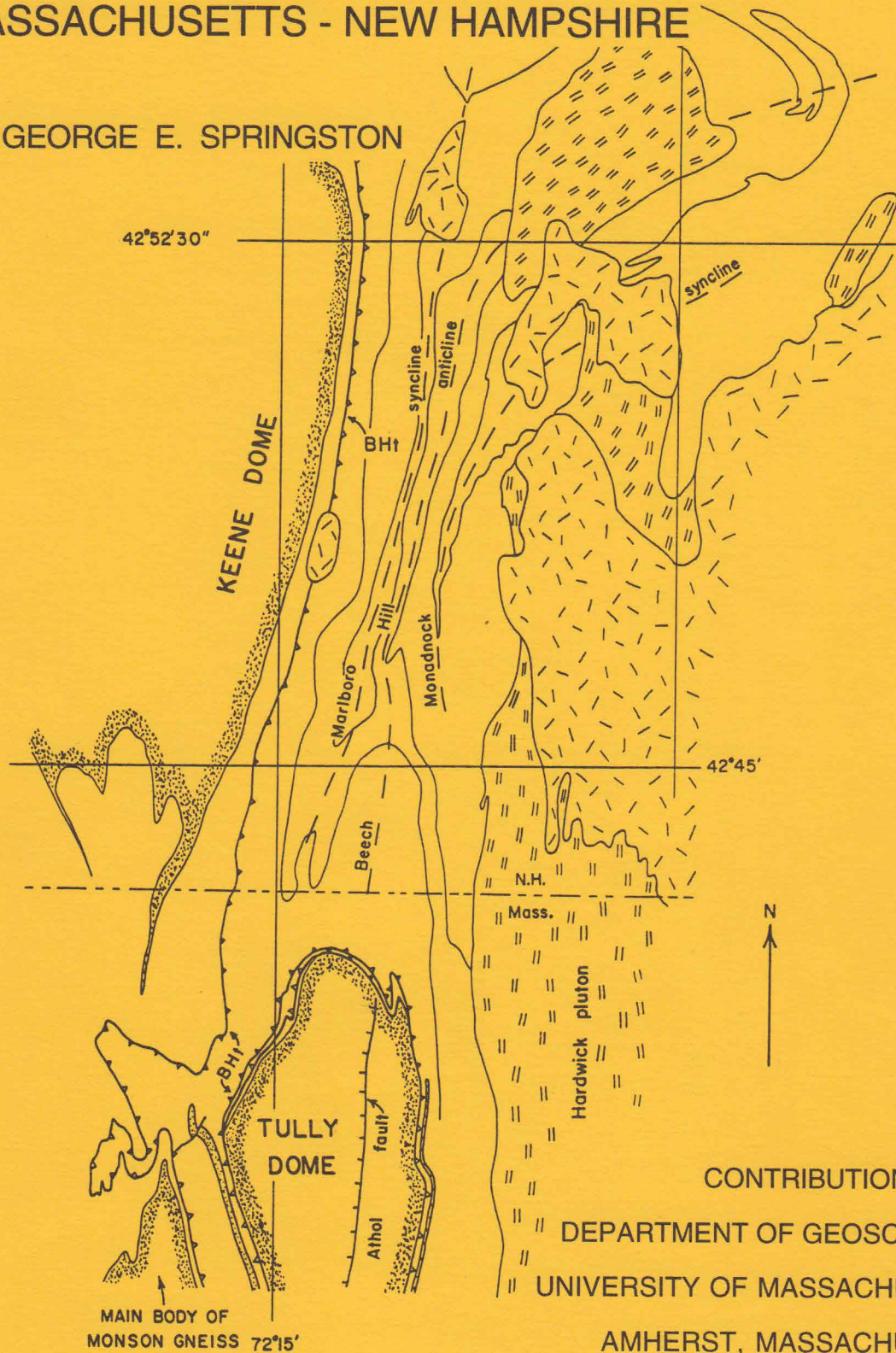


# STRATIGRAPHY AND STRUCTURAL GEOLOGY OF THE ROYALSTON - RICHMOND AREA MASSACHUSETTS - NEW HAMPSHIRE

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**STRATIGRAPHY AND STRUCTURAL GEOLOGY  
OF THE ROYALSTON-RICHMOND AREA  
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**(M.S. Thesis)**

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## ABSTRACT

The bedrock of the Royalston-Richmond area consists of Ordovician plagioclase gneisses in the cores of the Keene and Tully domes, stratified sequences of metamorphosed Upper Ordovician, Silurian, and Lower Devonian sedimentary and volcanic rocks, and Devonian and Mississippian granitic intrusive rocks. Following the work of P.J. Thompson in the Monadnock quadrangle, the stratified rocks have been divided into the Bronson Hill and Monadnock sequences.

In the Bronson Hill sequence, the amphibolites and sulfidic schist of the Ordovician Ammonoosuc Volcanics and Partridge Formation are overlain by the Silurian Clough Quartzite. The Clough represents thin, coarse clastic sediments deposited in a shelf environment located west of the Merrimack trough. The Clough is overlain by the Lower Devonian flysch of the Littleton Formation, which had its source to the east of the Merrimack trough.

The Monadnock sequence consists of a thick Silurian section, which represents a clastic wedge shed into the Merrimack trough from the west, overlain by Lower Devonian flysch of the Littleton Formation. The lowest unit in the Monadnock sequence is the Lower Silurian Rangeley Formation with three members, each dominated by feldspathic schist: a lower gray-weathering member with lesser amounts of gritty schist and rare granulite-matrix conglomerate lenses; a rusty-weathering middle member; and a gray- to rusty-weathering upper member. Calc-silicate granulite pods are common throughout but are most common in the middle member. A series of three thin, yet distinctive, Silurian formations overlies the Rangeley Formation. From oldest to youngest these are the Early Silurian Perry Mountain Formation, consisting of gray schist and garnet-grunerite-magnetite "iron formation", the Middle Silurian Frankestown Formation, consisting of rusty-weathering, sulfidic calc-silicate granulite and rusty-weathering schist, and the Late Silurian Warner Formation, consisting of layered calc-silicate granulite and feldspathic biotite granulite. In the Monadnock syncline the Warner Formation is overlain by the Littleton Formation.

Intrusive igneous rocks in the area include the syn-tectonic Devonian Hardwick Tonalite, the post-tectonic Mississippian(?) Fitzwilliam Granite, and minor Jurassic(?) diabase.

The principal deformation occurred during the Devonian Acadian orogeny. The dominant foliation formed parallel to axial planes of early, west-directed fold nappes. These nappes were then cut by the Brennan Hill thrust, which transported previously folded rocks of the Monadnock sequence westward over those of the Bronson Hill sequence. The rocks were then backfolded to the east and the Tully body moved northward relative to the cover rocks. The cores of the Tully and Keene domes then rose vertically relative to the cover rocks. Late map-scale and outcrop-scale folds formed prior to and during the rise of the domes. The dominant mineral lineation formed as a stretching lineation during the early part of the dome stage. Crenulation and broad warping locally deformed these structural features. Normal faulting and intrusion of diabase dikes and sills occurred in the Mesozoic.



Amphibolite facies metamorphism occurred during the Acadian orogeny. Pelitic schists in the westernmost parts of the study area contain the assemblage sillimanite + muscovite + staurolite + garnet + quartz +/- plagioclase while the assemblage sillimanite + muscovite + garnet + biotite + quartz +/- plagioclase occurs throughout the remainder of the study area. Peak metamorphism occurred after movement on the Brennan Hill thrust and before the dome stage. Pseudomorphs of sillimanite after andalusite in the eastern part of the area record an early Acadian low pressure contact metamorphism due to the intrusion of the Hardwick Tonalite. Staurolite and fine-grained muscovite partially overgrew the sillimanite after the peak of metamorphism.

## CHAPTER 1 INTRODUCTION

### Location, Access, and Vegetation

The study area is located on the Massachusetts-New Hampshire border approximately 45 kilometers north-northeast of Amherst, Massachusetts and 100 kilometers west-northwest of Boston, Massachusetts. It includes parts of four U.S. Geological Survey topographic quadrangles: the Royalston and Mt. Grace 7.5 minute quadrangles and the Winchester and Monadnock Mountain 7.5 x 15 minute quadrangles (Figure 1.1).

Most of the area is accessible by a network of paved highways, well maintained dirt roads, and rough logging roads. Today the area has a nearly continuous forest cover of white pine, eastern hemlock, and mixed hardwoods, with red spruce and balsam fir becoming important at the higher elevations. Wooded swamps, shrub swamps, marshes, and beaver ponds are common.

In the early nineteenth century this region was dotted with small farms, but until well into the present century the population dwindled and the farms were gradually abandoned. Today, stone walls, cellar holes, and rows of ancient sugar maples flanking long-abandoned roads are a common sight even in the most remote parts of the woods. At present, logging and tourism are the primary economic activities and active farms are rare.

### Physiography, Drainage, and Quaternary Cover

"From the highest ground on the road north from North Orange a fine view is obtained of the deep basin, with the white granite showing in the flanks of the Tully Mountains and all the ground above the sand level a 'felsenmeer' of great woolsack boulders of granite, while the bold hill in the extreme northeast of Orange shows by its jagged ridges of rust-brown rock that it is made up of the higher fibrolite-schists."

-Emerson, 1898, p.316

The Royalston-Richmond area is part of the Central Highlands physiographic province (Denny, 1982). Throughout most of the area the topographic relief is moderate. The highest elevation is 570 meters at the summit of Little Monadnock Mountain and the lowest elevation is 182 meters in the meadows south of Blissville, in the southwest corner of the study area. The area can be divided into three distinct physiographic zones: a highland with average elevations of 300-400 meters, which is underlain mostly by schist or amphibolite, and two lowlands with average elevations of 200-300 meters, which are underlain by less resistant plagioclase gneisses. The plagioclase gneisses occupy the cores of two gneiss domes: the Tully dome in the southern part of the study area and the Keene dome in the northwestern part of the study area. The escarpment

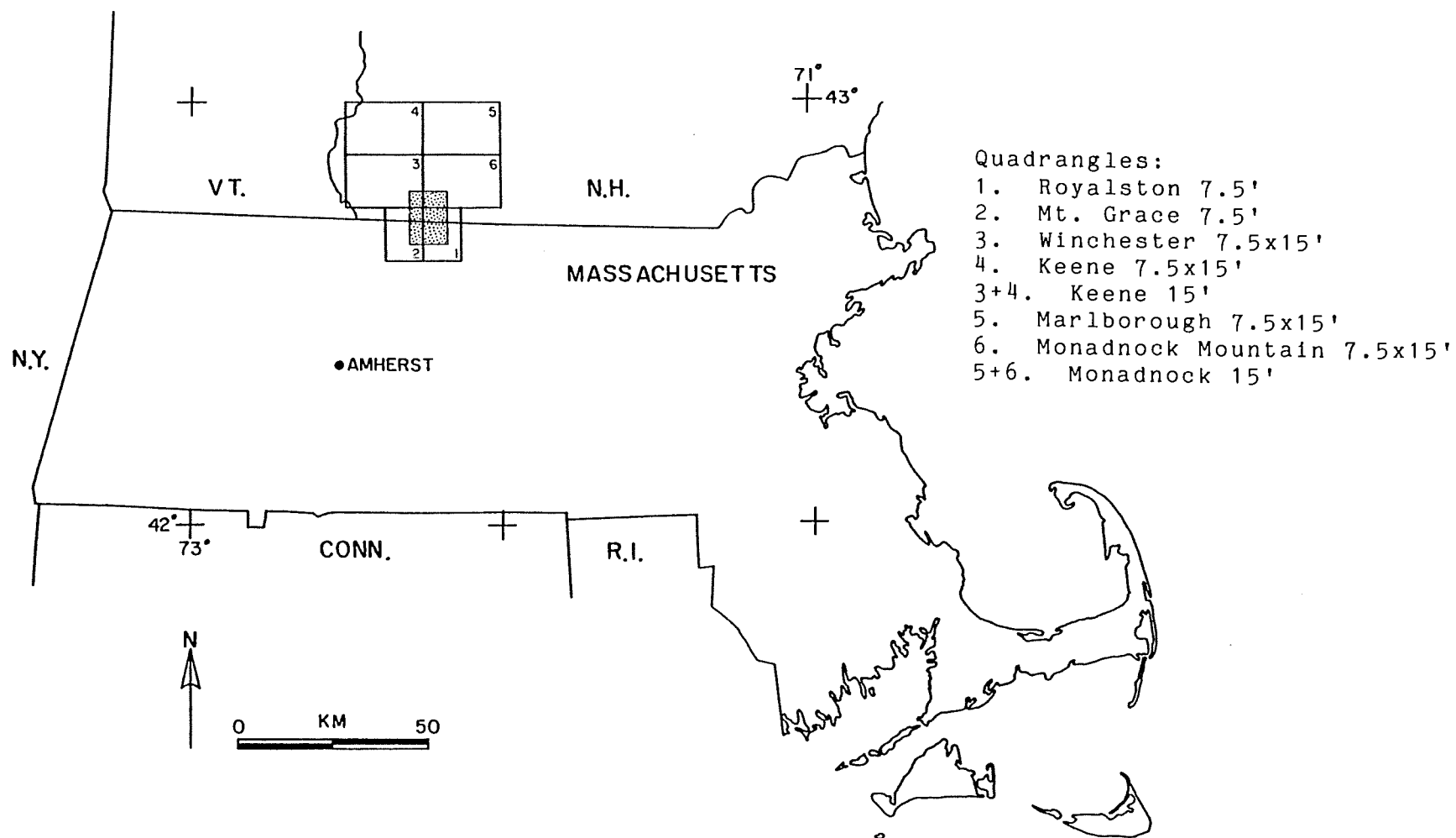


Figure 1.1 Location map for Royalston-Richmond area (stippled).

between the lowland of the Tully dome and the surrounding highlands is marked by Royalston Falls, located north of West Royalston, and by cascades at Spirit Falls, east of Long Pond.

Streams in the northwestern portion of the study area drain northward into the Ashuelot River while the rest of the area drains southward into the Millers River via Falls Brook, Tully Brook, Boyce Brook, and Kemp Brook. Both the Ashuelot River and the Millers River are tributaries of the Connecticut.

The Pleistocene deposits consist of a mantle of till on many of the hills and in the higher valleys, and outwash sand and gravel deposits in the lowlands. Holocene sand and gravel deposits are common along streams. Erratics occur throughout the area and talus blocks are common below prominent ledges.

Outcrops are most abundant on southern (lee) slopes and on tops of hills. Extensive outcrops also occur on the slopes surrounding the topographic basin of the Tully dome (Emerson's "jagged ridges of rust-brown rock"). Scattered outcrops occur in the lowlands where streams have eroded away the surficial deposits. Roadside outcrops are rare.

#### Regional Geology

The Royalston-Richmond area lies across the transition between the Bronson Hill anticlinorium and the Merrimack synclinorium (Figure 1.2). The Bronson Hill anticlinorium is a belt of mantled gneiss domes extending through central New England from western Maine to Long Island Sound. The cores of the domes are predominantly Ordovician felsic gneisses and are overlain by metamorphosed Ordovician, Silurian, and Lower Devonian sedimentary and volcanic rocks (Thompson et al., 1968; Robinson et al., 1988). The inner core of the Pelham dome of west-central Massachusetts, however, contains late Precambrian gneisses, quartzites, and related rocks. The Merrimack synclinorium to the east is a broad belt of metamorphosed sedimentary and volcanic rocks also of Paleozoic age. Deformation and metamorphism in both of these zones occurred chiefly during the Middle Devonian Acadian orogeny. Near the western margin of the Bronson Hill anticlinorium, in the lowlands of the Connecticut River Valley, are the Mesozoic rift basins. These are half-graben bounded on the east by west-dipping normal faults (Hubert et al., 1978; Zen et al., 1983). They are filled with interbedded clastic sedimentary rocks and basalts of late Triassic and early Jurassic age (Hubert et al., 1978; Robinson and Lutrell, 1985).

#### Previous Work

J.H. Huntington carried out reconnaissance mapping in the New Hampshire portion of the study area (reported in Hitchcock, 1877). His "Bethlehem gneiss" corresponds roughly to the Swanzeys Gneiss of this study and the fibrolite schist and ferruginous schist units of the "Montalban series" together correspond to the Silurian and Devonian rocks of the Bronson Hill and Monadnock sequences described below. His "Concord granite" correlates with the Fitzwilliam Granite of the present study.



Richmond area outlined. Modified from Robinson et al. (1986).

Detailed geologic mapping in the Massachusetts portion of the study area began with the work of Emerson (1898, 1917). Many of the units on his 1916 Geologic Map of Massachusetts and Rhode Island can be directly correlated with the modern stratigraphic units (compare with Zen et al., 1983). In the accompanying text he describes the Tully body as a batholith of "Monson granodiorite" that has intruded the surrounding rocks after they had been folded and metamorphosed. His "Brimfield schist" and "Amherst schist" correlate collectively with the Partridge, Littleton, and Rangeley Formations of this study. Emerson's "Quabin quartzite" and part of his "Northfieldite" unit, which he interpreted to be a siliceous igneous rock, correlate with the Clough Quartzite of later workers. The "Dana diorite" that encircles the Tully body was considered by him to be a mafic border facies of the "Monson granodiorite" (Monson Gneiss). It included rocks now variously assigned to the Ammonoosuc Volcanics and the Partridge Formation, as well as mafic portions of the Monson Gneiss. Emerson considered the foliation in the "Monson granodiorite" and the "Dana diorite" to be due to magmatic flow during the later stages of crystallization. The broad belt of "Hardwick granite" (Hardwick Tonalite) to the east of the Tully body was interpreted to be a mafic border of the Fitzwilliam Granite.

Modern geologic mapping began with the work of three associates of Professor Marland Billings of Harvard University. Moore (1949) mapped the Keene 15' quadrangle, the eastern portion of the Brattleboro 15' quadrangle, and the New Hampshire portions of the Northfield and Mt. Grace 7.5' quadrangles. Fowler-Billings (1949) mapped the Monadnock 15' quadrangle and the New Hampshire portion of the Winchendon 15' quadrangle to the south. Hadley (1949) mapped the Massachusetts portion of the Mount Grace 7.5' quadrangle. The results of their mapping are summarized on the 1956 Geologic Map of New Hampshire and in the accompanying text (Billings, 1956). Table 1.1, column 1, shows the stratigraphic column they proposed for western New Hampshire. The "Swansey gneiss" and "Monson gneiss" were assigned to the Oliverian magma series of Billings, (1937, 1956) and were thought to have been intruded into the cover rocks during the Acadian orogeny. These workers seemed to fully appreciate the complexity of these rocks and they succeeded quite well in outlining the cores of the gneiss domes and many belts of the overlying strata. However, because of a lack of sufficient stratigraphic markers the ductile deformation history of the area was only partially deciphered.

Fitzgerald (1960) mapped the western half of the Royalston 7.5' quadrangle using the stratigraphy of Billings and associates. According to Peter Robinson (personal communication, 1989), he was influenced by Robinson's preliminary results from mapping in the Orange area during 1959 and 1960. Fitzgerald interpreted the Tully Gneiss (Monson Gneiss of other workers) as a sill intruded below a sequence of Ammonoosuc Volcanics, Partridge Formation, and Littleton Formation. The Tully Gneiss was structurally above the other formations due to overturning of a large-scale nappe during the Acadian orogeny.

Robinson (1963, 1967) mapped the Orange quadrangle and adjacent parts of the Northfield, Mt. Grace, Athol, and Millers Falls quadrangles. He focussed on the stratigraphy and the structural geology of the cover rocks surrounding the Pelham dome, the Kempfield anticline, the main and

Table 1.1 Comparison of stratigraphic interpretations in the Royalston-Richmond area and vicinity. Time scale modified from Palmer (1983).

		Billings (1956) Notes 2,3	Robinson(1963,1967) Pike(1968) J.B. Thompson <i>et al.</i> (1968) Notes 3,4	P.J. Thompson(1985)		Elbert <i>et al.</i> (1988) Robinson <i>et al.</i> (1988) This study Note 5	
				Bronson Hill Sequence	Monadnock Sequence	Bronson Hill Sequence	Monadnock Sequence
408 Ma	LOWER DEVONIAN	Littleton Fm.	Erving Fm. Littleton Fm.	Erving Fm. Littleton Fm.	Littleton Fm	Erving Fm. Littleton Fm.	Littleton Fm.
	SILURIAN	Fitch Fm.	Fitch Fm.	Fitch Fm.	Warner Fm. Francestown Fm. Perry Mtn. Fm. Rangeley Fm.	Fitch Fm.	Warner Fm. Francestown Fm. Perry Mtn. Fm. Rangeley Fm.
		Clough Quartzite	Clough Fm.	Clough Quartzite		Clough Quartzite	
		Partridge Fm. Ammonoosuc Volcanics	Partridge Fm. Ammonoosuc Volcanics	Partridge Fm. Ammonoosuc Volcanics		Partridge Monson Ammonoosuc	
	UPPER ORDOVICIAN (see Note 1)						
458	MIDDLE ORDOVICIAN		Monson Gneiss (pre- Late Ordovician)	Monson Gneiss (pre- Late Ordovician)			
478	LOWER ORDOVICIAN						

Notes:

1. All available paleontologic and radiometric data point to a Caradocian age for the Ammonoosuc Volcanics and the Partridge Formation. In older North American stratigraphic nomenclature the Caradocian was assigned to the Middle Ordovician (Van Eysinga, 1978). The presently accepted DNAG timescale places the Caradocian in the early Late Ordovician, in conformity with European nomenclature.
2. The Monson Gneiss and equivalents were considered to have been intruded into these rocks during the Acadian orogeny.
3. Large areas mapped by these authors as Littleton or Partridge Formation are now mapped as Rangeley, Perry Mountain, Francestown, or Warner Formation.
4. Much of Robinson's gray schist member of the Partridge Formation was later remapped as Littleton Formation and following the work of P.J. Thompson (1985) was reassigned to the Rangeley Formation above the Brennan Hill thrust.
5. The nature of the Monson/Ammonoosuc contact is uncertain based on the latest radiometric dating and field criteria. An extensional detachment fault is a possibility.

Tully bodies of the Monson Gneiss, and the Warwick dome. Table 1.1, column 2, shows his interpretation of the stratigraphic column. The "Clough Formation" served as one of the key stratigraphic markers within the cover sequence. The structural geometry revealed by this increased understanding of the stratigraphy led to a much more detailed understanding of the deformation history. The basement gneisses were tentatively interpreted to be older than the cover rocks and both basement and cover were shown to have been deformed into map-scale recumbent folds before the formation of the gneiss domes.

Pike (1968) built on this new understanding in his mapping of the Tully body. His cross sections show a sausage-shaped body of Monson Gneiss transported northward relative to a cover sequence of Ammonoosuc Volcanics, Partridge Formation, and Littleton Formation.

J.B. Thompson et al. (1968) published a synthesis of the geology of the Bronson Hill anticlinorium in west-central New England. They proposed that the New Hampshire stratigraphic sequence of Billings and subsequent workers had been folded into a series of three west-directed recumbent fold-nappes during the early stages of the Acadian orogeny. From lowest to highest these were the Cornish, Skitchewaug, and Fall Mountain nappes. The rocks of the Royalston-Richmond area were correlated with the upright limb of the Skitchewaug nappe and the inverted limb of the Fall Mountain nappe. Although the details of recent interpretations are considerably more complex, the concept of large-scale nappes that are traceable throughout the region remains central to modern interpretations.

P.J. Thompson (1985, 1988) remapped the Monadnock 15' quadrangle based on new correlations of those rocks with the Silurian-Devonian sequence in central New Hampshire and western Maine (Hatch et al., 1983). He demonstrated that instead of a single stratigraphic sequence, as earlier workers had envisioned, there were actually two: the Bronson Hill and Monadnock sequences (Table 1.1, column 3). These correlations will be discussed in detail under Stratigraphy. His detailed mapping showed that the west-directed fold nappes of earlier workers were cut by major west-directed thrust faults, the Brennan Hill thrust and the Chesham Pond thrust, prior to the backfold and dome stages.

Elbert (1988) extended these new interpretations into the Bernardston-Hinsdale area to the west. He recognized P.J. Thompson's Monadnock sequence and an early thrust fault which he correlated with the Brennan Hill thrust. He also discovered lenses of "iron formation" within the Upper Silurian Perry Mountain Formation. This led to a reinterpretation of identical rocks in the Mount Grace and Royalston-Richmond areas by Robinson (1987), and Robinson et al. (1988).

#### Purpose of Study

The primary purpose of this study was to refine the stratigraphy of the Rangeley Formation in this critical area along the Massachusetts border and to improve the interpretations of map-scale structural features. Specific questions included the structural connection between the Tully body of the Monson Gneiss in Massachusetts and the Beech Hill anticline in New Hampshire, and the



location and geometry of the Brennan Hill thrust, particularly as it is involuted around the Tully body of the Monson Gneiss.

#### Methods of Study

Field mapping was done during the summers of 1986, 1987, and 1988 with supplementary work continuing until June, 1989. Contacts and outcrops were plotted on 1:25,000 scale topographic maps except in the area of abundant outcrop on Butterworth Ridge, for which an enlarged 1:6,000 scale base map was prepared. A pocket altimeter, frequently checked on points of known elevation, was used as an aid to location. Stations were labelled with prefixes according to the quadrangle within which they were collected: KE = Keene 15', MG = Mount Grace, MO = Monadnock Mountain, RO = Royalston. Orientations of planar and linear features were measured using a Brunton compass.

Orientation data was plotted on equal area nets using Netplot, a program written by Bruce Taterka and Professor Donald U. Wise.

Twelve oriented samples and 35 unoriented samples were selected for thin sections. Sixty thin sections prepared from these samples were examined using a transmitted light petrographic microscope. Modes were estimated with the help of a visual comparison chart.

## CHAPTER 2 STRATIGRAPHY

### Introduction

The bedrock of the Royalston-Richmond area consists of Ordovician plagioclase gneisses in the cores of the Keene and Tully domes, stratified sequences of metamorphosed Upper Ordovician, Silurian, and Lower Devonian sedimentary and volcanic rocks, and Devonian and Mississippian granitic intrusive rocks. Following the work of P.J. Thompson (1985) in the Monadnock quadrangle, the stratified rocks have been divided into the Bronson Hill and Monadnock sequences.

Each of the units in the tectono-stratigraphic diagram (Figure 2.1) is described below. The Rangeley, Perry Mountain, Frankestown, and Warner Formations are described in greatest detail. Since detailed descriptions already exist for the gneisses in the cores of the domes, the stratified rocks of the Bronson Hill sequence, and the intrusive rocks, the descriptions are brief and based largely on previously published material. The description of the Littleton Formation applies to both the Bronson Hill and Monadnock sequences.

### Monson Gneiss and Swanzeey Gneiss

The Monson Gneiss and the Swanzeey Gneiss are exposed in the cores of the Tully body and the Keene dome, respectively, and consist of gray-weathering plagioclase-quartz-biotite gneiss and interlayered plagioclase-hornblende-quartz amphibolite (Moore, 1949; Robinson, 1963; J.B. Thompson et al., 1968). Sample RO-551, Table 2.1, is a typical example of the felsic gneiss. Although this is the dominant rock type in both the Keene dome and the Tully body, amphibolite is a significant component. In two partial measured sections in the eastern portion of the Keene dome, Ahmad (1975) found 8% and 18% amphibolite. These gneisses are interpreted to be the plutonic roots of the Bronson Hill volcanic arc (Robinson et al., 1989).

The relationship between the dome gneisses and the cover rocks that structurally overlie them has been the source of considerable controversy. The dome gneisses were interpreted as Devonian intrusions into the cover by Fowler-Billings (1949), Moore (1949), Billings (1956), and Fitzgerald (1960). Eskola (1949) suggested that the dome gneisses might represent remobilized Precambrian basement. From field relations in Massachusetts and southern New Hampshire Robinson (1963, 1977) suggested that the Ammonoosuc rests unconformably on the plagioclase gneisses. Naylor (1969) interpreted the contact as a change in volcanic chemistry. Based on a review of contact relationships and available radiometric ages, Leo (1985) and Zartman and Leo (1985) favored an intrusive relationship. Recent U-Pb zircon dates obtained by Robinson et al. (1989) indicate an age of 454-443 Ma for the plagioclase gneisses and 453-449 Ma for the upper member of the Ammonoosuc Volcanics and the Partridge Formation. The authors suggest that this overlap in age between "basement" and cover may be the result of a detachment fault active either during the formation of the Bronson Hill arc during late Ordovician time or possibly during the early stages of the Acadian orogeny.

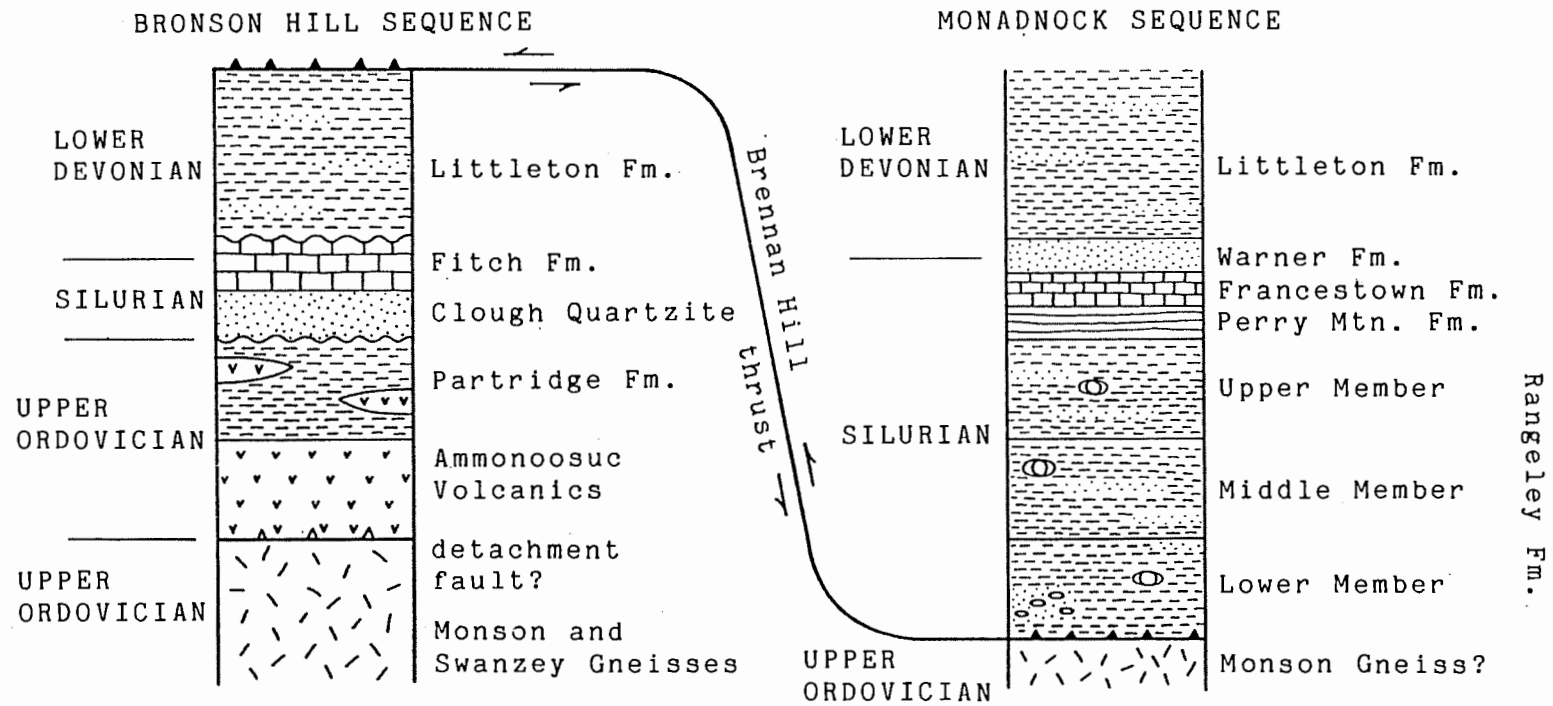


Figure 2.1 Tectono-stratigraphic diagram. Contact relationships across the Brennan Hill thrust are more complex than shown in that both sequences were recumbently folded prior to thrusting. Bronson Hill sequence after J.B. Thompson et al. (1968) and Tucker and Robinson (in press). Monadnock sequence after P.J. Thompson (1985). The suggestion of the Monson Gneiss as the original basement for the Rangeley Formation is based on the work of Berry (1985) in the Brimfield-Sturbridge, Massachusetts area.

Table 2.1 Estimated modes of samples from the Monson Gneiss and the Ammonoosuc Volcanics.

	Monson Gneiss	Ammonoosuc Volcanics		
	<u>RO-551</u>	<u>RO-562AX</u>	<u>RO-562B</u>	<u>G95*</u>
Quartz	35	18	9	9
Plagioclase	51 (26)	10 (63+)	20 (73+)	40 (lab)
Untwinned feldspar	3?	-	-	-
Mymekite	tr	-	-	-
Biotite	2	tr	-	tr
Hornblende	-	60	69	50
Garnet	-	9	-	-
Chlorite	8 (Fe-Mg)	tr (Mg-Fe)	-	-
Rutile	-	-	tr	-
Ilmenite	-	-	tr	tr
Pyrite	-	2	tr	-
Magnetite	tr	tr	tr	-
Hematite (weath.)	tr	-	-	-
Apatite	tr	-	tr	tr
Zircon	tr	tr	-	-
Tourmaline	tr	-	-	-
Prehnite	-	-	-	tr

\* From Robinson, 1963, Table 3.

#### Hand sample descriptions and locations for Table 2.1

RO-551 - Medium-grained, well foliated plagioclase gneiss. Outcrop located at elevation 775' (236m), 250m northeast of Warwick Road (state route 68), and 0.9 km north-northwest of the bridge where state route 68 crosses Boyce Brook (Royalston).

RO-562AX - Medium-grained, dark-green, garnet ammphibolite. Outcrop in Boyce Brook, 100m south of Falls Road (Royalston).

RO-562B - Medium-grained, dark amphibolite. Outcrop on the east bank of Boyce Brook, 100m south of Falls Road (Royalston).

G95A - "Medium-grained hornblende amphibolite. At 950-foot contour on east slope of northernmost of three small 980-foot knobs near the south end of Butterworth Ridge" (Robinson, 1963, Table 3).

### Explanation of Tables of Modes.

Modes were estimated visually using a comparison chart.  
tr - less than one percent.

#### Plagioclase:

- (24) - mole percent anorthite by Michel-Levy method.
- (lab) - labradorite.
- (seric.) - heavily sericitized.

Chlorite compositions were estimated based on interference color and sign of elongation.

- (Fe-Mg) - abnormal blue, positive elongation.
- (Mg-Fe) - abnormal brown, negative elongation.

### Ammonoosuc Volcanics

The Ammonoosuc Volcanics in the study area consist of two units: a lower unit composed dominantly of amphibolite and an upper unit composed mostly of brown- to reddish-brown-weathering felsic gneiss (Robinson, 1963; Robinson et al., 1979). The mineralogy of the Ammonoosuc amphibolites is much more varied than in the amphibolites of the Monson and Swanzey Gneisses. Amphiboles present in the Ammonoosuc amphibolites include hornblende, anthophyllite, gedrite, and cummingtonite, while the Monson and Swanzey amphibolites contain only hornblende (Robinson, 1963; Schumacher, 1983). Also, garnet is more abundant in the Ammonoosuc (Robinson, 1963; Schumacher, 1983).

A measured section of the Ammonoosuc Volcanics from the eastern margin of the Keene dome is shown in Figure 2.2. The predominance of amphibolite in this section suggests that the upper part may have been truncated by erosion before deposition of later formations. The layering evident in this section seems to be typical of the Ammonoosuc Volcanics on this side of the Keene dome. A more complete section is exposed to the north of the study area in a roadcut on state route 12 in Swanzey and is described in detail in Robinson et al. (1979, Stop 4). There, the Swanzey gneiss is overlain by about 25m of interbedded amphibolite and felsic gneiss, with felsic gneiss becoming dominant in the upper part.

### Partridge Formation

The Partridge Formation consists of rusty-weathering, sulfidic quartz-muscovite-biotite-plagioclase-sillimanite-garnet schist and interbedded hornblende-plagioclase-quartz amphibolite (Moore, 1949; Robinson, 1963). Correlative rocks in Maine contain Caradocian graptolites (Harwood and Berry, 1967) and a U-Pb zircon age from a rhyolite tuff within the Partridge Formation near Bernardston, Massachusetts yields a late Caradocian age of  $449 \pm 3/-2$  Ma (Robinson et al., 1989). The protoliths of the Partridge Formation were black shales and interbedded volcanics (Robinson et al., 1979).

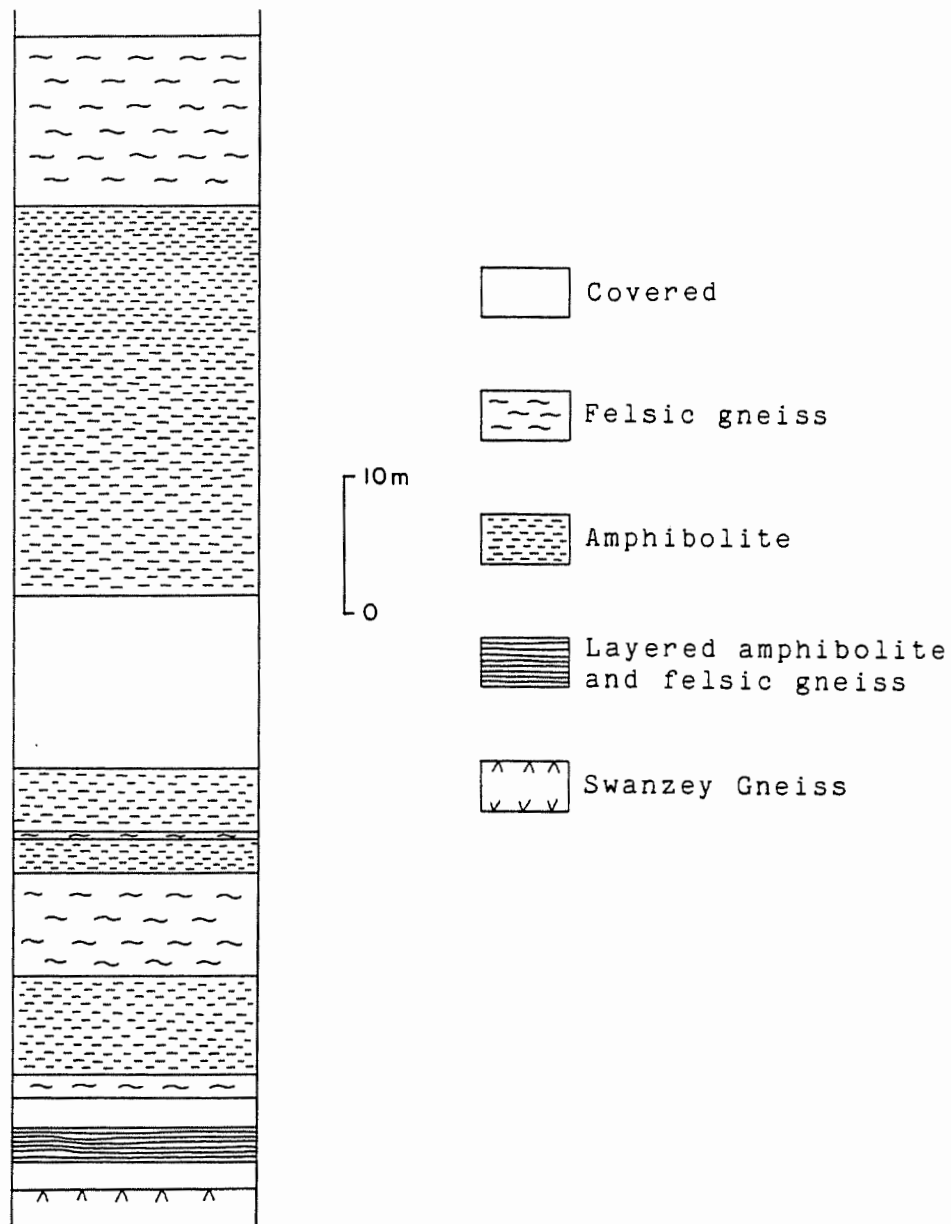


Figure 2.2 Measured section of the Ammonoosuc Volcanics on the eastern flank of the Keene dome. Interlayered plagioclase-hornblende amphibolite and brown-weathering felsic gneiss of the Ammonoosuc Volcanics overlie the Swanzey Gneiss. Above the Ammonoosuc, after a short covered interval, are outcrops of the Clough Quartzite. Section located on a south-facing slope 0.2km east-southeast of intersection 234 on Fish Hatchery Road, Richmond.

### Clough Quartzite

The Clough Quartzite is a distinctive unit consisting of metamorphosed quartzite and quartz-pebble conglomerate with lesser amounts of quartz-cobble conglomerate, micaceous quartzite, and other rock types (Moore, 1949; Robinson, 1963). The age of the Clough Quartzite is late Llandoveryan based on numerous fossil localities in New Hampshire and Massachusetts (Boucot et al., 1958; Boucot and Thompson, 1963).

### Fitch Formation

The Fitch Formation consists of gray quartz-plagioclase-biotite granulite and calc-silicate granulite (Robinson, 1963; P.J. Thompson, 1985). Although it does not occur in the Royalston-Richmond area, it is present as discontinuous lenses between the Clough Quartzite and the Littleton Formation on the northeastern flank of the Keene dome and in the Orange area (P.J. Thompson, 1985; Robinson, 1963). In the Bernardston, Massachusetts area the Fitch Formation contains Lochkovian (earliest Devonian) fossils (Elbert et al., 1988) while the Fitch Formation of the Littleton New Hampshire area contains fossils of Pridolian (latest Silurian) age (Harris et al., 1983).

### Littleton Formation

The Littleton Formation in the study area consists of gray-weathering quartz-muscovite-biotite-sillimanite schist (with or without plagioclase) and micaceous quartzite (P.J. Thompson, 1985). According to Thompson, it can be divided into two informal members: a lower part consisting of thick-bedded schist with sparse, thin quartzite beds, and an upper part characterized by abundant, thicker quartzite beds. The upper part is not exposed in the study area.

The Littleton Formation of the Monadnock region is correlated with the type Littleton Formation of northern New Hampshire and the Seboomook and Carabassett Formations of northwestern Maine (see Hatch et al., 1983 and P.J. Thompson, 1985 for discussions of these correlations). Although no fossils have been discovered in the Monadnock region, the age of the Littleton Formation in western New Hampshire is well established as Early Devonian (Boucot and Arndt, 1960; Boucot and Rumble, 1980).

In many places throughout the Bronson Hill anticlinorium the base of the Littleton Formation appears to represent an unconformity (P.J. Thompson, 1985). Although the absence of the rather discontinuous Fitch Formation in this area could well be due to non-deposition, the absence, in places, of the Clough Quartzite, the Partridge Formation, and even the Ammonoosuc Volcanics, is better explained as the result of erosion in pre-Littleton time (J.B. Thompson et al., 1968; P.J. Thompson, 1985).

## Rangeley Formation

### Introduction

Following the work of Hatch et al. (1983) and P.J. Thompson (1985), the Rangeley Formation in the study area is divided into three informal stratigraphic members: lower and upper units dominated by gray-weathering feldspathic schist and gneiss, and a middle member of rusty-weathering feldspathic schist and gneiss. These are the southward continuations of the units described in the Monadnock Quadrangle by P. J. Thompson. As will be clear from the descriptions, the distinctions between these units can be quite subtle. The lower and upper members, in particular, are very difficult to tell apart. Although it is not always possible to assign a given outcrop to one of these units with absolute certainty, the larger context of the surrounding outcrops usually allows an accurate assignment to be made.

Calc-silicate granulite pods occur in all three members and since they are very similar throughout the formation they will be discussed separately.

### Lower Member

The lower member is exposed on the flanks of the Tully body of Monson Gneiss and in a broad band east of the Keene dome. This member consists mostly of gray- to slightly rusty-weathering schist, gritty schist, and gneiss dominated by biotite, muscovite, quartz, and garnet, with or without plagioclase and sillimanite (Table 2.2). These rocks have a strong foliation defined by biotite, muscovite, and sillimanite. These three minerals typically define a single, strong mineral lineation within the foliation. Quartz-plagioclase segregations occur both as 2-10mm thick layers oriented parallel to the foliation and as isolated "blebs." Biotite is pale tan or pale brownish-tan in the X direction and brown or reddish-brown in the Y = Z direction. Garnet is euhedral against biotite and subhedral to anhedral against muscovite or quartz. The garnet typically contains inclusions of ilmenite. Sillimanite occurs most commonly as felty masses of fibrolite, less commonly as prisms 0.1-0.2mm in length oriented parallel to the mica lineation.

Rusty-weathering schist occurs throughout the lower member as scattered outcrops. The scattered distribution of these outcrops indicates that they probably represent lenses within the lower member, as opposed to being tectonically emplaced fragments of the middle member.

Gray- to rusty-weathering feldspathic biotite granulite also occurs throughout the lower member, usually as beds less than one meter thick. The dominant minerals are quartz, plagioclase, biotite, and garnet (Table 2.3). Plagioclase is unzoned and compositions range from  $An_{40}$  to  $An_{65}$ . Biotite is pale tan or pale brownish-tan in the X direction and dark reddish- or orangeish-brown in the Y = Z direction. Garnet tends to be euhedral where in contact with biotite and commonly has corroded margins when in contact with quartz or plagioclase. It is commonly sieved with quartz. Apatite commonly occurs as fine-grained, euhedral crystals. Figure 2.3 is a sketch of dark-gray-weathering biotite granulite showing a dominantly granoblastic texture with a weak biotite foliation. Note the highly corroded garnets and the lens of fine-grained euhedral apatite. This lens may represent a phosphate-rich fossil fragment of unknown derivation.



Table 2.2 Estimated modes of schist and gneiss samples from the lower member of the Rangeley Formation.

	KE-16X	KE-25X	MG-11X	MG-102X	RO-94A	RO-94B	RO-364	RO-396	RO-493	RO-502X
Quartz	20	20	32	46	83	15	36	47	18	30
Plagioclase	1	15 (24)	19 (24)	10 (24)	10 (seric.)	-	tr	22 (10)	22 (seric.)	17 (17-39)
Biotite	37	25	25	15	-	-	28	24	-	20
Muscovite	34	20	20	20	tr	-	32	1	2	30
Garnet	2	2	2	6	3	8	tr	2	-	tr
Sillimanite	4	15	tr	tr	-	-	tr	2	-	-
Chlorite	-	-	-	-	2 (Fe-Mg)	tr (Fe-Mg)	-	-	48 (Fe-Mg)	-
Graphite	tr	tr	tr	-	-	-	-	1	-	-
Ilmenite	1	3	1	2	tr	3	tr	1	2	2
Pyrite	-	-	-	-	-	-	-	-	-	tr
Hematite	-	-	-	-	tr	-	-	tr	tr	-
Apatite	tr	tr	tr	-	1	73	tr	tr	6	tr
Zircon	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Tourmaline	-	tr	-	-	-	-	-	-	-	-
Allanite	-	-	-	-	-	-	-	-	1	tr

Note - Chlorite is of retrograde origin.

## Hand sample descriptions and locations for Table 2.2

KE-16X - Medium-grained, gray-weathering schist with lenses of fibrolite and muscovite. Outcrop on the western side of a sandpit, 1.25km east of the intersection of state routes 32 and 119 (Richmond).

KE-25X - Medium-grained, gray-weathering gneiss with coarse lenses of fibrolite. Ledges located on a west-facing slope at elevation 350m, 1.2km east-southeast of the intersection of state routes 32 and 119 (Richmond).

MG-11X - Medium-grained, gray-weathering garnet schist with elongate lenses of muscovite. Outcrop on the western slope of Butterworth Ridge at elevation 1030' (314m), 1.0km east of the intersection of Bliss Hill Road and Tully Road (Orange).

MG-102X - Gray-weathering, medium-grained gneiss with 2-10mm thick quartz-feldspar layers. Outcrop on north side of state route 32, 0.2km northwest of Newton Cemetery (Royalston).

RO-94 - Slightly rusty-weathering, granulite-matrix conglomerate. Two modes from one thin section are listed as follows: RO-94A poorly foliated quartz-plagioclase-garnet granulite matrix; RO-94B weakly foliated apatite-quartz-garnet granulite clast (8x2mm). Clasts consisting of recrystallized quartz are also common. Small outcrop located at elevation 1020' (311m), 150m south of state route 68 and 0.95km west of the church at Royalston.

RO-364 - Medium- to fine-grained, gray-weathering schist. Ledge located at elevation 1000' (305m) on the west slope of Jacob Hill, 250m north of Spirit Falls (Royalston).

RO-396 - Medium-grained, slightly rusty-weathering, slabby gneiss. Outcrop in a sandpit located roughly 50m east of a cart road and 1.0km south-southeast of Beechwood Corners (Fitzwilliam).

RO-493 - Fine-grained, green chlorite schist. Outcrop on the southeast bank of Tully Brook at elevation 740' (226m) (Royalston).

RO-502x - Medium-grained, gray-weathering schist with abundant 2-4mm thick quartz-feldspar layers oriented parallel to the foliation. Outcrop in Tully Brook at elevation 815' (248m), 15m south of an old stone bridge abutment (Richmond).

**Table 2.3 Estimated modes of biotite granulite samples from the lower member of the Rangeley Formation.**

	<u>KE-16</u>	<u>RO-453</u>	<u>RO-541X</u>	<u>RO-546</u>
Quartz	58	37	62	75
Plagioclase	21 (62)	30 (65)	12 (40)	2
Biotite	17	17	18	18
Muscovite	-	-	tr	-
Garnet	3	5	4	tr
Chlorite	-	7 (Fe-Mg)	tr (Fe-Mg)	-
Graphite	-	-	tr	tr
Ilmenite	-	tr	1	tr
Pyrite	tr	-	tr	4
Hematite	-	tr	-	tr
Apatite	tr	3	2	tr
Zircon	tr	tr	tr	tr
Tourmaline	-	-	tr	-

Note - Chlorite is of retrograde origin.

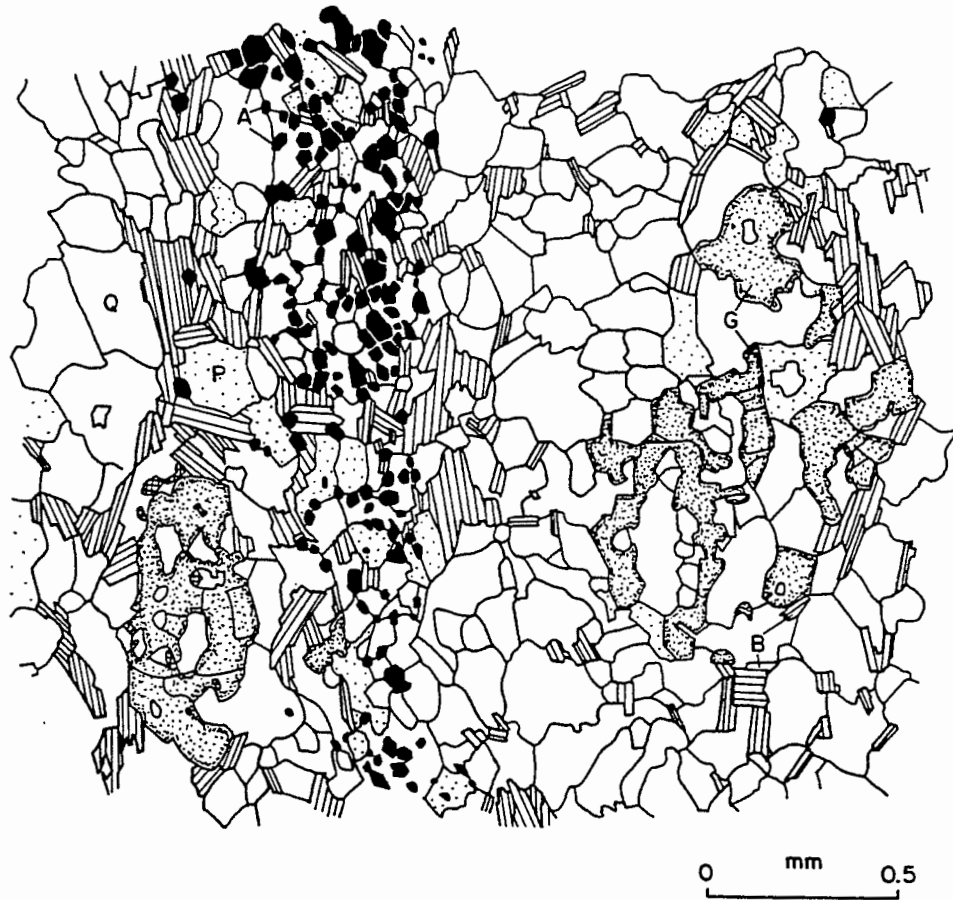
#### Hand sample descriptions and locations for Table 2.3

**KE-16** - Fine-grained, gray-weathering, layered quartz-feldspar-biotite granulite with 3-5mm thick quartz-feldspar layers. Outcrop on the western side of a sandpit 1.25 km east of the intersection of state routes 32 and 119 (Richmond).

**RO-453** - Fine-grained, gray-weathering granulite. Outcrop on the western slope of Cook Hill at elevation 1140' (347m), located 1.6km south of the intersection of Greenwood Road and Fay Martin Road (Richmond).

**RO-541X** - Fine-grained granulite that weathers to a dark gray color. Outcrop in the stream east of Greenwood Road at elevation 1050' (320m), 0.35km south-southeast of the intersection with Fay Martin Road (Richmond).

**RO-546** - Fine-grained, dark, slightly rusty-weathering quartzose granulite. Rubbly outcrop at elevation 915' (279m) on a southwest-facing slope 100m southwest of Falls Road and 650m northwest of the bridge over Boyce Brook (Royalston).



A = apatite  
B = biotite  
G = garnet

P = plagioclase  
Q = quartz

Figure 2.3 Sketch of a thin section of biotite granulite from the lower member of the Rangeley Formation. Note apatite-rich lens to the left of center and irregular garnet porphyroblasts. Sample RO-541X.

Two outcrops of brownish-rusty-weathering, metamorphosed conglomerate occur in the lower member. Station RO-94 is located south of state route 68 near Royalston. A thin section from this locality contains clasts of vein quartz and apatite-quartz-garnet granulite set in a matrix of quartz-plagioclase-garnet granulite (Table 2.2, samples RO-94A and RO-94B). The long axes of the clasts are oriented parallel to the local mineral lineation and the intermediate axes lie within the plane of the foliation. Station RO-540I is a north-south trending rib of rusty-weathering schist and granulite-matrix quartz pebble conglomerate located roughly 100m south-southeast of the summit of Hill 978 and 100m west of Falls Road, Royalston. As at the previous station, the long axes of the clasts appear to be oriented parallel to the mineral lineation and the intermediate axes lie within the plane of the foliation.

A third conglomerate locality in the lower member was discovered by Peter Robinson in the fall of 1986 (personal communication). The outcrop is located south of Butterworth Ridge on the east flank of Temple Hill in Orange, outside of the study area.

#### Middle Member

The middle member is exposed in a sweeping band extending south from Grassy Hill, in the northern part of the study area, through Beechwood Corners and Royalston, and also in the northeastern corner of the study area, east of Little Monadnock Mountain. This member consists mostly of rusty-weathering, commonly sulfidic schist and gneiss dominated by quartz, biotite, muscovite and plagioclase, with or without garnet and sillimanite (Table 2.4). These rocks have a strong foliation defined by biotite, muscovite, and sillimanite. As in the lower member, these minerals form a strong mineral lineation on the foliation planes. Quartz-plagioclase segregations occur both as 2-20mm thick layers oriented parallel to the foliation and as isolated blebs.

Biotite in the schist and gneiss is pale tan to pale green in the X direction and orangeish-brown to reddish-brown in the Y = Z direction. Plagioclase is unzoned and ranges in composition from  $An_{23}$  to  $An_{35}$ . Garnet typically has corroded outlines and locally has ilmenite inclusions oriented parallel to the foliation outside the garnet. Sillimanite occurs as fine needles in quartz or plagioclase and as 0.1-0.4mm long prisms oriented parallel to the mica lineation.

Dark, rusty-weathering massive calc-silicate granulite beds are fairly common in the middle member, especially near the contact with the upper member, south-southeast of Little Monadnock Mountain in Fitzwilliam. These beds are typically one half to one meter thick and occur within outcrops of schist or gneiss. The dominant minerals are quartz, calcic plagioclase, and hornblende (Table 2.5). Plagioclase is unzoned and has compositions greater than  $An_{73}$ . Hornblende occurs as corroded porphyroblasts with X = very pale green, Y = green, Z = bluish green. Sphene is subhedral and is pleochroic from colorless to pale reddish-brown and sometimes forms a rim around opaque grains. Clinozoisite occurs as a late vein mineral and as rims around plagioclase. It has an anomalous blue interference color, polysynthetic twins, and inclined extinction. Diopside occurs as corroded porphyroblasts. Pyrrhotite and graphite are common. Figure 2.4 is a sketch of a typical example.

Table 2.4 Estimated modes of gneiss and schist samples from the middle member of the Rangeley Formation.

	MO-42X	RO-303	RO-461X	TR-21*
Quartz	52	26	40	52
Plagioclase	10 (26)	2 -	20 (35)	10 (23)
Biotite	30	35	16	25
Muscovite	tr	30	20	2
Garnet	-	4	1	-
Sillimanite	4	-	tr	10
Chlorite	-	-	tr (Mg-Fe)	-
Opagues				
Graphite	tr	tr	1	tr
Ilmenite	-	2	1	tr
Pyrrhotite	3	-	-	-
Undifferent'd	-	-	-	tr
Apatite	tr	-	tr	-
Zircon	tr	tr	tr	tr
Allanite	-	tr	-	-

Note - Chlorite is of retrograde origin.

\* From P.J. Thompson, 1985, Table 1a.

#### Hand sample descriptions and locations for Table 2.4

MO-42X - Coarse-grained, rusty-weathering sulfidic gneiss with lots of irregular quartz-plagioclase segregations. Outcrop on the north side of state route 119, just east of a gravel drive 0.2km east of Beechwood Corners (Fitzwilliam).

RO-303 - Medium-grained, dark, gray-weathering garnet schist. The outcrop consists of both rusty-weathering and gray-weathering schist. At elevation 1100' (335m) on a knob east of Grant Hill Road, 1.15km north of state line bound number 26 (Fitzwilliam).

RO-461X - Medium-grained, rusty-weathering schist with a 1cm thick quartz-feldspar layer oriented parallel to the foliation. Outcrop at western corner of the intersection of Greenwood Road and Monument Road (Fitzwilliam).

TR-21 - Rusty-weathering foliated to granular schist. Route 12 roadcut 3.5km west of Troy Village.

**Table 2.5 Estimated modes of granulite samples from the middle member of the Rangeley Formation.**

	<u>MO-47</u>	<u>MO-52</u>	<u>RO-315</u>
Quartz	40	66	63
Plagioclase	30 (73+)	15 (73+)	20 (24)
Biotite	-	tr	14
Muscovite	-	tr	1
Garnet	tr	-	tr
Sillimanite	-	-	tr
Diopside	tr	-	-
Hornblende	25	11	-
Chlorite	-	-	tr (Fe-Mg)
Clinozoisite	tr	-	-
Zoisite	-	tr	-
Sphene	2	3	-
Graphite	-	tr	tr
Ilmenite	tr	-	1
Pyrrhotite	2	tr	-
Hematite	tr	-	-
Zircon	tr	-	tr
Apatite	tr	tr	tr

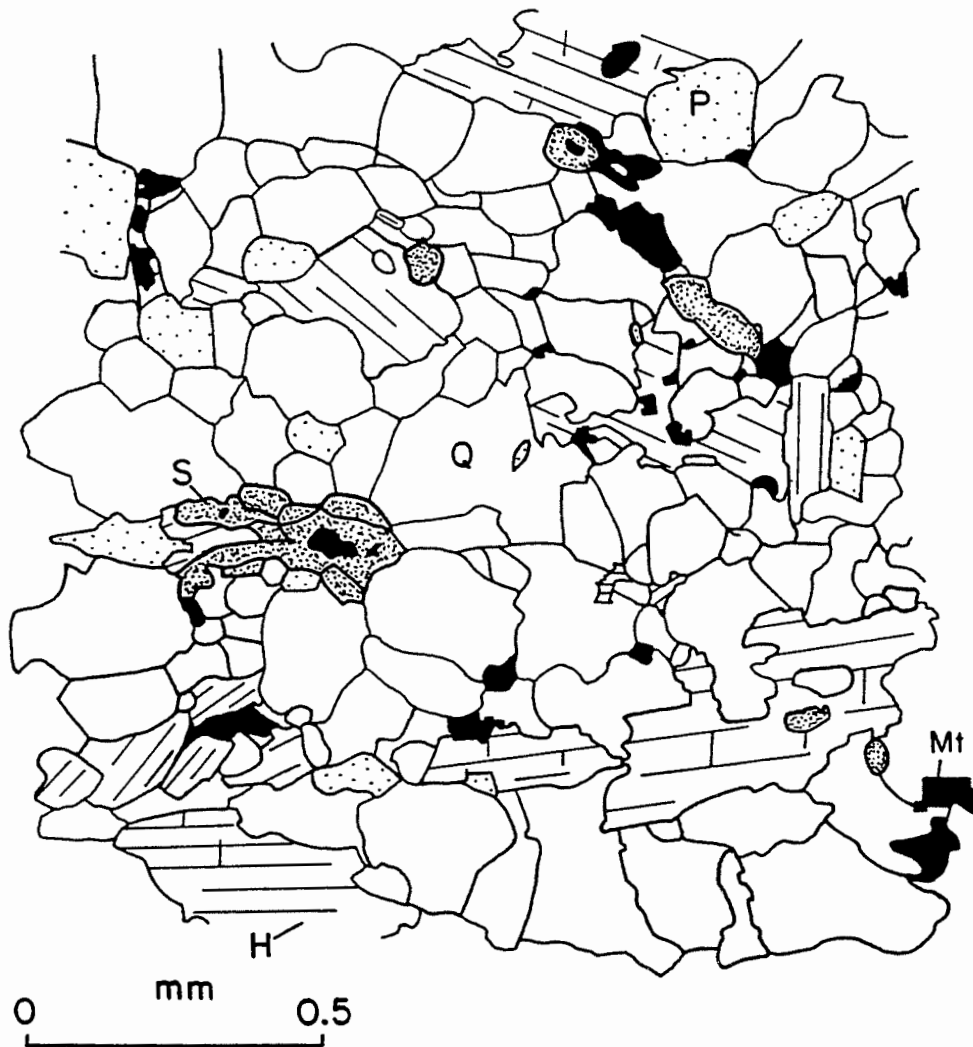
Note - Chlorite is of retrograde origin.

#### Hand sample descriptions and locations for Table 2.5

**MO-47** - Dark green, medium-grained calc-silicate granulite/gneiss. Small outcrop located 0.35km north of the intersection of Old Troy Road and Rhododendron Road on a hummock east of a large beaver marsh (Fitzwilliam).

**MO-52** - Dark, fine-grained, rusty-weathering calc-silicate granulite. Occurs as 2-5cm thick beds within rusty schist. Outcrop at elevation 404m, located 0.65km north of the intersection of Old Troy Road and Rhododendron Road northeast of a large beaver marsh (Fitzwilliam).

**RO-315** - Gray-weathering, fine-grained biotite granulite/gneiss. Outcrop on top of a knob at elevation 1110' (338m), located 2.05 km southwest of the intersection of Royalston Road and Holman Road and 1.8km north of state line bound number 26 (Fitzwilliam). The outcrop is dominantly rusty-weathering schist.



H = hornblende  
Mt = magnetite  
P = plagioclase

Q = quartz  
S = sphene

Figure 2.4 Sketch of a thin section of calc-silicate granulite/gneiss from a bed in the middle member of the Rangeley Formation. Sample MO-47.



Beds of gray- to rusty-weathering biotite granulite occur throughout the middle member. Biotite flakes define a weak foliation within a granular matrix of quartz and plagioclase. In sample RO-315 (Table 2.5), plagioclase is unzoned and has a composition of  $An_{24}$ . Biotite is pale tan in the X direction and reddish-brown in the Y = Z direction. A few pale pink garnet porphyroblasts are visible in hand specimen. In thin section, the garnet has an irregular outline and is rimmed by plagioclase.

### Upper Member

The upper member is exposed in the core of the Monadnock syncline in the eastern part of the field area from Little Monadnock Mountain south to the Massachusetts border, and on the western side of the field area between the Beech Hill anticline and the Brennan Hill thrust. The rocks within this member are very similar in appearance to those of the lower member, although rusty-weathering schist and gneiss are more common here. Thus the dominant rock types are gray-weathering schist and gneiss composed mostly of quartz, biotite, muscovite, and sillimanite, commonly with plagioclase and/or garnet (Table 2.6). A strong mica and sillimanite lineation occurs on the foliation surfaces. Figure 2.5 is a sketch of a typical example of the gray-weathering schist. Biotite exhibits a range of colors in the X direction: including pale tan, pale brownish-tan, and pale greenish-white. It is brown or dark reddish-brown in the Y = Z direction. Muscovite occurs as aggregates of fine-grained (less than 0.1mm) flakes which have replaced earlier deformed porphyroblasts and as coarse-grained (greater than 0.2mm) porphyroblasts which grow across the dominant mica foliation. Sillimanite occurs as discrete prisms and as masses of fibrolite (in each case individual crystals are less than 0.1mm in length) and as large pseudomorphs after andalusite that range in length up to 10cm which are called "andalumps" by Peter Robinson (in Hatch et al., 1983). These pseudomorphs were only observed in a small area near the boundary with the Spaulding Tonalite. Their significance will be discussed under Metamorphism. Euhedral staurolite is observed in and around these pseudo-morphs. Plagioclase is unzoned and has compositions ranging from  $An_{14}$  to  $An_{27}$ . Garnet is pink in hand specimen and very pale rose-colored in thin section. Garnet is commonly euhedral when in contact with biotite and subhedral or anhedral otherwise. Although no indication of compositional zoning is visible, fine quartz inclusions are common in the cores. Ilmenite inclusions, commonly oriented parallel to the dominant mica foliation, are locally abundant.

The rusty-weathering schist and gneiss in this member are similar in appearance to some of the rusty but non-sulfidic parts of the middle member. Some rusty-weathering biotite granulite and dark, gray-weathering metamorphosed quartzite also occur in the upper member, especially near Rhododendron Road, south of Little Monadnock Mountain.

### Calc-silicate Granulite Pods

Calc-silicate granulite pods are most common in the middle member of the Rangeley Formation although they do occur sporadically throughout the lower and upper members. They consist of cores of massive to weakly foliated granulite that are highly resistant to weathering and 2-5cm thick rims of less resistant granulite that weather to form a shallow groove between the core and the enclosing rock (Figures 2.6 and 2.7).

Table 2.6 Estimated modes of samples from the upper member of the Rangeley Formation.

	<u>MO-41X</u>	<u>MO-63</u>	<u>MO-92X1</u>	<u>RO-407</u>	<u>RO-424X</u>
Quartz	44	18	20	35	41
Plagioclase	2	44 (27)	10 (24)	-	4 (24)
Biotite	35	29	35	25	21
Muscovite	9	-	30	32	29
Garnet	tr	-	-	3	1
Sillimanite	8	-	2	2	1
Chlorite	-	-	-	tr (Fe-Mg)	tr (Fe-Mg)
Graphite	tr	-	tr	tr	tr
Ilmenite	1	4	2	2	2
Hematite	-	tr	-	-	-
Apatite	tr	3	-	tr	tr
Sphene	-	1	-	-	-
Zircon	tr	tr	tr	tr	tr
Tourmaline	-	-	-	-	tr
Allanite	-	tr	-	-	-
	<u>RO-441AX</u>	<u>RO-441BX</u>	<u>RO-447</u>	<u>RO-448</u>	<u>FZ-30*</u>
Quartz	28	35	45	18	63
Plagioclase	tr (14)	-	-	-	7 (23)
Biotite	11	6	15	15	17
Muscovite	48	42	35	55	8
Garnet	6	tr	2	4	-
Sillimanite	-	-	-	-	-
Pseudomorphs**	-	5	-	-	-
Other	4	3	1	5	5
Staurolite	tr	6	-	tr	-
Chlorite	tr (Mg-Fe)	tr (Fe-Mg)	-	2 (Fe-Mg)	-
Opagues	-	-	-	-	-
Graphite	-	tr	tr	-	tr
Ilmenite	2	2	2	tr	-
Undifferent'd	-	-	-	-	tr
Apatite	tr	tr	tr	tr	-
Zircon	tr	tr	tr	tr	tr
Tourmaline	tr	tr	tr	-	-

Note - chlorite is of retrograde origin.

\* From P.J. Thompson, 1985, Table 1d.

\*\* Pseudomorphs of sillimanite after andalusite.

### Hand sample descriptions and locations for Table 2.6

MO-41X - Coarse-grained, gray-weathering schist with 1cm thick quartz-feldspar segregations. Outcrop on the north side of state route 119, 0.8km west of the intersection with Holman Road (Fitzwilliam).

MO-63 - Fine-grained, dark, biotite gneiss. From a slumped block on an east-facing slope at about 402m elevation, located 0.65km north-northeast of Beechwood Corners (Fitzwilliam).

MO-92X1 - Coarse-grained, gray-weathering schist with 2-5cm thick boudinaged quartz-plagioclase segregations. Outcrop located at elevation 338m, 100m west of Old Troy Road and 0.85km northwest of the intersection with Rhododendron Road (Fitzwilliam).

RO-407 - Medium-grained, slightly rusty-weathering, non-sulfidic gneiss. Outcrop located at elevation 1115' (340M), 330m south of hill 1217 and 150m west of Royalston Road (Fitzwilliam).

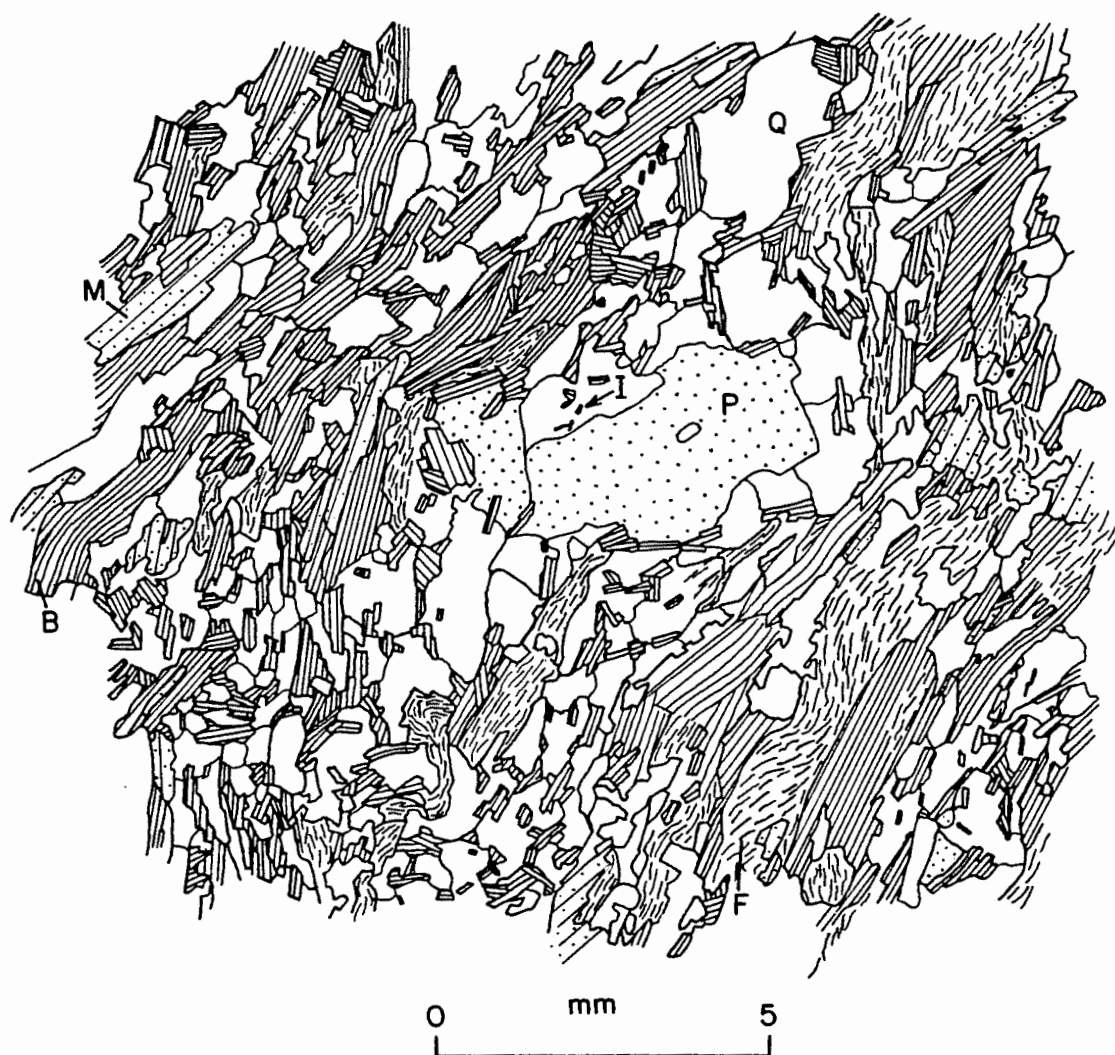
RO-424X - Coarse-grained, gray-weathering schist with spangles of coarse muscovite. Outcrop on top of a knob at elevation 1215' (370m), located 0.8km northeast of state line bound number 26 and 0.85 km northwest of state line bound number 27 (Fitzwilliam).

RO-441AX and RO-441BX - Coarse-grained, gray-weathering, staurolite-bearing andalump gneiss. Outcrops located 175m west of Royalston Road and 30m southeast of the summit of hill 1217 (Fitzwilliam).

RO-447 - Medium-grained, brown-weathering, non-sulfidic gneiss with muscovite spangles. From a slumped block located 225m west of Royalston Road and 125m north of hill 1217 at elevation 1190' (363m) (Fitzwilliam).

RO-448 - Coarse-grained, gray-weathering gneiss with muscovite spangles. From a pavement outcrop located 0.55km south of Holman Road and 100m west of hill 1217 at elevation 1195' (364m) (Fitzwilliam).

FZ-30 "Well foliated medium-grained quartzose sillimanite schist with strong fibrolite and mica lineations, gray with muscovite spangles in foliation plane. 1 cm-thick quartz-feldspar segregations. 40m due W from Little Monadnock summit, Fitzwilliam" (P.J. Thompson, 1985, p.27).



B = biotite	M = muscovite
F = fibrolite	P = plagioclase
I = ilmenite	Q = quartz

Figure 2.5 Sketch of a thin section of gray-weathering schist from the upper member of the Rangeley Formation. The slide is oriented perpendicular to both the foliation and the mica lineation. Note the quartz-plagioclase porphyroblast in the center and the lenses of fibrolite scattered throughout. Individual fibrolite needles are oriented both parallel to and perpendicular to the plane of the section. Although garnet is present in the slide, none is within the field of view. Sample MO-41X.

The cores consist mostly of quartz, calcic plagioclase, diopside, and hornblende or actinolite, with or without sphene (Table 2.7). Plagioclase is unzoned and has compositions  $An_{66}-An_{75}$ . Pale rose-colored garnet has corroded outlines and is sieved with quartz. Diopside is also corroded and has poikiloblastic quartz and plagioclase inclusions. Hornblende from sample RO-393A has  $X =$  very pale green,  $Y =$  pale brownish green, and  $Z =$  bluish green.  $Z \wedge c = 22^\circ$ . Sphene is a common accessory mineral. It is subhedral and is pleochroic from pale reddish brown to very pale brown. Pleochroic haloes in adjacent hornblende indicate that the sphene is radioactive. Figure 2.8 is a sketch of a portion of a thin section of a calc-silicate pod in the upper member of the Rangeley Formation. Note the large, corroded diopside porphyroblast partially rimmed by garnet.

No thin sections of the rims of the pods were made for this study but field observations indicate that they may contain less quartz and garnet than the cores. P.J. Thompson (1985, p.24) states that the cores are more "flinty" and the rims more feldspathic.

### Augen Gneiss

Outcrops of an augen gneiss occur north of the intersection of Greenwoods Road and Monument Road in Richmond. This distinctive rock contains asymmetrical quartz-feldspar augen within a schist matrix. Since quartz-feldspar stringers and lenses are quite common in the surrounding rocks, it is likely that the augen resulted from the breakup of these lenses and stringers during progressive shearing. A similar rock type occurs in the Orange area, where it is mapped as the Augen Gneiss Member of the Partridge Formation (Robinson, 1963). The Richmond outcrops are clearly a part of the Rangeley Formation but their tectonic significance is unclear.

### Contacts

The base of the Rangeley Formation is not exposed in the study area. Instead, the lower member is juxtaposed against several formations in both the Bronson Hill sequence and the Monadnock sequence by the Brennan Hill and related thrusts. North of Spirit Falls, in Royalston, the lower member is in contact with plagioclase gneiss that is tentatively correlated with the Creamery Hill band of the Monson Gneiss (Pike, 1968). On the hill west of Boyce Brook and south of Falls Road in Royalston it is in contact with the Warner Formation. On Butterworth Ridge, near West Royalston, outcrops of the lower member are juxtaposed against outcrops of the Perry Mountain and Warner Formations. Outcrops of the Littleton Formation occur on the west side of state route 32 at the state line, with outcrops of the lower member of the Rangeley Formation a few meters to the east, on the opposite side of the road. The Brennan Hill thrust will be discussed further under Stratigraphy.

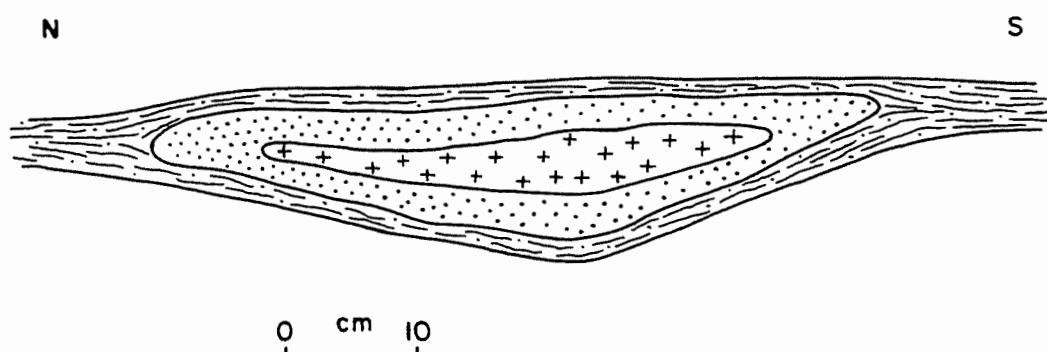


Figure 2.6 Sketch of a calc-silicate granulite pod in gray-weathering gritty schist (lower member of the Rangeley Formation). Crosses = core, stippled = rim, dash-dot = feldspathic biotite granulite, unpatterned = gritty schist. Located 150m east of the Richmond-Fitzwilliam town line and 1.05km south-southeast of Beechwood Corners (Fitzwilliam).

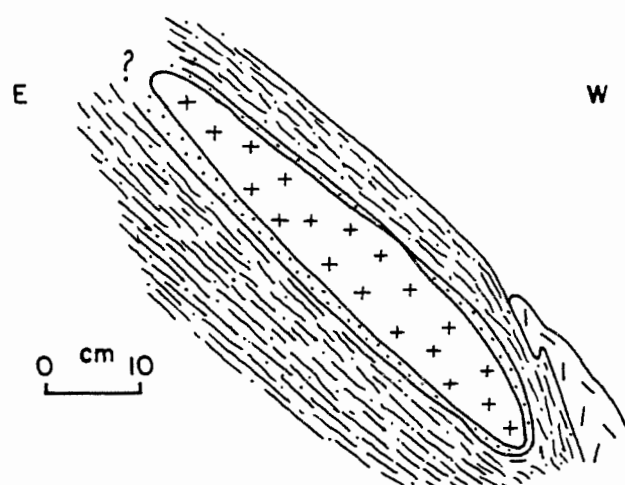


Figure 2.7 Sketch of a calc-silicate granulite pod in rusty-weathering feldspathic biotite granulite (middle member of the Rangeley Formation). Crosses = core, stippled = rim, dash-dot = biotite granulite, random dashes = pegmatite. The rim weathers to form a depression between the core and the surrounding biotite granulite. Located at the north end of a large outcrop 150m west of the town line and 400m north of Rhododendron Road (Richmond).

**Table 2.7 Estimated modes of samples of calc-silicate granulite pods from the Rangeley Formation.**

	Lower Member	Middle Member		Upper Member	
	<u>RO-393A</u>	<u>RO-293</u>	<u>TR-93*</u>	<u>MO-11</u>	<u>K40**</u>
Quartz	39	37	48	17	45
Plagioclase	28 (67)	43 (66)	39 (75)	62 (73+)	39 -
Biotite	-	-	3	-	-
Diopside	5	12	-	15	-
Hornblende	7	1	-	-	-
Actinolite	-	-	3	-	5
Garnet	18	-	4	5	9
Clinozoisite	-	tr	-	-	-
Zoisite	-	tr	-	-	-
Sphene	tr	3	-	tr	tr
Opakes					
Graphite	tr	2	1	tr	-
Hematite	tr	-	-	-	-
Ilmenite	-	tr	-	-	-
Undifferent' d	-	-	1	-	tr
Apatite	tr	2	1	tr	-
Zircon	-	tr	tr	-	-
Allanite	tr	tr	-	-	-

\* From Fowler-Billings, 1949, Table 3. \*\* From P.J. Thompson, 1985, Table 1c.

#### Hand sample descriptions and outcrop locations for Table 2.7

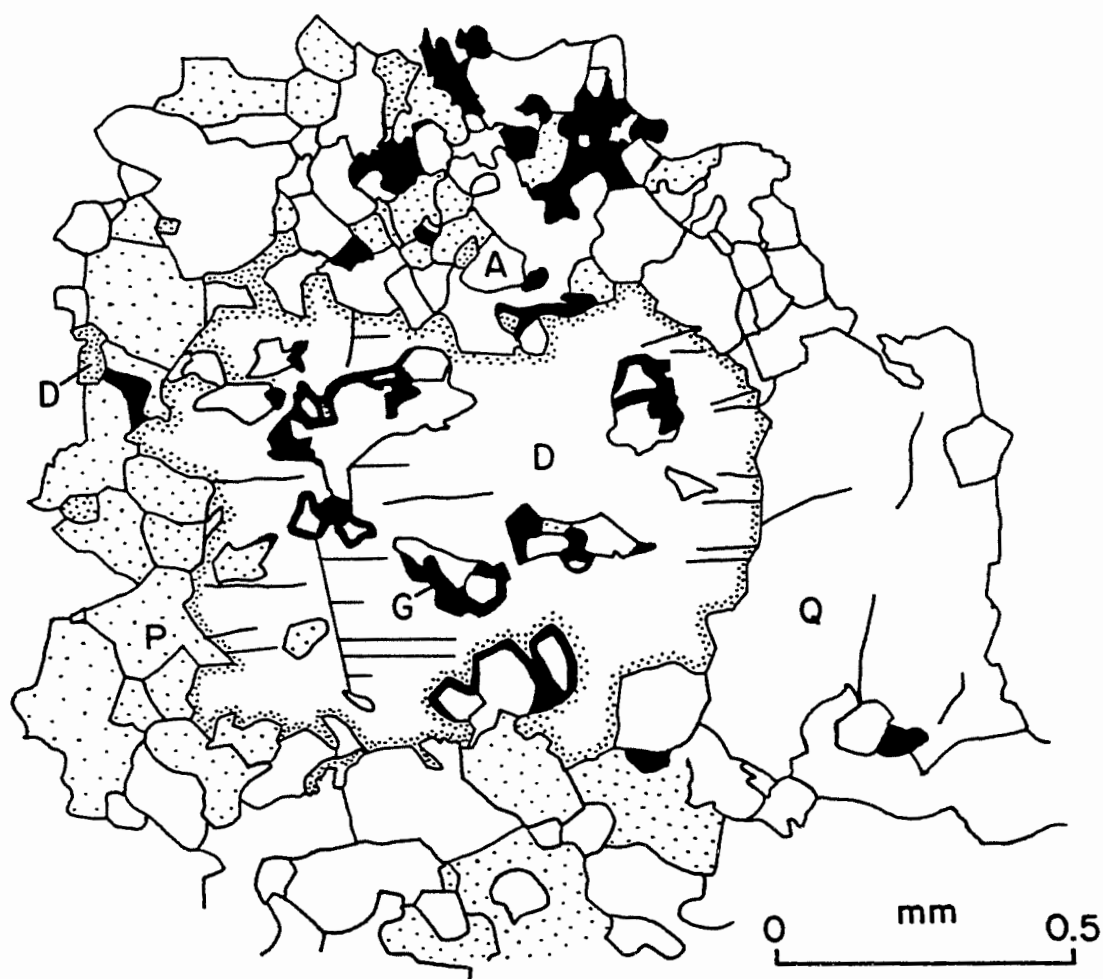
RO-393A - Coarse-grained, weakly foliated, pink, green, and gray calc-silicate granulite pod in gray-weathering, gritty schist. Low outcrop located 100 meters east of the Richmond-Fitzwilliam town line and 1.1km south-southeast of Beechwood Corners, Fitzwilliam.

RO-293 - Coarse-grained, massive, pink, green, and white calc-silicate granulite. From core of a calc-silicate pod in an outcrop of gray-weathering granular schist located at the southwest end of a ridge 0.4km east of Prospect Hill Road and 0.85 km north of the intersection with North Fitzwilliam Road, Royalston.

TR-93 - "Fine-grained, dark gray calc-silicate granulite with up to 2mm vitreous quartz grains. Pod in rusty schist. Ridge NW from Troy, elev. 390m" (P.J. Thompson, 1985, p.23).

MO-11 - Coarse-grained, massive, pink, green, and gray granulite. From the core of a calc-silicate granulite pod in an outcrop of gray-weathering schist on the Metacomet-Monadnock Trail at elevation 534m, 0.35km northeast of the summit of Little Monadnock Mountain in Fitzwilliam.

K40 - Calc-silicate granulite pod. Outcrop located 0.75km west-southwest of Little Monadnock Mountain, Fitzwilliam (Fowler-Billings, 1949, Table 3).



A = apatite	P = plagioclase
D = diopside	Q = quartz
G = garnet	S = sphene

Figure 2.8 Sketch of a thin section of a calc-silicate granulite pod from the upper member of the Rangeley Formation. Note that garnet and plagioclase are associated with the diopside porphyroblast. Sample MO-11.



The boundary between the lower and middle members is a sharp contact which does not truncate any outcrop-scale or map-scale features. It appears to be conformable. Along the ridge consisting of Jacob Hill, Prospect Hill, and Grant Hill, abundant outcrops permit this contact to be located within a few meters. In the area near the intersection of Greenwoods Road, Falls Road, and Monument Road, however, the location and geometry of the contact is very uncertain. There are large areas of outcrop that are clearly gray-weathering schist or rusty-weathering schist. However, they are not easily separable into two mutually exclusive map units. Whether this is due to complex folding or faulting or else to original sedimentary differences is unclear. Although the contact is shown on the geologic map as a simple fold, additional field mapping would be needed to solve this problem.

The contact between the middle and upper members is also probably conformable. The contact is particularly well constrained from state route 119 north to the vicinity of Little Monadnock Mountain. There, gray-weathering schist on the east is juxtaposed against rusty-weathering schist and dark, bedded, calc-silicate granulite to the west. North of Royalston the contact is truncated due to the intrusion of the Spaulding Tonalite.

The upper member of the Rangeley Formation is in contact with the overlying Perry Mountain Formation near the summit of Little Monadnock Mountain. This contact was mapped by P.J. Thompson (1985) as the first occurrence of sharply bedded quartzite and schist. It is apparently conformable.

#### Age and Correlation

As Table 1.1 shows, the rocks to which the name "Rangeley Formation" is now applied have been known in the past under several different names. Hadley (1949), Moore (1949), and Fowler-Billings (1949) assigned them to the Littleton Formation. Fitzgerald (1960) mapped the rusty-weathering schists surrounding the Tully body as Partridge Formation and the gray-weathering schists as Littleton Formation. Robinson (1963) mapped the rusty-weathering schists as Partridge Formation and recognized two distinct units composed of gray-weathering schist: a gray schist member of the Partridge Formation and the Littleton Formation. Subsequent field work led Robinson (1967) and Pike (1968) to include the gray schist member within the Littleton Formation.

Geologic mapping in New Hampshire and western Maine led Hatch et al. (1983) to propose important revisions to the Silurian-Devonian stratigraphy in New Hampshire. In brief, they proposed that many of the rocks in central New Hampshire that had previously been mapped as the Lower Devonian Littleton Formation actually correlate with the Silurian Rangeley Formation of western Maine. They proposed that the remainder of the Littleton Formation in central New Hampshire is separated from the Rangeley Formation by the Perry Mountain, Franconia, and Warner Formations.

P.J. Thompson (1985) and Elbert (1986, 1988) carried these new correlations into the Monadnock region and the Bernardston-Hinsdale area, respectively. Since Thompson's mapping

in the southwestern part of the Monadnock quadrangle was of a reconnaissance nature, one result of this study was to confirm his preliminary correlations. A second result was to successfully extend the new stratigraphy into Massachusetts.

### Perry Mountain Formation

The Perry Mountain Formation occurs in the southwestern corner of the study area on Butterworth Ridge. It is recognized on the basis of four outcrop-scale lenses or boudins of a distinctive "iron formation" that occur within a gray-weathering schist that is similar in appearance to the gray schists of the Rangeley Formation.

Station 35, located near the northern end of Butterworth Ridge, was discovered by Thomas Pike and Peter Robinson in the 1960's and was described by Huntington (1975) as dense, magnetic, fine-grained olivine-magnetite granulite that weathered to a dull black or rusty-brown color.

At station MG-4A, near the southern end of Butterworth Ridge, gray-weathering schist encloses a lens of orthopyroxene-garnet granulite, apatite-garnet-grunerite granulite, and garnet-magnetite-grunerite granulite (Table 2.8). The orthopyroxene was recognized in thin section by Peter Robinson and identified under oils by Howard W. Jaffe. In thin section, it occurs as pale brownish-green porphyroblasts. Based on a gamma refractive index of 1.770-1.772 and strong  $r > v$  dispersion (H.W. Jaffe, personal communication), this appears to be nearly identical to the Fe-Mn-Mg orthopyroxene from the Orange area described by Huntington (1975). Subhedral to euhedral pink garnets have numerous inclusions of quartz and opaques in their cores, while the rims are nearly inclusion-free. The grunerite has polysynthetic twins and is pleochroic from very pale green to colorless. Both the orthopyroxene and the grunerite appear to be overgrown by the garnet. Magnetite is most abundant in the garnet-magnetite-grunerite layer.

Station MG-56, on the southeast flank of Butterworth Ridge, is a small outcrop of iron formation flanked by outcrops of gray-weathering schist. In thin section the rock consists of garnet-grunerite granulite with local concentrations of magnetite (Figure 2.9). As in parts of sample MG-4A, grunerite is enclosed within a garnet matrix.

Similar lenses of iron formation have long been known to the west in the Orange area (Robinson, 1963). A detailed petrologic study was made of all known occurrences of these rocks in the Orange area by Huntington (1975). Following Robinson (1967) he considered them to be within the lowermost Littleton Formation. The present correlation is due to the discovery of lenses of similar iron formation within the gray-weathering quartzite and schist of the Perry Mountain Formation in the Hinsdale, New Hampshire area (Elbert, 1986, 1988).

**Table 2.8 Estimated modes of samples from the Perry Mountain Formation.**

	<u>MG-4A</u>			<u>MG-56</u>	<u>MG-101</u>
	A	B	C		
Quartz	-	-	-	tr	80
Plagioclase	-	-	-	-	tr
Garnet	43	18	40	94	12
Grunerite	20	10	tr	5	tr
Orthopyroxene	1	-	58	-	-
Apatite	1	70	tr	-	6
Chlorite	-	-	-	tr	tr
				(Fe-Mg)	(Fe-Mg)
Magnetite	35	2	1	1	1
Hematite	tr	tr	tr	tr	tr
Biotite	-	-	-	-	tr
Muscovite	-	-	-	-	tr
Zircon	tr	-	-	-	tr

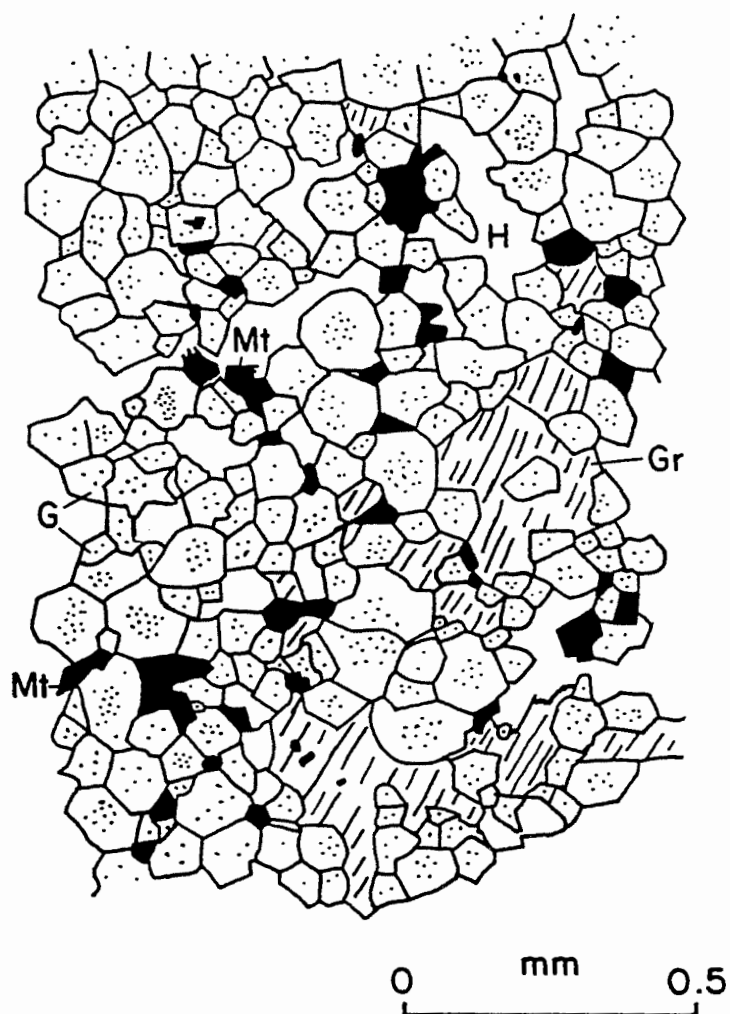
Note - Chlorite is of retrograde origin.

#### Hand sample descriptions and locations for Table 2.8

**MG-4A** - Dense, fine-grained, layered, nonfoliated granulite. Three modes from a single thin section are listed as follows: MG-4AA black- to dark-rusty-brown-weathering garnet-magnetite-grunerite granulite (strongly magnetic); MG-4AB very-pale-brown-weathering apatite-garnet-grunerite granulite; MG-4AC rusty-brown-weathering orthopyroxene-garnet granulite. Located on the west-facing slope of Butterworth Ridge at elevation 950' (290m), 0.45 km south of the county line (Orange).

**MG-56** - Fine-grained, massive, reddish-brown-weathering garnet-grunerite granulite. Parts of sample are strongly magnetic. Outcrop located at 945' (288m), 120m west of the county line bound on Butterworth Ridge (Royalston).

**MG-101** - Medium-grained, rusty-weathering, crudely layered granulite. Outcrop on Butterworth Ridge, 20m north of the county line at elevation 935' (285m) (Royalston).



G = garnet  
Gr = grunerite

H = hole  
Mt = magnetite

Figure 2.9 Sketch of a thin section of "iron formation" from the Perry Mountain Formation. Garnets contain abundant inclusions in cores and appear to overgrow grunerite. Sample MG-56.

### Fracestown Formation

The only known outcrops of the Fracestown Formation within the study area occur on the east flank of Little Monadnock Mountain in the northwentral part of the study area (P.J. Thompson, 1985). According to Thompson it is a distinctive unit composed of "extremely rusty-weathering, blocky calc-silicate granulite and rusty-weathering graphitic schist" (P.J. Thompson, 1985, p. 35). Despite the widespread distribution of this unit in south-central and central New Hampshire (Hatch et al., 1983), in the Bernardston-Hinsdale area (Elbert, 1988), and in the Orange area (Robinson et al., 1988), it appears to be completely absent on the flanks of the Tully body. This may be due either to local non-deposition, erosion, or stratigraphic omission due to early thrusting.

### Warner Formation

Good outcrops of the Warner Formation occur on the east flank of Little Monadnock Mountain and on the southern end of Butterworth Ridge, in the southwestern part of the study area. Scattered outcrops also occur north of state route 68 and west of Boyce Brook in the south-central part of the study area.

The Warner Formation of the Royalston-Richmond area consists of massive white, pink, gray, or green calc-silicate granulites dominated by calcic plagioclase, quartz, diopside, hornblende, and garnet and gray-weathering, fine-grained feldspathic biotite granulite (see Table 2.9). Although no thin sections were made from the biotite granulite, it does make up a significant portion of the formation.

In the calc-silicate rocks the plagioclase is unzoned and compositions range from  $An_{62}$ - $An_{73}$ . It is commonly partially altered to sericite. Diopside occurs as irregular porphyro-blasts. Hornblende occurs in two forms: as large inclusions within diopside porphyroblasts and as euhedral crystals which appear to have formed after the diopside. Subhedral to anhedral garnet has a pale pink color and commonly contains inclusions of quartz. Clinozoisite occurs as rims around plagioclase and as porphyroblasts with poikilitic plagioclase, hornblende, and diopside. Sphene is subhedral and is pleochroic from reddish brown to very pale reddish brown.

The Warner Formation in the Royalston-Richmond area is very similar to that of the Monadnock quadrangle as described by P.J. Thompson (1985). The calc-silicate granulites appear to correlate with those of Thompson's lower member while the gray-weathering "salt and pepper" granulite is very similar in appearance to the purplish-gray granulite of Thompson's upper member.

### Intrusive Igneous Rocks

#### Hardwick Tonalite

The Hardwick Tonalite is a dark, medium-grained, foliated biotite tonalite which crops out in the eastern part of the Royalston-Richmond area. It is part of the Hardwick pluton, a large syntectonic intrusive body of Devonian age which extends from south-central Massachusetts to

Table 2.9 Estimated modes of samples from the Warner Formation.

	<u>MG-4G</u>	<u>MG-20</u>	<u>MG-56</u>	<u>MG-99X</u>	<u>MG-99Y</u>	<u>RO-556</u>
Quartz	45	2	15	52	20	40
Plagioclase	31	3	40	32	9	28
	(seric.)	(67-73)	(63)	(62+)	(seric.)	(68)
Diopside	15	4	15	4	25	-
Hornblende	-	18	15	tr	5	25
Garnet	3	-	3	4	40	-
Clinozoisite	3	68	tr	1	-	tr
Zoisite	-	-	tr	-	tr	tr
Sphene	1	2	-	tr	1	-
Chlorite	-	-	12	tr	-	-
			(Mg-Fe)	(Mg-Fe)		
Graphite	1	-	-	3	-	-
Pyrrhotite	-	2	tr?	-	-	-
Pyrite	tr	-	tr?	tr	tr?	-
Hematite	-	-	12	-	tr	tr
Apatite	tr	tr	tr	tr	-	tr
Biotite	-	-	tr	3	-	4
Muscovite	-	-	-	tr	-	-
Zircon	tr	tr	-	tr	tr	tr
Allanite	-	-	tr	tr	-	tr
Calcite	-	-	tr	tr	-	2
Tourmaline	-	-	-	tr	-	tr

Note - Chlorite is of retrograde origin.

#### Hand sample descriptions and locations for Table 2.9

**MG-4G** - Medium-grained, massive, pink and gray calc-silicate granulite. Outcrop at elevation 960' (293m) on the western side of the southernmost knob of Butterworth Ridge (Orange).

**MG-20** - Fine-grained, massive, dark-green calc-silicate granulite. Outcrop located 100m south of MG-4G at elevation 900' (274m) (Orange).

**MG-56** - Medium-grained, massive, grayish-green calc-silicate granulite. Outcrop located at 945' (288m) elevation, 120m west of the county line bound on Butterworth Ridge (Royalston).

**MG-99X** - Medium-grained, layered, white, pink, and dark-green calc-silicate granulite. Outcrop on the southeast-facing slope of Butterworth Ridge at elevation 950' (290m) and 0.4km north of the county line boundary marker (Royalston).

**MG-99Y** - Fine-grained, bedded, pink and brownish-green calc-silicate granulite. Same location as MG-99X.

**RO-556** - Fine-grained, weakly-foliated, dark-green and gray calc-silicate granulite. From a slumped block located on an east-facing slope at elevation 765' (233m), 0.45km south-southwest of the bridge on Falls Road over Boyce Brook (Royalston).

southern New Hampshire (Shearer, 1983). Fowler-Billings (1949) and P.J. Thompson (1985) correlated the Hardwick Tonalite with the Spaulding Tonalite of the New Hampshire plutonic series. In central New Hampshire, the Spaulding Tonalite has a late Early Devonian age of 393  $\pm$  5 Ma based on the Rb/Sr whole-rock isochron method (Lyons et al., 1982).

The contact between the Hardwick Tonalite on the east and the middle and upper members of the Rangeley Formation on the west proved difficult to define during field mapping. At hill 1217 in Fitzwilliam the outcrop pattern indicates a reasonably distinct boundary that has been folded as shown on Plate 1, but to the south of there, between North Fitzwilliam Road and Lawrence Brook, outcrops of tonalite are mixed with outcrops of schist and no clear boundary can be drawn. This appears to indicate either sills of tonalite within the schist or xenoliths of schist enclosed within the tonalite.

#### Fitzwilliam Granite

The Fitzwilliam Granite is a light-gray, medium- to coarse-grained, massive to weakly foliated biotite-muscovite granite which crops out in the northeast corner of the Royalston-Richmond area. It is part of the Fitzwilliam pluton, a post-tectonic intrusive body which cross-cuts both the Hardwick Tonalite and dome stage folds (P.J. Thompson, 1985). It may correlate with the Sunapee pluton of central New Hampshire, which has a Mississippian age based on a Rb/Sr whole-rock isochron of 326  $\pm$  3 Ma (Lyons et al., 1982).

#### Minor Intrusive Rocks

Granitic Gneiss. A large outcrop of coarse-grained granitic gneiss occurs southwest of Little Monadnock Mountain in Fitzwilliam. It is composed of quartz, microcline, untwinned feldspar, and plagioclase with lesser amounts of biotite, muscovite, and myrmekite (Table 2.10). The mineralogy and texture indicate that this was originally a massive plutonic rock which was later ductilely deformed. Although Fowler-Billings (1949) mapped this outcrop as "Kinsman granite" (Kinsman Quartz Monzonite of later workers) its appearance is quite distinct from the Kinsman or any of the other igneous rocks in the region. Therefore the correlation with the Kinsman is very unlikely.

Granite Sills. Sills of weakly foliated to non-foliated two-mica granite occur throughout the study area (see Table 2.10). They range from 2-50cm thick and are oriented parallel to the dominant foliation. They may be related to the intrusion of the Spaulding Tonalite or the Fitzwilliam Granite.

Pegmatite. Pegmatite bodies are common throughout the area. Concordant bodies of coarse-grained muscovite-bearing pegmatite occur throughout the Rangeley Formation. They are commonly foliated and locally boudinaged. Late, discordant bodies of massive pegmatite are very common. In this study they were observed in the Rangeley Formation and the Spaulding Tonalite. Cameron et al. (1954) favored the "Concord granite" (Fitzwilliam Granite of this study) as the source for the major discordant pegmatite bodies in the area.

Table 2.10 Estimated modes of samples of intrusive rocks.

	<u>MO-94X</u>	<u>MG-106</u>	<u>RO-541A</u>
Quartz	26	32	26
Plagioclase	15	40	35
	(26)	(17)	(17)
Microcline	17	3	-
Untwinned feldspar	16	20?	34
Myrmekite	6	tr	-
Biotite	11	2	3
Muscovite	7	2	1
Chlorite	tr	tr	1
	(Fe-Mg)	(Fe-Mg)	(Fe-Mg)
Graphite	-	tr	-
Magnetite	2	-	-
Ilmenite	-	tr	tr
Apatite	tr	-	-
Zircon	tr	-	tr

Note - Chlorite is of retrograde origin.

Hand sample descriptions and locations for Table 2.10

MO-94X - Coarse-grained, well foliated granitic gneiss. From a sill in an outcrop of rusty-weathering biotite granulite (middle member of Rangeley Formation) located at 404m elevation, 50m east of Old Troy Road, and 1.55km south-southwest of Little Monadnock Mountain (Fitzwilliam).

MG-106 - Medium-grained, weakly foliated granitic gneiss. Sill in an outcrop of gray-weathering, laminated schist (lower member of Rangeley Formation) located on the Metacomet-Monadnock Trail, 100m east of Falls Brook and 460m north-northeast of the bridge where Greenwood Road crosses Falls Brook (Richmond).

RO-541A - Medium-grained, unfoliated granite from a sill in a streambed outcrop of gray-weathering schist, graphitic schist, and pegmatite (lower member of Rangeley Formation). Located in the stream west of Greenwood Road at elevation 1050' (320m), 0.35 km south of the intersection with Fay Martin Road (Richmond).



**Tourmaline Veins.** Thin, black tourmaline veins filling planar to irregular joints occur throughout the study area. These were described in the Orange area by Robinson (1963) and in the Monadnock quadrangle by P.J. Thompson (1985). Because they occupy brittle fractures which crosscut the ductile fabrics, and according to Thompson are associated with non-foliated pegmatites, they are clearly late- to post-Acadian. Their orientation and relationship to brittle fabrics are discussed under Structural Geology.

**Diabase.** Diabase occurs at two localities shown on Plate 1. At station G95, near the southern end of Butterworth Ridge, a sill-like body of diabase was discovered by Robinson (1963). Detailed work by McEnroe (1989) shows that the body extends for a distance of 230m along strike, varies in thickness from 0.8-1.1m, and locally cross-cuts the foliation in the surrounding rocks. In hand specimen, this is a fine-grained, dark gray, massive diabase that weathers to a rusty brown. In thin section, it consists of plagioclase and augite phenocrysts in a matrix of plagioclase, augite, and titanomagnetite (McEnroe, 1989, Table 2.3, sample But4). This body intrudes the Ammonoosuc Volcanics. The second locality consists of a jumbled pile of diabase blocks located in Fitzwilliam, 1.0km south-southeast of Beechwood Corners and just north of a small sandpit. The blocks occur within the middle member of the Rangeley Formation and are probably from a dike or sill of Mesozoic age. In hand specimen this is a fine-grained, dark-gray plagioclase-pyroxene diabase which weathers to a dark tannish-brown.

## CHAPTER 3 STRUCTURAL GEOLOGY

### Introduction

The rocks of the Royalston-Richmond area have undergone several phases of deformation during the Devonian Acadian orogeny and the Mesozoic rifting which led to the opening of the Atlantic (P.J. Thompson, 1985; Robinson et al., 1988; Robinson et al., 1989). The major structural features in the study area and the surrounding region are shown in Figure 3.1. The bedrock geology of the study area is shown in Plate 1. Planar and linear structural features are shown on Plate 2 and orientation data for the minor structural features in the study area are summarized in Figure 3.2.

The earliest structures of which there is evidence are west-directed fold-nappes which were cut by the Brennan Hill thrust. The dominant foliation visible throughout the area developed parallel to the axial planes of the fold-nappes. During the backfold stage, the fold axial surfaces and the thrust were overturned to the east and the Tully body of the Monson Gneiss and its cover rocks were transported northward relative to the more autochthonous rocks of the Keene dome. Continued compression and gravitational rise of the Keene and Tully domes deformed the earlier structures and produced most of the minor folds commonly observed in outcrop. The dominant mineral lineation appears to have developed during this period of deformation. Crenulation and gentle warping locally deformed all of these structural features either at the end of the Acadian orogeny or during the Permian Alleghenian "disturbance".

The Athol fault formed during the Mesozoic as a result of the crustal extension which formed the Mesozoic basins of the Connecticut Valley (Robinson, 1963, Pike, 1968).

### Minor Structural Features

#### Bedding

Compositional layering that is interpreted to represent bedding is commonly observed in the Royalston-Richmond area in the pelitic rocks, the amphibolites, and the layered calc-silicate rocks. Although quartzose layers are locally common in the pelitic units, no examples of graded bedding were observed in the study area. Bedding is essentially parallel to the dominant foliation throughout the study area. This relationship is discussed further in the next two sections.

#### Foliation

The strong foliation observed throughout the area is believed to have formed parallel to the axial surfaces of the fold-nappes formed during the first stage of deformation (Robinson, 1963; Pike, 1968; J.B. Thompson et al., 1968). In the schists this foliation is defined by the parallel alignment of micas. In the more gneissic rocks it is also defined by segregation layering of light and dark minerals. In the biotite granulites of the Rangeley Formation it is due to a rather weak alignment of biotite within a granular matrix. In the amphibolites of the dome gneisses and the Ammonoosuc Volcanics it is defined by the parallel alignment of hornblende crystals. Throughout the area this foliation appears to be essentially parallel to bedding.

Figure 3.1 Structural features of the Royalston-Richmond area and vicinity. BHt = Brennan Hill thrust. Cores of the gneiss domes are stippled. Bodies of Hardwick Tonalite and Spaulding Tonalite are shown by parallel dash pattern. Bodies of Fitzwilliam Granite are shown by random dashes. Base of the Littleton Formation and contacts between members of the Rangeley Formation are shown locally for reference. Modified from Robinson et al. (1988, Figure 4), P.J. Thompson (1985, Plate 4), and Zen et al. (1983).

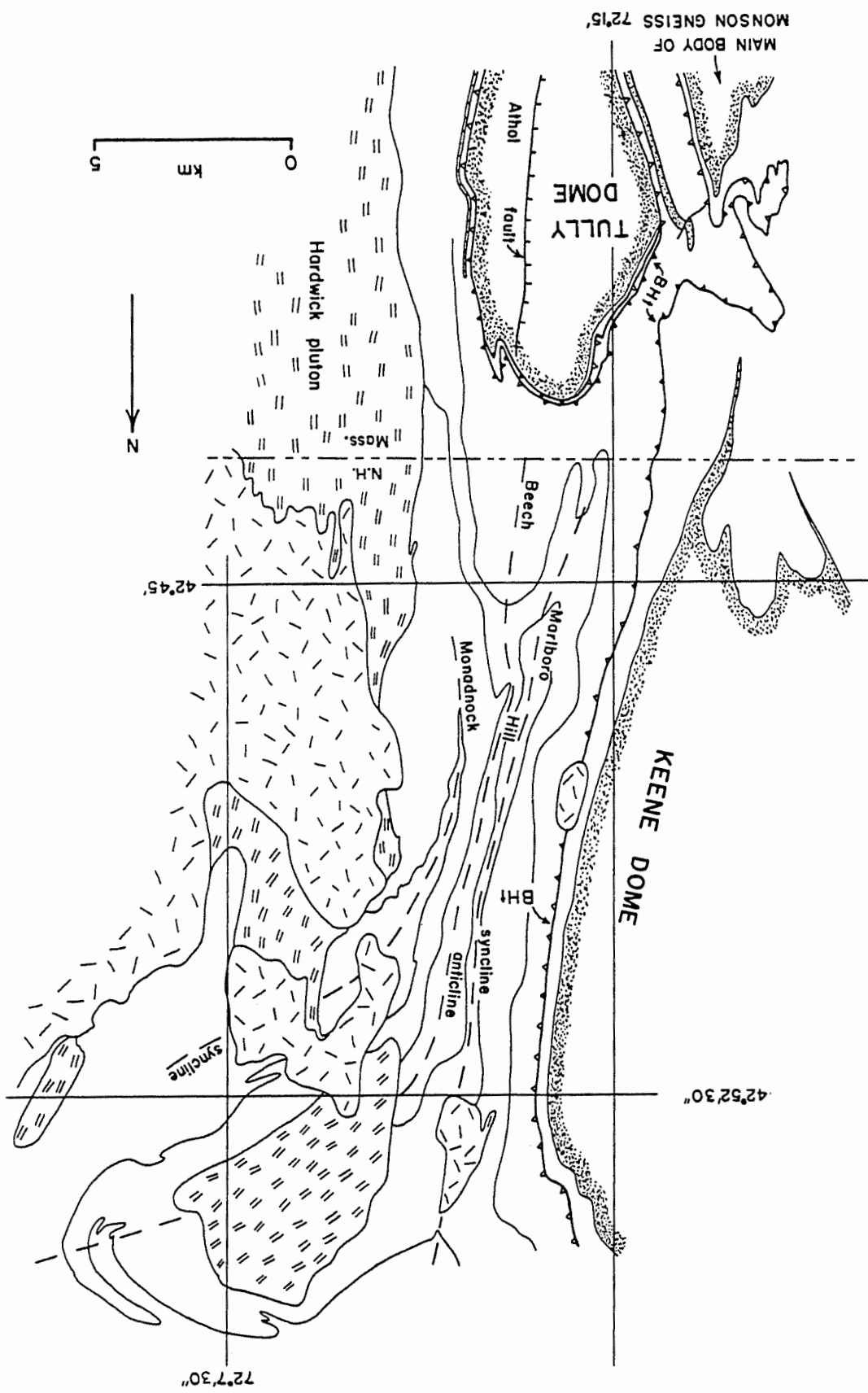
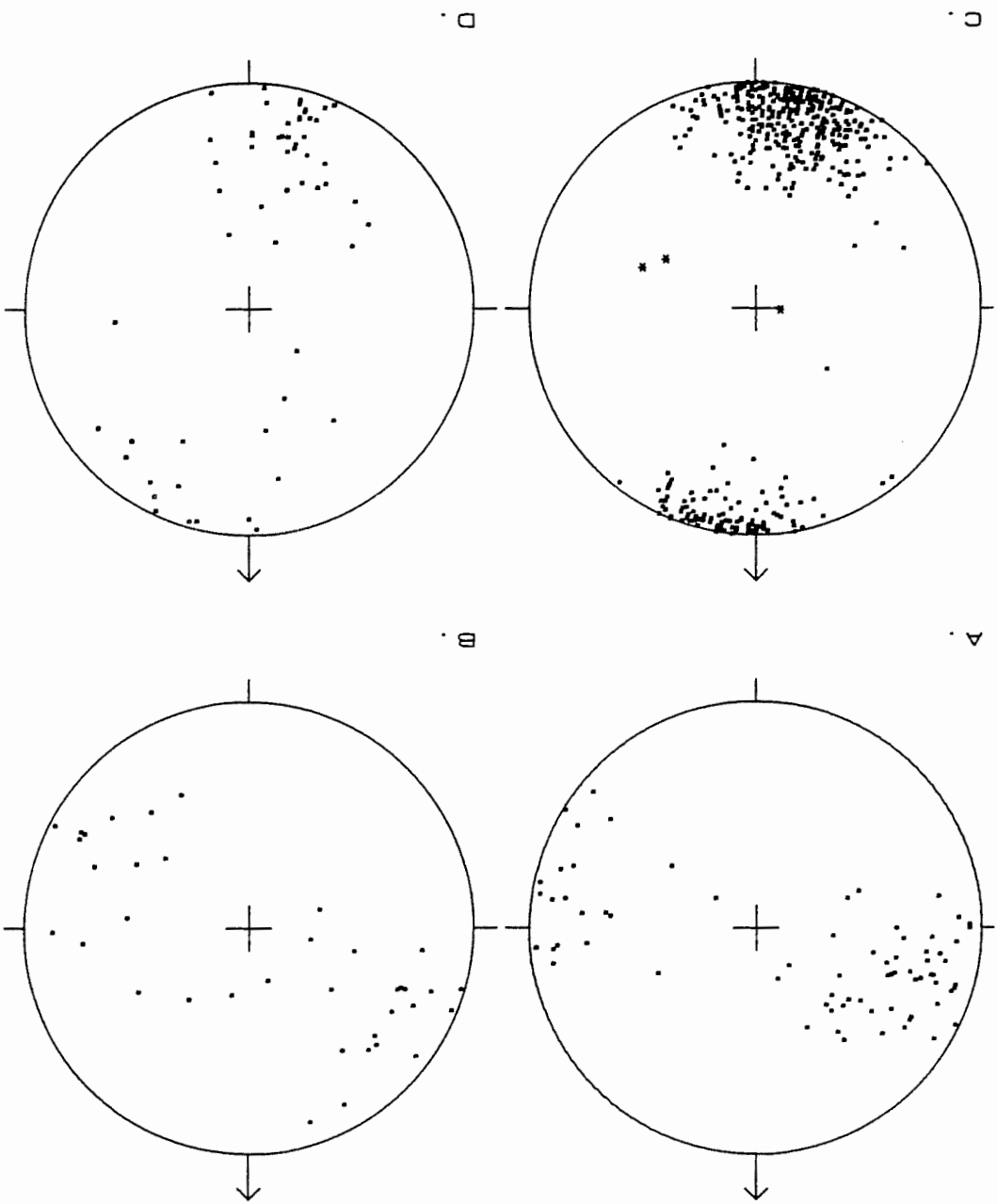
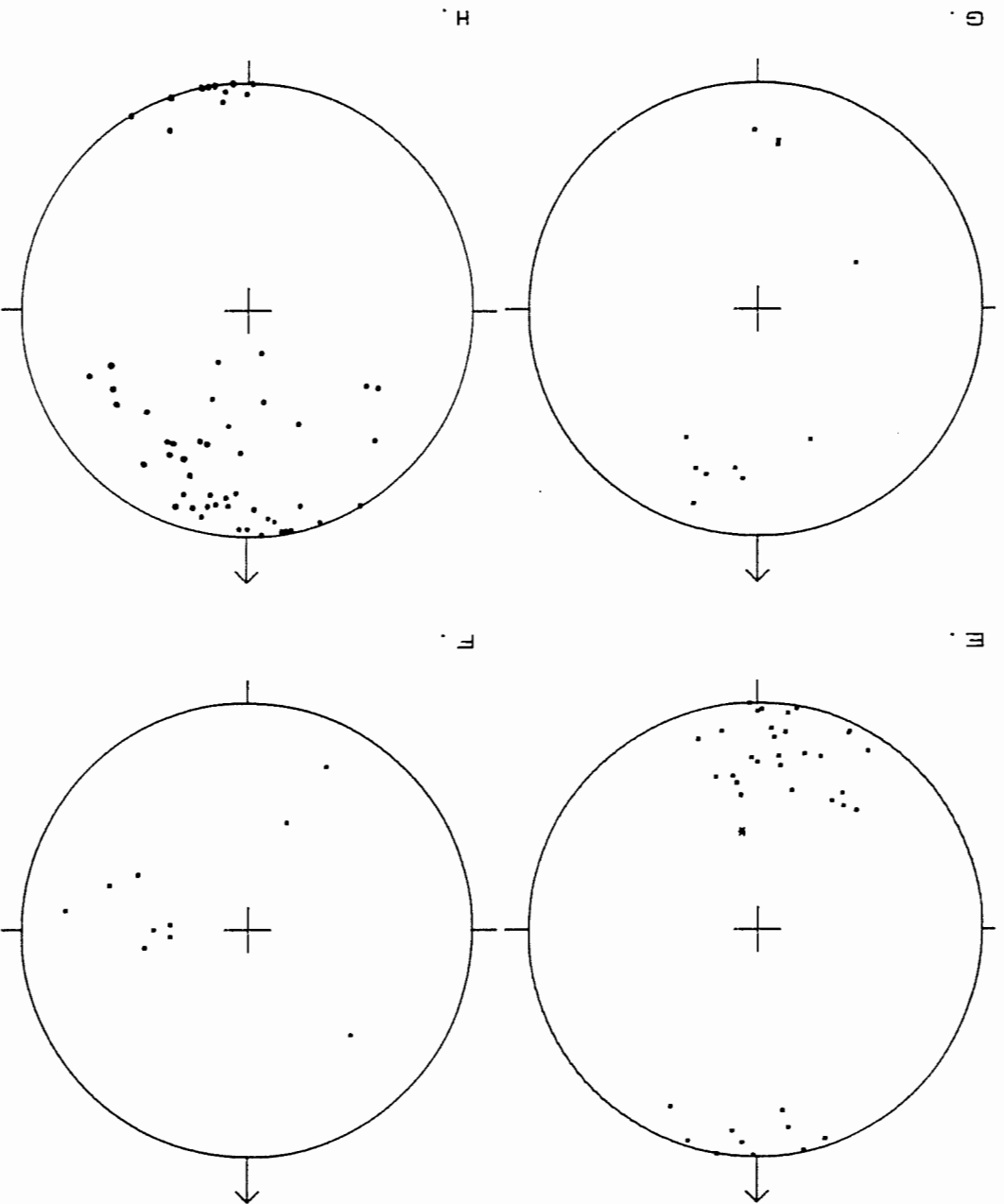


Figure 3.2 Equal area plots summarizing structural features for the entire study area.

- A. Poles to bedding.
- B. Poles to axial surfaces of minor folds.
- C. Mineral lineations (\* = early E-W lineations, • = later N-S lineation).
- D. Intermediate to late minor fold axes.
- E. Crenulation lineations (• = principal crenulation oriented parallel to mineral lineation, \* = late crenulation).
- F. Boudin neck line orientations.
- G. Poles to tourmaline veins.
- H. Poles to tourmaline veins for the Monadnock quadrangle (from P.J. Thompson, 1985, Figure 11G).





Foliation development during the formation of dome-stage folds appears to have been very limited. Traces of a faint foliation developed parallel to the axial surface of a dome-stage fold were observed at station RO-540, located 100m south of Hill 978 and 100m west of Falls Road in Royalston. Because axial surfaces of these folds are commonly at a very low angle to the dominant foliation, except in fold hinges, such foliations, even if present, would be difficult to distinguish from the dominant foliation produced during nappe formation.

## Folds

No outcrop-scale folds assignable to the nappe stage were observed in the study area. However, many examples do occur in the surrounding region. In the Orange area Robinson (1963) reports isoclinal folds in bedding with the dominant foliation parallel to the axial surfaces of the folds. In the Monadnock quadrangle such folds are especially well developed on Mount Monadnock (P.J. Thompson, 1985). Regional evidence suggests that these early folds are parts of large, west-verging fold-nappes (J.B. Thompson et al., 1968; Robinson et al., 1988).

Open to closed folds in foliation are very common throughout the study area. These occur at all scales, from folding of biotite layers observed in thin section up to map scale. Typical examples are shown in Figures 3.3 and 3.4. Although some of these folds may have formed during the backfold stage, most are associated with the dome stage. See Geometrical Analysis of Structural Features for further discussion.

A late warping of foliation is common at a number of sites in the study area. At station RO-526, located 1.0km northeast of the intersection of Greenwood Road and Falls Road in Richmond, these broad, open folds have moderate eastward plunges with upright fold axes. The wavelength varies from 1 to 2 meters with amplitudes from 15 to 40cm. Although it is clear that these folds formed quite late in the ductile deformation history, it is unclear whether they occurred before or after the late crenulation observed at other outcrops.

## Crenulation Lineations

Two distinct crenulation lineations have been observed in the study area. One is a strong crenulation which deforms the dominant foliation, has axes oriented parallel to the principal mineral lineation, and has axial surfaces roughly parallel to the axial surfaces of dome stage folds. It is common throughout the study area. In thin section it is defined by folded biotite layers and by folded lenses of fibrolite and/or prismatic sillimanite. The biotite flakes in these layers are undeformed, indicating recrystallization at some time during or after the formation of the crenulation. At station RO-471, located 0.4km north-northeast of the intersection of Greenwoods Road and Monument Road in Richmond, and again at station RO-278, located 0.3km south-southwest of Prospect Hill in Royalston, the crenulation axes are parallel to the axis of a minor dome-stage fold and have the same sense of asymmetry. Despite such cases, the late fold axes and the crenulation axes are sometimes divergent (Figures 3.2D and 3.2E). A possible explanation is that some of the folds assigned to the dome stage formed contemporaneously with the crenulation, while others formed after the end of crenulation development.



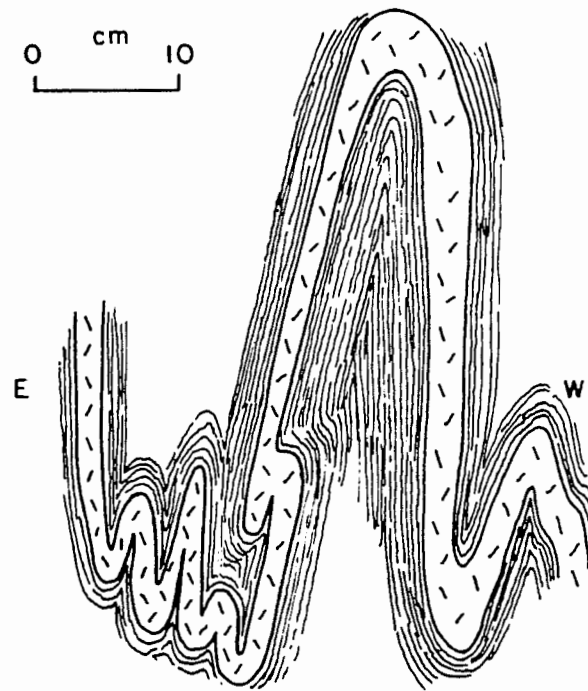


Figure 3.3 Down-plunge view of refolded fold in foliation. Fold plunges gently south. Random dashes = weakly foliated granite sill, irregular lines = red-brown-weathering schist. Pavement outcrop at front door of a log house on summit of hill 978. Located 0.8km northwest of the bridge over Boyce Brook on Falls Road (Richmond).

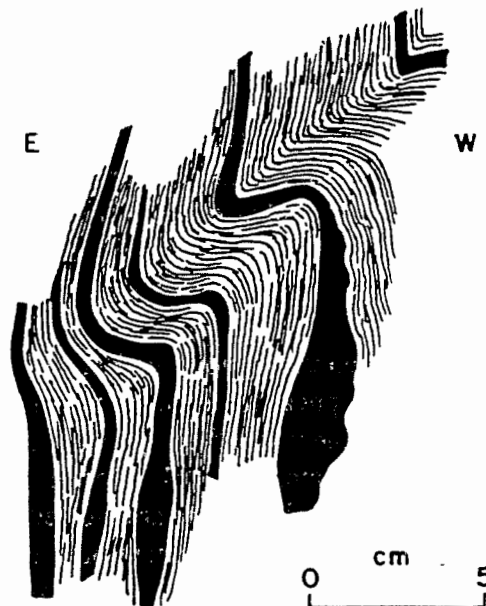


Figure 3.4 Down-plunge view of a typical late asymmetric fold in foliation. Irregular lines = schist, black = quartz-feldspar stringers. From a pavement outcrop on the Metacomet-Monadnock Trail, 30m north of Greenwood Road (Richmond).

The second crenulation occurs only at station MG-110, 0.6km east of Cass Pond in Richmond, where the dominant lineation appears to be folded over the crenulation. Crenulation axes plunge moderately to the south and southwest (Figure 3.2E), the wavelength is 1-2cm, and the amplitude is about 1cm. This crenulation is similar in orientation to the late folds observed on Mount Monadnock which Thompson (1985) believed to post-date the dome stage (see his Figures 11c and 11c'). This could be the same crenulation that Robinson (1963) recognized in the New Salem area. There, it is associated with a zone of retrograde metamorphism and most of the crenulation axes plunge to the north, although a few axes in his Sector 27 plunge to the southwest and east. The late crenulation in the study area is probably Late Acadian age.

### Mineral Lineations

A strong mineral lineation is common in the schists and gneisses in the study area. Biotite, fine-grained sillimanite, and aggregates of fine-grained muscovite commonly show a strong preferred orientation within the foliation planes. A lineation due to elongate quartz grains is also common. Outcrops in Tully Brook, north of Falls Road in Royalston, show a coarse rodding defined by quartz-feldspar augen that are elongate parallel to the dominant mica lineation.

Faint east-west lineations were observed in an outcrop of gray-weathering schist in a sandpit on the south side of state route 119, 1.25 km east of Richmond. These are plotted in Figure 3.2C as asterisks. It is possible that these are backfold-stage lineations similar to those observed in the Merrimack synclinorium to the east (Robinson, 1979; Peterson et al., 1990). However, the relative age of the east-west lineations in the study area could not be determined.

### Pebble Lineations

Pebbles within the conglomerates of the Rangeley Formation have long axes oriented parallel to the mineral lineation of the surrounding schist and gneiss. Because the most straight-forward interpretation is that the pebbles were stretched in this direction, it is reasonable to believe that the mineral lineation is also a stretching lineation. Robinson (1963) interpreted the pebble lineation of the Clough Quartzite in a similar fashion.

### Boudins

Boudins of massive pegmatite are common throughout the Rangeley Formation. At several locations there are trains of boudins which appear to be the remnants of disrupted pegmatite sills (Figure 3.5). The boudins have rounded outlines and they appear to have a low ductility contrast relative to the surrounding schist or gneiss (Ramsay, 1967). Masses of bull quartz are common in the necks between boudins. Boudin neck line orientations are plotted in Figure 3.2F. Most plot at a high angle to the mineral lineation and indicate a component of stretching parallel to the dominant mineral lineation. They are interpreted to have formed at the same time as the mineral lineation.

### Tourmaline Veins

Thin, planar to irregular, black tourmaline veins occur sporadically throughout the study area. They crosscut the ductile fabrics and according to Thompson are associated with non-foliated

pegmatites. Because there is no displacement of marker horizons across them, they are interpreted to be mineralized joints. Figure 3.2G shows that most of the veins dip in a southerly direction. Figure 3.2H is adapted from Thompson (1985, Figure 11G) and shows a broadly similar pattern for the veins observed in the Monadnock quadrangle.

These widespread mineralized joints indicate some sort of hydrothermal mineralizing episode that occurred after the rocks entered the field of brittle deformation and prior to the formation of later, unmineralized joints.

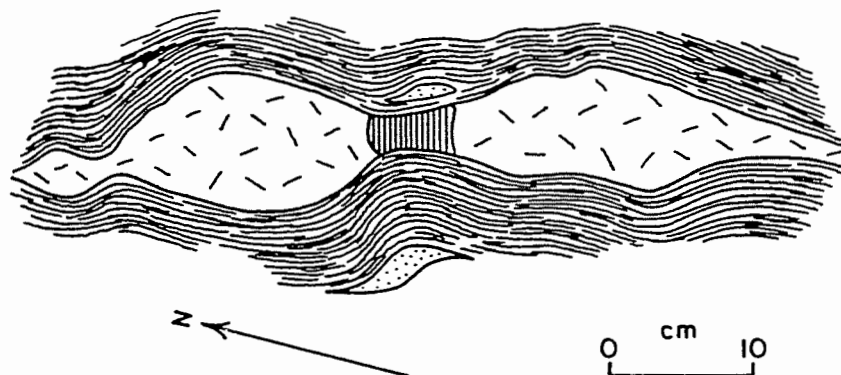


Figure 3.5 Sketch of a boudinaged pegmatite sill in an outcrop of gray-weathering gneiss (upper member of Rangeley Formation). Random dashes = pegmatite; irregular, closely spaced lines = gneiss; vertical ruling = vein quartz in neck; stippled = quartz-feldspar augen. From a pavement outcrop 0.7km west of the Richmond-Fitzwilliam town line and 0.5km northwest of Rhododendron Road (Richmond).

### Geometrical Analysis of Structural Features

For the purpose of structural analysis the study area was divided into subareas as shown in Figure 3.6. Subareas 1-12 are from this study, subareas R1, R2, and R3 are from Robinson (1963), and subareas P1 and P2 are from Pike (1968). The average foliation and mineral lineation values shown in Figure 3.6 provide a good overview of structural orientations within the study area. The strike of the foliation is generally constant, except in subarea R3, and mineral lineations are fairly constant throughout. As Plate 2 shows, attitudes of planar and linear features are unchanged across the Brennan Hill thrust.

Figure 3.7 contains equal area diagrams of orientation data for subareas 1-12. These diagrams show that the foliation in each subarea is folded into a broad girdle which has an axis corresponding fairly well to the cluster of fold axes for that subarea. Most of the mineral lineations trend north-northeast with shallow plunges to the south, or less commonly, north. This pattern is clearly evident both in the plots for the individual subareas and in the summary diagram shown in Figure 3.2C.

Orientation patterns of axial surfaces and fold axes are best discussed by reference to the summary diagrams shown in Figures 3.2B and 3.2D, respectively. Fold axes have a weak maximum with a shallow plunge to the south-southwest, although some of the axes appear to be spread out about an east-west axis. The axial surfaces of these folds have a rather wide distribution along a girdle that roughly coincides with the average foliation girdle for the study area. This divergence may be due to deformation subsequent to the principal dome-stage folding.

It is unclear why the mineral lineations are parallel to the dome stage crenulation axes shown in Figure 3.2E. Figure 3.7 shows that this pattern is present in each of the twelve subareas. This relationship is discussed further in the next section.

#### Origin of Foliation and Lineation

The foliation observed throughout the metamorphic rocks in the study area is considered to have formed parallel to the axial planes of nappe-stage folds early in the Acadian orogeny. This interpretation is based on numerous outcrops throughout the surrounding region where isoclinal folds in bedding have a strong foliation developed parallel to their axial surfaces (Robinson, 1963; P.J. Thompson, 1985). Although it is possible that the foliation observed may actually consist of one or more foliations which have been transposed into parallelism with the axial surfaces of the isoclinal folds, no evidence of this is seen in the study area. Although faint foliations do exist parallel to the axial surfaces of some dome stage folds, they appear to be of very localized extent.

The evidence at hand points to a single foliation-forming episode early in the deformation history. The mineral lineations observed in the study area have a pronounced north-south alignment indicating a north-south stretching during their development. Pebble lineations and most of the boudin neck lineations confirm this. The mineral lineations in the study area are commonly parallel or nearly parallel to the axes of minor dome-stage folds. Similar lineations are seen throughout the Bronson Hill anticlinorium and their possible origins have been discussed by several workers (Robinson, 1979; Michener, 1983; Robinson et al., 1989). Peterson et al. (1990) suggest that the lineation formed due to orogen-parallel stretching at conditions near or slightly after the peak of metamorphism. The relationship between the mineral lineation and the late minor folds remains a topic for further research.

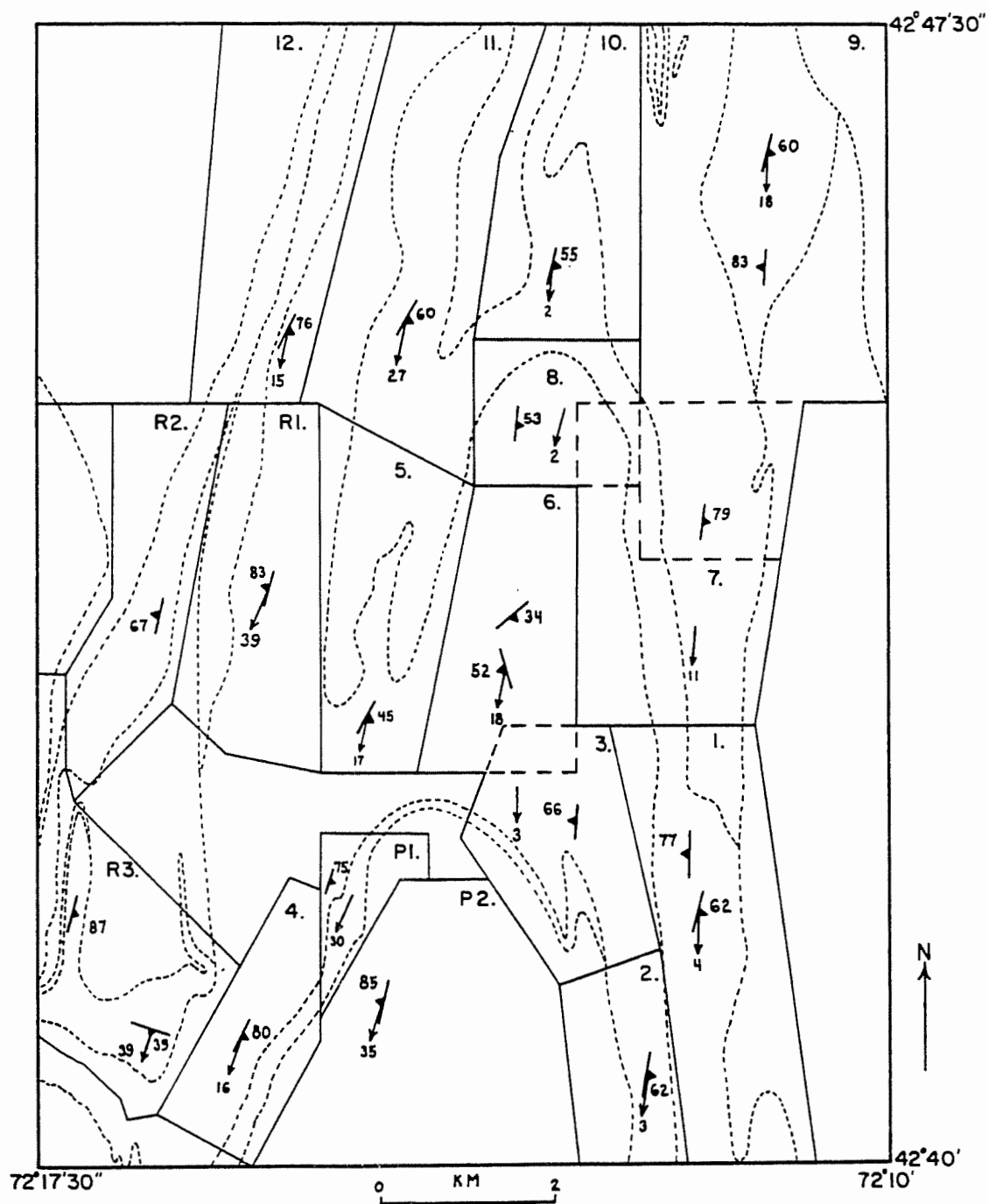


Figure 3.6 Location map for subareas shown in Figure 3.7.  $\nabla^{60}$  = average foliation (in sectors having no strong maximum, two representative values are shown),  $\nwarrow^u$  = average mineral lineation.

Figure 3.7 Equal area plots of planar and linear features for the subareas shown in Figure 3.6

PLANAR FEATURES			LINEAR FEATURES		
+	poles to bedding		.	dominant mineral lineations	
.	poles to foliation		#	early mineral lineations	
*	poles to axial surfaces of folds		.	crenulation lineations	
			.	fold axes	

Numbers of measurements:

Subarea	PLANAR FEATURES			LINEAR FEATURES					
	Bedding	Foliation	Average orientation	Axial surfaces	Early lineations	Intermediate to late lineations	Average Orientations	Crenulation lineations	Fold axes
1	2	112	016,62 184,77	5		78	185,04		7
2	8	56	012,62	2		43	189,03	1	5
3	2	68	187,66	2		24	182,03	1	4
4	1	68	029,80	4		17	203,16	1	5
5	8	120	030,45	9		65	192,17	8	18
6	10	99	052,34 167,52	6		69	195,18	6	6
7	10	131	005,79	2		82	187,11	8	4
8		31	006,53			18	196,02	4	
9	9	52	015,60 186,83	2		37	182,18	6	3
10	5	43	015,55	2		28	186,02	7	3
11		19	032,60	1		4	195,27		1
12	26	19	026,76	3	1	9	194,15	1	5

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Figure 3.7 continued

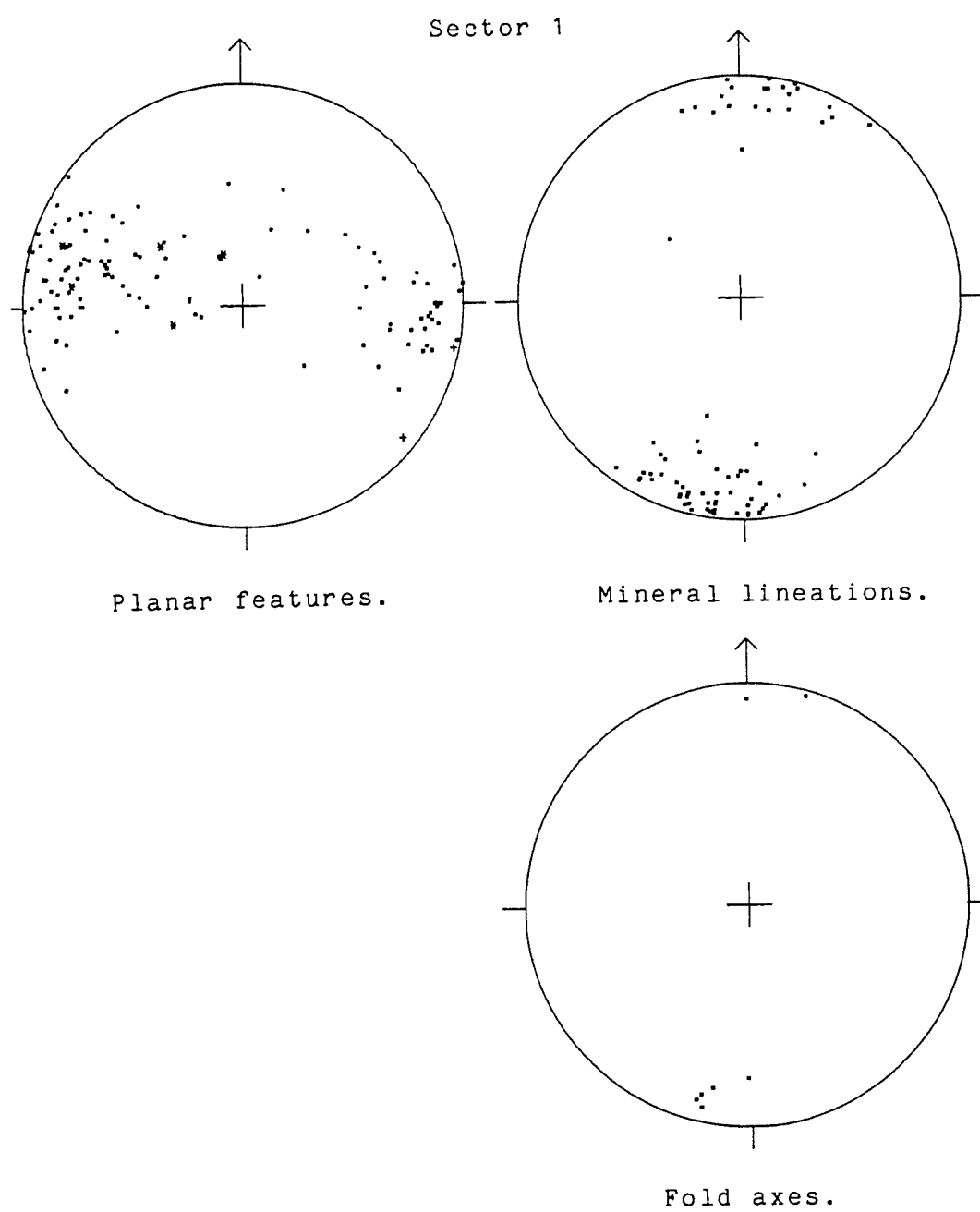


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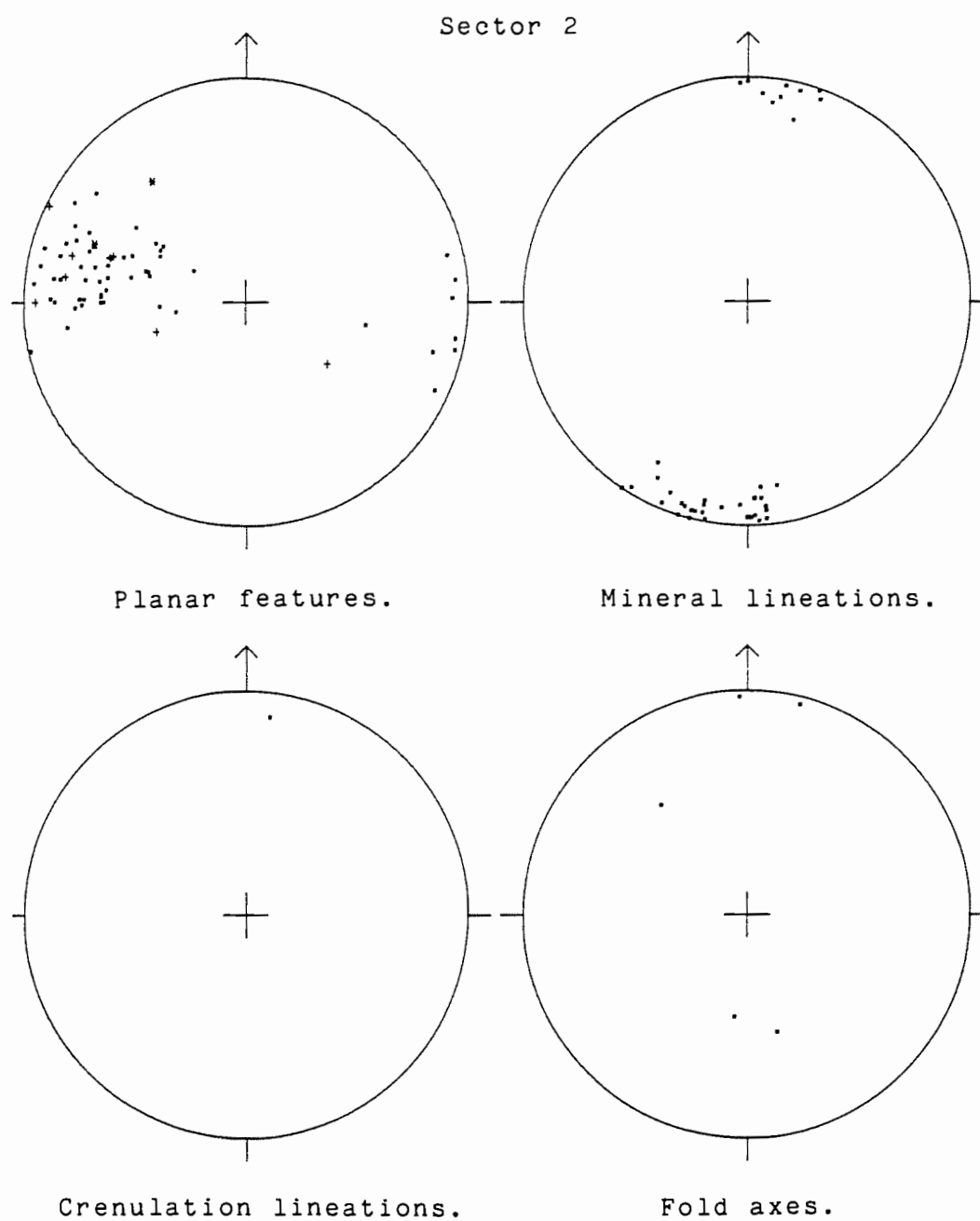




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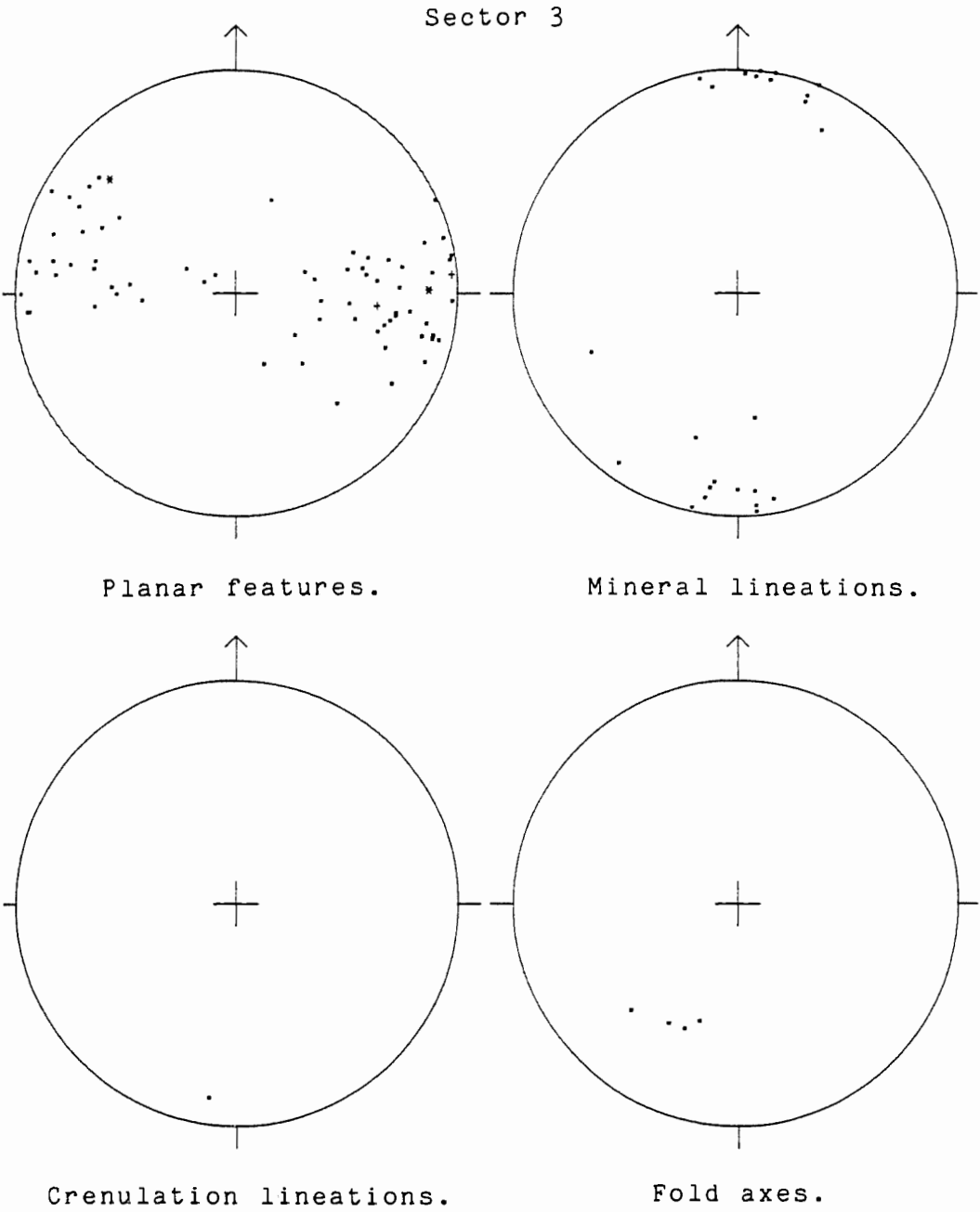


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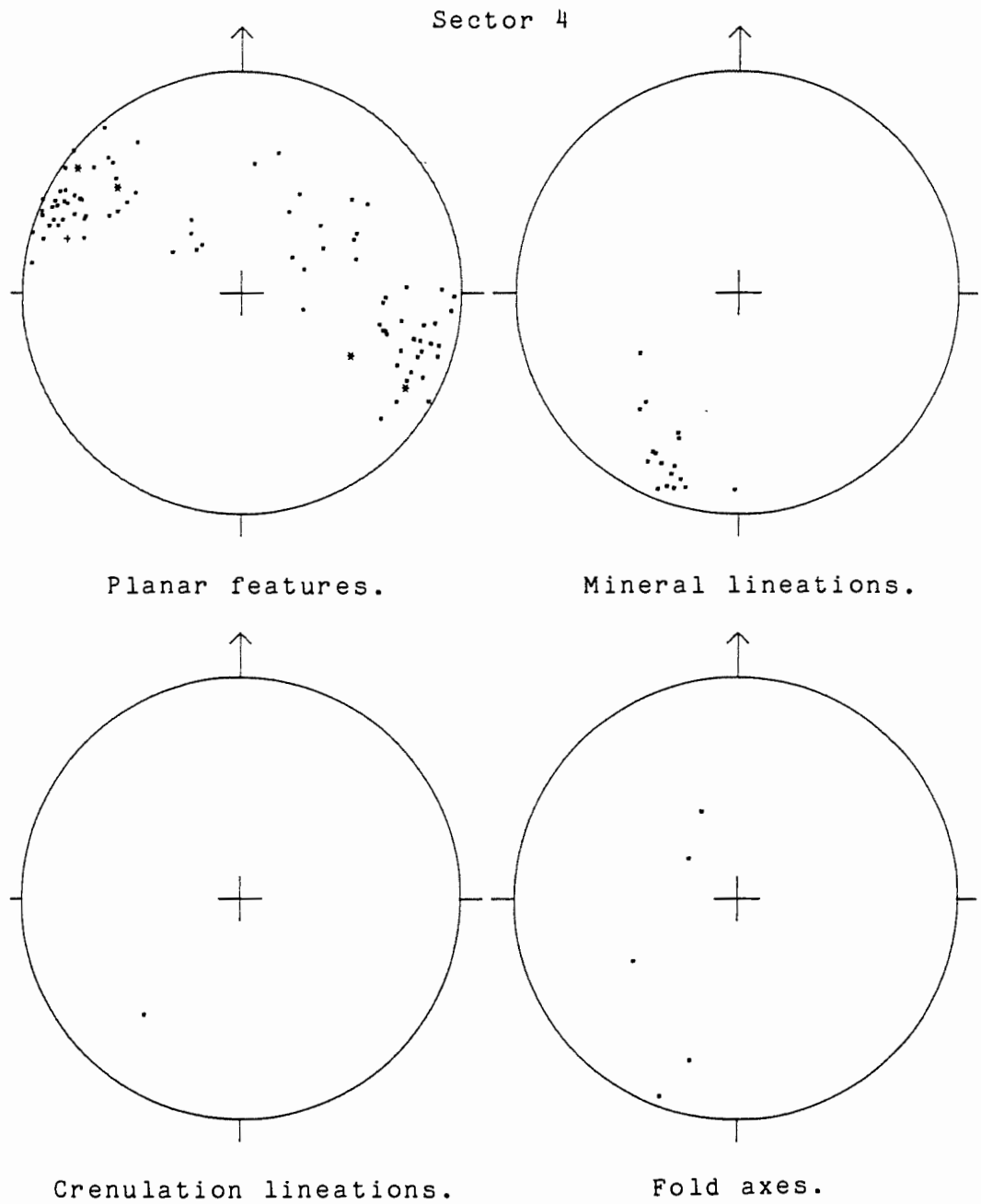


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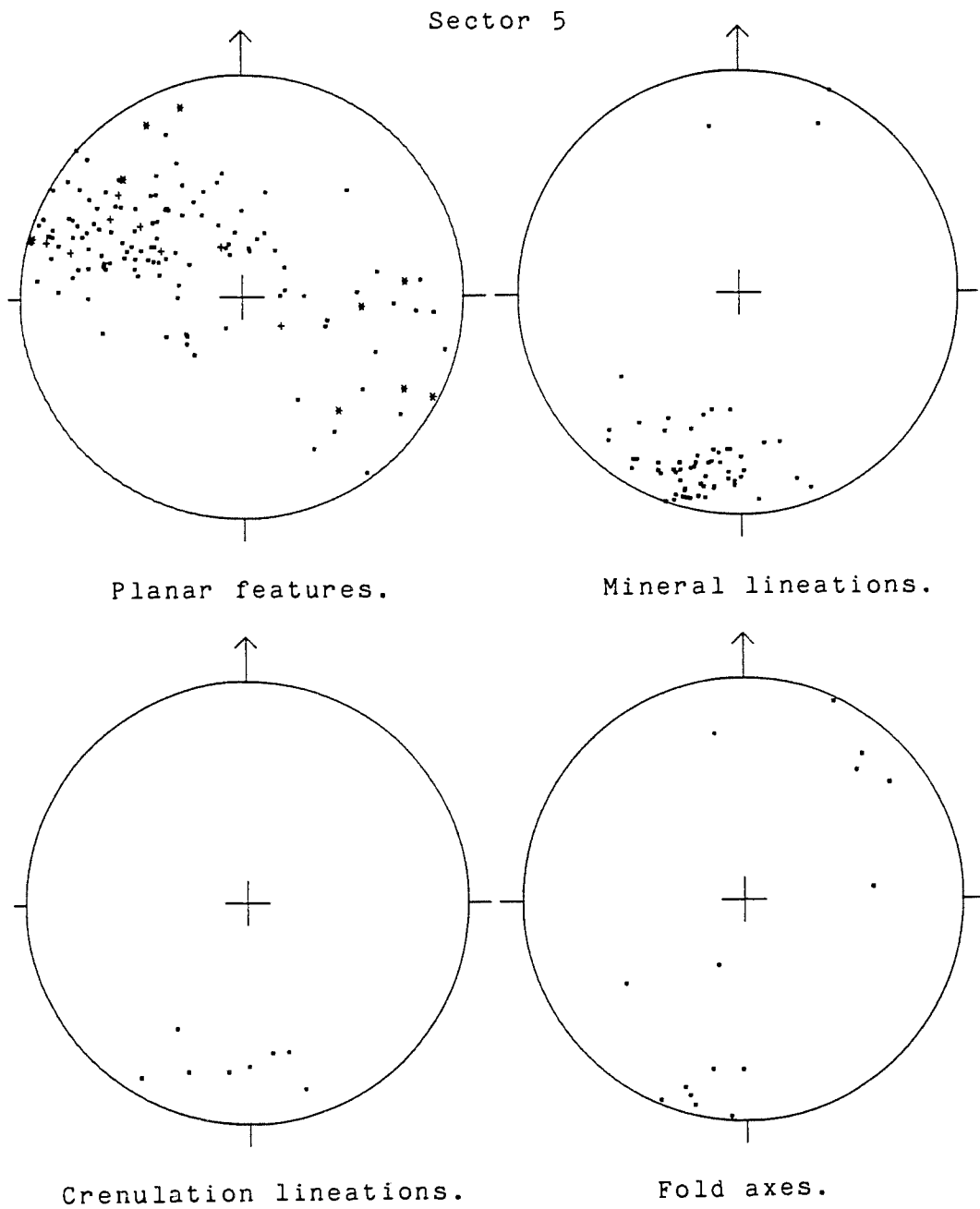


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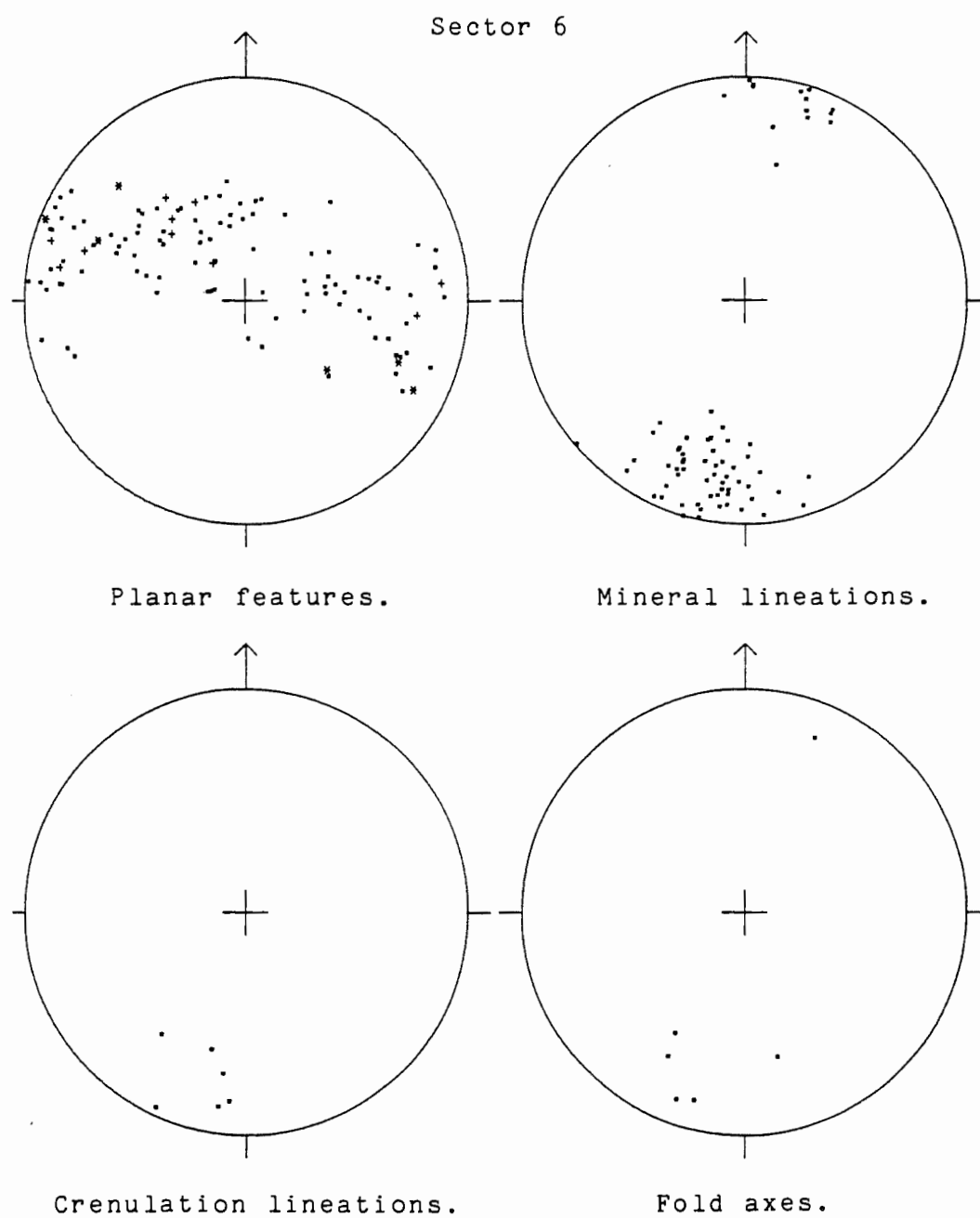


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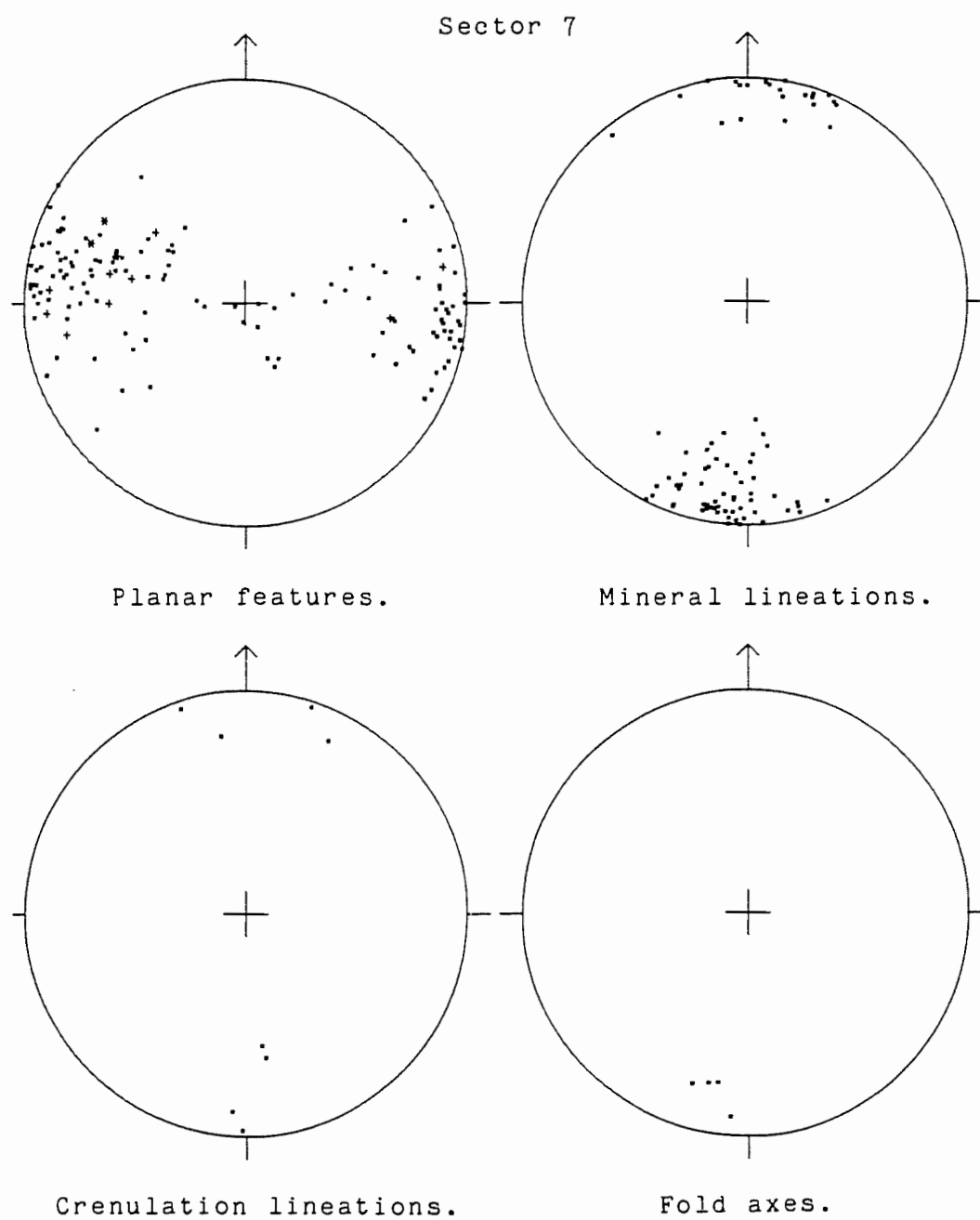


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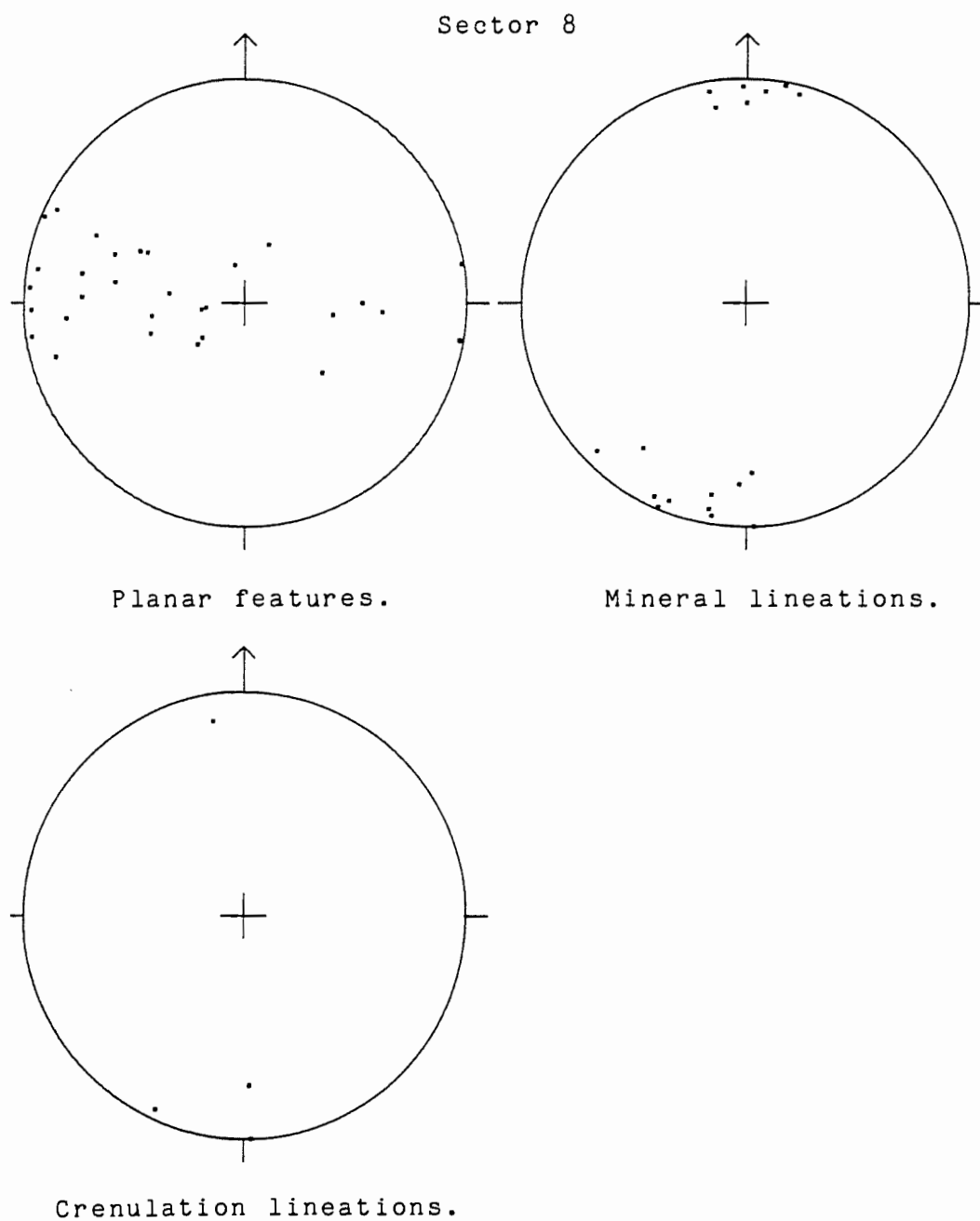


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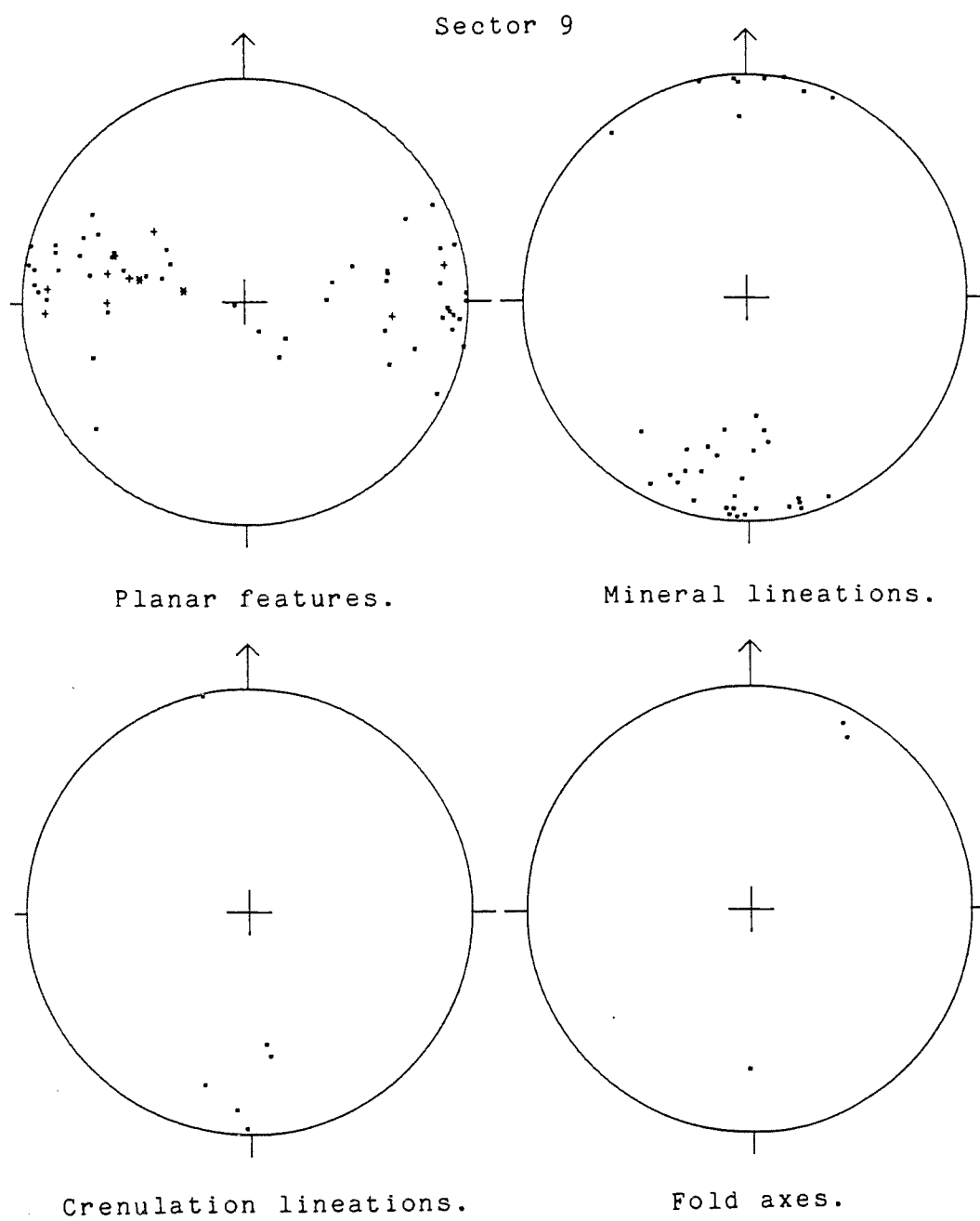


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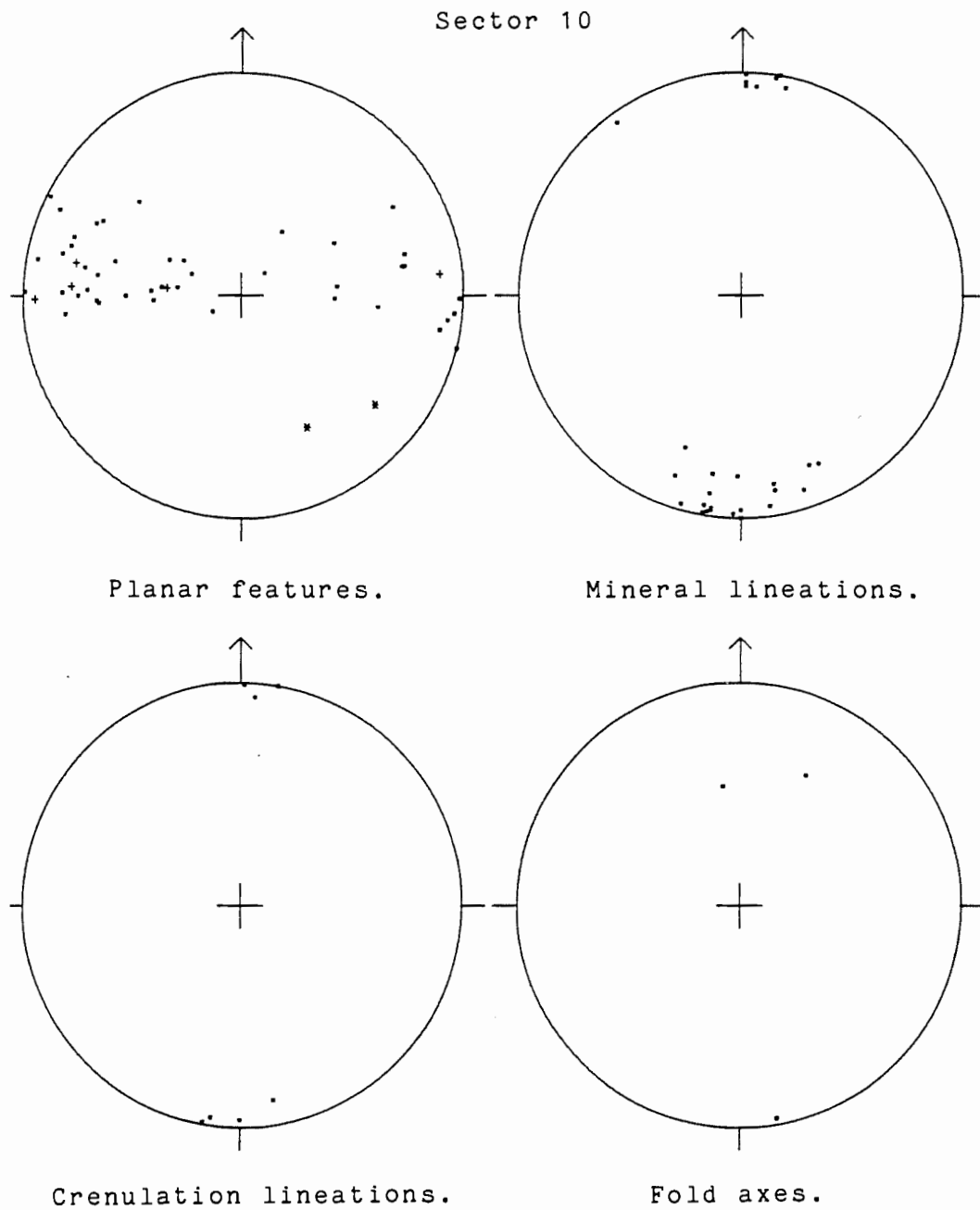




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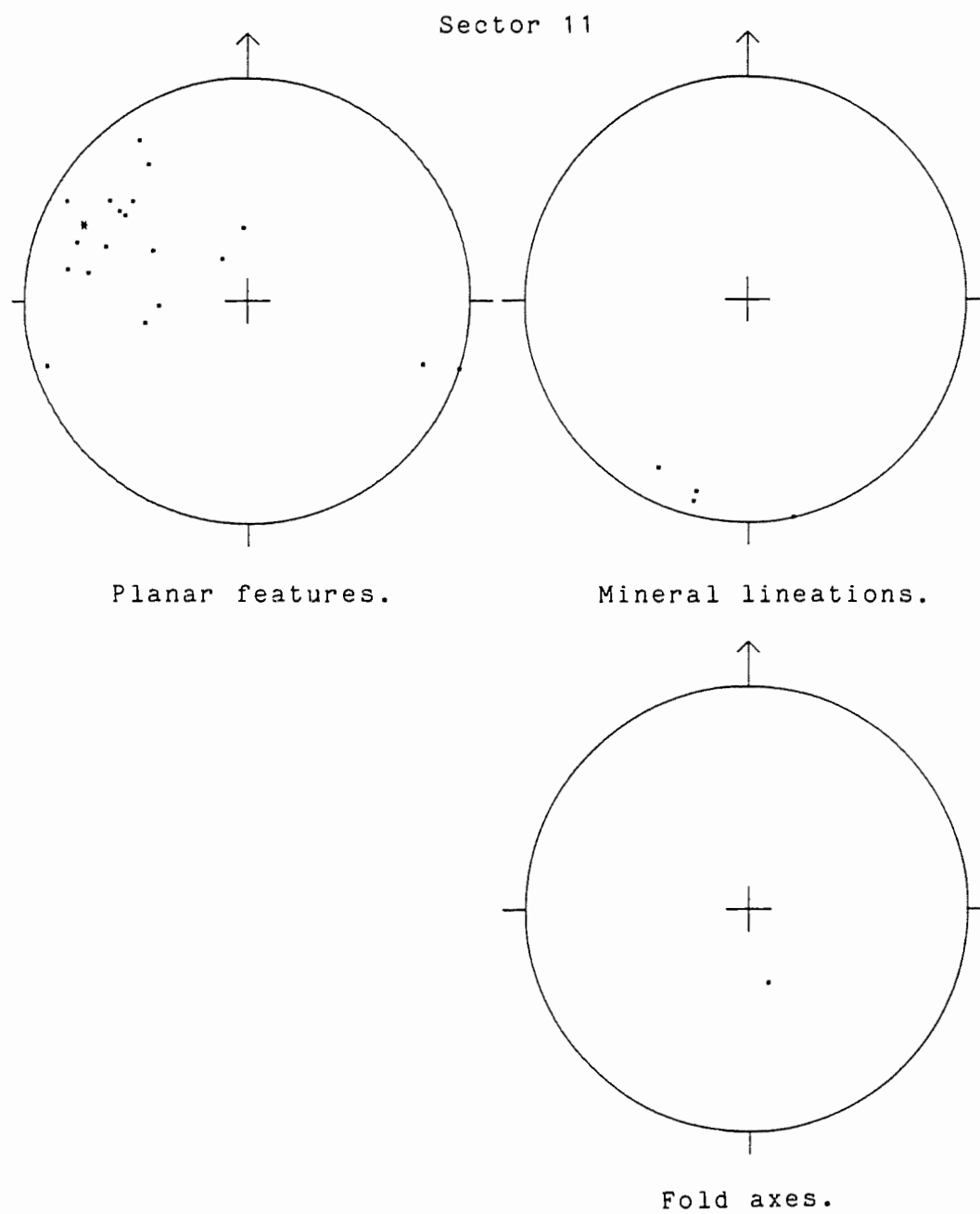
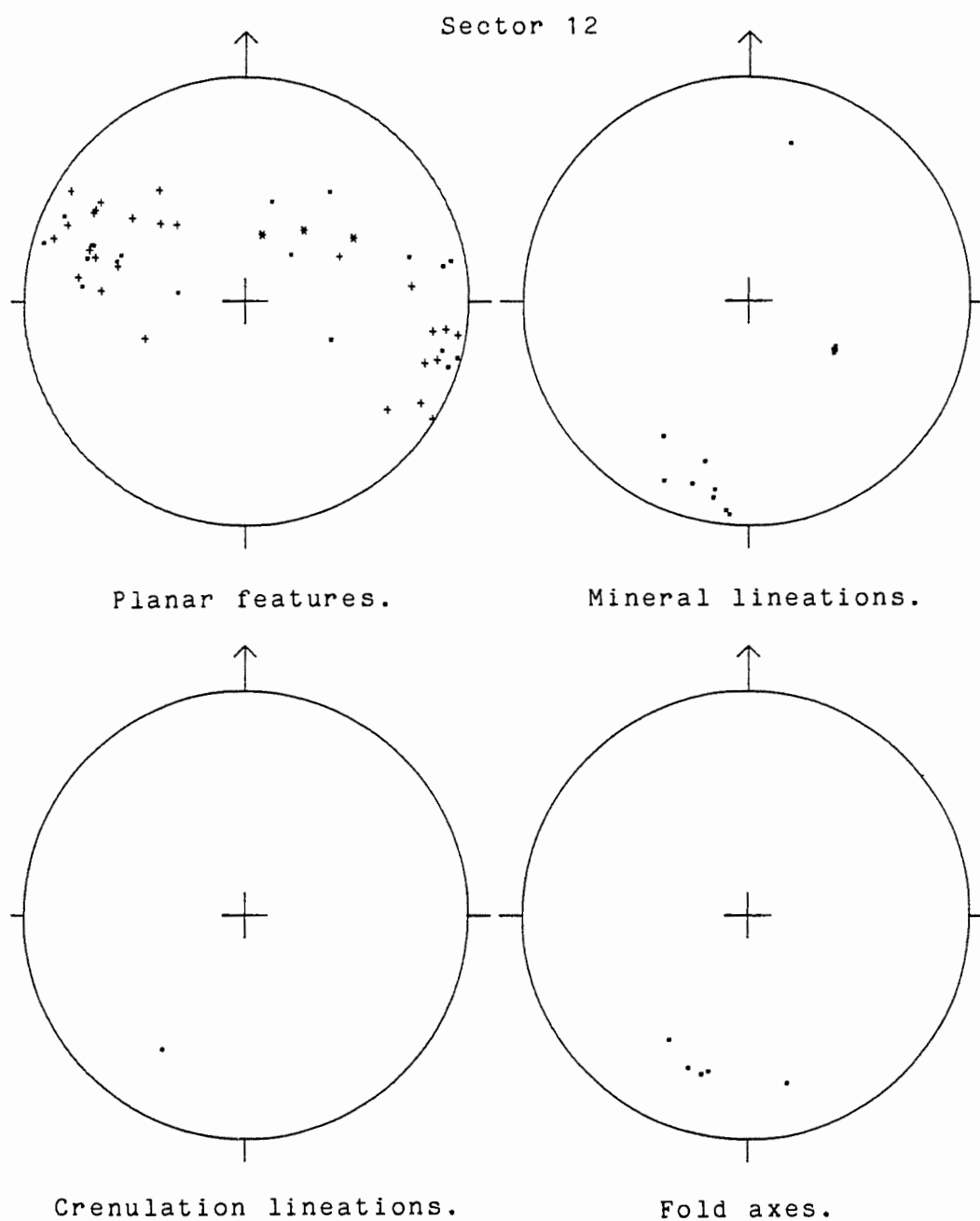


Figure 3.7 continued



## Major Structural Features

### Introduction

The outcrop pattern shown in Plate 1 is the result of a complicated sequence of Acadian deformations. Three east-west geologic cross sections were drawn at a scale of 1:25000 with no vertical exaggeration in order to illustrate the complex geometry (Plate 3). These were constructed by projecting major fold axes into the plane of the section, adjusting the plunges according to known changes in plunge of minor folds. As there are few constraints, the cross sections are highly speculative.

### Monadnock Syncline

The Monadnock syncline is located in the north-central part of the study area and was originally described by P.J. Thompson (1985). On Little Monadnock Mountain it is a tight structure with Littleton Formation in the core and Perry Mountain, Frankestown, Warner, and Rangeley Formations on the limbs (see Plate 1 and P.J. Thompson, 1985, Plate 4). An examination of the map pattern indicates that the syncline plunges to the north, although minor folds in the vicinity plunge south (Plate 2). Thompson tentatively assigned it to the nappe stage since the dominant foliation is parallel to the axial surface of the syncline. This interpretation has been followed in the construction of the geologic cross sections (Plate 3), where the Monadnock syncline is deformed by the Beech Hill anticline (see below).

### Brennan Hill Thrust

The Brennan Hill thrust of P.J. Thompson (1985) has been extended southward into Massachusetts from the Monadnock quadrangle. The Brennan Hill thrust crops out along the western edge of the study area, on the flank of the Keene dome. There, it juxtaposes the lower member of the Rangeley Formation and the Perry Mountain Formation against the Littleton Formation, the Partridge Formation, and the Clough Quartzite. The thrust also completely encircles the Tully dome in the southern part of the study area. This outcrop pattern is the result of transport of the Tully body northward and upward into the cover rocks during the backfold stage (Robinson et al., 1988). The thrust surface is thus bulged and overturned to the north.

On Butterworth Ridge, on the border between Orange and Royalston, a variety of rock types are included between two splays of the Brennan Hill thrust (Figure 3.8). The Monson Gneiss, Ammonoosuc Volcanics, and Partridge Formation of the Tully dome are in contact across the inner splay with slivers of the Warner Formation, Perry Mountain Formation, and perhaps the Rangeley and Partridge Formations. On the northwestern side of the zone, the rocks between the splays are in contact with the lower member of the Rangeley Formation.

Figure 3.9 is a model for the production of the observed sequence of units in the Butterworth Ridge area. In the lower diagram the strata of the Bronson Hill and Monadnock sequences have been folded by west-verging nappes. In the upper diagram two splays of the Brennan Hill thrust have stacked the Perry Mountain and Warner Formations on top of the Bronson Hill sequence and the lower member of the Rangeley Formation on top of the Perry Mountain and Warner

Formations. Although the amount of transport is not known, it was certainly on the order of tens of kilometers. Later deformations are not shown.

No textural evidence of shearing was observed in outcrops near the trace of the fault. This is in agreement with the idea that movement on the fault took place prior to the peak of Acadian metamorphism. Any shear fabrics produced during faulting would have been largely or perhaps completely destroyed by the subsequent metamorphism. Thus, the fault is defined purely on stratigraphic grounds.

#### Beech Hill Anticline

The Beech Hill anticline is a major stratigraphic anticline which is interpreted to deform the axial surface of the Monadnock syncline and the surfaces of the Brennan Hill and Chesham Pond thrusts (P.J. Thompson, 1985). Since the anticline is itself deformed by dome stage folding, Thompson assigned it to the backfold stage. Although the axial trace of the structure trends toward the Tully dome and the dome may indeed nestle snugly within the core of the anticline (Plate 3), it is not clear whether the Tully body was in position before the anticline formed or whether it was emplaced after the formation of the anticline. Although the emplacement of the Tully body must have taken place after the principal movement on the Brennan Hill thrust and before the major deformation of the dome stage, the exact timing remains unclear.

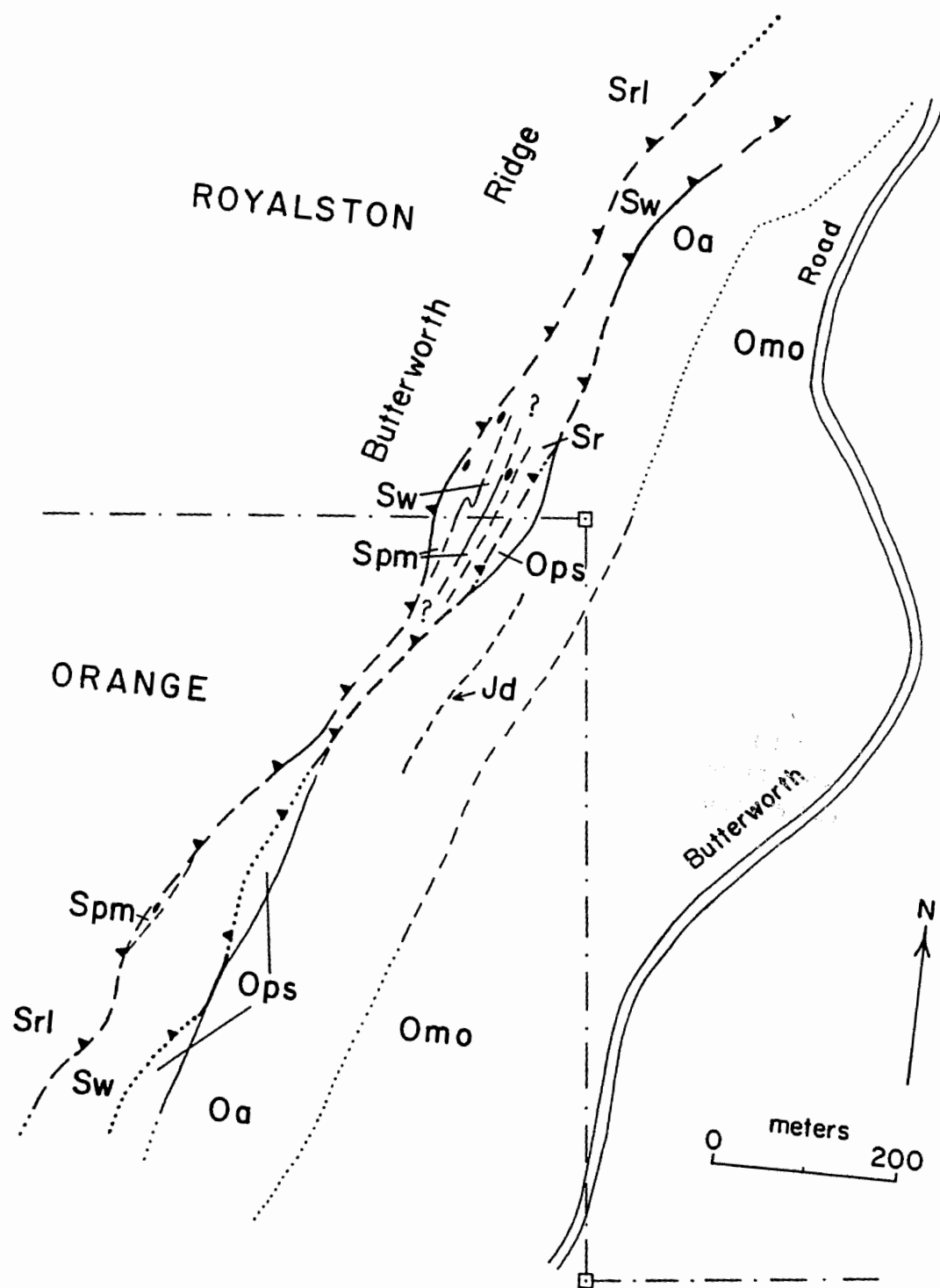
#### Tully Dome

The Tully dome is a prominent gneiss dome located in the southern part of the study area. At the northern end of the dome the Monson Gneiss, Ammonoosuc Volcanics, and Partridge Formation in the inner part of the dome are separated from the lower member of the Rangeley Formation by a complex zone of faulting bounded by thrust surfaces related to the Brennan Hill thrust. To the south, the rocks in the inner part of the dome appear to be directly in contact with the lower member of the Rangeley Formation across the Brennan Hill thrust surface. Foliation measurements in the cover rocks near the northern end dip in toward the center of the body, indicating that these rocks are overturned. Pike (1968) showed that the Tully body could be modelled as a "zeppelin-shaped" body of rock that had moved northward relative to its cover rocks, overturning them in the process. According to Robinson (1979) this longitudinal transport of the main and Tully bodies took place during the backfold stage, with vertical rising of the other domes taking place during the dome stage proper.

#### Keene Dome

The Keene dome is located on the western side of the study area. In the northwest the outcrop pattern is fairly simple. The Swanzey Gneiss in the core of the dome is overlain by an east-dipping homoclinal sequence of the Ammonoosuc, Partridge, Clough, and Littleton Formations. The Brennan Hill thrust separates these units from the lower member of the Rangeley Formation to the east. This sequence of units is well exposed on the hill west of Benson Cemetery in Richmond.

Figure 3.8 (facing page) Geologic map of the Butterworth Ridge area. Omo = Monson Gneiss, Oa = Ammonoosuc Volcanics, Ops = Partridge Fm., Srl = lower member of Rangeley Fm., Sr = undifferentiated Rangeley Fm. (probably upper member), Spm = Perry Mountain Fm., / = boudin of iron formation within the Spm, Sw = Warner Fm., and Jd = sill-like diabase intrusion of probable Jurassic age. The area between the two thrust faults contains a complex mix of rock types, in which the calc-silicate granulite and gray weathering feldspathic biotite granulite characteristic of the Warner Formation predominate. The syncline at the town line has a core of biotite granulite (upper member of the Warner Fm.) and is flanked on both sides by bedded calc-silicate granulite (lower member of the Warner Fm.) and gray schist with boudins of iron formation (Perry Mountain Fm.). The areas shown as Partridge Fm. and Perry Mountain Fm. may be more extensive than shown.



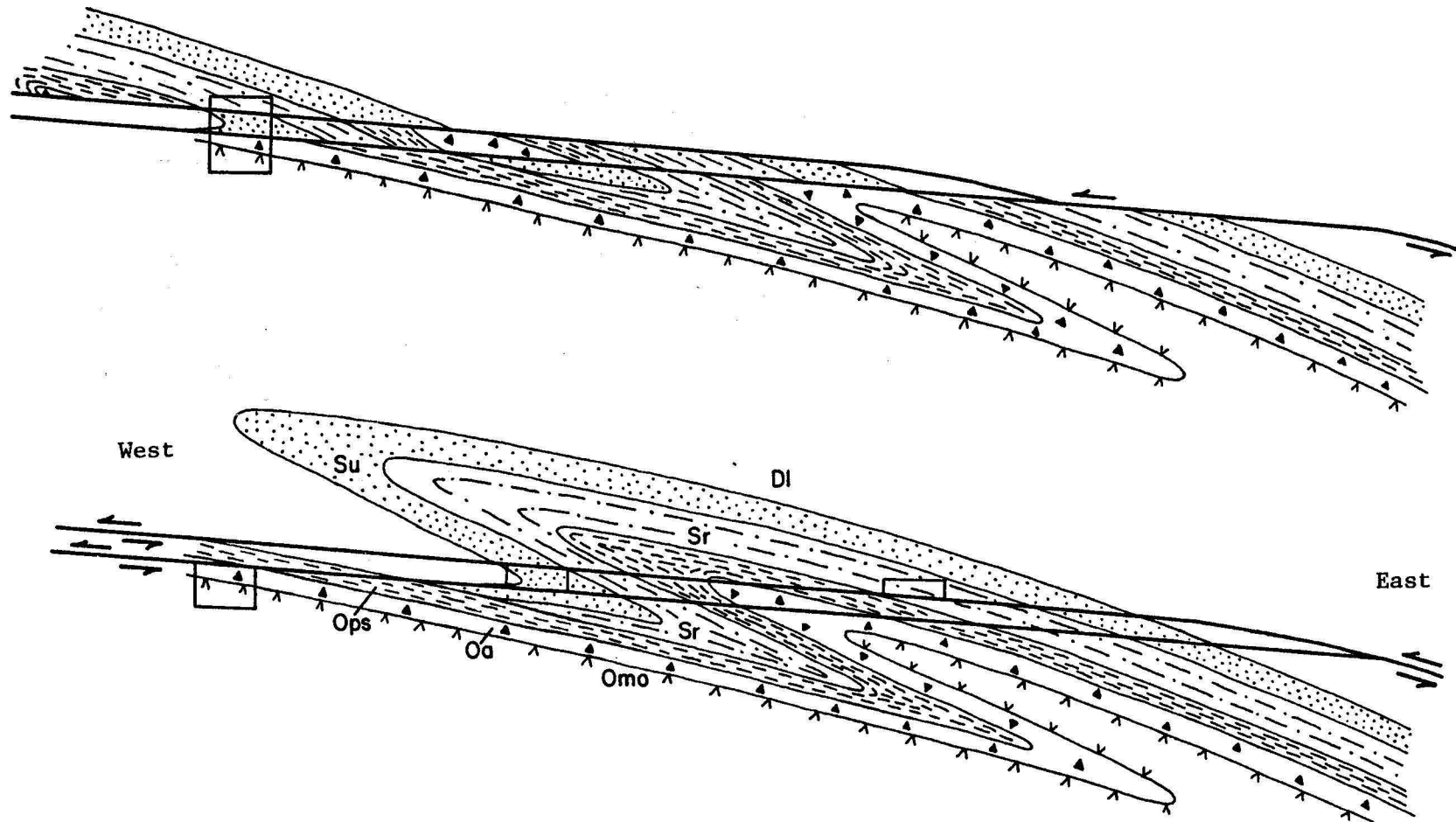


Figure 3.9 Model for the development of features observed on Butterworth Ridge.  
 Su = Perry Mountain, possible Francetown and Warner Formations. Other symbols  
 as in Plate 1. See text for description.

The pattern at the southern end of the dome is considerably more complicated (Figure 3.1). Detailed mapping by Robinson (1963, 1968) demonstrated that the complex digitations there are best explained as isoclinal folds that originally verged to the southeast and were subsequently refolded toward the west. Thus, the Swanzey Gneiss was intimately involved in the deformation affecting the cover rocks.

## Brittle Structural Features

### Introduction

A complete analysis of brittle deformation in the study area has not been attempted here because of time constraints and because of a lack of the large, fresh, natural or man-made exposures necessary for meaningful fracture analysis. The discussion is limited to a description of the Athol fault and some notes on jointing.

### Athol Fault

The Athol fault is a west-dipping, post-metamorphic, Mesozoic normal fault located in the southern part of the study area. The northernmost exposures of the fault are outcrops of silicified breccia and brecciated Monson Gneiss located north of state route 68 and east of the East Branch of the Tully River at the northern end of the Tully body. The fault is also exposed to the south of the study area at the spillway below Tully Reservoir (Pike, 1968) and in the large road cuts south of Athol on Route 2 (Robinson, 1963). According to Peter Robinson (personal communication, 1988), the fault may extend southwestward from there, offsetting the main body of the Monson Gneiss and the Greenwich syncline, and linking up with a previously mapped Mesozoic normal fault on the western margin of the main body. At the outcrops north of Route 68 no estimate of the dip of the fault zone can be made, but at the exposures to the south the fault planes have dips varying from 32 degrees west at Tully Reservoir to 60 degrees west at Route 2 (Pike, 1968). Robinson (1963) estimates that the western side moved downward about 1300 feet.

### Joints at Spirit Falls

At Spirit Falls an unnamed brook cascades westward over ledges of gray- to rusty-weathering schist and rusty-weathering biotite granulite, descending more than 60 meters toward the valley of the Tully River. In these outcrops the dominant metamorphic fabrics appear to have exercised a strong control over the later brittle features (Figure 3.10). The principal set of unmineralized joints is rigorously parallel to the foliation (Set 1). Next in prominence are unmineralized, slightly wavy to irregular joints (Set 2) which terminate onto Set 1. The intersection lineation of Set 2 on the foliation is parallel to the mineral lineation. Set 3 consists of unmineralized, planar to irregular joints which crosscut Set 2 with no apparent offset and terminate onto Set 1. Apparently, the foliation acts as the major anisotropy and the mineral lineation as a secondary one. Complicating the picture are three tourmaline veins which have orientations within the field of Set 3. Because the tourmaline mineralization did not affect the unmineralized joints of Set 2 or the older unmineralized joints of Set 1, the tourmaline veins probably pre-date all of the unmineralized joints.



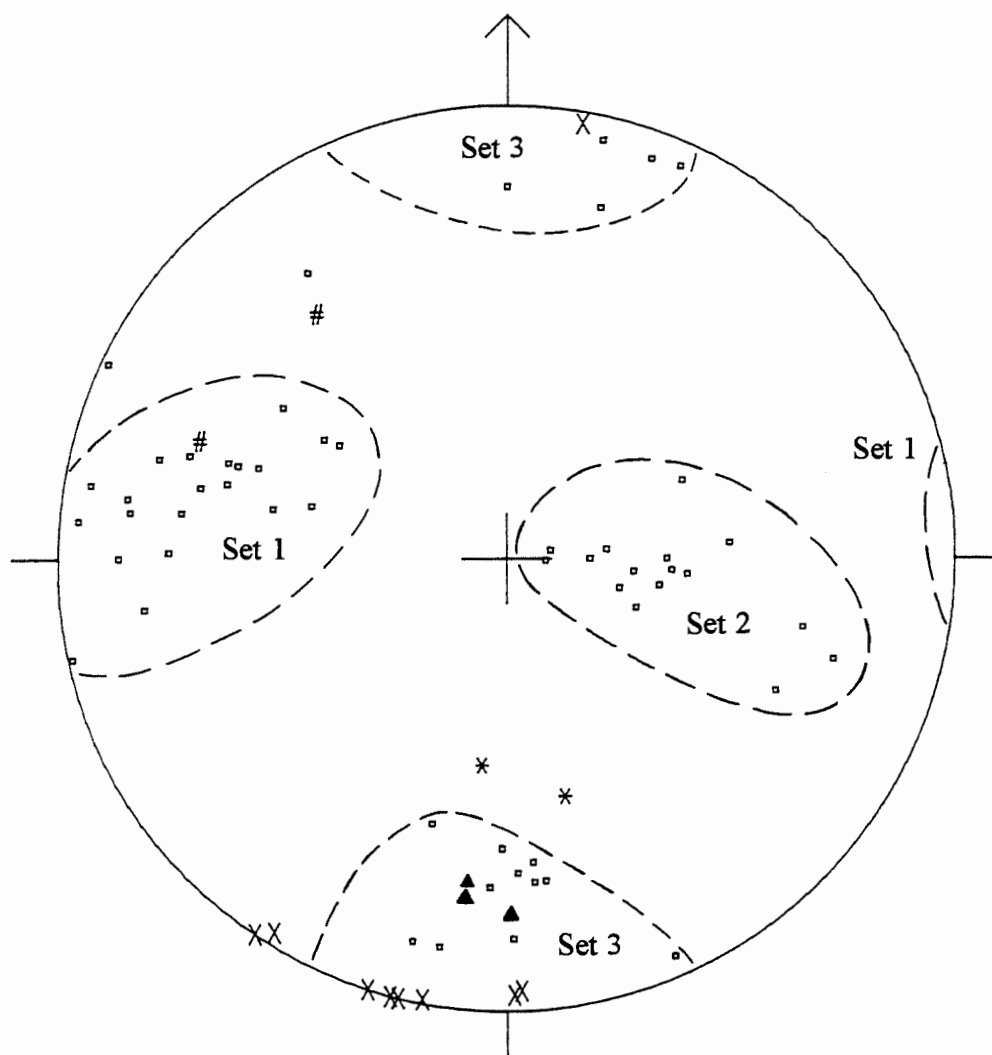


Figure 3.10 Lower hemisphere equal area diagram of structural features at Spirit Falls, Royalston. Set 1 = poles to foliation and associated joints. Sets 2 and 3 = poles to unmineralized joints. X = mineral lineations on foliation surfaces. \* = minor fold axes. # = axial surfaces of minor folds. ▲ = poles to tourmaline veins.

### Sheeting Joints

Subhorizontal, planar to wavy, unmineralized joints are common throughout the more massive portions of the Monson Gneiss. These are interpreted to be sheeting joints formed due to unloading resulting from erosion of overlying rock layers. Sheeting joints are well developed at station RO-382 on the northeast side of state route 32, 1.0 km south of the intersection with Butterworth Road (Figure 3.11). Although very few cross-cutting relationships were observed, the other joint sets appear to terminate against the sheeting joints and are thus younger. This includes joints developed parallel to the very weak foliation present in the gneiss. If this is indeed the case it indicates that much of the joint formation in the study area is comparatively recent and considerably post-dates the brittle deformation associated with Mesozoic rifting. In the better foliated parts of the Monson Gneiss the foliation seems to act as the major anisotropy and sheeting joints are not developed.

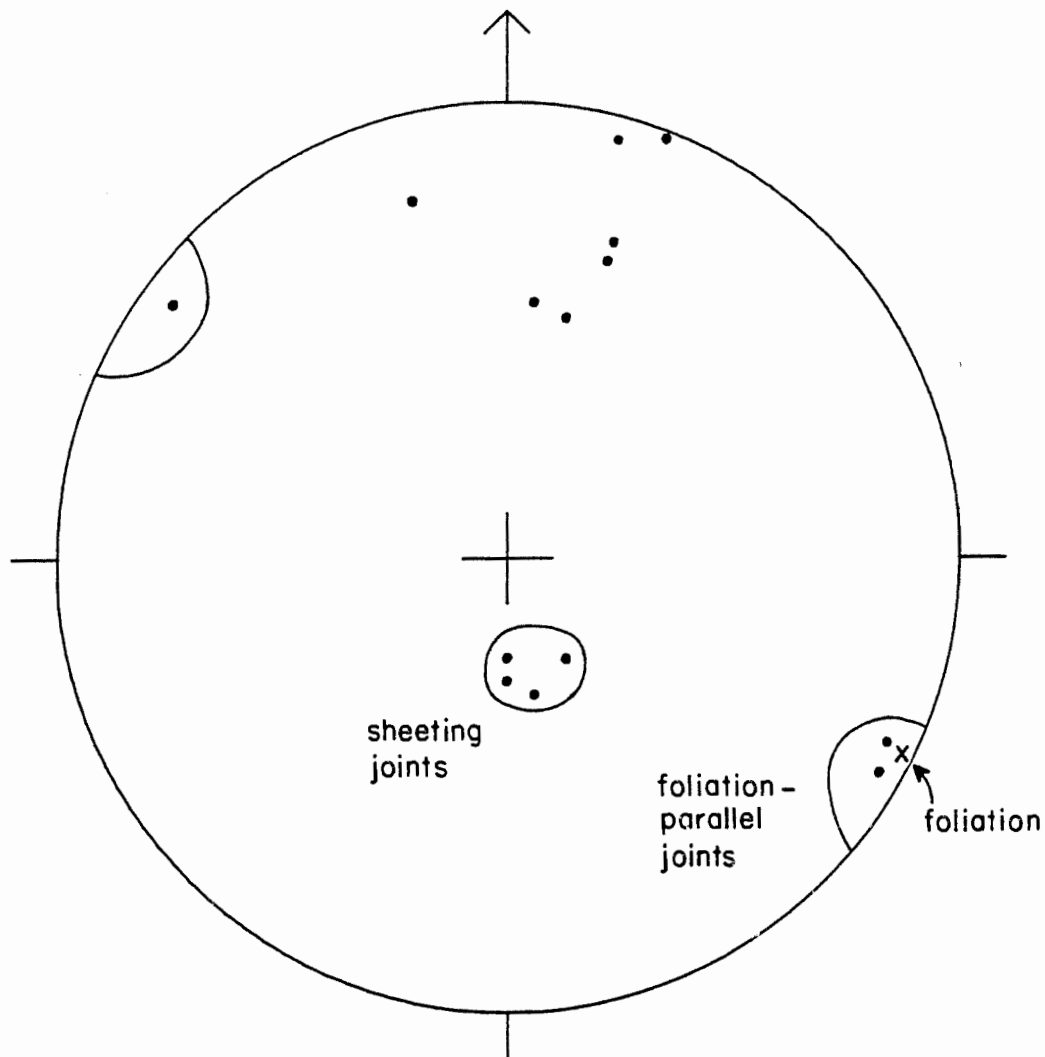


Figure 3.11 Lower hemisphere equal area diagram of jointing in Monson Gneiss at station RO-382, Royalston. Note subhorizontal sheeting joints. See text for description.

## Chapter Four METAMORPHISM

### Introduction

Regional metamorphism has affected most of the rocks in the Royalston-Richmond area. Metamorphic zones in the study area and the surrounding region, based on assemblages in pelitic schists, are shown in Figure 4.1. The plagioclase gneisses, the stratified rocks of the Bronson Hill and Monadnock sequences, and the Hardwick Tonalite were metamorphosed to the lower and upper sillimanite zones of the amphibolite facies during the Devonian Acadian orogeny (Robinson et al., 1986). The Mississippian (?) Fitzwilliam Granite was only weakly metamorphosed following intrusion, probably during the Permian Alleghanian "disturbance" (P. J. Thompson, 1985; Zartman, 1988). The tourmaline veins are a late product of metamorphism and the diabase is unmetamorphosed. The effects of the Acadian metamorphism on the pelitic rocks and on the calc-silicate rocks are discussed below.

### Pelitic Rocks

The pelitic rocks in the study area have prograde assemblages corresponding to Zones II and III of Tracy (1975). The Zone II assemblage of sillimanite + muscovite + staurolite + garnet + quartz +/- plagioclase occurs in the western part of the field area. The easternmost occurrences of this assemblage are in the belt of Littleton Formation east of the Keene dome and in the Rangeley Formation at Blissville, in the southwestern corner of the study area (Robinson, 1963; P.J. Thompson, 1985). The Zone III assemblage, sillimanite + muscovite + garnet + biotite + quartz +/- plagioclase, occurs throughout the remainder of the study area. Higher grade rocks containing the Zone IV assemblage, sillimanite + muscovite + garnet + biotite + K-feldspar + plagioclase, occur to the north and south of the study area.

Pseudomorphs of sillimanite after andalusite occur in gray-weathering schist of the lower member of the Rangeley Formation on hill 1217 in Fitzwilliam, near the contact with the Hardwick Tonalite. This is apparently the locality visited by J.H. Huntington in the late nineteenth century where he reported outcrops of "andalusite [sic] schist" associated with "a dark gneiss" [Hardwick Tonalite] (in Hitchcock, 1877). These pseudomorphs are elongate prisms that range in length from 2-3cm up to 10cm. A cross-section of one is shown in Figure 4.2. The pseudomorph is composed of a mosaic of sillimanite prisms which has been overgrown by euhedral staurolite and is heavily altered on its margins to fine-grained muscovite. Fibrolite occurs in patches throughout the matrix and is commonly overgrown by the staurolite. The staurolite has therefore formed after the peak metamorphism recorded by the fibrolite and prismatic sillimanite, perhaps in conjunction with the fine-grained muscovite by the reaction



This is a reverse of the prograde reaction for the production of sillimanite during the transition from Zone II to Zone III (Thompson and Norton, 1968; Tracy, 1975). The growth of staurolite and muscovite after conversion of andalusite to sillimanite constrains the P-T path of the rocks in the eastern part of the study area as shown in Figure 4.3.

**Metamorphic Zones and Features:**

- VI Garnet-Cordierite-Sillimanite-K-feldspar
- V Sillimanite-K-feldspar
- IV Sillimanite-Muscovite-K-feldspar
- III Sillimanite-Muscovite
- II Sillimanite-Staurolite
- I<sub>k</sub> Kyanite-Staurolite
- I<sub>a</sub> Andalusite-Staurolite
- G Garnet
- Bio Biotite
- C Chlorite
- [F-J]** Mesozoic Sedimentary and Volcanic Rocks
- Pre-Acadian Metamorphism (Roll, 1987)
- ◆ Sillimanite Pseudomorphs after Andalusite

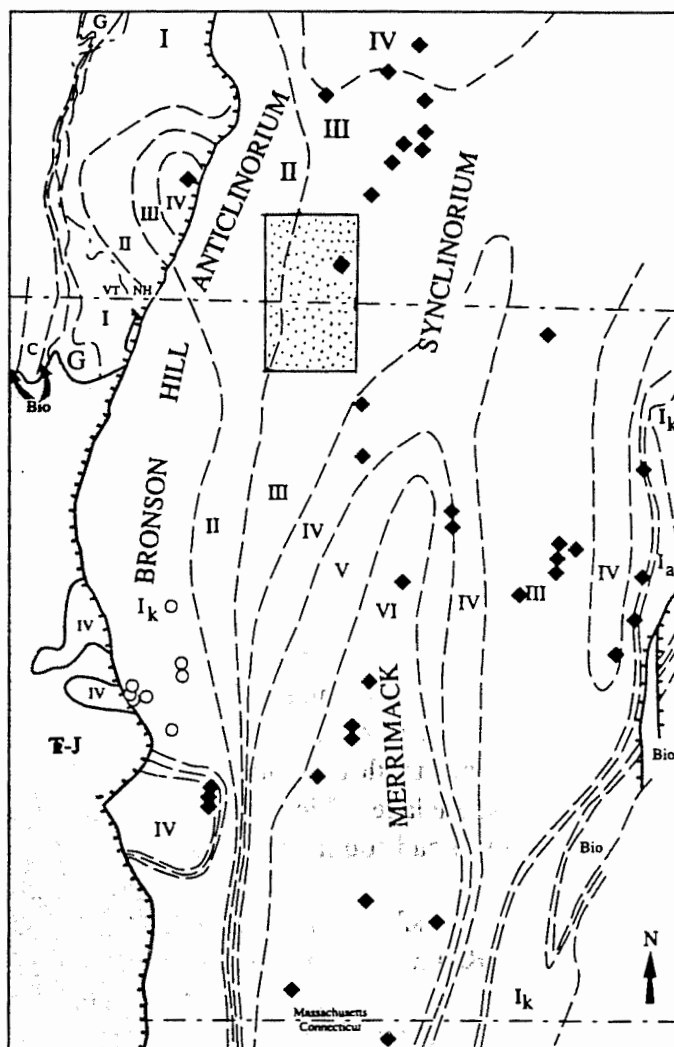
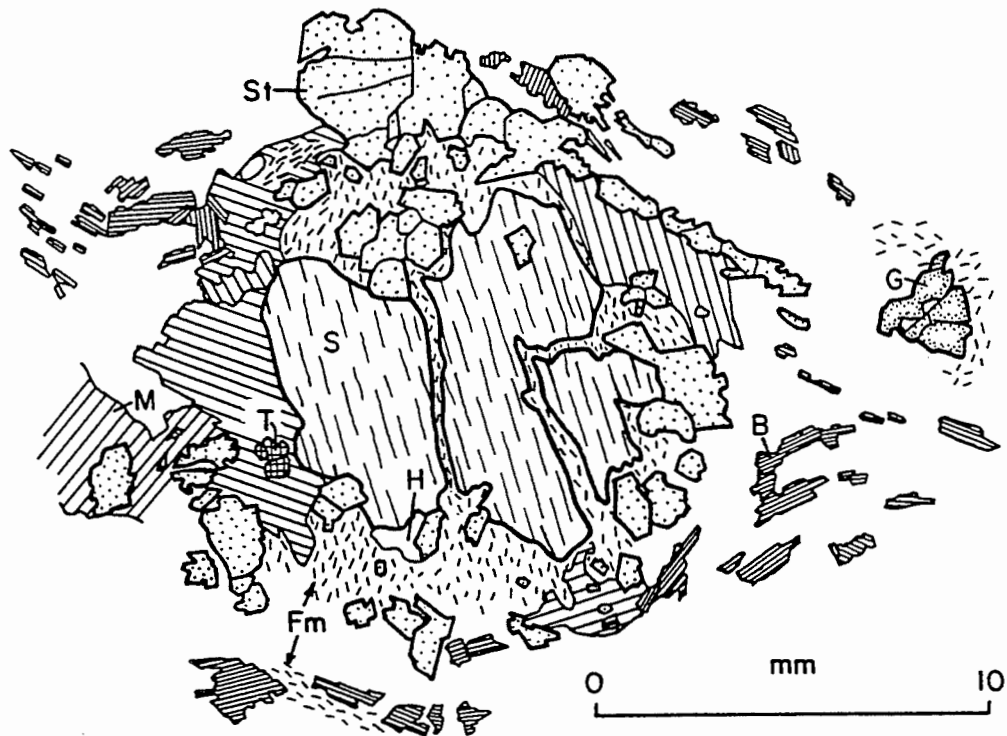


Figure 4.1 Generalized map of metamorphic zones in north-central Massachusetts and adjacent New Hampshire and Vermont. Royalston-Richmond area stippled. Modified from Elbert (1988).



B = biotite  
 Fm = fine muscovite  
 G = garnet  
 H = hole

M = coarse muscovite  
 S = pseudomorphs of sillimanite  
     after andalusite  
 St = staurolite  
 T = tourmaline

Figure 4.2 Sketch of a thin section of a pseudomorph of sillimanite after andalusite with a distinct rim of staurolite and muscovite. In gray-weathering gneiss of the upper member of the Rangeley Formation. Unpatterned areas represent a matrix of quartz, fine muscovite, and biotite. Although the boundary of the pseudomorph is shown as a heavy solid line, the actual boundary is indefinite due to alteration to fine muscovite. Sample RO-441BX.

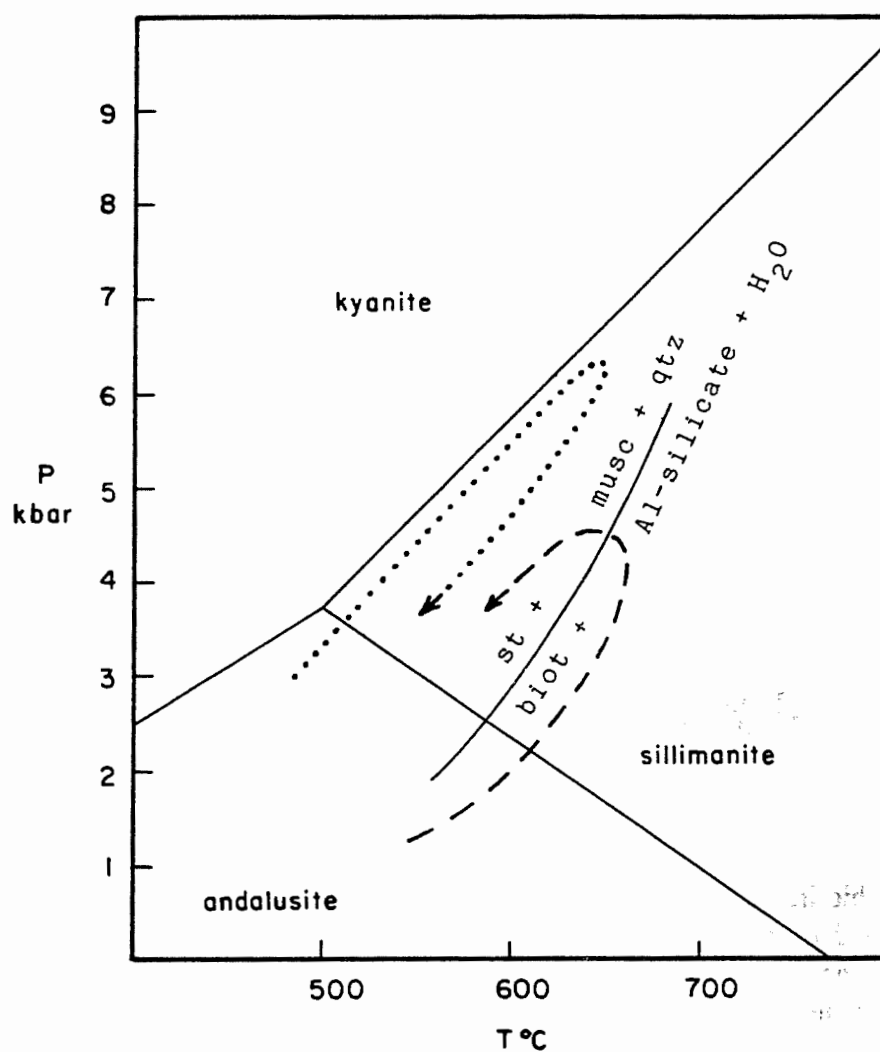


Figure 4.3 Contrasting P-T trajectories for rocks of the eastern part of the Royalston-Richmond area (dashed; this study) and the Monadnock area (dotted; P.J. Thompson, 1985). The aluminum silicate triple point is from Holdaway (1971) and the reaction  $st + musc + qtz \rightleftharpoons biot + Al\text{-}silicate + H_2O$  is from Hoschek (1969). This reaction assumes a pure H<sub>2</sub>O fluid.

The westernmost occurrences of the pseudomorphs define the approximate trace of a surface representing the aluminum silicate triple point, with early kyanite converted to sillimanite west of the line and andalusite converted to sillimanite to the east of the line (J.B. Thompson et al., 1968) (Figure 4.1). This indicates early low pressure (Buchan type) metamorphism in the eastern region and higher pressure (Barrovian type) metamorphism in the west. The pseudomorphs observed at hill 1217 may well be due to the high heat flow resulting from the intrusion of the Hardwick Tonalite. However, the occurrence of the pseudomorphs in other parts of the region where no nearby synmetamorphic plutons are known indicates that these are the result of regional metamorphism.

Two distinct varieties of retrograde muscovite are common in the pelitic rocks of the study area. These correspond to the varieties described in the Ashburnham-Ashby area by Peterson (1984). The first consists of coarse grains that have overgrown the folded biotite and sillimanite layers of the dominant foliation. Inclusions of sillimanite are commonly oriented parallel to the foliation outside the porphyroblast. This coarse muscovite commonly shows on outcrop surfaces as distinctive "spangles." The second variety consists of aggregates of randomly oriented, fine-grained muscovite which locally replace the coarser muscovite. This variety also occurs on the margins of the andalusite pseudomorphs (Figure 4.2). The most common occurrence is as elongate, commonly asymmetrical, lenses within a biotite matrix (sample RO-303, Table 2.4). These lenses are very similar in outline to lenses of fibrolite and fine-grained prismatic sillimanite which are observed in other samples (sample MO-41X, Table 2.6). Although no transition examples are present, it seems probable that the lenses of fine-grained muscovite formed from earlier fibrolite lenses.

Minor retrograde chlorite is common in many samples from the study area. In the pelitic rocks, chlorite occurs as an alteration product along the (001) cleavage of biotite. The chlorite is usually the Fe-Mg variety (based on anomalous blue interference colors and positive sign of elongation). Fe-rich chlorite also occurs as a fracture filling in a garnet porphyroblast in sample RO-94 (Table 2.2). This probably formed as a result of a garnet hydration reaction as described by Hollocher (1981).

Several outcrops showing the effects of strong retrograde metamorphism were encountered during field mapping. One example is a chlorite-sericite schist from a stream bed outcrop in Tully Brook, north of Falls Road, Royalston (sample RO-493, Table 2.2). It consists of Fe-rich chlorite, sericitized plagioclase, quartz, apatite, ilmenite, and allanite. The protolith seems to have been a coarse-grained, granular rock, perhaps a mafic igneous rock. No mappable zones of retrograde metamorphism were encountered.

#### Calc-silicate Rocks

Calc-silicate granulites occur as both pods and continuous beds, with similar mineral assemblages in each. These are shown in Table 4.1. Quartz and calcic plagioclase are present in all assemblages and diopside is present in most. Garnet and hornblende/actinolite are rarely in contact

and are usually not present in the same thin section. Clinozoisite commonly rims calcic plagioclase and appears to have formed from the breakdown of this mineral. This may be by the following reaction from Winkler (1979):

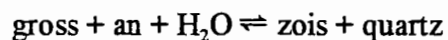


Table 4.1 Mineral assemblages in calc-silicate rocks. All contain quartz and calcic plagioclase.

Assemblage	diopside	hornblende/ actinolite	garnet	zoisite/ clinozoisite	sphene	biotite	graphite
1.	x		x				
2.		x	x				
3.	x	x	x				
4.	x	x	x		x		
5.		x		x	x		
6.	x	x		x	x		
7.	x		x	x	x		
8.		x	x			x	
9.		x		x		x	
10.	x		x	x		x	x

1.	MO-11
2.	K40
3.	RO-393A, MG-56
4.	MG-99Y
5.	MO-52
6.	MO-47, RO-293, MG-20
7.	MG-4G
8.	TR93
9.	RO-556
10.	MG-99X



Mineral compositions are plotted on an ACF diagram in Figure 4.4 and tie lines have been drawn connecting coexisting species. Plotting parameters are after Winkler (1979). The crossing tie lines violate the phase rule and may indicate the need to consider other components, such as  $\text{Na}_2\text{O}$ ,  $\text{Fe}_2\text{O}_3$ , or a variable Fe/Mg ratio. Alternatively, they may indicate that these are not all equilibrium assemblages. The partial rimming of plagioclase by clinozoisite and of diopside by garnet are evidence of the latter. These assemblages are typical of calc-silicate rocks in the amphibolite facies (Williams et al., 1982).

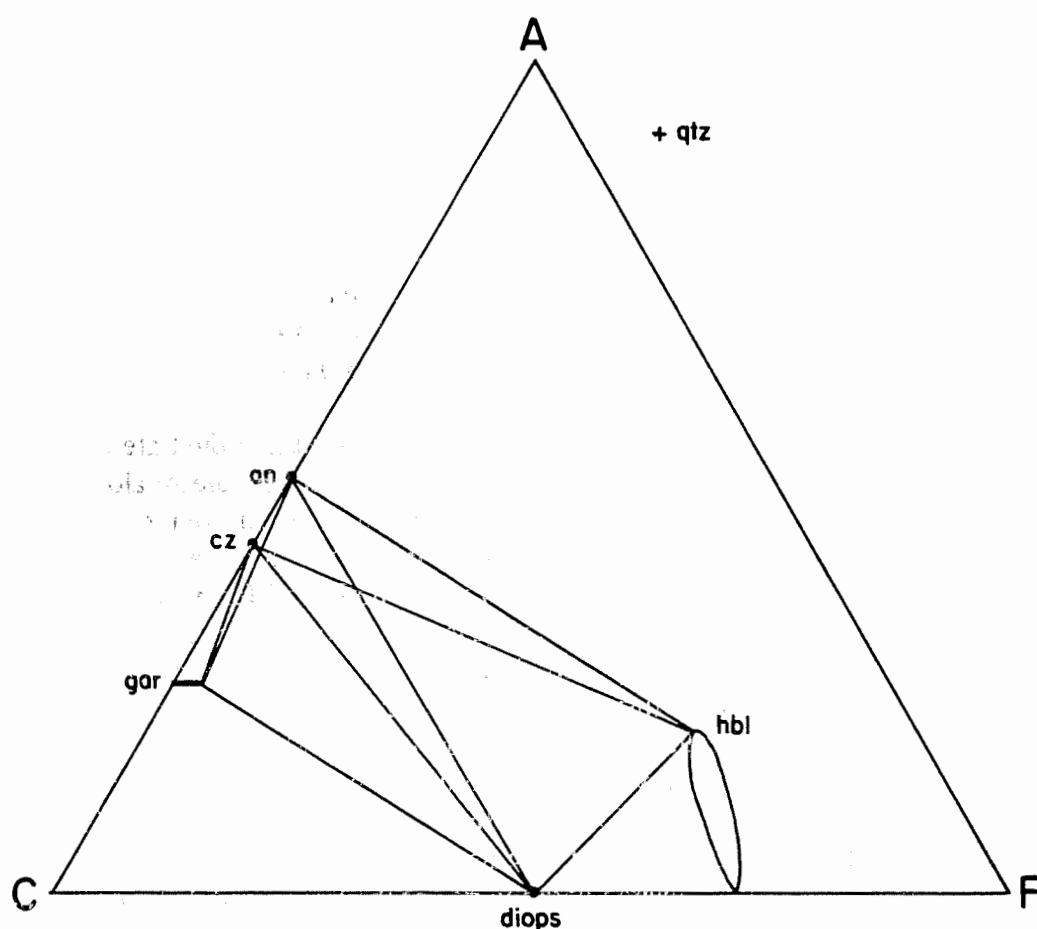


Figure 4. 4 ACF diagram showing mineral assemblages observed in calc-silicate rocks in the Royalston-Richmond area. A =  $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ , C = CaO, F = FeO + MgO + MnO. Mineral abbreviations: an = anorthite, cz = clinozoisite/zoisite, diops = diopside, gar = garnet, hbl = hornblende/actinolite, qtz = quartz.

## Chapter Five GEOLOGIC HISTORY

The plagioclase gneisses now exposed in the cores of the Tully dome and the Keene dome formed as the plutonic roots of a Late Ordovician volcanic arc located somewhere east of the North American plate. The Ammonoosuc Volcanics and the volcanic rocks with black shales of the Partridge Formation formed in another volcanic arc, the Bronson Hill arc, and although they are of approximately the same age as the plagioclase gneisses they appear to be geochemically distinct (Robinson et al., 1989). The rocks of the Bronson Hill arc were formed east of an east-dipping subduction zone (Robinson and Hall, 1980). They were probably joined to the plagioclase gneisses by some sort of detachment fault prior to the beginning of the Acadian deformation described below (Robinson et al., 1989). The black shales of the Partridge Formation were deposited in restricted basin environments near the Bronson Hill volcanic arc during Late Ordovician time as the Bronson Hill arc collided with the North American plate during the late stages of the Taconian orogeny (Robinson and Hall, 1980).

By early Silurian time, the restricted basin conditions had disappeared and volcanic activity had ceased. The eroded remains of the Bronson Hill arc were overspread by the coarse clastic shelf sediments of the Clough Quartzite and the thin, discontinuous, calcareous sediment of the Fitch Formation. The marine sedimentary trough known as the Merrimack trough developed to the east and was filled by the thick, pelitic sediments of the Rangeley Formation. These were followed by the relatively thin Perry Mountain, Franconia, and Warner Formations.

The Acadian orogeny began in Early Devonian time and continued into the Late Devonian. In Early Devonian time the ocean east of the Merrimack trough closed and the Avalon plate began to collide with the North American plate. Although the location of the suture between the two plates has been the source of much controversy (see Zartman, 1988), it is clear that the thick flysch deposits of the Littleton Formation, which overspread both the Merrimack trough and the shelf to the west, were derived from uplifted lands to the east. The rocks of both the western and eastern parts of the study area were subsequently folded into large-scale, west-verging fold nappes and then cut by west-directed thrust nappes. These thrust nappes brought the rocks of the Merrimack trough into contact with the rocks of the Bronson Hill belt. The rocks were then backfolded to the east and northward flowage of the Tully body of the Monson Gneiss occurred. Peak metamorphic conditions were reached at about this time. The Hardwick Tonalite was intruded sometime after the movement on the thrust nappes and before the peak of metamorphism. Extensive folding associated with the rise of the Keene and Tully domes occurred.

The Fitzwilliam Granite was intruded during the Mississippian and seems to have been weakly metamorphosed during the Permian Alleghenian orogeny.

Continental rifting began in the region during the Triassic and continued into the Jurassic. During this time, the rift basins of the Connecticut valley formed and were filled with terrigenous sediments and basalt flows. The Athol fault formed sometime during the Mesozoic. Dikes and sills of diabase were intruded during the Jurassic and Cretaceous (Robinson, et al., 1988).

Erosion and Pleistocene glaciation have modified the region since the Mesozoic.

## Chapter Six CONCLUSIONS

The stratigraphic sequence proposed for the Monadnock quadrangle by P.J. Thompson (1985) has been successfully extended into Massachusetts. Extensive areas previously mapped as Ordovician Partridge Formation and Lower Devonian Littleton Formation have been remapped as Silurian Rangeley Formation.

The Brennan Hill thrust, an early, west-directed thrust originally proposed by P.J. Thompson, has been extended southward through the study area and is interpreted to completely encircle the Tully dome. A thin belt of rocks on the northern flanks of the Tully dome, previously mapped as Partridge Formation, has been reinterpreted to be a structurally complex zone which contains several rock types and is bounded on both sides by splays of the Brennan Hill thrust. The zone is dominated by Perry Mountain and Warner Formations, with significant amounts of probable Rangeley Formation and possible minor Frankestown and Partridge Formation.

The Beech Hill anticline has been extended into Massachusetts, where it occupies a common axial surface with the south-plunging Tully dome. Its relationship to the Tully body remains unclear. Although it deforms the nappe stage Monadnock syncline and is deformed by folds associated with the rise of the gneiss domes, it is unclear whether it formed before or during transport of the Tully body northward relative to the cover.

Pseudomorphs of sillimanite after andalusite discovered in the eastern part of the study area shed some light on the Acadian metamorphic history. The pseudomorphs record early contact metamorphism associated with the intrusion of the Devonian Hardwick Tonalite, followed by higher pressure regional metamorphism. Staurolite and fine-grained muscovite partially overgrew the pseudomorphs during retrograde hydration after the peak of metamorphism and provide an additional constraint on the P-T path.

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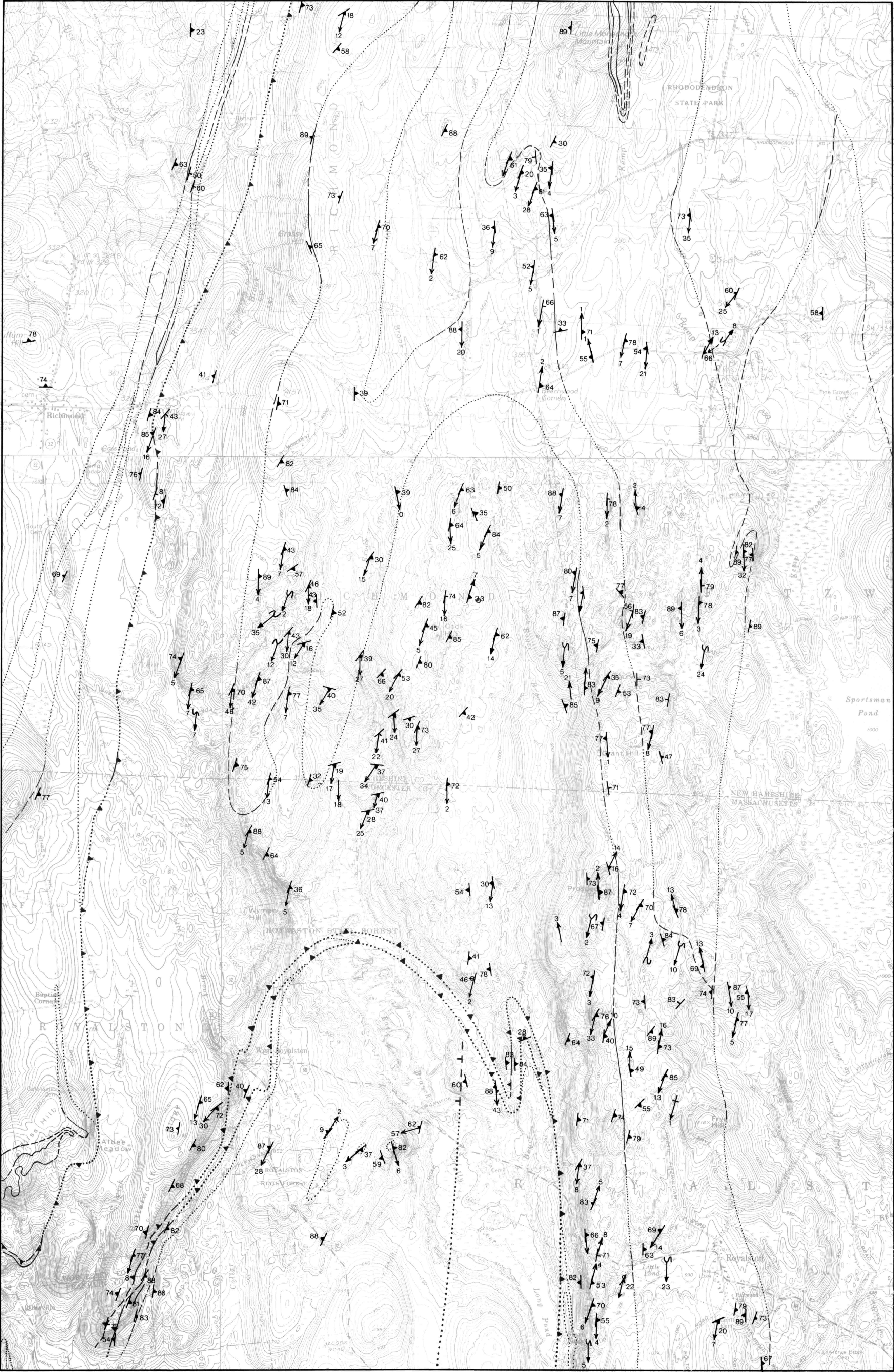


## This is a detailed topographic map of the Concord, New Hampshire area. The map features contour lines indicating elevation, with major peaks like Grassy Hill and Little Mountain labeled. It shows a network of roads, including Route 103 and Route 102, and several bodies of water such as Concord Lake and Little Pond. The map is divided into sections by latitude and longitude lines, with coordinates like 72° 15' and 43° 00' visible. Various geographical features and landmarks are labeled, including 'RHOBODENSON STATE PARK', 'ROYALSTON STATE FOREST', and 'CONCORD STATE FOREST'. The map also includes a grid system with letters and numbers for location finding.

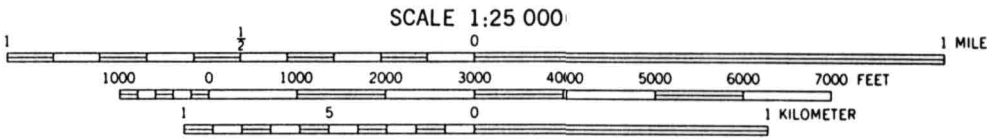
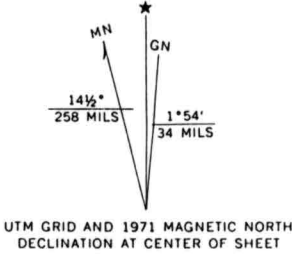
Contour Interval: North of 42° 45', 6 meters; South of 42° 45', 10 feet



PLATE 2. PLANAR AND LINEAR STRUCTURAL FEATURES.



See Plate 1 for explanation of symbols.



George Springston  
1990



PLATE 3. GEOLOGIC CROSS SECTIONS.

