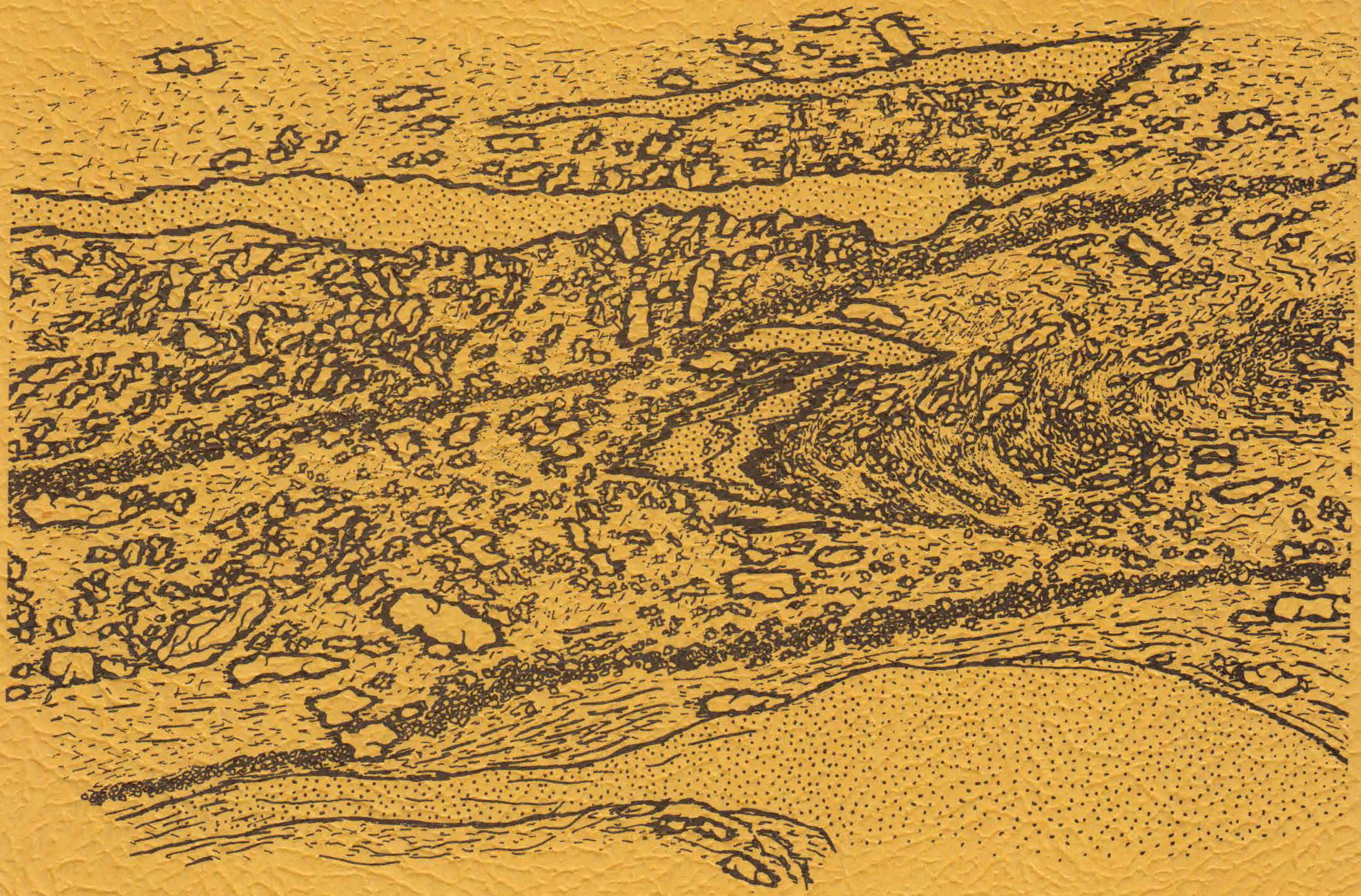
BEDROCK GEOLOGY OF THE BARRE AREA, CENTRAL MASSACHUSETTS

BY ROBERT D. TUCKER



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ABSTRACT

The Barre area lies within the Merrimack synclinorium, a major tectonic zone of the northern Appalachians, which extends from central and west-central Maine through New Hampshire into central Massachusetts and eastern Connecticut. The bedrock in the area consists of complexly deformed Ordovician, Silurian and Lower Devonian rocks, regionally metamorphosed to sillimanite-orthoclase grade in the western part of the area, and to sillimanite-orthoclase-muscovite grade in the eastern part. The stratified rocks in the western part of the area correlate in part with the sequence of the Bronson Hill anticlinorium of Billings (1937). The rocks in the eastern part of the area correlate with the stratigraphic sequence recognized in central and northwestern Maine (Osberg et al., 1968; Ludman and Griffin, 1974).

The stratigraphic sequence of the western part of the area consists of the Middle Ordovician Partridge Formation, the Middle-Upper Silurian Fitch Formation, and the Lower Devonian Littleton Formation. The Partridge Formation consists of pyrrhotite-bearing sillimanite-orthoclase-biotite-garnet schist and granular schist with small lenses of amphibolite. The Fitch Formation occurs as a thin, continuous layer of graphitic pyrrhotite-calc-silicate granulite. The Littleton Formation is sub-divided into the Gray Schist Member, the Feldspathic Gneiss Member and the Cummingtonite Gneiss Member. The Gray Schist Member, the dominant lithology, consists of gray, well bedded, quartz-rich biotite-garnet-sillimanite-orthoclase schist. The Feldspathic Gneiss, a biotite-microcline-quartz-plagioclase gneiss, and the Cummingtonite Gneiss Member, a cummingtonite-hornblende-plagioclase gneiss, are believed to be

metamorphosed volcanic rocks and generally are found at the top and near the base of the Littleton Formation.

The stratigraphic sequence of the eastern part of the area consists of the Partridge Formation overlain by the Middle and Upper Silurian Paxton Schist subdivided into three members, the White Sulfidic Schist, the Gray Graphitic Schist, and the Gray Granulite Member. This sequence consists of extremely magnesian sulfidic schist interbedded with impure quartzite (White Sulfidic Schist Member), minor amounts of gray-weathering, graphitic schist (Gray Graphitic Schist Member), and a major section of calc-silicate gneiss and biotite-plagioclase-granulite and interbedded sulfidic schist (Gray Granulite Member), believed to represent a zone of eastward thickening of euxinic shales, organic-rich silts and feldspathic clastic sediments in Silurian time. These members are correlated on lithic grounds with fossiliferous rocks in central and northwestern Maine.

Three major syntectonic Devonian intrusions are present in the Barre area, the Hardwick Quartz Diorite, correlated with the Spaulding Quartz Diorite of New Hampshire, the Coys Hill Granite, correlated with the Kinsman Quartz Monzonite of New Hampshire and the garnet-biotite granitic gneiss of Pleasant Brook. The Hardwick Quartz Diorite and the Coys Hill Granite appear as sill-like sheets confined largely to the Lower Devonian Littleton Formation. The gneiss of Pleasant Brook forms sill-like intrusions in the Partridge Formation. Two cross-cutting diabase dikes of probable Jurassic age were also mapped.

Six stages of deformation have been recognized in the area subsequent to emplacement of the sill-like intrusions. The first phase of folding resulted in large-scale west-directed isoclinal folds, analogous to the nappes of the Bronson Hill anticlinorium ten miles to the west. This was followed by an episode of east-directed recumbent folding which caused the axial surfaces of earlier folds to dip west in the western part of the area. This folding was accompanied by an episode of cataclasis and by the development of northwest- and west-trending lineations in some rocks. This was followed by development of asymmetric folds with east-side up movement sense in the western part of the area and west-side up movement sense in the eastern part of the area. These folds are the most abundant in the area and have been equated in timing and style to the "main stage" of gneiss dome formation in the Bronson Hill anticlinorium. West- and northwest-trending open folds in foliation followed this episode and were followed by broad open north-south trending folds which clearly deform all tectonic elements of earlier generations. Analysis of joints and faults from the Quabbin Aqueduct Tunnel, which traverses the area, reveals the same general pattern of brittle fractures as in the Mesozoic Montague Basin to the west.

Mineral assemblages in the western part of the Barre area are typical of the sillimanite-orthoclase zone of regional metamorphism, those in the eastern part are typical of the sillimanite-orthoclase-muscovite zone. Electron microprobe analyses of coexisting garnets and biotites across the area suggests prograde equilibration at about 650°C and pressures of at least 5.1 to 5.8 kbar suggesting tectonic burial to depths of approximately 20 kilometers.

INTRODUCTION

Location

The Barre area, located in the Central Massachusetts Upland Province (Alden, 1924), lies approximately 12 miles west-southwest of Wachusett Mountain, 33 miles south of Mt. Monadnock, New Hampshire and 22 miles east of Amherst (Figure 1). The area covered in this report consists of approximately 25 square miles located in the southern two-thirds of the Barre 7 1/2 minute quadrangle. It includes a large portion of the township of Barre as well as small portions of Petersham, Oakham and Hubbardston.

The study area is rather rugged, with north-south trending hills rising four to five hundred feet above their bases. The quadrangle is drained by the east and west branches of the Ware River which join at the Barre Falls Dam to flow southwest out of the area. The Prince, Burnshirt and Canesto Rivers, and Natty Brook, the major tributaries of the Ware River have their headwaters to the north and provide limited exposures of bedrock. The highest elevation in the area is 1271 feet on Hawes Hill in the northwestern portion of the map area and the lowest elevation is 589 feet on the Ware River in the southwest corner of the quadrangle. The main roads passing through the area include state highways 122, 62, 32 and 67. In addition, other town-supported, light-duty all-weather roads and unimproved roads provide easy access to outcrops throughout the area.

Vegetation and Quaternary Cover

The Barre area is rather heavily vegetated, much of it deciduous

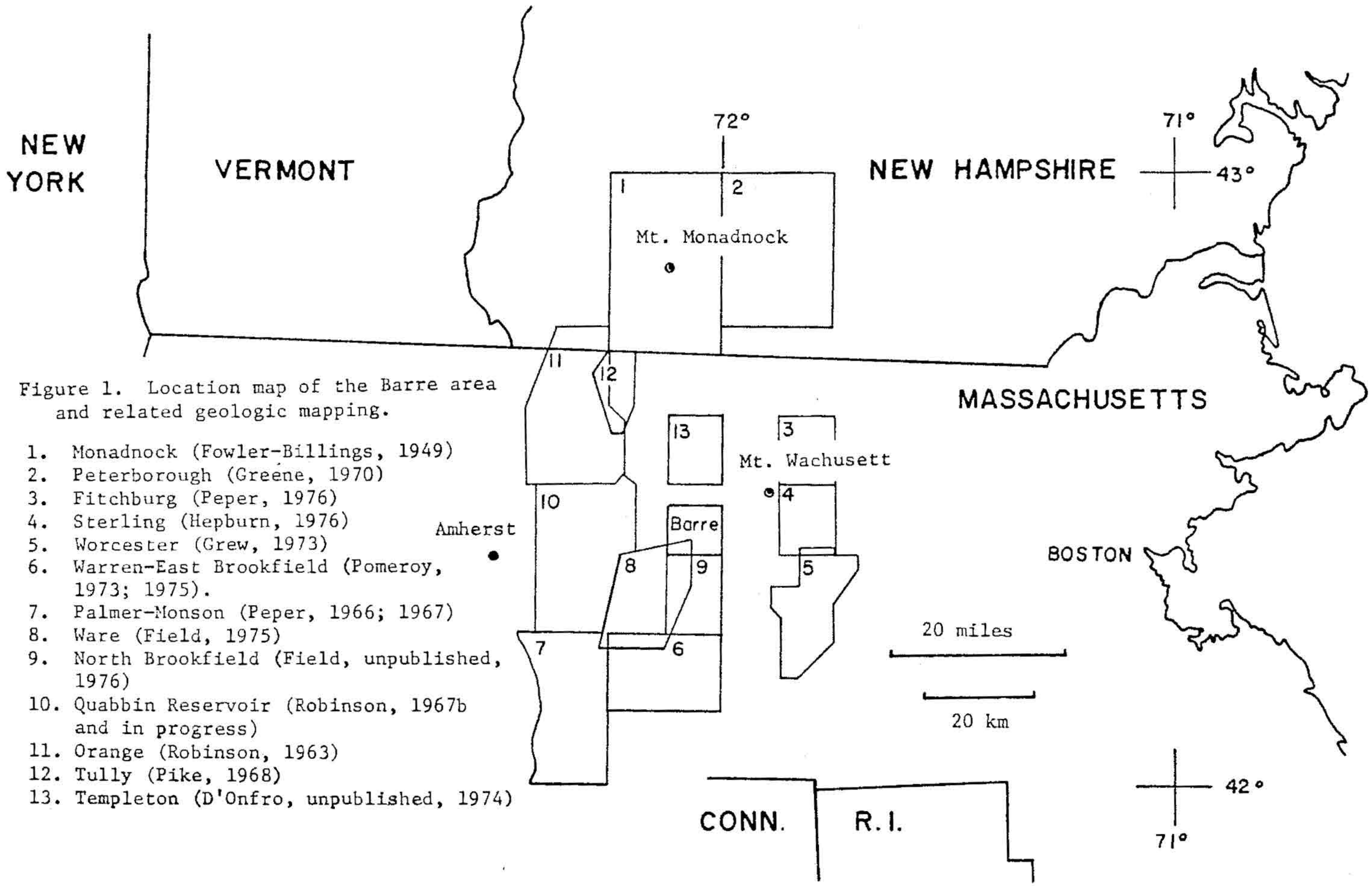

Figure 1. Location map of the Barre area and related geologic mapping.

1. Monadnock (Fowler-Billings, 1949)
2. Peterborough (Greene, 1970)
3. Fitchburg (Peper, 1976)
4. Sterling (Hepburn, 1976)
5. Worcester (Grew, 1973)
6. Warren-East Brookfield (Pomeroy, 1973; 1975).
7. Palmer-Monson (Peper, 1966; 1967)
8. Ware (Field, 1975)
9. North Brookfield (Field, unpublished, 1976)
10. Quabbin Reservoir (Robinson, 1967b and in progress)
11. Orange (Robinson, 1963)
12. Tully (Pike, 1968)
13. Templeton (D'Onfro, unpublished, 1974)

hardwood growth on old grazing lands. Some abandoned pastures are now overgrown to juniper and mountain laurel. Several locally supervised, state-owned reserves are in the study area, most of them marked by fairly recent plantings of pine.

Outcrops of bedrock are scarce in the southern portion of the area, especially in the vicinity of South Barre and Barre Plains. Fahlquist (1935) reports that the original line of the Quabbin Aqueduct had to be re-routed to the north at South Barre because test borings reported over 160 feet of subsurface glacial fill and alluvium here. The majority of bedrock exposures are found on the east slopes of hills in the western portion of the area and on the western slopes in the eastern part of the area. Bedrock on the north slopes of hills is typically covered by glacial till, and valley floors are covered by deposits of stratified glacial drift or alluvium. Sand and gravel pits are found throughout the area.

In addition to surface exposures, the Quabbin Aqueduct Tunnel passes through the southern part of the map area. The geology of the tunnel was studied by Fahlquist (1935) during construction and hand specimens were collected. These specimens are stored in the intake works on Route 122 near the Ware River in the town of Barre, and were thoroughly examined during this study.

Regional Setting

The Appalachian orogenic belt is a northeast-trending belt of deformed and metamorphosed sedimentary, volcanic and plutonic rocks of Precambrian through Permian age that lies southeast of the Canadian

Shield and interior platform of central North America. To the east this province is bordered by the Atlantic Ocean and by undeformed Mesozoic and Cenozoic rocks of the Atlantic coastal plain.

The northeastern Appalachians and more specifically the rocks that underly New England, can be divided into several broad tectonic zones. East of Grenvillian basement of the Green Mountain anticlinorium, lies a 5,400 m section of metamorphosed Cambrian through Lower Devonian clastic and volcanic eugeosynclinal rocks (Hatch et al., 1968). These rocks constitute the east limb of the Green Mountain anticlinorium and the Connecticut Valley-Gaspé synclinorium, which extends from Quebec south through Vermont and Massachusetts to Long Island Sound. In Vermont and western Massachusetts the synclinorium may be thought of in two subzones: 1) a western predominantly eastward dipping sequence of Cambrian through Lower Devonian clastics and volcanics representing a homoclinal sequence dipping off the Precambrian highlands to the west, 2) an eastern subzone characterized by late Acadian domes superimposed on early and probably recumbent isoclinal folds (Rosenfeld, 1968).

The Bronson Hill anticlinorium consists of approximately twenty én echelon mantled gneiss domes extending from the Maine-New Hampshire border south through west-central Massachusetts and central Connecticut. In the domes of west-central Massachusetts, pre-Middle Ordovician basement is unconformably overlain by metamorphosed sedimentary and volcanic rocks of Middle Ordovician, Silurian and Lower Devonian age (Robinson, 1963). All of these rocks have been severely deformed and folded into at least three structural levels of nappes, with east over west movement sense (Thompson et al., 1968), somewhat analogous to the

Pennine Nappes in the Swiss Alps. Large scale isoclinal, recumbent folds directed from west toward east, deform earlier axial surfaces and pre-date the upward gravitational rise of the gneiss domes at the height of the Acadian orogeny and metamorphism (Thompson et al., 1968).

East of the Bronson Hill anticlinorium, the Merrimack synclinorium extends from central and western Maine through New Hampshire into central Massachusetts and eastern Connecticut. Thought at first to be a simple synclinorium (Billings, 1956), it now is believed to consist of a complex series of overturned isoclinal folds (Dixon and Lundgren, 1968b; Field, 1975) some of which may represent root zones of the nappes described in the Bronson Hill anticlinorium to the west (Thompson et al., 1968). In eastern Connecticut (Dixon and Lundgren, 1968a) and central Massachusetts (Fahlquist, 1935) the Merrimack synclinorium is occupied by broad foliation arches and basins which are thought to deform earlier-formed Acadian structures. In northeastern Connecticut and south-central Massachusetts (Pease and Peper, 1968; Peper et al., 1975; Pomeroy, 1973; 1975) the synclinorium is thought to represent a westward dipping homoclinal sequence cut by major west-dipping thrust faults which separate lithologically distinct formations.

The eugeosynclinal clastic sediments and volcanic debris that compose the rocks which underly the Merrimack synclinorium in central Massachusetts can be shown, in part, to be identical to the New Hampshire stratigraphic sequence (Billings, 1956) exposed in the Bronson Hill anticlinorium to the west (Field, 1975). In the eastern part of the synclinorium in Massachusetts, there appears to be a thickening of the

Silurian stratigraphic section as noted elsewhere by workers in Maine (Osberg et al., 1968; Boone et al., 1970; Boone, 1973), and lithic correlations to the Maine stratigraphy have been made where apparent (Field, 1975).

East of the Merrimack synclinorium lies a belt of poorly understood, probable lower Paleozoic and older metamorphic rocks. The Milford anticlinorium in southeastern Massachusetts is separated from the rocks of the Merrimack synclinorium by several west-dipping, thrust faults of the Clinton-Newbury and Bloody Bluff systems. Gneisses in the core of the Milford anticlinorium may correlate with Precambrian gneisses in the core of the Pelham dome (Naylor et al., 1973). Elsewhere to the east, unmetamorphosed Avalonian age rocks are unconformably overlain by Cambrian clastics and minor amounts of dirty carbonates comprising the "shaley" eastern Cambrian facies (Theokritoff, 1968) characterized by Cambrian trilobites (Paradoxides) of the Acado-Baltic province.

Superimposed on these older formations are numerous isolated basins of post-Acadian rocks. These include: 1) metamorphosed Pennsylvanian lacustrine and non-marine sedimentary rocks in southern Rhode Island and eastern and east-central Massachusetts, 2) Mesozoic arkoses, sandstones and conglomerates and basaltic lavas of the Connecticut Valley and the offshore region.

Purpose of Study

The Barre area is located in the heart of the Merrimack synclinorium and was known to lie geologically in one of the least studied and perhaps most complicated regions of New England. The primary purpose of this study was to investigate the stratigraphic changes, to determine the deformational history of the rocks within the area, and to relate these findings to regional considerations across and within the synclinorium. There is a considerable difference between the stratigraphic interpretation of workers to the south (Pease and Peper, 1968; Peper et al., 1975; Pomeroy, 1973; 1975) and that of workers to the southwest (Field, 1975) so one task of this study was to determine which model is more appropriate. In the Ware area, Field studied the transition from the stratigraphic sequence of the Bronson Hill anticlinorium to that of the western Merrimack synclinorium. His stratigraphy extends into the Barre area and proved to be of tremendous help. In addition, the Barre area proved to have sufficient outcrop to define more adequately the eastern stratigraphy, a necessary initial step for others working in adjacent eastern quadrangles.

Previous Work

The bedrock of the Barre area was mapped in reconnaissance by Emerson (1917) as part of the geologic map of Massachusetts. Fahlquist (1935) studied the geology of the Quabbin Aqueduct Tunnel, which passes through the southern part of the area. Field (1975) has extensively studied the rocks in the Ware area including the extreme southwest corner of the Barre quadrangle. Peter D'Onfro (unpublished data, 1974) has done reconnaissance work in the Templeton quadrangle to the north and in the northwest part of the Barre quadrangle.

Field Work

Field work for this report was done in the summer of 1975 with follow-up visits in Fall 1975 and Spring 1976. Extension of this work was resumed in the summer of 1976 to include the northern part of the Barre quadrangle, the southern part of the Templeton quadrangle, and western portions of the Wachusett Mountain quadrangle. Outcrops were plotted directly on a 1:24,000 topographic base map with assistance of a Brunton compass and a pocket aneroid altimeter. Planar and linear features were measured with a Brunton compass at recorded stations. Some data was taken from the published work of Fahlquist (1935), Field (1975) and the unpublished work of D'Onfro (1974, unpublished field data on file at the University of Massachusetts).

Acknowledgements

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STRATIGRAPHY

The present study has shown that the stratigraphy of the Barre area can be sub-divided into two distinctive stratigraphic sequences that appear in two stratigraphic-tectonic zones. The stratigraphy of the western zone (Figure 2), that section on the map west of the axial surface of the Wickaboag Pond anticline (Field, 1975) (Plate 6), consists of Middle Ordovician rusty-weathering aluminous mica schist, feldspathic granular schist and minor amphibolite and of Lower Devonian gray-weathering, cyclically bedded, quartzose schist, with minor amounts of calc-silicate granulite and felsic volcanic gneiss. Small amounts of graphitic calc-silicate granulite of the Silurian Fitch Formation is exposed in one anticline beneath Lower Devonian schist. This sequence of rocks is thought to represent regionally metamorphosed sedimentary and volcano-clastic rocks, and is correlated with part of the stratigraphy of the Bronson Hill anticlinorium in western New Hampshire (Billings, 1937; 1956), and west-central Massachusetts (Robinson, 1963; 1967a; Thompson, et al., 1968) and with the stratigraphy in the western and central portions of the Ware area (Field, 1975).

Since the work of Billings (1937), his stratigraphic sequence has been traced along the axis of the Bronson Hill anticlinorium to Long Island Sound (Moore, 1949; Billings, 1956; Robinson, 1963; 1967a; Rosenfeld and Eaton, 1956; Lundgren, 1962; Thompson et al., 1968). It has since been argued that parts of a similar stratigraphic sequence can be seen on the west limb of the Connecticut Valley-Gaspé synclinorium (Doll et al., 1961) and to the east in the Merrimack synclinorium (Fowler-Billings, 1949; Dixon, 1968; Dixon and Lundgren, 1968a, 1968b).

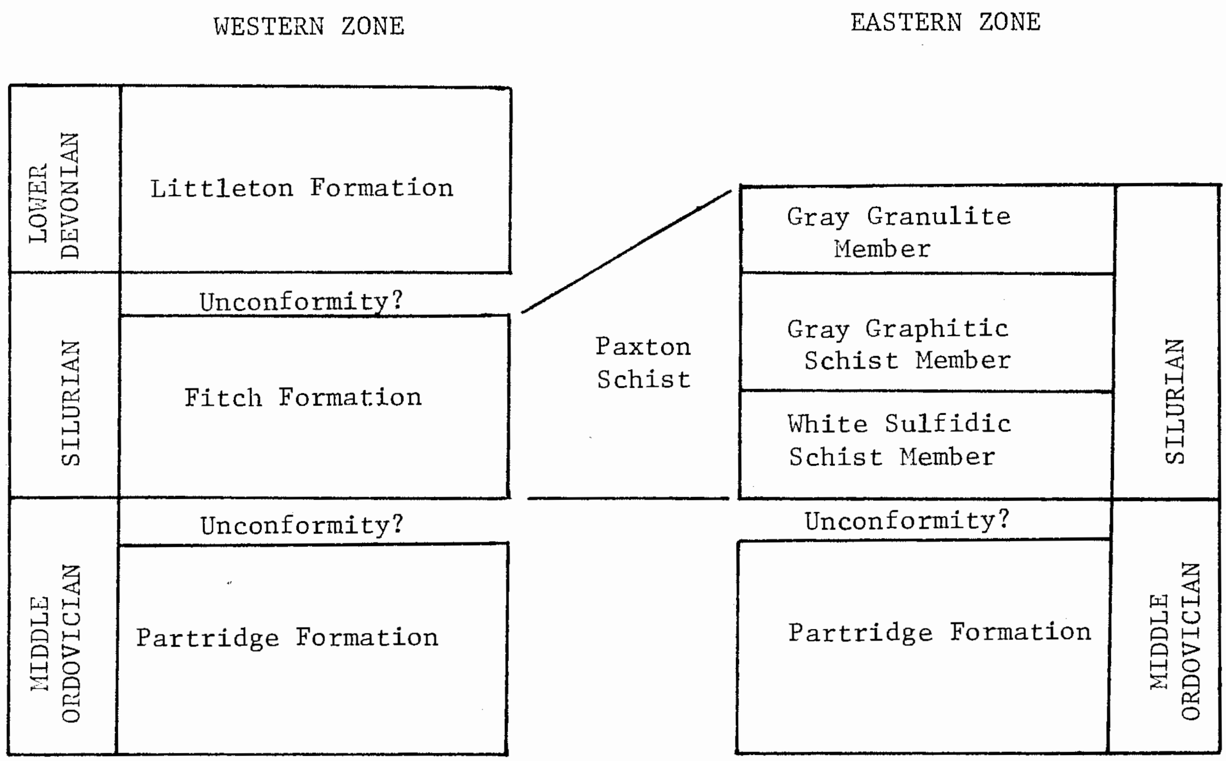


Figure 2. Simplified columnar section of stratigraphic units in the Barre area.

Field (1975), studying the transition in the stratigraphy from the Bronson Hill anticlinorium of central Massachusetts into the Merrimack synclinorium, has found that the stratigraphy does not change greatly across the zone. Moreover, he has concluded that the dominant stratigraphic units of the Ware area are the Partridge and Littleton Formations, which are repeated several times by isoclinal folding (Figure 3). This tectonic style continues north to the Barre area where many of the same anticlinal and synclinal belts have been mapped.

The eastern zone of the Barre area, defined as that stratigraphy east of the axial surface of the Wickaboag Pond anticline, is exposed in an east facing recumbent syncline whose lower limb has been refolded across a north-plunging open anticline (Plate 2). The eastern stratigraphy is composed of Middle Ordovician rusty-weathering schist overlain by extremely magnesian pyrrhotite schist interbedded with impure quartzite, minor amounts of gray-weathering graphitic schist, and a major section of calc-silicate gneiss and granulite. This upper sequence is believed to represent a thickened section of pelite and carbonate-rich clastic sediments deposited in a subsiding basin during middle to late Silurian time (Wenlock-Ludlow). The basis for this hypothesis rests on lithic comparisons with the stratigraphy of western and central Maine (Moench, 1971; Boone, 1973; Osberg and others, 1968; Ludman, 1969; Ludman et al., 1972; Ludman and Griffin, 1974; Pankiwskyj et al., 1976), and the physical tracing of some lithically similar rocks from Maine through southeastern New Hampshire to Massachusetts (Hussey, 1968).

As presently understood, the boundary between these two zones is the axial surface of a major recumbent anticline in Middle Ordovician

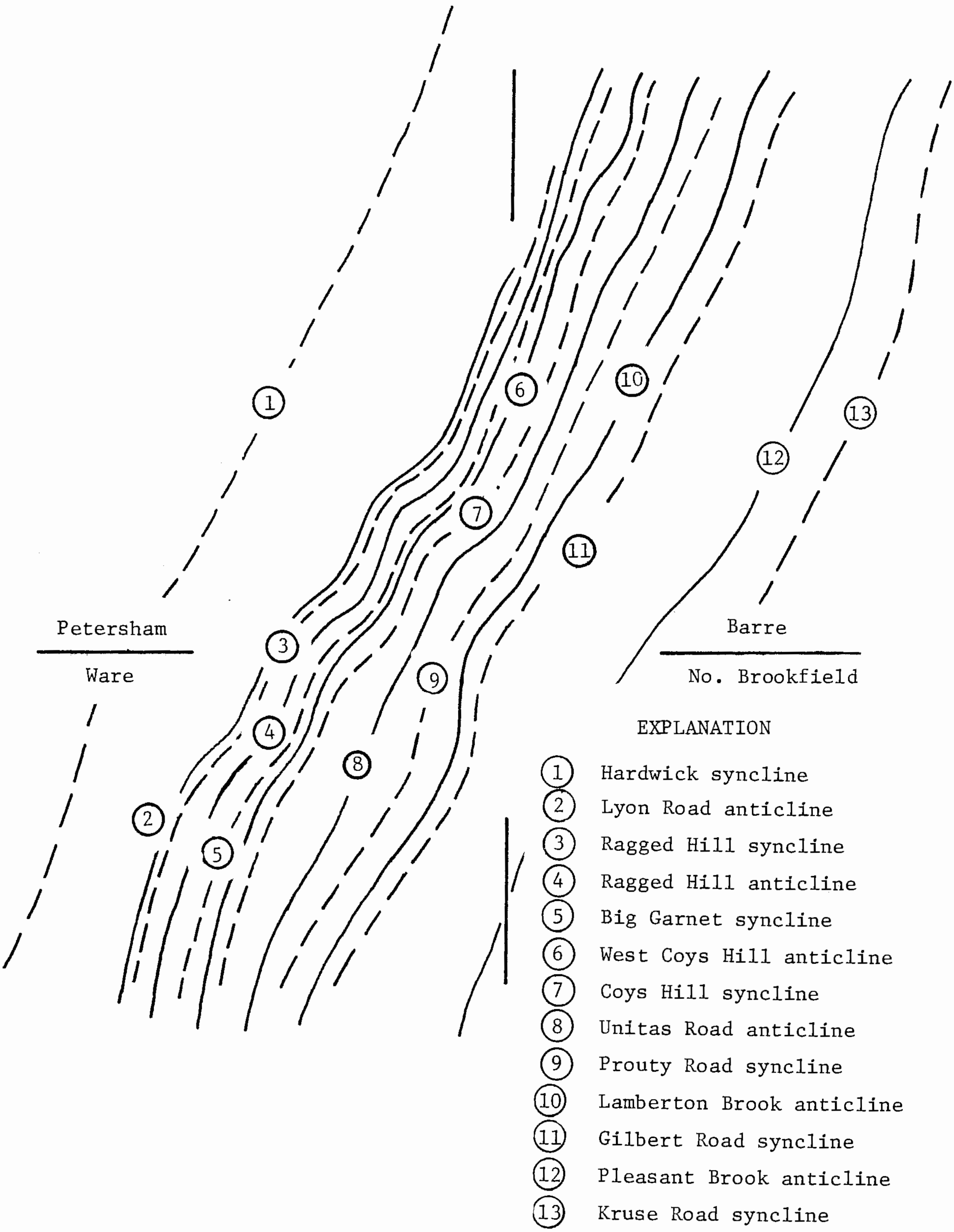


Figure 3. Map of Phase 1 axial surfaces near the junction of the Ware (Field, 1975), Petersham, North Brookfield, and Barre quadrangles.

rocks with the stratigraphy of the eastern zone representing the eastward thickened Silurian section. The facies change from thin to thick Silurian is presumably in the hinge region of the recumbent anticline that has been eroded away at this latitude. This boundary has been extended to the southwest, through the North Brookfield and Ware quadrangles by Field (Field, 1975; personal comm. 1976) and to the north at least to the middle of the Templeton quadrangle (personal observation). To the southwest this contact falls within the Hamilton Reservoir Formation of Pomeroy (Pomeroy, 1975) and does not appear on his map as a boundary of regional significance. This boundary is well known as far north as the middle of the Templeton quadrangle on the basis of reconnaissance in 1976, and it is hoped it can be extended to Winchendon and beyond in 1977.

PARTRIDGE FORMATION

The Partridge Formation in the western portion of the Barre area is exposed in the cores of five isoclinal anticlines that trend northeast across the area. Three belts have been mapped from surface exposures and one belt (Ragged Hill anticline) is located on the basis of field relations to the north and southwest and from sub-surface data. To the southeast, the Partridge Formation is exposed in the Oakham area where it forms the core of a late generation anticline. Because the rocks exposed in each of the anticlines of the Partridge Formation vary somewhat, the details within each anticlinal area are discussed separately.

Lithology

The Partridge Formation consists essentially of rusty-weathering, sillimanite mica schist with minor amounts of cummingtonite-hornblende amphibolite and calc-silicate granulite. The mica schist, consisting of quartz, biotite, garnet, sillimanite, pyrrhotite, plagioclase, orthoclase, and less commonly muscovite or cordierite, is fine- to medium-grained, slabby and very well foliated. Cummingtonite-hornblende amphibolite is found generally in the lower part of the section, and calc-silicate granulite appears dispersed throughout. In spite of the variation in the degree of weathering, the Partridge Formation is always more sulfidic than members of the Littleton Formation and generally is more feldspathic. The White Schist Member of the Paxton Schist can be confused with extremely rusty-weathering varieties of the Partridge Formation, however, it generally doesn't have dark-colored biotite, has no garnet and has abundant quartzite and feldspathic quartzite beds. Estimated modes of specimens of the Partridge Formation are given in Tables 1 and 2.

Ragged Hill anticline. The Partridge Formation is not exposed in the core of this anticline in the map area, but is inferred to lie between the Coys Hill Granite and the Hardwick Quartz Diorite, from known exposures to the north and south and from sub-surface data. Field (1975) in the Ware area, has mapped an anticline of rusty-weathering schist which extends northeast from the village of Ware into the Petersham quadrangle (Field, 1975). North from here, this belt has been identified in sub-surface (Quabbin Aqueduct specimen #950+00) and picked up again in a single surface exposure northwest of Mt. Pleasant, 0.05 miles east and 0.17 miles north of the intersection of Petersham Road and Gilbert Road in the northwest portion of the Barre quadrangle (D'Onfro, unpublished field notes, University of Massachusetts; Tucker, personal observation). The Partridge Formation in this belt is composed primarily of rusty-weathering feldspathic and micaceous schist, generally with more sillimanite than in other belts. No garnet was recorded in the tunnel specimen (950+00 Table 1), but there is 7% of secondary muscovite and some Fe-rich chlorite.

Unitas Road anticline. This belt of rusty-weathering schist lies immediately east of the Coys Hill Granite in the southern portion of the map area but is separated from the Coys Hill body by the Littleton Formation west of Quabbin Regional High School (Figure 3) and extends northeast to the Barre Foundry where it pinches out apparently in a Phase 1 fold hinge (see Structural Geology). The Partridge Formation in this belt is dominated by feldspathic mica schist, typically well foliated and exhibiting faint bedding traces of alternating feldspathic and mica-rich layers. Typical modes of pelitic schist in this anticline yield quartz, plagioclase and orthoclase as the principal constituents with lesser sillimanite and biotite (Table 1, TB-307). Thinly bedded calc-silicate layers and boudins are also present and identified in the field as consisting of equidimensional grains of plagioclase and quartz with minor amounts of biotite, garnet and sphene. Field (1975) has reported two characteristics of the rock types in this belt: 1) they display a heterogeneity of rock types, including minor amounts of gray schist, calc-silicate granulite, mafic gneiss and amphibole gneiss. 2) to the south the rock becomes considerably more quartzose and less rusty-weathering than usual (Field, 1975). Neither of these characteristics is typical of this belt in the Barre area, although the presence of limited amounts of calc-silicate rock is confirmed.

Lamberton Brook anticline. This anticline is cored by the next belt of rusty-weathering schist east of the Unitas Road anticline. It is superbly exposed in Galloway Brook, in the section east of the Audubon Reserve known as Cooks Canyon approximately 3/4 mile south of Barre. Here one can walk across the core of a recumbent anticline with nearly 100 percent of the section exposed. The rocks in the Lamberton Brook anticline consist of rusty-weathering, sillimanite-biotite-garnet schist, blue- to gray-colored, medium-grained, graphite and pyrrhotite-rich, plagioclase-quartz-biotite granulite and medium- to fine-grained slightly rusty-weathering, sillimanite-garnet-biotite granular schist. The granular schist in this zone is generally quite rich in sillimanite, up to 8 percent, as well as biotite and quartz. Substantial amounts of secondary muscovite (3 percent) and Fe-rich chlorite (5 percent) have been found in specimen TB-105 (Table 1).

Pleasant Brook anticline. The Wickaboag Pond anticline of Field (1975) has been sub-divided into a western anticline (the Pleasant Brook anticline) and an eastern anticline (the Wickaboag Pond anticline) based on the occurrence of a belt of gray-weathering, quartz-rich biotite-garnet schist mapped between them (Figure 3). These gray schists form an elongate north-northeast trending syncline, the Kruse Road syncline, which has been traced from the north-central part of the Barre quadrangle

Table 1. Estimated modes of specimens of schist, granular schist and one amphibolite from the Partridge Formation.

-------------schist---------------granular schist---a--------------------------------schist-------------------------

	Ragged Hill	Unitas Road	Lamberton Brook			Pleasant Brook						Wickaboag Pond			
	950+00	TB-307	TB-542	TB-105	TB-669	TB-91	TB-591	TB-590	TB-526	860+50	858+50	TB-434	TB-63	793+50	782+50
Quartz	27	37	36	30	1	38	32	22	36	34	20	32	53	28	59
Plagioclase	32	34	40	33	35	49	41	52	41	24	7	38	15	15	9
Orthoclase	8	8	tr	3		x	x	4	4	2	33	5	4	18	14
Biotite	13	5	18	12	5	9	18	18	7	25	22	18	7	22	7
Garnet			1	7		1	6	3	2	2	6	3	5		
Sillimanite	12	5	4	8			3	1	5	10	12	2	1	6	10
Cordierite									2			1			
Pyrrhotite	x	1	1	1		1	tr	tr	1	1	x	tr	1	x	x
Graphite	1	x	x	tr		1	tr		tr		x	x			
Ilmenite	x	tr	x	1	1	x	tr	x	1	1	x	tr	x	x	x
Rutile	tr		x			x									
Allanite		tr	x	x		x		x	x	tr		x			x
Tourmaline						x	x	x		x				x	
Zircon	tr	tr	x	x			x	x	tr	tr	tr	x	x	tr	tr
Apatite		x	x	x	tr	tr		tr	tr	tr	tr	x	x	x	tr
Muscovite	7*	5*		3*				x*	x*	1*	tr*	1*	10*		
Chlorite	$\bar{x}$	$\bar{4}$		$\bar{2}$					$\bar{x}$	$\overline{tr}$	$\overset{+}{tr}$		$\bar{4}$	$\bar{1}$	$\bar{1}$
Sericite		3				3			3					10	
Hornblende					31										
Cummingtonite					27										

$^{-}$ Denotes Fe-rich chlorite

$^{+}$ Denotes Mg-rich chlorite

* Denotes secondary muscovite

a Denotes amphibolite body

List of specimens in Table 1.

950+00 Rusty- to red-weathering, muscovite-biotite-garnet-sillimanite schist, very rich in sillimanite. 95,000 feet from east end of Quabbin Aqueduct at Wachusett Reservoir.

TB-307 Well foliated, slightly rusty weathering, muscovite-biotite feldspathic schist. Taken from outcrop behind Barre Foundry on School St.

TB-542 Fine- to medium-grained, garnet-biotite-plagioclase granular schist with calc-silicate. 1000 feet north of the junction of James St. and Rt. 122 in the town of Barre.

TB-105 Dark-gray, fine- to medium-grained, graphitic pyrrhotite granulite. At 750 foot mark in Cooks Canyon Gorge. Stream cut of Partridge schist in west-central portion of the map area.

TB-669 Massive, well foliated, biotite-cummingtonite-hornblende-plagioclase amphibolite. 0.28 miles north and 0.1 miles west of White Valley.

TB-91 Fine- to medium-grained, well foliated, slightly rusty-weathering, feldspathic garnet-biotite schist. Strong biotite lineation is evident. 0.48 miles north and 0.22 miles west of Nichols Rd. and Rt. 122 intersection on top of Town Farm Hill Road at 882' elevation.

TB-591 Moderately well foliated, slightly rusty-weathering, garnet biotite-feldspathic schist. 500 feet south of TB-590.

TB-590 Rusty-weathering, fine- to medium-grained, biotite-quartz-garnet feldspathic schist. On crest of Town Farm Hill, in southwest portion of the map area.

TB-526 Medium- to coarse-grained, well foliated garnet-cordierite-biotite feldspathic schist. 1500 feet due west of the intersection of South Barre Road and Summer St. in the west-central portion of the quadrangle.

860+50 Somewhat rusty-weathering, quartz-biotite-sillimanite-garnet schist. 86,500 feet from east end of Quabbin Aqueduct.

858+50 Well foliated, rusty weathering, feldspathic biotite-garnet-sillimanite schist. 85,850 feet from east end of Quabbin Aqueduct.

TB-434 Rusty weathering, fine- to medium-grained, biotite-sillimanite-garnet schist with crinkled foliation. 1.28 miles north and 0.21 miles west of intersection of Gilbert Rd. and Rt. 62 in central portion of the map area.

Table 2. Estimated modes of specimens from the Partridge Formation in the Oakham area.

	----------schist----------			granulite		calc-silicate
	Oakham area					
	722+00	713+75	614+75	608+75		692+50
Quartz	22	14	18	23	Quartz	2
Plagioclase	20	14	30	53	Plagioclase	6
Orthoclase	25[#]	14[#]	22	9	Microcline	28
Biotite	15	10	11	12	Diopside	22
Garnet	2		1	2	Actinolite	14
Sillimanite	16	5	6		Clinozoisite	12
Cordierite		22			Scapolite	8
Pyrrhotite	1	19[*]	x		Sphene	3
Graphite	x	1	tr		Graphite	x
Ilmenite	x		tr		Ilmenite	tr
Rutile		1				
Allanite				tr	Allanite	tr[@]
Tourmaline		x			Calcite	3
Zircon	tr	tr	x	tr	Zircon	1
Apatite	tr	tr	x	tr	Apatite	tr
Muscovite	x[¢]	tr[¢]	10			
Chlorite			$\overline{2}$	$\overline{1}$		

[#] Denotes microcline as the alkali feldspar present in thin section.

[*] Denotes both magnetic pyrrhotite and pyrite.

[@] Denotes allanite rimmed by clinozoisite.

[¢] Denotes secondary muscovite.

[¯] Denotes Fe-rich secondary chlorite.

TB-63 Well foliated, slightly rusty-weathering, biotite-sillimanite schist. 0.4 miles east and 0.8 miles north of intersection of Gilbert Road and Rt. 62 in north-central portion of the map area.

793+50 Evenly foliated, biotite-orthoclase schist, slightly rusty-weathering. 79,350 feet from east end of Quabbin Aqueduct.

782+50 Rather dense, fine- to medium-grained sillimanite-biotite schist. 78,250 feet from Wachusett Reservoir.

List of specimens in Table 2.

722+00 Magnetic, well foliated, biotite-sillimanite schist. Located 72,200 feet from east end of Quabbin Aqueduct.

713+75 Pyrrhotite-rich, gray to slightly rusty-weathering, biotite-cordierite schist with quartz-feldspar inclusions. 71,375 feet from east end of Quabbin Aqueduct.

614+75 Well foliated, garnet-biotite-sillimanite schist, gray to slightly rusty-weathering. Streaked with quartz-feldspar segregates. 61.475 feet from Wachusett Reservoir.

608+75 Massive, medium-grained, gray-weathering, garnet-biotite granulite. 60,875 feet from east end of Quabbin Aqueduct.

692+50 Light gray, medium-grained, equigranular microcline-diopside-actinolite calc-silicate. 69,250 feet from east end of Quabbin Aqueduct.

south to the southern limit of the map area. Pomeroy (1973) in the Warren quadrangle (Figure 1), has mapped similar looking rocks (husn) which strike into the Wickaboag Pond anticline of Field (1975).

The Pleasant Brook anticline, named for the excellent exposures in Pleasant Brook east and north of Glen Valley Cemetery, contains the widest belt of the Partridge Formation in the area and the rocks are generally extremely feldspathic and pyrrhotite-rich. The dominant lithology in this anticline is rusty-weathering, feldspathic, garnet-biotite-silimanite schist (Table 1, TB-91 through 858+50). Granular minerals such as quartz, plagioclase and orthoclase usually total 60 to 80 modal percent with garnet, biotite and sillimanite in varying proportions making up the remainder of the rock. Although no polished thin sections were analyzed, the iron-sulfide in these rocks appears to be magnetic pyrrhotite. Rocks exposed along strike in the northern portion of the Barre quadrangle are thinly bedded and consist of 2-4 cm laminae of feldspar and quartz intercalated with layers rich in biotite, sillimanite and garnet.

Other rock types in this zone include slabby granulite composed largely of quartz, plagioclase (oligoclase), biotite and minor pyrrhotite. Individual beds vary in thickness but commonly are on the order of 7-12 cm thick. The color of the granulites where fresh is purplish to medium-gray, and the pyrrhotite appears as small disseminated crystals throughout the specimen. Calc-silicate rocks appear as fine- to medium-grained boudins in schist or as attenuated, one- to three-inch beds and are characterized by the assemblage diopside-orthoclase-plagioclase-quartz.

Wickaboag Pond anticline. As in the Pleasant Brook anticline, the Partridge Formation in the Wickaboag Pond anticline are generally more feldspathic and quartz-rich than rocks in the Partridge Formation to the west. The best exposures in this belt are in Burrow Brook in the south-western portion of the map area, in the meadows southeast of the junction of Old Worcester Road and Chapman Road, and on the hills due east of the Burnshirt River north of Route 62.

The rocks exposed in this anticline have a rather abnormal abundance of pegmatite, and many of the exposures of pelitic schist are under pegmatite ledges. One of the few occurrences of garnet-cordierite rock has been found in this belt (TB-434) although it is not considered to be an equilibrium assemblage. Cordierite-garnet occurrences are reported in several localities to the south in this anticline (Field, 1975) and the lack of identification of more garnet-cordierite assemblages in these rocks in the Barre area may be due to inadequate sampling.

Other rock types exposed in the Wickaboag Pond anticline include rusty-weathering, slabby, granular schist, medium- to fine-grained equigranular calc-silicate granulite, and coarse-grained, massive amphibolite (Table 2, TB-669). The best exposure of the amphibolite is due west of Chapman Road approximately 2000 feet north of White Valley, where it occurs as boudins and as attenuated, dark colored tiger-striped massive beds in pelitic schist and consists mainly of plagioclase (35%), hornblende (31%), cummingtonite (27%), biotite (5%), and quartz.

Oakham area. The eastern-most exposure of the Partridge Formation in the Barre area occurs in the south-southeastern section of the area in the township of Oakham (Plate 1). Here rusty-weathering, pelitic schist, structurally under the Paxton Schist, is exposed in the core of a late north-plunging anticline between Quabbin Aqueduct stations 599+00 and 722+75 (Plate 2).

The rock types in this zone consist largely of dark-brown to rusty-weathering, pyrrhotite-sillimanite-biotite-garnet schist (Table 2, 722+00 through 688+75), but other rock types, including pyrite-pyrrhotite sillimanite-cordierite-biotite schist, and scapolite-diopside-actinolite calc-silicate granulite (Table 2, 692+50) are also present.

Fahlquist (1935, p. 20 Appendix) reports a wider variety of lithologies in this belt of schist including "thin layers of feldspathic schist...gneissoid granite occurring as large lens-shaped bodies...and the rather unique occurrence of limestone beds from 6 inches to fifteen feet in thickness". Fahlquist also admits that this belt of rock "is very similar to that of the Brimfield Schist but is separated from the Brimfield Formation by the Paxton Schist".

Derivation

The schists that make up the Partridge Formation are interpreted to be metamorphosed marine shales and silts deposited in a euxinic environment. The variation in the feldspar/quartz ratio across and within each anticline is probably due to depositional differences, although no systematic trends in the amount of granular minerals within any section can be proved. Associated calc-silicate granulite may represent metamorphosed dolomitic sands or silts. Plagioclase-hornblende-cummingtonite amphibolite are probably metamorphosed mafic volcanic rocks, possibly basaltic flows or ashes. Field (1975) has noted a general decrease in the iron-sulfide content toward the top of the section of the Partridge Formation in the Ware area, but no evidence was found for such a conclusion in the Barre area.

Thickness

Since the base of the Partridge Formation is not exposed, only minimum thicknesses can be estimated. However, the greatest width of any of the belts in map pattern is found across the Pleasant Brook anticline which is approximately 4500 feet across. Assuming simple doubling up due to an isoclinal fold and an average westerly dip of 20° (Figure 9) a thickness of at least 770 feet is obtained.

FITCH FORMATION

The Fitch Formation was found in only one locality in the Barre area, and that is as a discontinuous lens due east of the Big Garnet syncline in the Prince River at the 820 foot contour. It has, however, been extended the length of the quadrangle to connect with outcrops of known Fitch lithology in Phillipston (Robinson, personal comm., Tucker, personal observation) and with the West Coys Hill anticline of Field (1975).

Lithology

In the one exposure of the Fitch Formation, the rock is a sulfidic graphite calc-silicate granulite. It is equigranular and fine- to medium-grained, composed largely of 0.2 - 0.4 mm crystals of quartz, labradorite and biotite with lesser diopside, sphene, and clinozoisite and minor actinolite, and scapolite (Table 3, TB-386). The pleochroic color scheme of the sphene in the Fitch Formation is strong with x = colorless to yellow, y = pale brown, z = light pink to light red. It is interesting to note that the sphene in the Fitch Formation in the Ware area as well as in the Rusty Quartzite Member of the Littleton Formation in the Monadnock area, New Hampshire (Figure 1), show an even darker red pleochroic color.

Although of obviously limited extent, the Fitch Formation is found between two belts of the Littleton Formation, and thus in the correct stratigraphic position to occupy the core of an anticline.

Contacts

The basal contact of the Fitch Formation with the Partridge Formation is not exposed, but the upper contact with the overlying Littleton Formation is exposed quite well at the one outcrop. It generally is sharp with no sign of gradation and is inferred to be an unconformity by this author, based on regional considerations (Robinson, 1963; Field, 1975). The contact of the Fitch Formation with the Littleton Formation is equally well exposed in Phillipston in the Templeton quadrangle on Williamsville Road, 1100 feet south of Queen Lake Road.

Derivation

The Fitch Formation is believed to be derived from calcareous silts and impure calcareous shales which were deposited in a strongly reducing environment. The graphite is presumably of organic origin. In northern New Hampshire, at the type locality, the association of marbles and quartzites with the Fitch Formation is suggestive of deposition in fairly shallow water.

Thickness

The minimum thickness calculated for the Fitch Formation in the Barre area is nine feet, based on the limited exposure in the Prince River. However, for purposes of visibility, the Fitch Formation is shown as approximately 150 feet thick on cross-section line B-B' on Plate 2.

PAXTON SCHIST

The youngest (?) sedimentary unit in the eastern zone is mapped as the Paxton Schist after Emerson (1898; 1917), who named it after the town of Paxton 12 miles southeast of Barre. Although unidentified by him, Emerson's type locality may be the well exposed ledges of biotite-plagioclase-quartz granulite in Turkey Hill Brook southwest of Eames Pond, in the township of Paxton. This rock type together with two other members here assigned to the Paxton Schist, a gray-weathering, graphitic schist and a white, pyrrhotite-rich schist, constitute the major Silurian (?) units of the area, and represent a thickened eugeosynclinal section in the Merrimack synclinorium.

The Paxton Schist in the Barre area, is exposed only in the eastern and southeastern portions of the quadrangle. The gray granulite unit is the easiest of all the units mapped in the area to identify in the field, as it is typically seen as slabby, commonly flaggy, 2-inch to 5-inch plates of gray-weathering granulite. The other units of the Paxton Schist, the Gray Graphitic Schist Member and the White Sulfidic Schist Member also have their own unique characteristics discussed below.

Lithology

Gray Granulite Member. The Paxton Schist is composed chiefly of thin- to medium-bedded, gray- to purplish-weathering, quartz-labradorite-biotite granulite. Calc-silicate beds and boudins of actinolite, diopside, calcite and plagioclase are common in the gray granulites in the Barre area, and are especially well exposed in large outcrops of the Paxton Schist east of Gilweg Road near the Ware River, on Harding Hill, and in the spillway to the Ware River at the Barre Falls Dam. Boulders of hornblende-plagioclase amphibolite, such as that found by Field (1976, personal comm.) in the North Brookfield quadrangle to the south have been seen on the hillside north of Rt. 62, west of Fairweather Hill and east of the Burnshirt River, but no outcrop was found.

Crystals of quartz and labradorite in the granulite are typically equigranular, approximately 3/4 mm in diameter and exhibit a granoblastic texture. Less abundant minerals found in the Paxton granulite and calc-silicate include microcline, garnet, diopside and sphene. Trace amounts of apatite, zircon, allanite, clinozoisite, scapolite and calcite also occur in some specimens (Table 3).

Sulfidic schist is commonly interbedded with granulite in the Gray Granulite Member, and consists chiefly of pyrrhotite-graphite-garnet-biotite-plagioclase-quartz- and sillimanite with or without muscovite (Table 4). These schists closely resemble those of the Partridge Formation and conceivably could be structural infolds of the Partridge. However, such a conclusion would involve structural complications far more intricate than are presently believed to be the case, and the layers of sulfidic schist are presently thought to represent interbeds within the Gray Granulite Member. Excellent exposures of these sulfidic schists occur on the eastern-most crest of Harding Hill in the east-central portion of the map area, in large exposures due west of Riverside Cemetery and in the Ware River Spillway at the Barre Falls Dam.

Tourmaline-bearing pegmatites are extremely common in the Paxton Schist, and in many areas comprise much of the outcrop. Commonly the pegmatites, like the calc-silicate beds, are boudinaged, indicating their less ductile behavior under conditions of high-grade regional metamorphism.

White Sulfidic Schist Member. The basal member of the Paxton Schist is a rusty-weathering, pelitic schist and feldspathic quartzite that occurs in a narrow belt at the western contact of the Paxton Schist against the Partridge Formation. This belt appears to widen to the north and has been mapped northward into the Templeton quadrangle where it apparently terminates on Mine Hill just south of Route 2.

The pelitic schist contains magnesium-rich silicates together with graphite, and pyrite or pyrrhotite. In weathered outcrop, large pits up to 7 cm across are conspicuous where iron-sulfide has been leached out. The White Sulfidic Schist typically weathers white to buff with an intense rusty stain, but when broken fresh is characteristically a bluish-gray rock. Associated rock types of this member include feldspathic and micaceous quartzites which typically are very hard and tough. These rock types seem to make the White Sulfidic Schist less susceptible to erosion, and where these lithologies are present, the outcrops tend to form prominent ledges. Some of these quartzites are

Table 3. Estimated modes of specimens of the Fitch Formation and Gray Granulite Member of the Paxton Schist.

	Fitch	Gray Granulite Member, Paxton Schist												
	TB-368	TB-209	TB-276A	TB-276B	TB-466	TB-470	TB-523	A 745+00	B 745+00*	743+50	737+50*	692+50	608+75	597+00
Quartz	44	33	38	44	51	31	20	28	23	29	31	8	23	22
Plagioclase	33	35	29	35	25	38	48	35	28	24	18	8	53	31
Orthoclase		8	5	2	5	9	4	9	17	16	26	28	9	12
Biotite	12	3	15	7	13	13	21	9	10	10	12		11	6
Diopside	4	16	7	5	2		7	10	7	8		22		12
Actinolite	x		2	6	4			6	5	6		14		11
Garnet									tr				2	
Scapolite	x											7		
Sphene	4	2	2	1	x	1		2	1			3		1
Pyrrhotite	x													
Graphite	tr		x	x	x			tr	1	1	1	tr	tr	tr
Apatite	x	x	x	x	x			tr	1	tr	tr	tr	x	1
Zircon	tr	x	x	x	x			tr	tr	tr	x	1	tr	tr
Allanite			x				x	tr		x	tr	tr	tr	x
Clinozoisite	3	1	2	x	x	3		1	1	1		6	1	2
Calcite	x		x					tr	tr			3	tr	1
Sillimanite									6		3			
Muscovite	tr				tr					5	9			tr
Chlorite		$\bar{2}$	$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{5}$	$\bar{x}$				$\overset{+}{tr}$		$\overset{+}{1}$	$\bar{1}$

* Denotes thin section taken across calc-silicate granulite and pelitic interbed.

− Denotes Fe-rich chlorite.

\+ Denotes Mg-rich chlorite.

List of specimens in Table 3.

TB-368	Rusty-weathering, graphitic biotite granulite. Taken from a small stream cut in the Prince River at the 820 foot elevation mark.
TB-209	Medium-grained, slabby, foliated feldspar granulite. 0.15 miles north and 0.36 miles west of intersection of Blake Road and Coldbrook Road in east-central portion of the map area, southeast of Harding Hill.
TB-276 (A,B)	Medium-grained, dark-colored granular biotite gneiss. Located 0.1 miles southeast of junction of Hubbardston, Barre, and Oakham townships in east-central portion of the map area.
TB-466	Fine- to medium-grained, hard, biotite granulite. Collected from north entrance to Barre Falls Dam in stream cut of the Ware River.
TB-470	Well foliated, biotite-plagioclase granulite with thin calc-silicate beds evident in hand specimen. 0.13 miles due south of Barre Falls near the Ware River.
TB-523	Massive, well foliated, gray-weathering, biotite-plagioclase granulite. 0.05 miles south and 0.57 miles west of Barre Falls Dam on the Ware River, east-central portion of the map area.
745+00 (A,B)	Purplish to gray-weathering, massive granulite with green calc-silicate bed in contact with pelitic schist bed. 74,000 feet from the east end of Quabbin Aqueduct.
743+50	Gray-weathering, well foliated, feldspathic schist in the Paxton Schist. 74,350 feet from the east end of Quabbin Aqueduct.
737+50	Gray-weathering, biotite granulite with thin sillimanite-pelitic schist bed in it. 73,750 feet from Wachusett Reservoir.
692+50	Light gray to green, plagioclase-rich calc-silicate bed in the Paxton Schist. 69,250 feet from the east end of the Quabbin Aqueduct.
608+75	Gray-weathering, medium- to coarse-grained plagioclase-garnet-biotite gneiss. 60,875 feet from the east end of the Quabbin Aqueduct.
597+00	Gray- to purple-weathering, well foliated, fine- to medium-grained biotite granulite with 1 inch calc-silicate bed. 59,700 feet from Wachusett Reservoir.

Table 4. Estimated modes of specimens from the White Sulfidic Schist Member, Gray Graphitic Schist Member and pelitic interbeds of the Paxton Schist.

	White Sulfidic Schist				Gray Graphitic Schist					pelitic interbeds	
	TB-55	TB-54A	TB-278A	TB-278B	TB-268	TB-509	TB-137	TB-146	TB-180	772+00	750+00
Quartz	50	42	46	42	37	40	30	54	51	55	42
Plagioclase	40	40	7	20	27	22	23	11	21	5	16
Orthoclase	6	6	26	31	2	3	3	4	tr	22	13
Biotite	tr	4	8	5	21	20	35	11	13	11	23
Garnet					1	5	5	3	1	tr	2
Sillimanite	tr	tr	10	2	2	2	tr			7	2
Cordierite	1	2	1								
Pyrrhotite	tr	x	1	x						x	tr
Graphite	1	1	x	x	1	1	tr	1	1	x	x
Ilmenite					x	x	x	tr	tr	x	x
Rutile	1	x	x	x							
Hematite							x	x			
Allanite					tr					x	tr
Tourmaline								tr			
Zircon	x				1	x	tr		x	tr	tr
Apatite	x				1	x	tr		x		
Muscovite	1*	5*	1*		5	1	2	10	10		2
Chlorite					$\bar{2}$	$\bar{2}$	$\bar{2}$	$\bar{6}$	$\bar{3}$		
Sericite					tr	4					

* Denotes secondary muscovite

‾ Denotes Fe-rich chlorite

List of specimens from Table 4.

TB-55	Medium- to coarse-grained, feldspathic quartzite and rusty-weathering pelite. 0.4 miles east and 0.8 miles north of intersection of Gilbert Road and Rt. 62 in the north-central portion of the map area.
TB-54A	Rusty-weathering, feldspathic granulite and sillimanite schist. Same locality as TB-55.
TB-278 (A,B)	Rusty-weathering, quartzose granulite and pyrrhotite schist. 0.44 miles north and 0.05 miles east of intersection of Barre Depot Road and Hunt Road in south-central portion of the map area.
TB-268	Gray, fine-grained, biotite-garnet-sillimanite schist. 0.44 miles north and 0.15 miles west of the junction of Hubbardston, Oakham and Barre twonships. Taken from outcrop behind a small spring house.
TB-509	Well-bedded, gray, sillimanite-garnet-biotite schist. Specimen taken from a large stream exposure 0.33 miles downstream from Natty Brook Pond near Hale Brook crossing.
TB-137	Gray-weathering, biotite schist with 1 mm garnets. Taken from large exposure 0.4 miles east and 0.58 miles north of Fruitland Road and Granger Road in the central portion of the map area.
TB-146	Well foliated, gray-weathering, biotite-graphite schist with quartzo-feldspathic pods and streaks. 0.47 miles east and 0.9 miles north of Fruitland and Granger Roads in the central portion of the map area at the 790' elevation contour.
TB-180	Gray-weathering, biotite-garnet schist with clots of intergrown biotite and graphite. 0.25 miles due north of intersection of Fruitland and Granger Roads in central portion of the map area.
772+00	Slightly rusty-weathering, sillimanite-biotite-garnet schist. Double sillimanite fabric is evident. 77,200 feet from east end of the Quabbin Aqueduct.
750+00	Gray- to rusty-weathering, muscovite-biotite-sillimanite schist. 75,000 feet from the east end of the Quabbin Aqueduct.

particularly slabby and may have 2- to 3-inch laminations defined by mica-rich layers and quartzo-feldspathic ribs.

The dominant minerals in the schist are quartz, orthoclase, plagioclase and lesser amounts of cordierite, sillimanite, muscovite and light-brown biotite. Minor amounts of graphite, rutile, pyrrhotite, apatite and zircon, and, in rare cases, pyrite are also present. Electron microprobe analyses of mineral assemblages from specimens in the Templeton and Ware areas indicate that the silicates are extremely iron deficient and that nearly all the iron in these rocks is in the sulfides (Field, 1975; Tracy, Robinson, and Field, 1976; Robinson and Tracy, 1977).

Gray Graphitic Schist Member. This member is stratigraphically beneath the Gray Granulite Member and above the White Sulfidic Schist Member, and extends continuously around the crest of the late foliation arch where it presumably thickens to the north. It appears to pinch out southward in the North Brookfield quadrangle or at least was not seen by Field (pers. comm., 1976) in that area. Excellent exposures of this rock type occur in the outcrops just west of the powerline west of Riverside Cemetery (Plate 6), in the hills in the Hubbardston State Forest north of Fairweather Hill, and in outcrops north of the triple junction of the townships of Rutland, Barre and Hubbardston.

This schist is a gray- to slightly rusty-weathering pelitic schist, with subordinate amounts of calc-silicate beds, and typically has quartzo-feldspathic segregations 5 to 6 inches long strung throughout the rock. The dominant minerals (Table 4) are quartz, plagioclase, feldspar, biotite, garnet and sillimanite. Accessory minerals include graphite, rutile and ilmenite. The schist is medium-grained and evenly foliated and in places slight compositional layering results from a differential concentration of the various light and dark minerals. Graphite, where present, may be clotty, and commonly is intergrown with biotite in thin section.

Contacts

The contact of the White Sulfidic Schist Member of the Paxton Schist with the Partridge Formation of the Wickaboag Pond anticline is well exposed on the hills east of the Burnshirt River north of Route 62 and in the outcrops north of the intersection of Fruitland Road and Granger Road. Since the White Sulfidic Schist Member of the Paxton Schist and the Partridge Formation are both extremely rusty-weathering in outcrop, some stringent criteria were set up to distinguish between these units in the field. The criteria for the White Schist Member as contrasted with the Partridge Formation are: 1) association with impure quartzite beds, 2) absence of garnet, 3) absence of dark-colored biotite, 4) large pits on weathered surfaces due to weathering of pyrite cubes, 5) blue-gray color of the rock where fresh, 6) presence of black porphyroblastic cordierite.

The contact of the Gray Graphitic Schist with the White Sulfidic Schist has been mapped with close certainty in the same vicinities as those mentioned above. This contact is extremely easy to map because the differences in weathering characteristics of the two rock types are readily apparent.

Contacts of the Gray Granulite with the Gray Graphitic Schist are well exposed in several localities. These include exposures west of Granger Road in the central portion of the map area, and on the hills east of Brigham Road in the east-central portion of the map area. Over most of this contact, the boundary has been drawn based on the last appearance of the Gray Granulite going toward the bottom of the section. The interfingering nature of this contact along most of its length is taken as evidence for a conformable sequence with the Gray Granulite Member lying above the Gray Graphitic Schist Member.

In the Oakham area, the contact of the Partridge Formation with the Gray Granulite Member of the Paxton Schist is exposed northeast of the intersection of Bullard Road and Edson Road in the south-central portion of the map area. Along this contact one outcrop of a graphitic quartzite was found that looks similar to some of the feldspathic quartzites of the White Sulfidic Schist. In addition, Quabbin Aqueduct specimen 713+75, which is very near this contact, has much the same mineralogy of the White Sulfidic Schist (Table 2). Thus there is indirect evidence that the White Sulfidic Schist may be present near the inner contact of the Gray Granulite Member with the Partridge Formation. This would imply that the Gray Graphitic Schist Member is either pinched out tectonically or stratigraphically in the Oakham area.

Derivation

The White Sulfidic Schist Member probably consists of metamorphosed sulphur-rich aluminous shales interbedded with feldspathic quartzites. The Gray Graphitic Schist Member characteristically contains graphite and probably represents metamorphosed organic-rich silts and shales.

The Gray Granulite Member is probably derived from calcareous silts and sands, interbedded with carbonate-rich layers and lenses along with sulphide-rich pelites.

Thickness

As interpreted in cross-section (Plate 2), the Paxton Schist is doubled up in a recumbent syncline with the Partridge Formation exposed on both limbs. Since the top of the Paxton Schist is not exposed, only a minimum true thickness can be obtained. This being the case, assuming an average westerly dip of 24° (Figure 9) and using the measured map width of 2900 feet, a minimum thickness of 1180 feet for the Paxton Schist is obtained. Calculated thicknesses of individual members are: White Sulfidic Schist = 100 feet; Gray Graphitic Schist = 470 feet, Gray Granulite Member = 610 feet.

LITTLETON FORMATION

The Littleton Formation is exposed in seven isoclinal synclines that trend north-northeast through the Barre area. One of these synclines is composed principally of the Coys Hill Granite (Coys Hill syncline), and another is dominated by feldspathic gneiss derived from felsic volcanics (Prouty Road syncline). These two synclines merge north of the Barre Foundry in the west-central portion of the map area where the Partridge Formation of the Unitas Road anticline hinges out. Elsewhere the Littleton Formation is composed primarily of gray-weathering, quartzose aluminous schist, the Gray Schist Member (Dl), which locally exhibits graded beds from one to two inches and locally up to four inches thick (Figure 4a).

Lithology

The dominant rock type of the Littleton Formation in the Barre area (Table 5) is quartz-rich biotite schist with variable amounts of plagioclase, orthoclase, garnet and sillimanite. Quartz averages 40 to 45 percent, plagioclase 30 percent, biotite 20 percent, and orthoclase, garnet and sillimanite are normally less than 10 percent. Trace minerals in the Littleton Formation include secondary muscovite, Fe-rich chlorite, allanite, zircon and tourmaline. Opaque minerals commonly are graphite, and ilmenite. Distinctly subordinate rock types of the Littleton Formation include quartz-feldspar granulite, calc-silicate granulite, and distinctly mappable members of feldspathic gneiss and plagioclase-hornblende-cummingtonite gneiss. The quartz-feldspar granulite is composed mostly of quartz and plagioclase, with considerable biotite and some garnet. The calc-silicate granulites are white in color with equant 1 mm crystals of garnet and diopside peppered in a matrix of quartz, plagioclase, clinozoisite, sphene and calcite (Table 5 TB 248). The feldspathic gneiss and the plagioclase-hornblende-cummingtonite gneiss are discussed below for those synclines where they are most abundant.

Pyrite and pyrrhotite are absent in all the rock types of the Littleton Formation. Thus the gray-weathering character of the Gray Schist Member of the Littleton Formation was a tremendous aid in distinguishing it from rocks of the Partridge Formation or the White Sulfidic Schist Member of the Paxton Schist. The various synclines of the Littleton Formation with local lithic variations are discussed below.

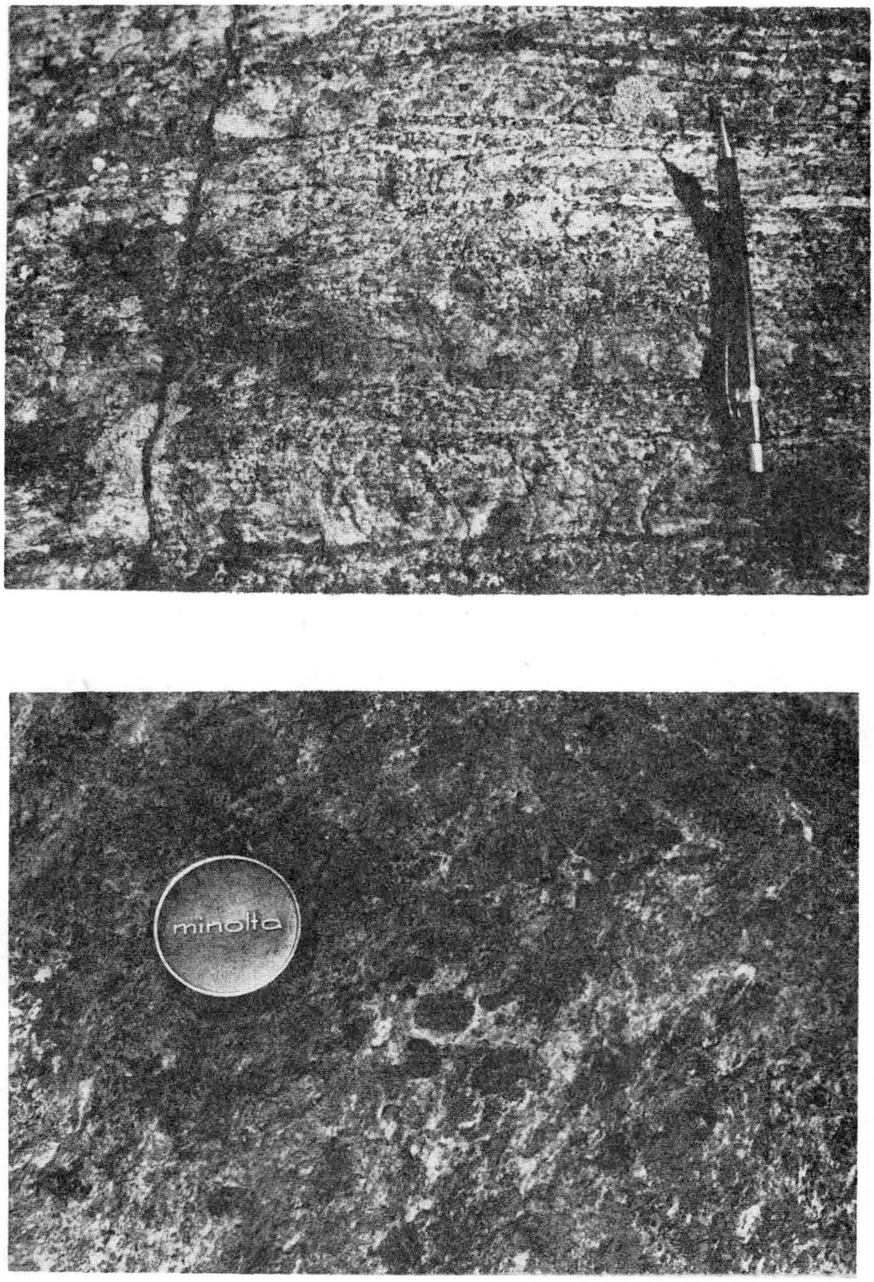


Figure 4. a. Graded beds in the Lower Devonian Littleton Formation, Gilbert Road syncline, Barre area. Tops point toward the top of the photograph as demonstrated by the garnet-sillimanite-rich layers. Graded beds are on the order of two inches thick. b. Garnets rimmed by orthoclase and quartz, from the Littleton Formation. Both photographs were taken from the same outcrop (graded bed locality 10, Figure 6).

Table 5. Estimated modes of specimens from the Gray Schist Member, Littleton Formation.

	Hardwick syncline					Big garnet	Prouty Road		Gilbert Road			Kruse Road
	966+50	965+50	965+50	962+00	960+50	TB 649	928+00	TB 332B	897+50	TB 249	TB 248	TB 653
Quartz	34	44	42	42	35	38	39	36	60	54	41	41
Plagioclase	27	15	21	34	31	20	31	26	15	12	45	27
Orthoclase	6	10	8	9	2	10	7	4	3	3		9
Biotite	29	21	17	5	27	21	17	14	19	19		11
Garnet	3	6	9	7	3	2	5	12	2	6	4	3
Sillimanite	1	3	2		1	7	1	5	tr	5		8
Ilmenite	x	1	tr	tr	1	x	tr	2	x	1	tr	1
Graphite	x	x			tr	1		x		x		x
Allanite					x			tr		tr		x
Tourmaline		x								tr		
Zircon	tr	tr	1	tr	tr		tr	x	x	x		x
Apatite	tr	x	x	1	tr	x	x	x	tr	tr	tr	x
Muscovite*		x	tr		x			tr			tr	
Chlorite					x+	tr−		1−				x−
Actinolite				1 pg								
Sphene				1							1	
Diopside											8	
Calcite			x		x						tr	
Clinozoisite											1	

* Denotes secondary muscovite.
\+ Denotes Mg-rich secondary chlorite.
− Denotes Fe-rich secondary chlorite.

pg Denotes actinolite which is pleochroic from pale green to colorless.

List of specimens in Table 5.

966+50	Gray-weathering, sillimanite-biotite-garnet schist, well foliated. 96,650 feet from the east end of the Quabbin Aqueduct.
965+50 (A,B)	Extremely well foliated, dark gray-weathering, garnet-biotite-sillimanite quartzose schist. Contains two sillimanite lineations at right angles. 96,550 feet from east end of Quabbin Aqueduct.
962+00	Well foliated, gray-weathering, garnet-biotite, granulite with a thin calc-silicate bed evident. 96,200 feet from the east end of the Quabbin Aqueduct.
960+00	Well foliated and crinkled, garnet-sillimanite-orthoclase schist. Medium-grained garnets rimmed by orthoclase evident in hand specimen. 96,000 feet from the east end of Quabbin Aqueduct.
TB-649	Well bedded, gray-weathering, feldspathic schist from the Big Garnet syncline. Taken from intermittent stream cut at the 920 foot elevation, 0.22 miles east and 0.39 miles north of the intersection of Washburn Road and Pleasant Street.
928+00	Gray-weathering, sillimanite-orthoclase-biotite schist with 1 cm garnets rimmed by leucocratic material. Sillimanite lineation is obvious. 92,800 feet from east end of Quabbin Aqueduct.
TB-332 (B)	Well foliated, gray-weathering, biotite-sillimanite-garnet schist. Located in Audubon campground, 0.3 miles south from Barre Common next to dining hall.
897+50	Light-gray-weathering, well foliated, fine- to medium-grained, garnet-sillimanite-biotite schist. 89,750 feet from the east end of the Quabbin Aqueduct.
TB-249	Gray-weathering, sillimanite-biotite-garnet schist with graded bedding. From the Gilbert Road syncline, 0.2 miles southeast of South Street directly under the powerline.
TB-248	White-colored, massive calc-silicate rock in the Littleton Formation. Located in the same outcrop as TB-249.
TB-653	Extremely well bedded, gray-weathering schist from the Kruse Road syncline (atypical). Collected 0.38 miles north and to the west of Walnut Road near the intersection with Cut-Off Road in the central portion of the map area.

Hardwick syncline. Gray-weathering, pelitic schist immediately next to the Hardwick pluton is very poorly exposed in the Barre area, with the exception of small stream exposures north of the Old Reservoir in the Barre quadrangle just out of the map area. However, Quabbin Aqueduct Tunnel specimens from this syncline have been collected and estimated modes are given in Table 5. These specimens are gray, medium-grained, garnet-sillimanite-biotite-quartz-plagioclase schists. Grading or cyclical bedding are not evident in hand specimen. They are well foliated, and contain migmatite layers composed of quartz, plagioclase and orthoclase 1/2 inch to 1 inch across, striking parallel to the prominent foliation. Although the bulk of the Hardwick syncline is not exposed in the Barre area, specimens from the Quabbin Aqueduct Tunnel show that gray pelitic schist of the Littleton Formation occurs at both the east and west contacts of the Hardwick Pluton. Reconnaissance mapping of the eastern contact of the Hardwick Quartz Diorite with the Littleton Formation some 5 miles to the north near Queen Lake in the Templeton quadrangle, also proves the existence of the Littleton Formation on the east side of the Hardwick Pluton (D'Onfro, unpublished notes).

Big garnet syncline. Well bedded, gray-weathering, pelitic schist is exposed in continuous outcrop for over 2000 feet south of the Old Reservoir in the Prince River. The Big Garnet syncline is extrapolated south through an area of no outcrop past Route 122 where it joins Field's (1975) Big Garnet syncline in the southeast corner of the Petersham quadrangle. Since not all of the Phase 1 axial surfaces mapped in the Ware area have been recognized in the Barre area, the present interpretation of connecting these axial surfaces is shown in Figure 3. Note that in this interpretation, the Partridge Formation in the core of Lyon Road anticline hinges out to the north in an early fold hinge with the Littleton Formation in the Hardwick and Ragged Hill synclines merging.

The Littleton Formation in the Big Garnet syncline is typically rich in quartz, plagioclase, biotite and sillimanite (Table 5, TB-649). Minor Fe-rich chlorite after biotite is also present. Generally, the rock types in this syncline do not differ much in texture and mineralogy from the pelitic schist in the Gilbert Road or Prouty Road synclines to the east. Field (1975) reports the Littleton Formation in the Big Garnet syncline as an aluminous schist commonly with garnets 1 cm and more in diameter. Although some rather large garnets with leucocratic rims consisting of orthoclase and quartz (Figure 4b) have been seen in this syncline, these textures are not considered to be more characteristic of this syncline than of any others in the area.

Coys Hill syncline. The next syncline to the east in the Barre area is underlain principally by the Coys Hill Granite, but the eastern and western contacts of Granite with the underlying Littleton Formation are well exposed in several localities including the 760-foot and 810-foot elevations on Prince River, southwest of the intersection of Dick's Brook and Rt. 122, and near the powerline south of Crogan Road. The Littleton Formation in this syncline is typically well bedded and aluminous with large garnets up to 1 inch across and with conspicuous sillimanite. Odtside of the larger crystal textures and more aluminous-rich composition, it is similar to the Littleton Formation seen elsewhere in the western portion of the Barre area.

Prouty Road syncline. The Littleton Formation exposed in this syncline is dominated by white, well foliated, layered feldspathic gneiss derived from felsic volcanics, and by gray-weathering, well bedded quartzose schist typical of the pelitic schist exposed elsewhere in the Littleton Formation. The feldspathic gneiss is separately mapped as the White Feldspathic Gneiss Member. A single exposure of cummingtonite gneiss also occurs in this syncline and is mapped separately as the Cummingtonite Gneiss Member of the Littleton Formation. It probably correlates with the Orthopyroxene Gneiss Member (Dlo) of Field (1975).

The best exposures of the Feldspathic Gneiss Member in the Prouty Road syncline can be seen south-southeast of the intersection of Root Road and South Street and at the head of Cooks Canyon in the Audubon Campground. Pelitic schist of the Littleton Formation is beautifully exposed in the Audubon Campground, on the hillside east of Barre, south of Rt. 62 and in a few isolated outcrops northeast of the Barre Foundry in the west-central portion of the map area.

The pelitic schist in this syncline has graded beds up to 5 inches thick, and is composed largely of quartz (37 percent), plagioclase (28 percent), and biotite (18 percent). Less abundant minerals, commonly conspicuous in hand specimen, include sillimanite, garnet and orthoclase (Table 5). Trace amounts of Fe-rich chlorite, secondary muscovite, allanite, zircon, apatite, graphite and ilmenite are also present.

In many instances the mineralogy of the schists of the Littleton Formation is an aid in determination of graded bedding tops. For example, the basal sandy beds of these rocks are commonly seen to consist of equigranular crystals of quartz, orthoclase and plagioclase while the more aluminous shaley tops are composed of sillimanite, garnet and biotite.

The Feldspathic Gneiss Member (Dlf) is a white, well foliated, feldspar-rich rock, commonly with small pink garnets and a minor percentage of biotite (Table 6). Plagioclase (45 percent), quartz (39 percent), microcline (6 percent) and biotite (7 percent) are the major constituents; muscovite, chlorite, apatite, zircon and allanite occur in trace amounts. The Feldspathic Gneiss is somewhat similar to pegmatites seen in the Barre area but has been distinguished from them by the smaller grain size, the presence of small pink garnets and the strongly foliated texture. The Feldspathic Gneiss is assumed to be Devonian in age because of its intimate association with the Littleton Formation. It appears at or near the base of the Littleton Formation in the Prouty Road syncline and as discontinuous lenses in the Gilbert Road and Coys Hill synclines. An associated rock type in the Feldspathic Gneiss Member is gray-weathering, biotite granulite, too thin to map separately, exposed in the Cooks Canyon section in the west-central portion of the map area.

Only one outcrop of the Cummingtonite Gneiss Member of the Littleton Formation has been identified in the Barre area, and that is beneath the powerline at the intersection of Root Road and South Street. No thin sections of this rock are available but field identification of

Table 6. Specimens of the Feldspathic Gneiss Member of the Littleton Formation.

	TB-339	TB-256
Quartz	41	39
Plagioclase	34 (ol)	45 (ol)
Orthoclase	19	tr
Biotite	1	7
Garnet	x	tr
Sillimanite	19	tr
Secondary Muscovite		1
Secondary Chlorite		x
Allanite		x
Zircon	x	x
Apatite	tr	x

List of Specimens in Table 8.

TB-339 White, well foliated, feldspathic sillimanite gneiss. Sample from outcrop 0.4 miles west and 0.38 miles south of intersection of Loring Road and South Street.

TB-256 Well foliated, white gneiss with pink garnets. Taken from outcrop at the top of Cooks Canyon north of Galloway Brook.

this rock yields the assemblage cummingtonite-hornblende-plagioclase-quartz. This rock occurs at exactly the same stratigraphic position as the Orthopyroxene Gneiss of Field (1975), near the top of the section in the Prouty Road syncline.

Gilbert Road syncline. Rocks in this syncline of the Littleton Formation exhibit the best examples of graded bedding in the area (Figure 4a). The dominant rock type is gray-weathering, well bedded, sillimanite-garnet-biotite schist with beds 2 to 4 inches thick. Three- to four-inch beds and boudins of calc-silicate rock appear in this syncline and consist of quartz (42 percent), plagioclase (47 percent), garnet (4 percent), diopside (8 percent), clinozoisite (1 percent) and lesser amounts of apatite, sphene and ilmenite (Table 5, TB-248). These rocks are in most occurrences distinctly white in color and are equigranular with crystals on the order of 2 to 4 mm in diameter.

The Gilbert Road syncline is known to extend south through the Ware quadrangle (Field, 1975) and from there similar rock types have been mapped as various members of the Hamilton Reservoir Formation by Peper et al. (1975). Pomeroy (1973), in the Warren quadrangle, designated similar rock types as unit husg of the Hamilton Reservoir Formation. To the north, mapping by this writer has extended this syncline into the southern third of the Templeton quadrangle.

The pelitic schist exposed in the Gilbert Road syncline is typically more quartzose than that in the other synclines of Littleton Formation, with up to 60 percent quartz reported in specimen 897+50 (Table 5). Plagioclase and orthoclase commonly average less than 15 modal percent and 4 percent respectively. Other minerals include biotite, garnet, and sillimanite,and trace amounts of chlorite, allanite, zircon, apatite, ilmenite and graphite are also reported.

Kruse Road syncline. This is the easternmost syncline of the Littleton Formation in the Barre quadrangle. To the south this syncline was not mapped in the Ware quadrangle (Field, 1975) possibly due to scarcity of outcrop. However, in the Warren quadrangle Pomeroy (1973) has mapped a belt of gray-weathering, sillimanite schist, the East Hill belt (husn), which is similar to the schist considered to be Littleton here. North of the Barre area, in the northern part of the Barre quadrangle, this belt of rock is best exposed on Kruse Road.

Generally speaking, the rock in this syncline is well foliated, gray-weathering schist, commonly with a streaked appearance due to the abundance of pegmatite veins. The schist commonly exhibits large, deep-black biotite crystals along with garnet-sillimanite-plagioclase and quartz with or without muscovite (Table 5). It is easily distinguished from the more typical Littleton schist by the poorly developed bedding, absence of noticeable sandy beds, and the small size of the garnets (1/4 inch) which might be a function of metamorphic grade.

Lower Contacts

The contacts of the Littleton Formation with underlying strata are generally poorly exposed throughout much of the western portion of the map area. However, the eastern and western contacts with the Fitch Formation are beautifully exposed in the Prince River at 820 foot and 830 foot elevations respectively. Likewise, the eastern and western contacts with the Partridge Formation in the core of the Unitas Road anticline are approachable to within a few feet along South Street in the town of Barre and again north of the Barre Foundry on School Street. The eastern contact of the Littleton Formation in the Prouty Road syncline with the Partridge Formation in the core of the Lamberton Brook anticline is well exposed and easily identified on the hillside north of Glen Valley Cemetery and again along Galloway Brook in Cooks Canyon. This contact is also approachable to within a few feet in the southwest corner of the map area.

The western contact of the Littleton Formation in the Gilbert Road syncline with the Partridge Formation in the Lamberton Brook anticline is sharp and clearly displayed at the 750 foot contour on Galloway Brook in Cooks Canyon and on the hillside to the north of Galloway Brook near Route 122. Although sharp and clearly non-gradational, these contacts could never be walked out for more than a few hundred feet, due to lack of outcrop.

The western contact of the Gray Schist Member of the Littleton Formation in the Kruse Road syncline was never located to within 10 feet but was located on the basis of boulders of the Littleton Formation just north of Cadwell Cemetery in the central portion of the area, south of the junction of Walnut Hill Road and Route 62, and in the north-central portion of the map area west of the Burnshirt River. The eastern contact of the Littleton Formation in the Kruse Road syncline with the Partridge Formation in the Wickaboag Pond anticline is approachable just north of the triple junction of Walnut Hill Road, Gilweg Road and Everett Road, and to within a few feet on the hills south of Worcester

Road in the central portion of the map area.

In contrast, the contacts of the White Feldspathic Gneiss Member with the Littleton schist and Partridge Formation are less well exposed, with the exception of outcrops at Cooks Canyon, near the Barre Foundry and in the southwest portion of the area.

Derivation

The Littleton Formation probably consists of metamorphosed aluminous pelite and quartz-rich sands together with minor mafic and falsic volcanics. It commonly has cyclical and graded bedding which suggest rapid sediment influx into a rather deep sedimentary basin (Blatt et al., 1972) possibly as a result of turbidity currents. The abundance of graphite suggests deposition under reducing conditions but the lack of abundant iron-sulfides indicates absence of sulfur-reducing bacteria. Calc-silicate beds probably represent metamorphosed carbonate-rich horizons within the turbidite sequence.

Thickness

Because the top of the Littleton Formation is not exposed, only a minimum thickness can be estimated. Assuming a complete doubling up of the Littleton Formation across each of the synclines in which it has been mapped, its minimum thickness for each syncline can be calculated from the map pattern width and the average dip of the syncline axial surface. Calculated minimum thicknesses for the Littleton Formation in the Prouty Road and Gilbert Road synclines are 680 feet and 410 feet respectively.

INTRUSIVE IGNEOUS ROCKS

Most of the intrusive rocks in the Barre area are probably of Devonian age and appear to have been intruded as sills early in the deformational history. Evidence for the age comes from the fact that the major igneous bodies in the Barre area, the Coys Hill Granite and the Hardwick Quartz Diorite, are correlated with the Kinsman Quartz Monzonite and Spaulding Quartz Diorite respectively in New Hampshire that have been recently dated by the Rb/Sr whole rock method (J.B. Lyons, personal comm., 1976), as well as from the fact that these sills appear to be largely confined to the Lower Devonian Littleton Formation. The other main intrusive body, the gneiss of Pleasant Brook, is a foliated, biotite granitic gneiss. Foliated pegmatite, a common rock in all of the stratified rocks, is thought to have been intruded during the Acadian (Devonian) orogeny. One diabase dike has been mapped and is probably Jurassic in age.

COYS HILL GRANITE

The Coys Hill Granite is exposed in the Coys Hill syncline which extends north-northeast through the western portion of the map area, and in the northern portion of the area is bordered on both sides by rocks of the Littleton Formation. The Coys Hill Granite has been traced southward from the Barre area through the Ware area (Field, 1975) into the northwestern corner of the Warren quadrangle (Pomeroy, 1973), and the eastern portions of the Palmer (Peper, 1976) and Monson quadrangles (Peper, 1974). To the north of the Barre area, the Coys Hill Granite has been mapped in reconnaissance through the western portion of the

Templeton and Winchendon quadrangles and the eastern part of the Monadnock quadrangle, New Hampshire, and probably is continuous with the Cardigan Pluton of Kinsman Quartz Monzonite (Billings, 1956).

Lithology

The Coys Hill Granite is perhaps the most striking unit in the map area. Phenocrysts of microcline, as long as 4 inches but averaging approximately 2 inches are the major constituent and are set in a matrix of biotite, quartz, plagioclase and garnet (Figure 5). Much of the Coys Hill is a true granite with microcline phenocrysts, containing an average of 33 percent potassium feldspar, 21 percent oligoclase, 40 percent quartz, 6 percent biotite, 1 percent garnet and trace amounts of ilmenite, apatite and zircon (Table 7). Sillimanite is seen in a few outcrops. Commonly the microcline phenocrysts exhibit a "chewed up" or cataclastic margin, and have a rim of re-crystallized plagioclase and quartz. In Barre on Route 122 and Union Street, there is a spectacular clean exposure of Coys Hill Granite in which it is possible to study the temporal relations between crystallization of the microcline phenocrysts and tectonic features. The significant conclusion reached here is that the plutonic event responsible for the microcline phenocrysts in the Coys Hill Granite took place before the earliest stage (Phase 1) of folding, and cannot be equated in time with the generation of most pegmatites or the peak of regional metamorphism. Fine-grained aplitic biotite granitic dikes can be seen to intrude the Coys Hill Granite in the Barre and their temporal relations were also studied. It was determined that the granitic dikes were intruded prior to Phase 2A (see Structural Geology Chapter) fold-

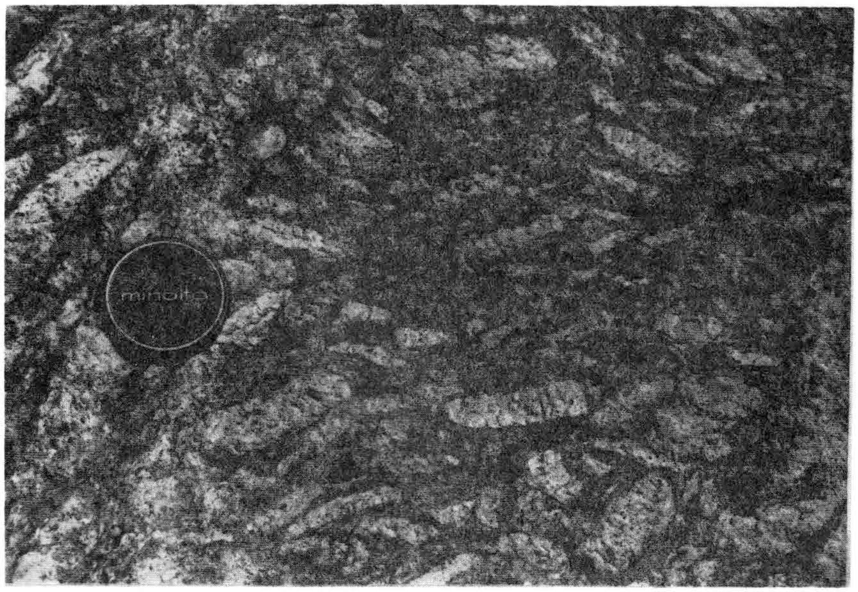


Figure 5. Photograph of the Coys Hill Granite, Barre area. Note the microcline phenocrysts with their "nipped off" appearance and granulated margins. Taken from an exposure near the intersection of Union Street and Route 122 in the village of Barre.

ing, clearly cross-cuts the foliation in the groundmass of the Coys Hill Granite, and post-dates the alignment of the microcline phenocrysts. This is consistent with the observation in the Quabbin area that "leucocratic and restite layers" are involved in Phase 2A folds and appear to have been largely crystalline and competent by that time (Tracy, 1975; Robinson, 1967b).

One specimen taken from the Quabbin Aqueduct Tunnel (941+50) represents a metamorphosed mafic volcanic layer and is characterized by the assemblage hornblende-cummingtonite-plagioclase-garnet-sphene-biotite-quartz (Table 7). The hornblende is very coarse, pleochroic from pale green to colorless, and makes up approximately 10 percent of the rock. Andesine (34 percent) and quartz (10 percent) are the major

Table 7. Estimated modes of specimens from the Coys Hill Granite.

	TB-303	TB-490	941+50
Quartz	41	38	10
Plagioclase	19 (An_{23})	23 (An_{27})	34 (An_{37})
Microcline	33	32	
Biotite	5	7	13
Garnet	x		x
Magnetite	tr		x
Ilmenite	x	x	2
Apatite	tr	x	1
Zircon	tr	x	1
Secondary Muscovite	2	x	
Secondary Chlorite		¯tr	
Hornblende			26*
Cummingtonite			10@
Sphene			tr

*Hornblende is pleochroic from dark green, light green to pale green

@Cummingtonite is coarse-grained and pleochroic from light green to colorless

¯Denotes Fe-rich chlorite

List of Specimens in Table 7

TB-303 Porphyritic quartz monzonite with 2-3 cm microcline phenocrysts. Taken from 790-foot elevation in the Prince River.

TB-490 Strongly foliated, medium-grained granite porphyry. Sample taken from the east side of Prospect Hill directly under the powerline, in the western portion of the map area.

941+50 Strongly foliated, hornblende-cummingronite gneiss. Mafic lens in the Coys Hill Granite is located 94,150 feet from the east end of the Quabbin Aqueduct.

constituents of the rock with garnet (4 percent), biotite (13 percent) and ilmenite (2 percent) and trace amounts of sphene, apatite and zircon making up the remainder.

Since the Coys Hill Granite is apparently continuous with the Cardigen Pluton of Kinsman Quartz Monzonite of New Hampshire (Billings, 1956), it must be genetically related to it. Thompson and others (1968) suggest the possibility that the Kinsman Quartz Monzonite was derived from remelted ignimbrites similar to those mapped in the Lower Devonian of central Maine (Smith, 1933). Nielson and others (1976) postulate that the Kinsman Quartz Monzonite was injected synchronous with the development of large-scale nappes during the early stages of the Acadian orogeny. Other authors interpret the origin of the Kinsman either as concordant plutons emplaced by forceful injection (Billings, 1937; Hadley, 1942; Chapman, 1939; 1942; Kruger, 1946; Moore, 1949; Heald, 1950; Dean, 1977) or as metasomatic replacement of the Littleton Formation (Chapman, 1952). The mafic gneiss in the Coys Hill Granite probably represents a metamorphosed basaltic flow or ash deposit.

Lower Contact and Thickness

The contact of the Coys Hill Granite with the Littleton Formation on the west limb of the Coys Hill syncline is well exposed at four localities. Where seen, the contact is well defined, with little evidence for a contact metamorphic zone with the exception of the larger garnet size in adjacent pelitic schist. The best examples of this contact are in the Prince River at the 810-foot and 750-foot elevations, at Crogan Road underneath the powerline, and at the intersection of Union Street and Route 122 in the village of Barre.

The Coys Hill Granite in the Quabbin Aqueduct Tunnel is an intrusive sill 1,000 feet wide, having an average westerly dip of 20°. Assuming that it lies in the core of an isoclinal syncline, its minimum thickness is calculated to be 170 feet.

HARDWICK QUARTZ DIORITE

The western portion of the map area includes the eastern contact of the main body of the Hardwick Quartz Diorite against the Littleton Formation (Plate 1). The shape of the Hardwick Quartz Diorite on regional maps, is like that of an elongate tongue which extends from southern New Hampshire (Spaulding Quartz Diorite) south to the Ware area where it appears to wedge out in an intense cataclastic zone (Field, 1975). In the Barre area, it is interpreted by this author to have been intruded as a thin plutonic sheet early in the structural history. Lyons (personal comm. 1976) gives a Rb/Sr whole rock age on the Spaulding of 402 $\pm$ 5 m.y. Nielson and others (1976) also believe the Spaulding Quartz Diorite was intruded into the Littleton Formation early in the deformational history.

Lithology

The Hardwick Quartz Diorite in the Barre area grades from quartz diorite to granodiorite. Typically it is strongly foliated, dark biotite-rich gneiss, forming massive low-lying outcrops in the western portion of the map area. Rarely it is porphyritic with andesine (An_{38}) phenocrysts up to one centimeter across. Where this texture is present, the rock retains a mottled appearance defined by subhedral andesine phenocrysts in a groundmass of biotite, quartz and orthoclase. Biotite

Table 8. Estimated modes of specimens from the Hardwick Quartz Diorite.

	TB-578A	TB-578B	TB-600	TB-589
Quartz	29	34	35	42
Plagioclase	41 (An_{35})	39 (An_{33})	29 (An_{38})	37 (An_{37})
Orthoclase	5	8		18
Microcline			3	
Biotite	23	18	31	3
Apatite	x	tr	x	x
Sphene	x	1	1	
Magnetite		tr	x	
Clinozoisite			x	
Zircon	x	x	x	x
Allanite	tr	x	tr	tr
Secondary Muscovite	x	x	x	tr
Secondary Chlorite	$\bar{2}$	$\bar{x}$	$\bar{1}$	$\overline{tr}$

¯ Denotes Fe-rich chlorite

List of Specimens from Table 8

TB-578 (A,B) — Dark, well foliated, quartz diorite gneiss. Taken from blasted pieces 0.38 miles west on Washburn Road from Pleasant Street intersection.

TB-589 — Medium-grained, foliated quartz diorite gneiss, massive low-lying outcrop. Located on top of hill 1060 feet high, due west of dam on Prince River south of Old Reservoir in the northwest corner of the map area.

TB-600 — Medium-grained, well foliated, gray-weathering, porphyritic quartz diorite gneiss. Outcrop is 0.15 miles due south of Allen Hill and north of Washburn Road.

and less commonly ilmenite or magnetite are the major mafic minerals. The biotite is typically pleochroic from olive green to pale brown indicating a high Fe^{+3} content relative to Ti^{+4} in the octahedral site (Deer, et al., 1966). In most specimens the rock contains 1-2 percent sphene with accessory apatite, zircon and allanite. Clinozoisite occurs in trace amounts in TB-600 (Table 8).

Contacts and Thickness

The contact of the Hardwick Quartz Diorite and the Little Formation tion is exposed only north of the Old Reservoir just out of the map area. The contact is also located within a few feet, fifty feet west of the Old Reservoir and is inferred on the basis of Littleton float southeast of the Barre Town Reservoir. Field (1975) has noted that in the Quabbin Aqueduct Tunnel, the Hardwick Quartz Diorite is bordered on both sides by the gray-weathering, pelitic schist of the Littleton Formation. Since only the eastern contact of the Hardwick body is exposed in the Barre quadrangle, no thickness can be determined. Fahlquist (1935) reports the Hardwick Quartz Diorite to be 16,200 feet wide and assuming an average westerly dip of 22°, and compensating for tectonic doubling up, a minimum thickness of 3035 feet is obtained.

GNEISS OF PLEASANT BROOK

This rock type forms two separate belts in map pattern (Plate 1), restricted to the Wickaboag Pond and Pleasant Brook anticlines. The best exposure of the rock is under the powerline west of Nichols Road in the southwest portion of the map area and in scattered outcrop west of Caldwell Cemetery. Other good exposures can be found on the hillside north of the junction of Fruitland Road and Old Worcester Road, and in scattered outcrop on the hill west-southwest of the junction of Gilbert Road and Route 62.

Lithology

The gneiss of Pleasant Brook is a biotite granitic gneiss, with very minor amounts of garnet (Table 9). It commonly forms large massive outcrops with characteristically flat dips.

The gneiss averages 40 percent quartz with varying plagioclase feldspar content, averaging 32 percent. The amount of orthoclase varies but is typically less than 20 percent. Garnets account for one percent, of the mode and are typically 1-3 mm across, in many cases rimmed by biotite or chlorite.

Contacts and Thickness

The contacts of the gneiss of Pleasant Brook with the Partridge Formation are exposed only in one locality but are approachable in several others. In the exposure north of Nichols Road the contact is sharp with little evidence of interfingering. The greatest width of the gneiss in map pattern (Plate 1) is approximately 1000 feet and assuming an average dip of 18°, a calculated thickness of 309 feet is obtained.

PEGMATITE

Intrusive pegmatites occur in many rock types throughout the Barre area. They are particularly common in the meadows of the central portion of the map area in the Pleasant Brook and Wickaboag Pond anti-

Table 9. Estimated modes of the gneiss of Pleasant Brook.

	TB-79	TB-89	TB-429	TB-84	TB-414
Quartz	53	47	42	40	36
Plagioclase	28 (An_{30})	31 (An_{26})	25 (An_{18})	20 (An_{20})	28 (An_{25})
Orthoclase	12	13	21	26	24
Biotite	4	9	12	13	11
Garnet	1	tr	x	tr	tr
Ilmenite	x	x	x	tr	tr
Zircon	tr	tr	x	x	x
Apatite	x	x	x	tr	tr
Secondary Chlorite	$\bar{x}$	$\overline{tr}$	$\overline{tr}$	$\bar{x}$	$\bar{1}$
Secondary Muscovite	2	tr	x	1	tr

‾ Denotes Fe-rich chlorite

List of Specimens from Table 9.

TB-79 Medium- to corase-grained, well foliated garnet-biotite granitic gneiss. Taken from a large outcrop due west of Nichols Road under powerline.

TB-89 Well foliated, medium-grained biotite-garnet granitic gneiss. Located 0.38 miles west and 0.05 miles north of Nichols Road and Route 122 intersection.

TB-429 Well foliated granitic gneiss. Outcrop is 1 mile north and 0.14 miles east of Gilbert Road and Route 62 in the Burnshirt Hills.

TB-84 Gray-weathering, medium-grained biotite gneiss. Located 0.7 miles due west of White Valley.

TB-414 Well foliated, gray-weathering, medium-grained granitic gneiss. Taken from an outcrop 0.1 miles north and 0.18 miles west of the intersection of Gilbert Road and Route 62.

clines where they are exposed in large rounded outcrops, commonly with rusty-weathering schist underneath them. The pegmatites are generally foliated parallel to the dominant regional foliation, and commonly are boudinaged. None of the pegmatites were studied in thin section, but most of them appear to be of granitic composition. Field identification showed them to be sillimanite-bearing, muscovite-bearing and muscovite-free, although the distribution of these types was not mapped.

DIABASE

One diabase dike was mapped on the surface in the Barre area (Plate 1), another thin dike is shown on the map on the basis of the report on the geology of the Quabbin Tunnel, an aeromagnetic anomaly (U.S.G.S., 1971) and distribution of float on the ground. The mapped dike, north of the intersection of Fruitland Road and Granger Road, is vertical, has a trend of N56E and cross-cuts contacts of all other units.

The dike consists of 52 percent plagioclase, 46 percent augite and 2 percent magnetite. Crystal size of the plagioclase and augite is approximately 1/2 mm. The dike typically displays a weakly developed subophitic texture.

STRUCTURAL GEOLOGY

Introduction

The deformational history of the Barre area as presently understood involved five phases of folding, probably synchronous with the Acadian (Devonian) orogeny and metamorphism, and an episode of post-metamorphic brittle fracture of probable Mesozoic age. Cataclasis can be shown to have occurred contemporaneously with intermediate stages of Acadian folding.

The stratigraphic units of Ordovician, Silurian and Devonian schists and gneisses seen in map pattern are repeated by a series of recumbent isoclinal folds analogous to the major nappes described in the Bronson Hill anticlinorium. In the western portion of the area, recumbent anticlines with west-dipping axial surfaces are separated by synclines of graded-bedded quartzose schist which show a reversal of top sense across these early folds. The axial surfaces of these early folds were then deformed by a large-scale recumbent anticline exhibiting west over east movement sense and a west-dipping axial surface. This folding re-oriented the first axial plane schistosity to the westward dip it now has in the western portion of the study area and was accompanied or immediately followed by local cataclasis and the development of a penetrative east-west trending mineral lineation. A third deformation produced southwest plunging folds characterized by west-dipping axial surfaces and east-side up asymmetry in the western portion of the map area and west-side up asymmetry in the eastern portion of the area. They also produced a penetrative mineral lineation so that many outcrops show two mineral lineations at nearly right angles. Formation of west-trending open folds in foliation followed this episode of deformation. In the eastern part of the area all of these structural features are deformed around a broad open anticline which plunges very gently north-northeast and results in east-dipping foliations at the east edge of the area.

SUMMARY OF STRUCTURAL HISTORY

The sequence of deformations as understood in the Barre area and as related to the nearby Orange (Robinson, 1967a), Quabbin Reservoir (Robinson, 1967b), and Ware (Field, 1975) areas is as follows:

1. Recumbent, isoclinal folding of large amplitude with an east over west overfolding. Prior to or early in this folding, thin sheet-like bodies of Devonian plutonic rocks were intruded. This phase was analogous to Phase 1A in the Orange, Quabbin Reservoir and Ware areas, and probably took place under medium- to high-grade conditions of metamorphism (Thompson et al., 1968).

2A. Overfolding toward the east of Phase 1 axial surfaces about gently plunging axes (Robinson, 1967b) causing the axial surfaces of the earlier isoclinal folds to dip west in the western part of the Barre area. Evidence for this deformation is fairly scarce in the Barre area, but has been described elsewhere. It was probably related to an early phase of gneiss doming in the Orange and Quabbin Reservoir areas (Robinson, 1967a, 1967b) and the formation of the Colchester nappe and the Chester-Hunts Brook syncline in Connecticut (Dixon and Lundgren, 1968b). This folding was accompanied or immediately followed by cataclasis along narrow shear zones and by the development of penetrative east-west or northwest trending sillimanite, biotite and quartz lineations in some rocks.

2B. Formation of southwest-plunging folds with a distinct, gently dipping axial plane foliation. Associated with this development of the dominant southwest-plunging "b" mineral lineations. This folding is equated with Phase 2B in the Ware area (Field, 1975, Robinson, 1967a) and with the "main stage" of gneiss dome formation (Phase 2B) in the Bronson Hill anticlinorium (Robinson, 1967a, 1967b).

3. Formation of symmetric west-trending open folds in foliation.

4. Broad open folding about a north-trending axis that is responsible for the broad foliation arch that deforms earlier-formed structural elements in the eastern part of the area.

5. Post-metamorphic brittle fracture and diabase dike intrusion.

DESCRIPTION OF MINOR STRUCTURAL FEATURES

Bedding

The contacts between distinctive rock types such as pelitic schist, calc-silicate, amphibolite and gneiss is suggestive of primary bedding. Fortunately, in pelitic units, graded bedding is evident and was used to obtain unequivocal evidence for the direction of primary tops. In schist where bedding is not directly evident, foliation was measured. In nearly every instance bedding is parallel or subparallel to foliation. This foliation is generally taken to be the axial plane foliation of the first phase of folding unless it can be shown to be related to a younger phase of folding.

Graded bedding was found at ten localities (Figure 6), all in the Gilbert Road and Prouty Road synclines of Lower Devonian Littleton Formation (Field, 1975). Graded bedding at these localities is consistent with the interpretation that the Littleton Formation rests above the Middle Ordovician Partirdge Formation and that the belts of Littleton Formation occupy the cores of isoclinal synclines. This is exactly the same interpretation obtained by Peper (1976) on the basis of graded bedding in the Mt. Pisgah syncline, approximately along strike to the south.

Foliations

Foliation is used here to refer to all types of mesoscopically recognizable planar surfaces defined by compositional layering, surfaces of discontinuity, preferred orientation of planar grain boundaries or a combination of these (Turner and Weiss, 1963). Schistosity is used to describe foliations defined by parallel alignment of tabular minerals, especially micas.

The dominant foliation in the Barre area is believed to be axial plane foliation of the early phase of recumbent folding. On the average its attitude is N28E20W (Figure 7a) in the western portion of the map area and N13E21E in the eastern portion of the study area. The one reasonable example of a Phase 2A fold (see below) shows a weakly developed axial plane foliation cutting across Phase 1 foliation.

The other conspicuous foliation is that associated with Phase 2B folds. This foliation is generally not so strongly developed, except in well indurated and more massive rocks, and typically is less steep than the first foliation and commonly is seen as a wrinkling of the first. Attitudes of the second foliation vary considerably in strike but dip moderately northwest and southwest (Figure 7). Other axial plane foliations were not immediately evident in the Barre area, for example no penetrative axial plane cleavage could be identified with confidence for third or fourth phase folds.

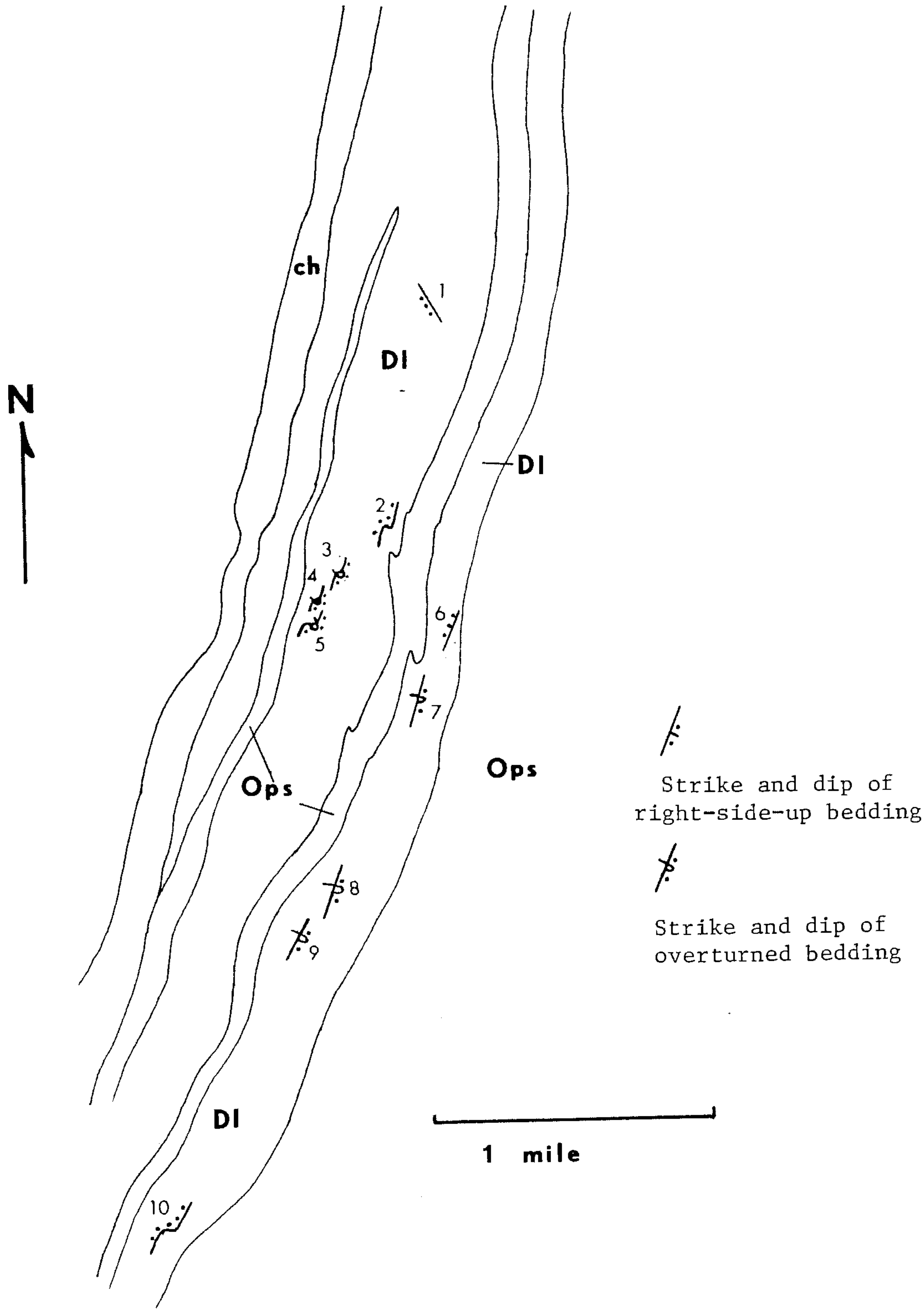


Figure 6. Location map of graded bedding localities in the Gilbert Road (eastern) and Prouty (central) Road synclines of the Littleton Formation, Barre area. Symbols show outcrop pattern of Phase 2B minor folds where observed.

Location of graded beds in the Barre area

1. Small stream exposure 300 feet north of Valley Road near School Street. Top sense indicated by graded beds is equivocal. Bedding trends N48W27W and is right-side-up. Outcrop is located in the Littleton Formation of the Prouty Road syncline.

2. Beautifully exposed outcrop of the Littleton Formation 100 feet east of bend in cut-off road to Route 62. Bedding trends N10E12W measured on the long limb of Phase 2B minor folds, and is right-side-up.

3. Low-lying ledge of the Littleton Formation exposed behind house on James Street. Bedding trends N18E20W and is overturned.

4. Littleton Formation exposed in the Audubon Campground yields overturned bedding trending N10E29W. Graded beds seen here are somewhat ambiguous.

5. Overturned graded bedding in the Audubon Campground trends N22E15W. Southern-most graded bedding exposure in the Prouty Road syncline.

6. Small outcrop of the Littleton Formation in the Gilbert Road syncline, 200 feet east of Route 122 and James Street intersection. Right-side-up bedding trends N42E31W.

7. Graded beds in the Lower Devonian Littleton Formation behind the South Barre IGA, west of Route 122. Low-lying outcrop in the Gilbert Road syncline yields overturned beds trending N12E29W.

8. Three hundred feet north-northeast, along strike from locality 9, is another large exposure of the Littleton Formation with overturned bedding trending N17E21W.

9. The best exposure of graded bedding in the Barre area, located on the powerline southeast of the intersection of South Street and Root Road. Overturned beds trend N5E33W.

10. Outcrop is approximately 1000 feet west of Adams Cemetery off of Root Road. Right-side-up bedding on the long limb of Phase 2B folds trends N70E28NW.

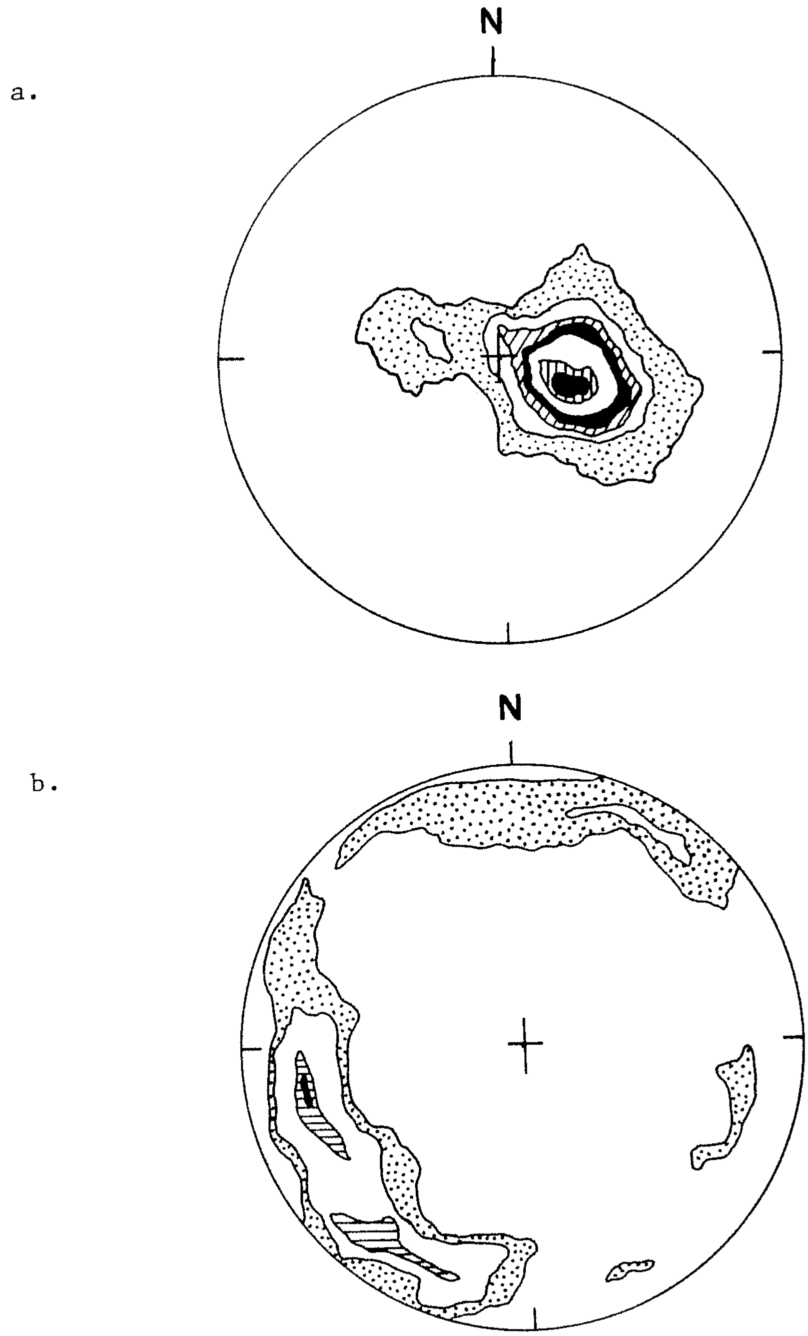


Figure 7. a. Equal area, lower hemisphere plot of poles to foliation measured in the Barre area. Contouring is on 1%, 3%,..... 13% per one percent area. b. Equal-area, lower hemisphere plot of lineations measured in the Barre area. Contouring is 1%, 3%,.....per one percent area.

Cataclastic Zones

Cataclastic rocks in the Barre area appear as three- to four-inch narrow shear zones seen to cross-cut Phase 2A or older foliation. Typically these rocks are fine- to medium-grained blastomylonites commonly with alkali feldspar porphyroclasts in a fine-grained matrix of biotite, plagioclase feldspar and quartz. Actual occurrences of these mylonites are rare in the Barre area but may best be seen in an outcrop of the Coys Hill Granite in the township of Barre (Figure 11).

Minor Folds

The majority of asymmetric minor folds measured in the Barre area were recognized as belonging to Phase 2B. Minor folds associated with this deformation are varied in size and style but generally are several inches in wavelength and similar in style. Where rotation sense is determinable for these folds, it was generally east-side-up (or clockwise rotation sense looking southwest down the plunge of the fold). Minor folds associated with Phase 1 or Phase 2A are extremely scarce and are discussed separately below. Minor folds associated with Phase 3 structures were found to be generally west or northwest plunging, upright, symmetric folds. In some cases these folds deformed cataclastic zones of Phase 2A or Phase 2B axial plane foliation. In other cases northwest plunging folds have been assigned to Phase 3 based on their similarity of orientation.

No minor fold axes were identified that could conclusively be attributed to Phase 4 folding. Apparently this last stage of open folding was not penetrative enough to develop minor folds. However, Phase 4 major folds clearly rotated Phase 2A lineations and Phase 2B

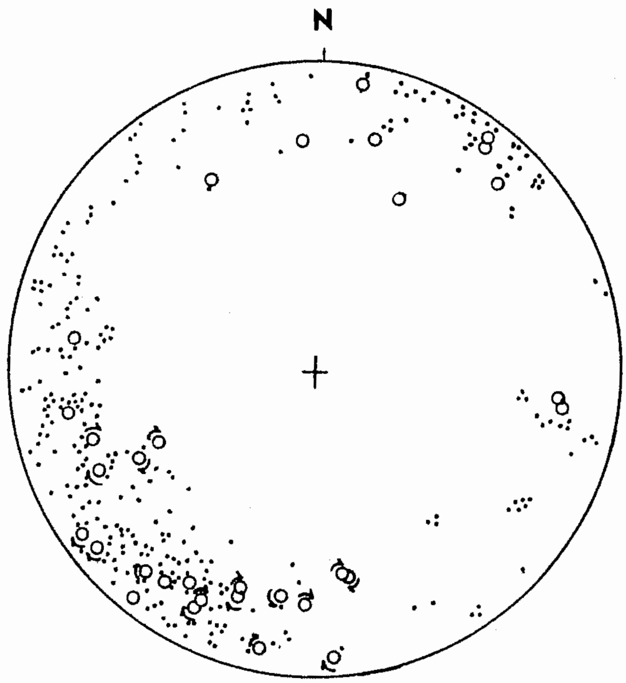


Figure 8. Equal-area, lower hemisphere plot of all fold axes and mineral lineations measured in the Barre area.

and Phase 3 folds and lineations from southwest and west plunges to northeast and east plunges respectively (Figure 8).

Lineations

Crystals of sillimanite, quartz and feldspar rods, and clusters of tabular minerals such as biotite and muscovite form the dominant linear elements. Intersection lineations, generally those formed by the intersection of first and second fold axial plane foliations and schistosities were also measured and recorded. The greatest concentration of all the lineations in the Barre area was found to be S80W @ 21° (Figure 7b) and may correspond in part to the dominant direction of Phase 2A lineations. The scatter is essentially parallel to first-fold axial-plane foliation within which most lineations lie. A second concentration within this plane at S33W @ 20° probably best approximates the trend of Phase 2B folds and related features. A third cluster at N30E @ 12°, is probably the result of rotation of Phase 2B lineations about the major fourth phase anticline.

Boudinage

Boudinage was a commonly observed phenomenon in the Barre area, most commonly involving pegmatite and in rarer instances calc-silicate beds. For the most part, the neck lines of the boudins trend southwest and generally parallel the axes of Phase 2B folds.

GENERAL PATTERN OF MINOR STRUCTURAL FEATURES

The study area was divided in 14 sectors shown in Figure 9. In each sector the poles to foliation and individual measurements of mineral lineations were plotted directly (see Appendix). In Figure 9 the dominant foliation and lineation orientations for each sector are shown. The most obvious features of the study area are as follows: 1) the general uniformity of minor structural elements in the western portion of the map area, 2) the gradual change to nearly horizontal and then to east dips in the central and eastern portions of the map area, 3) the change in plunge of mineral lineations from west-southwest in the western portion of the area to northeast and east in the eastern part of the area.

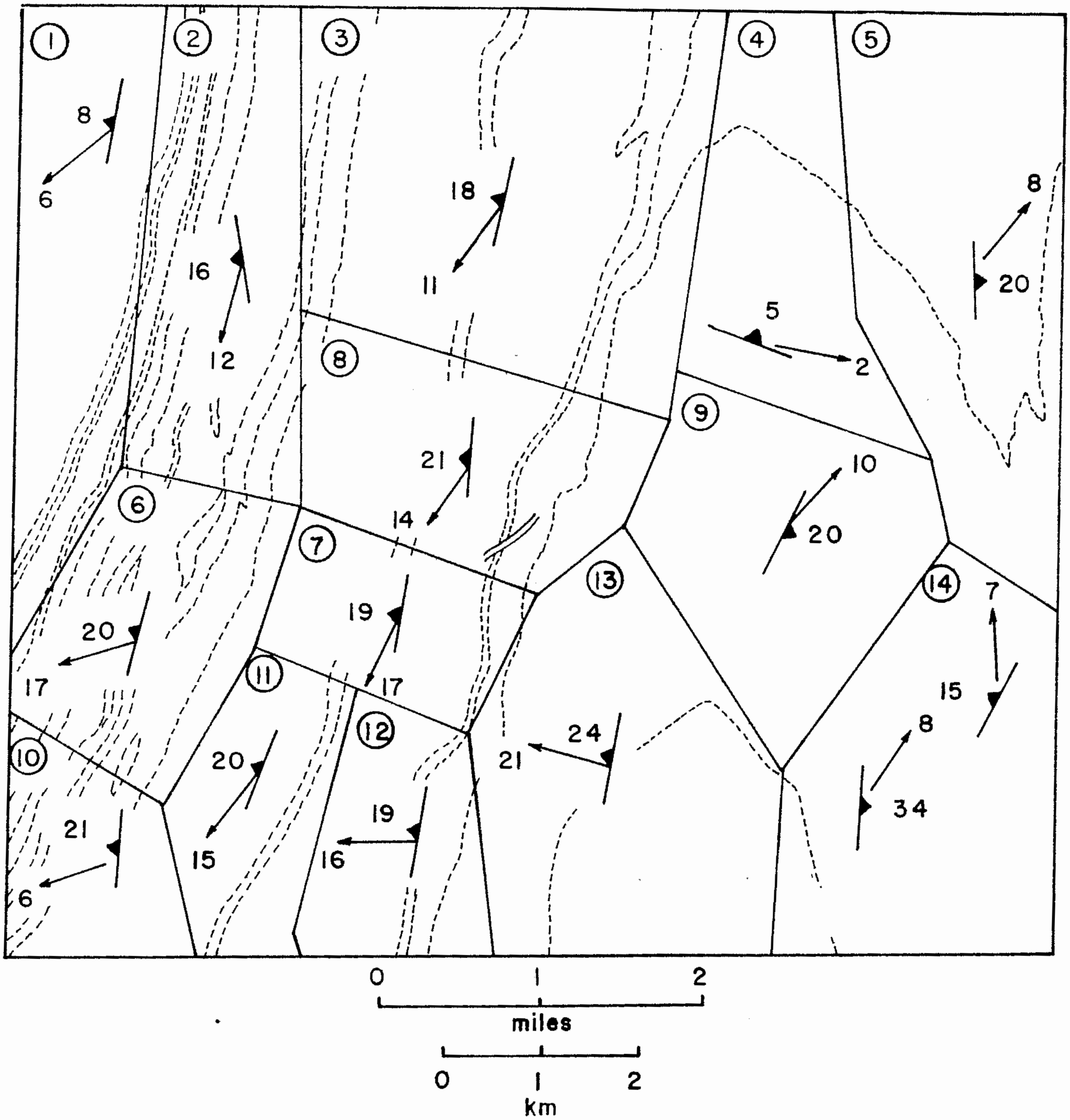


Figure 9. Structural sectors within the Barre area. The Barre area is outlined with the contacts between lithologic units shown dashed. In each sector the average planar attitude (bedding and foliation) and linear orientation (fold axes and lineations) is shown. Sector area is numbered in upper left-hand corner of each domain.

DETAILED INTERPRETATION OF STRUCTURAL FEATURES

Features Formed During Earliest Recumbent Folding

Minor folds. Four candidates for early minor folds were recognized in the field. All of these exhibit an ambiguous rotation sense and plunge in various directions. Their orientations are shown in Figure 10. The criterion for identifying early folds was that they have isoclinally folded compositional layering with a strong axial plane schistosity that intersects bedding at a high angle in the hinge area of the fold but is parallel or subparallel to bedding elsewhere. These are the only folds that do not deform foliation and therefore are interpreted to be the oldest folds in the study area. The very best candidate for an early fold has been found in the Littleton Formation (Figure 10), others are in the Partridge Formation and in the Paxton Schist. Generally, the angle between the limbs of the minor folds formed during Phase 1 folding is small, with evidence for passive slip movement along the axial surface of the fold. Each of the four folds are similar in style.

Foliation. At the four localities where Phase 1 minor folds were found their axial planes have an orientation close to that of the regional foliation. Since this foliation was observed to be near parallel to bedding everywhere but near the early fold hinge, the regional foliation is believed to have developed during Phase 1. No mineral lineations were found that were proven to have developed during Phase 1.

Major folds. Phase 1 major folds are by far the most obvious structural features in the Barre area, forming belts of Ordovician, Silurian

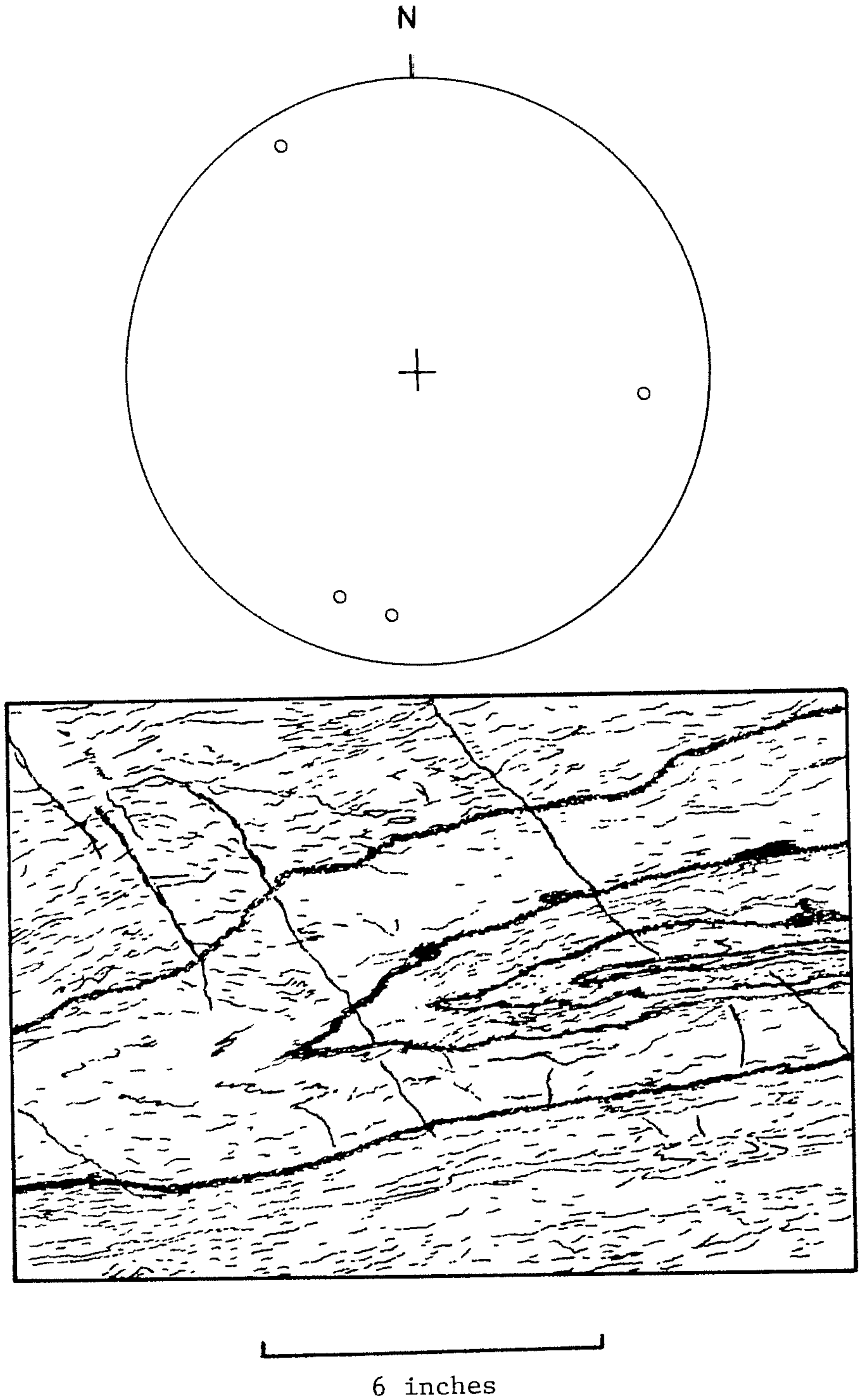


Figure 10. a. Equal-area lower hemisphere plot of Phase 1 minor fold axes in the Barre area. Note that no rotation sense was observed for any of the minor folds. b. Sketch of Phase 1 isoclinal minor fold in the Littleton Formation, Gilbert Road syncline. Minor fold is exposed in outcrop 100 feet east of bend in cut-off road to Route 62 in the central portion of the Barre area.

and Devonian rocks that extend north-south across the area. In the Barre area, five Phase 1 anticlinal belts cored by Ordovician rocks and six Phase 1 synclinal belts underlain by Siluro-Devonian rocks have been identified. Apparently because of a combination of large amplitude and of low angle plunge, only one Phase 1 fold hinge has been mapped. It has been postulated (Thompson et al., 1968; Field, 1975) that the highest of the three westward-transported nappes of the Bronson Hill anticlinorium, the Fall Mountain nappe, may have its roots southwest of Barre in the western part of the Ware area. This being the case, it is possible to interpret the early isoclinal folds mapped in the Barre area as representing structurally still higher nappes of the same stratigraphic sequence that were not transported as far west. Due to the great distances these anticlines and synclines can be traced, in excess of twenty miles, the axes of these early folds would appear to have a shallow plunge and a north-south trend. The fact that adjacent anticlines and synclines contain considerably different stratified and plutonic rocks, for example the Coys Hill Granite of the Coys Hill syncline is not repeated in any adjacent synclines, strongly suggests that the early folds had large amplitude with respect to wavelength.

Features Formed During Regional Backfolding

As in the Ware area (Field, 1975), the Barre area showed little minor structural evidence that either proved or disproved an intermediate folding event between Phase 1 and Phase 2B. Regional considerations and the map pattern of the Orange area have led others (Robinson, 1967a; Thompson et al., 1968) to suggest large-scale east-directed backfolding of the axial surfaces of the earlier west-directed nappes giving them their present west dip. This recumbent backfolding was believed to have been synchronous with the development of the east-directed Colchester nappe of southern Connecticut (Dixon and Lundgren, 1968a), and was referred to by Robinson (1967a; 1967b) as Phase 2A.

Minor folds and foliation. Only one occurrence of minor folds has been found in the Barre area that can reasonably be assigned to Phase 2A. They are folds in Phase 1 foliation in the Coys Hill Granite (Figure 11) which plunge west-southwest and exhibit east-side-up movement sense, the same as Phase 2B folds in the same region. The Phase 1 foliation in the Coys Hill Granite is cut by fine-grained aplitic dikes, which are in turn deformed by thè folds and contain and incipient very fine axial plane foliation.

Cataclasis and mylonization. Within the outcrop of Coys Hill Granite (Figure 11) cataclastic zones are recognized that cut across the axial surfaces of the west-plunging folds assigned to Phase 2A. In one place an apparent left-lateral offset of approximately four inches can be seen on a cataclastic zone. The cataclastic rocks themselves appear to contain later west-plunging (down-dip) mineral lineations and in a few places later southwest plunging mineral lineations and crenulations that could be assigned to the later Phase 2B (see below). In the Quabbin Reservoir area, nine miles to the west, Robinson (1967b) reported the occurrence of cataclastic zones that cross-cut the axial surfaces of folds equated with regional Phase 2A, and that are folded about folds of Phase 2B and contain Phase 2B mineral lineations. These

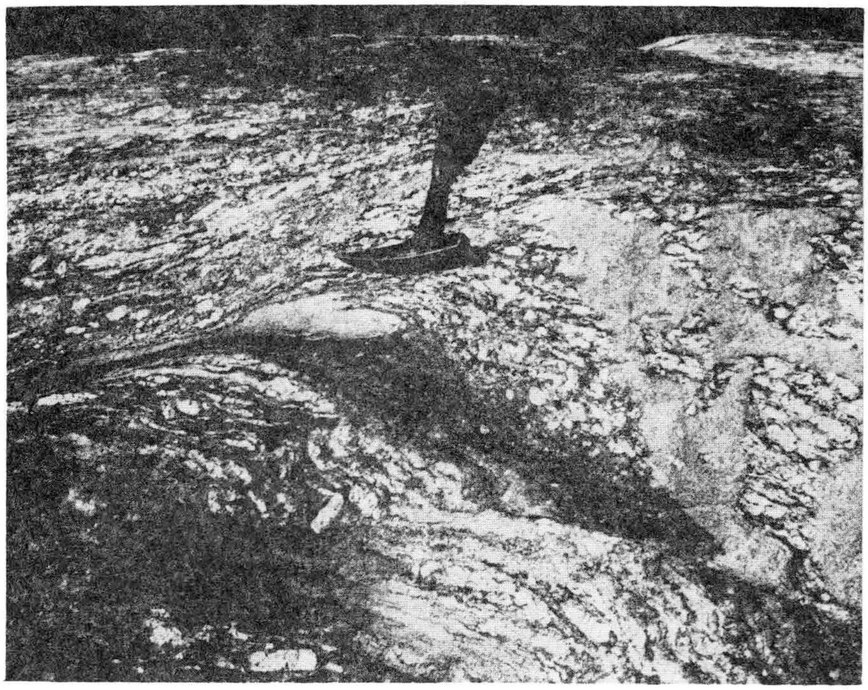


Figure 11. Photograph of relationship of cataclastic zones to regional Phase 2A folds. Note presence of fine-grained granite that cross-cuts Phase 1 feldspar foliation but was injected prior to Phase 2A folds. Outcrop is located on Route 122 in the village of Barre.

cataclastic zones also showed left-lateral shear sense. In the Ware area, Field (1975) also recognized cataclastic rocks in which mineral lineations of Phase 2B were superimposed and which had to have formed before or during Phase 2B. It is this relationship with cataclastic zones that supports the view that the fold in Figure 11 should be assigned to Phase 2A. In an alternative interpretation long supported by this writer, the fold in Figure 11 was assigned to Phase 2B on the basis of orientation and asymmetry, thus requiring both the cataclastic zones and the down-dip mineral lineations to post-date Phase 2B.

Lineation. Lineations that can be assigned to Phase 2A are extremely difficult to identify with certainty. They are pervasive, fine lineations composed of oriented silimanite needles, elongated quartz and feldspar grains, and mica aggregates, and locally are superimposed

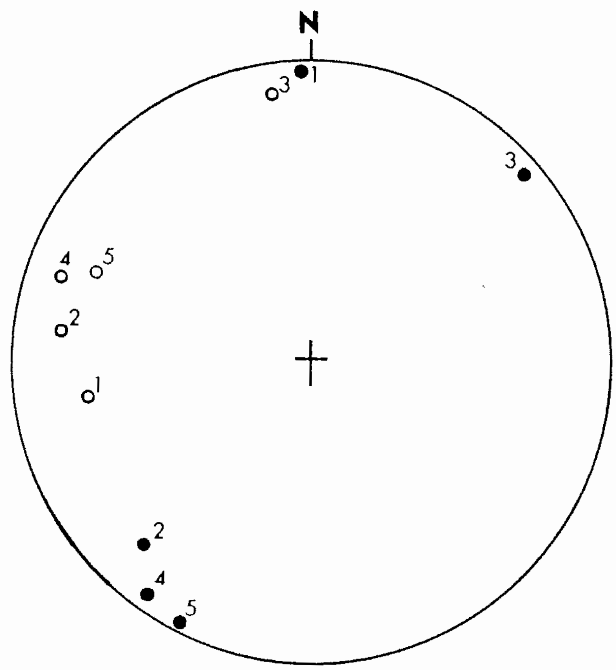


Figure 12. Equal-area, lower hemisphere plot of mineral lineations from outcrops exhibiting a double fabric in the Barre area. Early (Phase 2A) mineral lineations are shown in open circles (o) and plunge moderately west and northwest. Later (Phase 2B) mineral lineations are shown in darkened circles (o) and plunge southwest and northeast. Superscripts indicate the lineations measured from the same outcrop. Locations of outcrops where this texture is evident can be found on Plate 4.

on cataclastic rocks. They are best identified by their west or northwest trend in outcrops where a definite southwest-trending lineation of later Phase 2B can also be identified (Figure 12) (Plate 4). However, even among outcrops where two lineations nearly at right angles can be identified, there are only a handful where the relative ages can be determined with reasonable certainty.

Major folds. The map patterns in the Orange area (Robinson, 1967a) and in eastern Connecticut (Dixon and Lundgren, 1968a; 1968b) have led several authors to suggest large-scale east-directed recumbent folds. In the eastern portion of the Barre area (Plate 6), repetition of the Middle Ordovician Partridge Formation on both sides of the west-dipping

Silurian (?) Paxton Schist suggests the existence of an early east-facing recumbent syncline. In addition, Quabbin Aqueduct Tunnel specimen 713+75, found near the contact of the Gray Granulite Member of the Paxton Schist with the Partridge Formation, closely resembles the White Sulfidic Schist Member of the Paxton Schist in both mineralogy and chemistry. If this repetition is indeed due to recumbent folding, the evidence suggests a Phase 2A synclinal axial surface within the Gray Granulite Member of the Paxton Schist on the western limb of the Phase 4 anticline (Plate 6). In this interpretation the Gray Graphitic Schist Member of the Paxton Schist would pinch out stratigraphically before being repeated on the east limb of the fold. It is interesting to note that in this interpretation the structure invoked here is similar to the east-facing recumbent syncline of the Colchester nappe (Dixon and Lundgren, 1968a; 1968b) although the two axial surfaces are difficult to connect on a regional map.

Southwest "Main Stage" Folding

The dominant minor structural features recognized in the Barre area probably correspond with late stage folds (Phase 2B) in the Ware (Field, 1975) and Quabbin Reservoir (Robinson, 1967b) areas.

Minor folds. The majority of minor folds seen in the area belong to Phase 2B. They are seen in all rock types, but are especially well developed in stratified rocks. The minor folds appear to be similar in style, plunge moderately south-southeast and, in the western part of the area, exhibit east-side-up asymmetry (clockwise rotation sense looking down plunge). East of the axial surface of the Kruse Road syncline, Phase 2B minor and macroscopic folds continue to plunge southwest but exhibit west-side-up asymmetry. Discussion of this asymmetry reversal appears under Major folds. Figure 13a shows an equal-area net plot of Phase 2B minor folds. Those that plunge northeast are all from the eastern part of the area on the east limb of the late (Phase 4) foliation arch. Axial plane features attributed to this phase are evident in the more massive, plutonic rock types, and generally dip less steeply than the dominant (presumably Phase 1) foliation.

Foliation. The dominant planar structural feature attributed to Phase 2B deformation is a moderately developed axial plane foliation, generally striking north-northeast and dipping about 20° northwest. Where best developed, in more massive, medium-grained foliated gneiss, it is a late slip cleavage deforming Phase 1 axial surfaces. Figure 13b shows a plot of all measurements of axial plane foliation associated with Phase 2B folds.

Lineation. Minor folds of Phase 2B have a strong "b" lineation statistically parallel to their axes. Mineral lineations oriented parallel to the axes of Phase 2B folds, including long axes of sillimanite crystals, quartz and feldspar rods, and elongate aggregates of biotite or muscovite, are by far the most commonly observed and measured linear fabric element. Lineations formed by intersection of Phase 1 and Phase 2B axial plane foliations were also observed. Figure 13a shows an equal-area plot of all measured mineral lineations believed to have formed during Phase 2B.

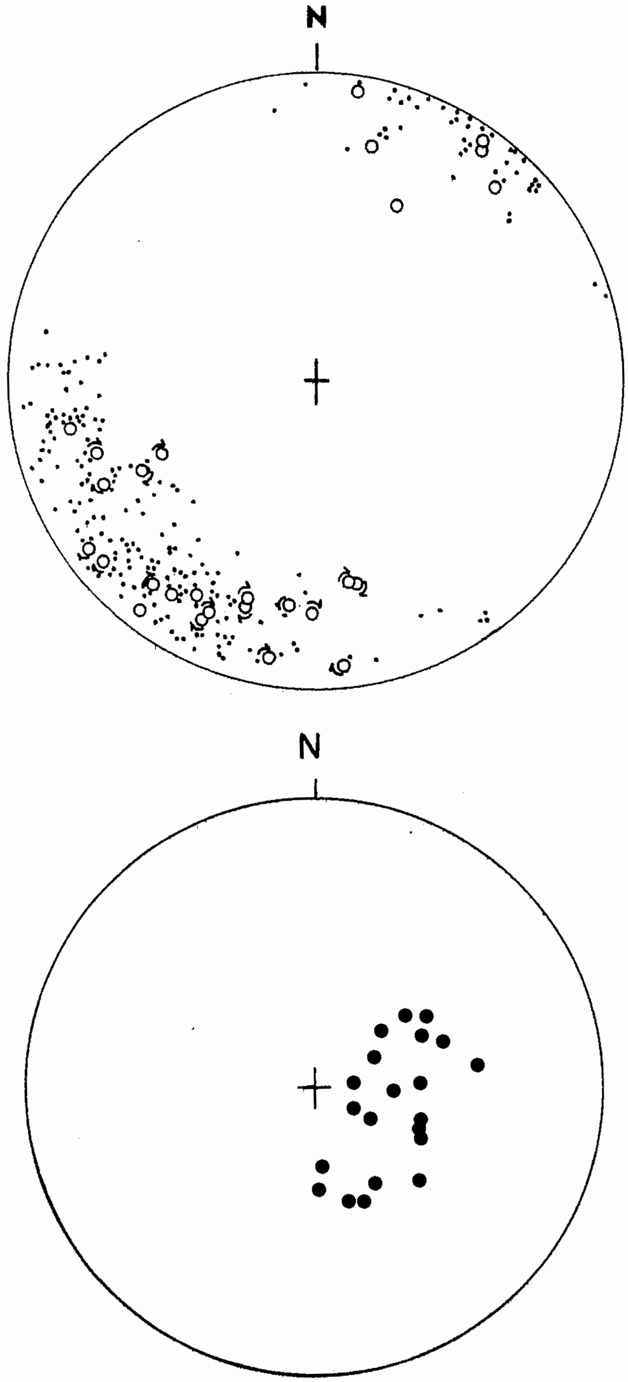


Figure 13. a. Equal-area lower hemisphere plot of fold axes and mineral lineations related to Phase 2B folds. b. Lower hemisphere equal-area net plot of poles to axial plane foliation of Phase 2B minor folds in the Barre area. Foliations associated with Pahse 2B minor folds dip less steeply than Phase 1 foliation.

Major folds. Phase 2B minor folds and lineations in the Barre area closely resemble Phase 2B folds in the Ware, Quabbin Reservoir, and Orange areas (Field, 1975; Robinson, 1967b; 1963) in both style and timing. If the Phase 2B folds of the Barre area correspond with Phase 2B folds in the Quabbin and Ware areas, then the plunge and asymmetry of these folds appear to be consistent in a broad north-south zone from the Tully Dome in the Orange area across central Massachusetts to the western portion of the Barre area (Figure 14). However, recent mapping in the northern portion of the Barre quadrangle and the southeastern part of the Templeton quadrangle (Ragged Hill, Mine Hill and roadcuts of Route 2) shows large-scale southwest plunging Phase 2B folds with the opposite asymmetry (i.e. west-side-up movement sense). Based on the limited data uncovered in the Barre area and in areas to the north, a regional synclinal axial surface of Phase 2B folding is postulated through the central portion of the Barre area, east of the Kruse Road syncline (Plate 6).

Late Northwest Trending Folds

Minor folds attributed to Phase 3 occur in the western part of the area and are open symmetric folds plunging moderately to gently west and northwest (Figure 15). They do not have a strong "b" lineation parallel to their axes but downdip (westerly and northwest trending) mineral lineations, here assigned to phase 2A, could in some cases be attributed to this deformation. It is worth noting that Phase 3 minor folds, in some instances, are broad warps of foliation with no recognizable asymmetry and in other cases could be due to flowage and boudinage. No penetrative axial planar feature attributed to Phase 3 was seen in the Barre

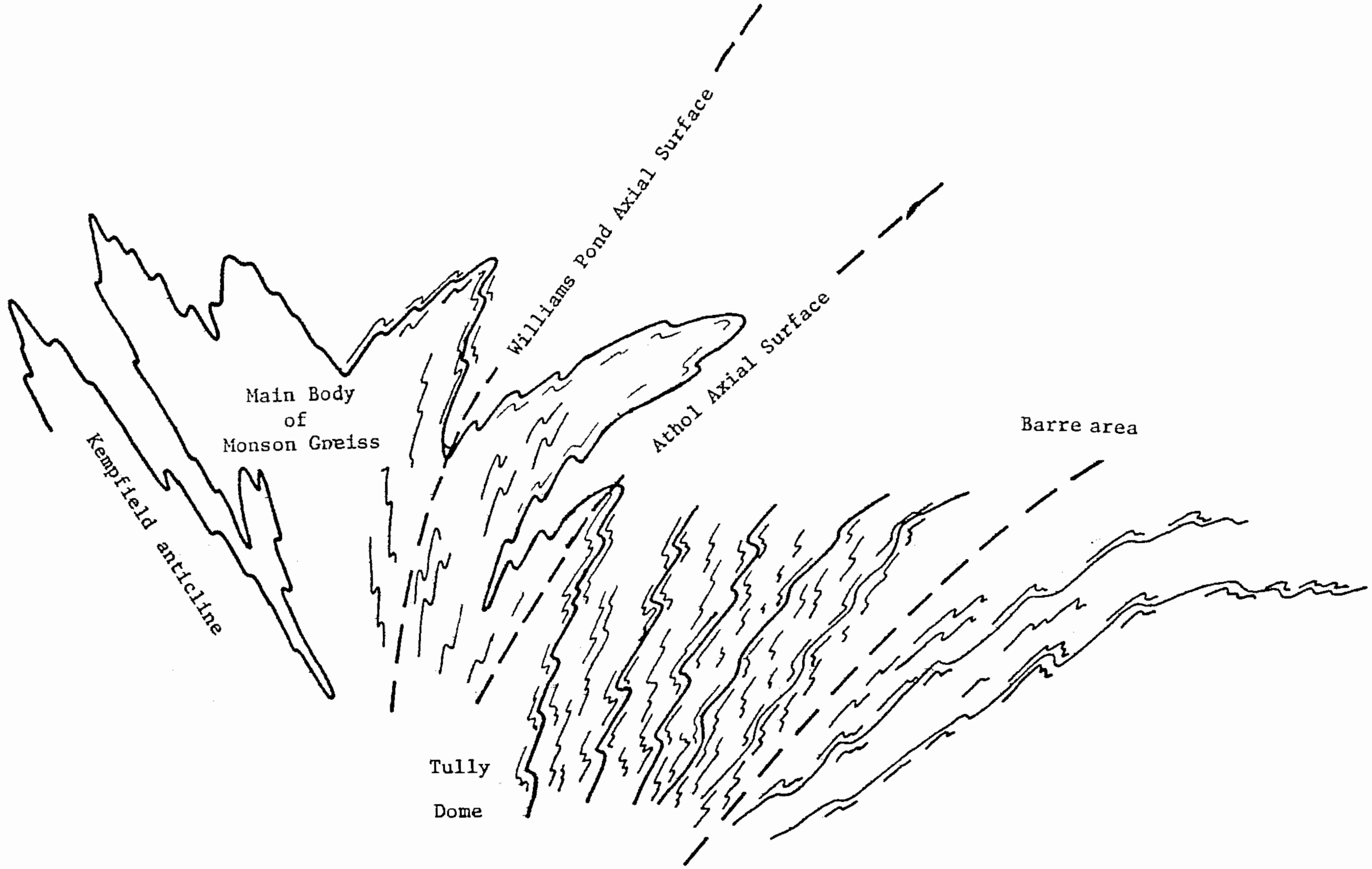


Figure 14. Diagrammatic sketch of relationship of Phase 2B fold asymmetry across central Massachusetts. Note that east from the Athol Axial Surface to the central portion of the Barre area, Phase 2B minor folds exhibit east-side up asymmetry. East of Barre, minor folds apparently reverse their asymmetry.

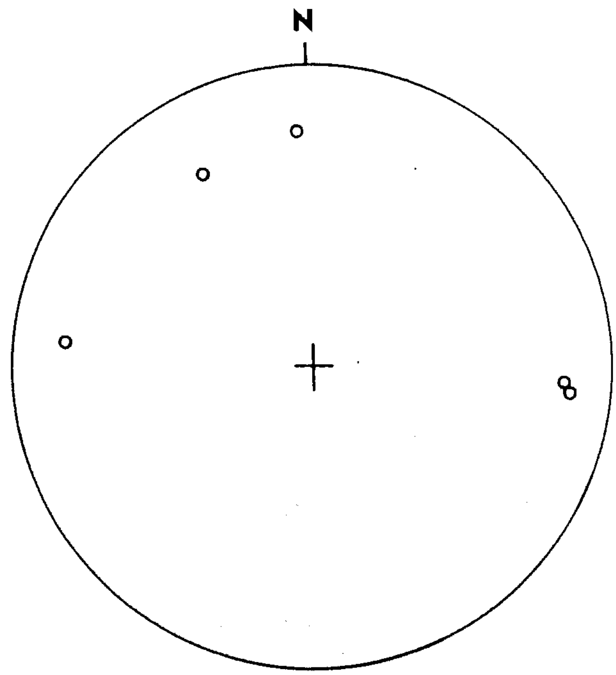


Figure 15. Equal-area, lower hemisphere plot of Phase 3 minor folds in the Barre area. Note that Phase 3 folds are symmetric open folds, which in the eastern part of the area, plunge east due to rotation about a Phase 4 anticline.

area. This deformation is known to have little effect on the map pattern and is thought to have been only locally developed. A few Phase 3 fold axes plunge east or southeast due to a later refolding during Phase 4.

Late Open Folding

The last folding in the Barre area is demonstrated by the rotation of previously formed lineations and fold axes. During this last phase, earlier structures were deformed in a broad smooth warping, whereas folds of the earlier generations appear to deform minor structural elements to a much greater degree. This open folding appears to be restricted to the east-central portion of the area and is clearly seen in map

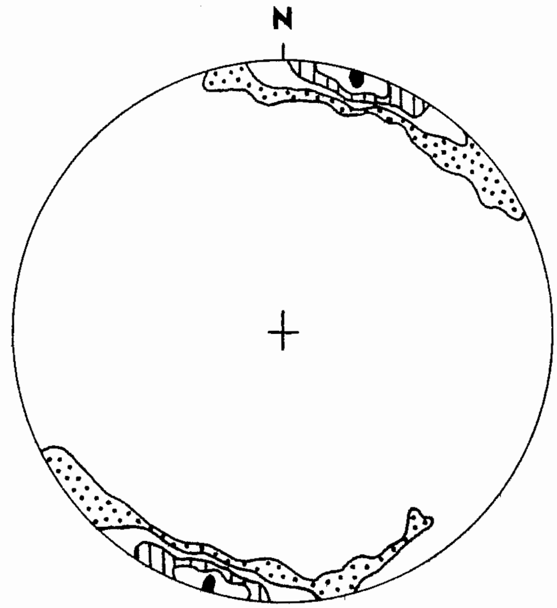


Figure 16. Lower hemisphere, equal-area diagram showing beta intersections of selected foliation planes used to determine orientation of Phase 4 foliation arch. Fifty planes of either side of the structure were used, which resulted in 1225 intersections. Contouring is 1%, 3%,...9% per one percent area.

pattern. No minor structural features were seen associated with this deformation. A determination of the trend of the axis of this fold was done by taking representative foliations on either side of the arch and finding beta intersections (Figure 16). A plunge of 1-2° at N16E was obtained. To try to lessen the influence a large number of westerly dips would have, the maximum of poles to foliation for the five easternmost sub-areas (Fig. 9) were plotted and used to obtain a beta maximum. This suggested the trend and plunge of the Phase 4 major anticline is N12E @ 4°N.

Identification of the foliation arch supports the notion that the Merrimack synclinorium is not a simple synclinorium but rather a complex zone of refolded folds masked by late broad open flexures. Moreover, it is in direct contradiction to the hypothesis that the synclinorium is essentially a westward dipping homoclinal sequence. Recent mapping by this author in the Gardner, Paxton and Wachusett Mountain quadrangles has uncovered additional late open folds, that also plunge gently north, which likewise are to be related to Phase 4 folding.

Post-Metamorphic Brittle Fracture

To better determine the brittle fracture history of the Barre area, 683 joints and 20 faults were compiled directly from Fahlquist's report on the geology of the Quabbin Aqueduct Tunnel (1935) and plotted on three equal-area nets across the area. Each sector has approximately an equal number of readings, the maximum number in Sector C (241 joints and 6 faults) and the minimum number in Sector B (206 joints and 9 faults) (Figure 17). In Sector A, the joints are dominated by a N47W and vertical set with a weakly developed set striking generally N35E to N70E and dipping moderately 30° to 80° NW, is also present but clearly is less well defined. North-south trending vertical joints are also present (Figure 17).

Sector B between the tunnel footages 720+00 and 640+00, has a strong maximum with attitudes centered around N66E80NW. A second weakly defined set striking N10E to N20E and moderately west dipping appears and trends into the N66E and 80NW set. Vertical joints with a wide variety of strike directions also are recorded but no statistical cluster is apparent.

Sector C is dominated by joints with attitudes of N62E80NW to vertical. A second set of joints generally trending N15E to N20°E and

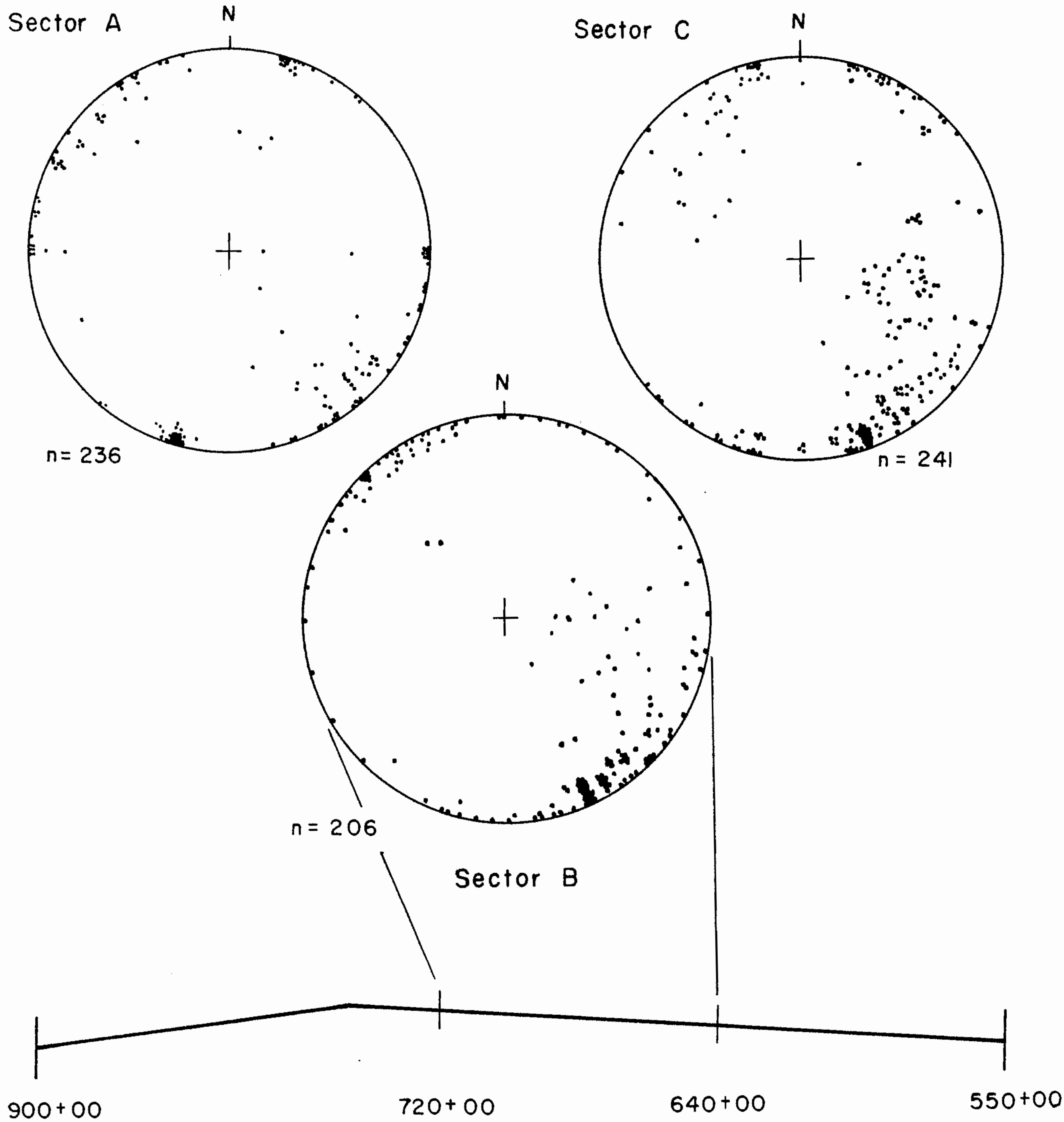


Figure 17. Equal-area diagrams of poles to joints and faults across the Barre area, taken from the report of the region of the Quabbin Aqueduct Tunnel (Fahlquist, 1935). Joint measurements were arbitrarily separated into three sectors based only on approximate equal number of readings per sector.

dipping west at 40 to 50 is more prominent in this sector and a third weakly developed set which trends N7W and dips 80 to 90NE. is also present.

In the analysis of this joint data, it as apparent that several Mesozoic trends are recorded in the rocks across the Barre area. Goldstein (1976) working in the Montague Basin reports three major joint sets with the following orientations; 1) N65E to N75E and vertical, 2) N70W to N80W and vertical, best developed in the northern portion of the basin, 3) N30E and moderately west-dipping, more or less restricted to the Turners Falls area. He also reports, citing evidence from Onasch (1973), Laird (1974) and Pferd (personal comm., 1976) that sets 1 and 2 (above) exist both within the Mesozoic basin rocks and in the Paleozoic rocks to the east and west of the Connecticut Valley (Goldstein, 1975; p. 34). Data from the Barre area suggests all three of these joint sets are present. Furthermore, in the Barre area a Jurassic dike was mapped with a N56E trend. Presumably this dike intruded along an extensional fracture zone active in Mesozoic time. Although no direct evidence is available in the Barre area for age relations of the other major trends, the prominence of these sets in the Mesozoic basin to the west suggests similarity of stress orientations across most of central Massachusetts in Triassic-Jurassic time.

CORRELATION AND AGE OF STRATIGRAPHIC UNITS

General Statement

No fossils have been discovered in the Barre area, hence the dating of the formations is dependent on the continuity of geologic mapping with several areas to the north and south. Indirect evidence that the stratigraphy of the western portion of the Barre area is broadly equivalent to the stratigraphic sequence in the Bronson Hill anticlinorium is suggested below. The correlation of the formations thus proposed (Table 10) is based on the following observations:

1. The Partridge and Littleton Formations have been traced south from the Orange area down the east limb of the Bronson Hill anticlinorium to the western part of the Ware area, Massachusetts. From there eastward, Field (1975) has mapped alternating isoclinal anticlines and synclines developed in these units to Wickaboag Pond. These isoclinal folds can be followed for great distances north, up to 20 miles, and appear to strike into the Mt. Monadnock area of New Hampshire mapped by Fowler-Billings (1949) who assigned most rocks to the Littleton Formation.

2. The lithology of the rock types in the Partridge, Fitch and Littleton Formations of the Ware area is very similar to that in the adjacent anticlinorium. The gross lithology of each of these formations and relative abundance of accessory rock types within each formation of the Bronson Hill stratigraphy can also be recognized in corresponding units in the Barre area. Discussion of the specific details of each formation is given below.

	Bronson Hill anticlinorium (Robinson, 1963)	Ware-Barre area west (Field, 1975)	Mt. Monadnock, N.H. (Fowler-Billings, 1949; Nelson, 1974)	Hillsboro-Warner area, N.H. (Nielson, Lyons)
DEVONIAN	Erving Fm. Littleton Fm.	Littleton Fm.	Littleton Fm.	Littleton Fm.
SILURIAN: Ludlow Wenlock Llandovery	Fitch Fm. Clough Quartzite	Fitch Fm.	Gray calc-silicate (Dublin Pond) "Rusty Quartzite" (Dlr)	Warner Member Francestown Member
MIDDLE ORDOVICIAN	Partridge Fm. Ammonoosuc Volcanics	Partridge Fm.	Sulfidic schists (outcrops at W. Rindge, for example)	Rusty-weathering schists
PRE-MIDDLE ORDOVICIAN	Monson Gneiss			

Table 10. Possible correlations of lower and middle Paleozoic stratigraphic units in the Bronson Hill anticlinorium and Merrimack synclinorium of southern New England.

3. The similarity of stratigraphic sequences in the western portion of the Barre area to that of the Bronson Hill stratigraphic sequence suggests correlation of formations. Although most of the key Silurian rocks of the Bronson Hill anticlinorium, in particular the Clough Quartzite, are not present in the Barre area, graded-bedding in the Littleton Formation is consistent with the interpretation that it occupies the cores of early synclines. However, nowhere in the Barre area are there conclusive examples of graded-bedding at the contact between the Partridge and Littleton Formations. Where the Fitch Formation is present it is inferred to lie in the core of an early anticline bordered on both sides by the Littleton Formation.

4. The Coys Hill Granite and the Hardwick Quartz Diorite, two of the most conspicuous igneous rocks in the Barre area, can be correlated with the Kinsman Quartz Monzonite and the Spaulding Quartz Diorite (Billings, 1956) in New Hampshire which are intimately associated with the Littleton Formation of the Bronson Hill anticlinorium stratigraphy.

Correlation of the rocks in the eastern portion in the Barre area is much more tenuous and is based on lithic similarities to the stratigraphy of western and central Maine (Moench, 1971; Boone, 1973; Osberg et al., 1968; Ludman, 1969; Ludman et al., 1972; Ludman and Griffin, 1974; Pankiwskyj et al., 1976) and the physical tracing of some lithically similar rocks from Maine through southeastern New Hampshire to Massachusetts (Hussey, 1968) (Table 11). Moreover, the similarity of the stratigraphic sequence in western and central Maine (Boone, 1973; Ludman and Griffin, 1974) to that of the Paxton Schist of the Barre area is striking. In western Maine, the granular calc-silicate unit of the Madrid Formation (Paxton Gray Granulite Member) is underlain by sulfidic pelite and quartzite of the Smalls Falls Formation (Paxton Sulfidic White Schist Member). In central Maine similar rocks have been assigned to the Fall Brook and Parkman Hill Formations respectively, which overlie the Late Llandovery to Early Ludlow Sangerville Formation (Ludman and Griffin, 1974; Boone, 1973). In addition, further east in central Maine, the western facies of the Waterville Formation (Wenlock) (Osberg, 1968) together with the underlying Mayflower Hill Formation are considered to be lateral equivalents of the Sangerville Formation (Ludman and Griffin, 1974). This suggests the meta-pelite and meta-siltstones of the Vassalboro Formation (Osberg, 1968) to be correlative of the Fall Brook Formation (Ludman and Griffin, 1974).

Possible correlations of these rocks to the south and west is presented in Table 11.

Partridge Formation

Correlation. The Partridge Formation in the Bronson Hill anticlinorium has been traced south from the type locality at Partridge Lake, New Hampshire (Billings, 1937; 1956) down the axis of the anticlinorium and into Connecticut (Thompson et al., 1968; Robinson, 1963; 1967a and 1967b; Moore, 1949; Rodgers et al., 1959; Dixon and Lundgren, 1968b). At Partridge Lake, the Partridge Formation consists of sulfidic black-gray slates interbedded with thin-bedded gray quartzites and soda-rhyolite tuffs at the base (Billings, 1956, p. 20). The slates and schists of the Partridge Formation weather rusty brown to red, commonly with crusts of sulfates on fracture planes.

Robinson (1967a and unpublished data) and Thompson and others (1968) have traced the Partridge Formation on the east limb of the

	Ware-Barre area-east (Field, 1975)	Philips-Rangeley Little Bigelow Mtn. Maine (Moench, 197], Boone, 1973)	Central Maine (Ludman and Griffin, 1974)	South-Central Maine (Osberg, et. al., 1968)	Southwestern Maine (Hussey, 1968)	Sterling-Shirley area (Hepburn, 1977)	Southwestern Connecticut (Dixon and Lundgren, 1968)
DEVONIAN	Possible Littleton Fm. on summit of Wachusett Mtn.	Seboomook Fm.	Solon Fm.	not exposed	Towow Fm. Rindgemere Fm. Gonic Fm.	Units 3 and 4 of Peck (1976) and Holden Fm. of Grew (1973).	Scotland Schist Franklin Qtzite.
SILURIAN: Ludlow	Gray Granulite Member Gray Graphitic Schist Member	Madrid Fm.	Fall Brook Fm.	Vassalboro Fm.	Berwick Fm. Eliot Fm.	Unit 2 (Peck) Oakdale Fm.	Hebron Fm.
SILURIAN: Wenlock	White Sulfidic Member	Smalls Falls Fm.	Parkman Hill Fm.				
SILURIAN: Llandovery		Perry Mtn. Fm. Rangeley Fm.	Sangerville Fm.	Waterville Fm. Mayflower Hill Fm.	Kittery Fm.	Unit 1 Tower Hill Qtzt.	
MIDDLE ORDOVICIAN	Partridge Fm.				Rye Fm.	Tadmuck Brook Fm. Nashoba Fm.	Tatnic Hill Fm.
PRE-MIDDLE ORDOVICIAN						Marlboro Fm.	Quinebaug Fm.

Table 11. Possible correlations of lower and middle Paleozoic stratigraphic units across the Merrimack synclinorium as applied to New England.

North Orange band (Robinson, 1963) south from the Orange area to the Ware area (Field, 1975), where it overlies the pre-Middle Ordovician Monson Gneiss. East from here, the Partridge Formation is exposed in the cores of early isoclinal anticlines that trend north-northeast across the Ware area and have been mapped into the Barre area. The sulfidic schist, minor amphibolite and calc-silicate granulite in the core of these folds resembles the Partridge Formation mapped in the Orange area, and elsewhere in the Bronson Hill anticlinorium. The eastern-most anticline in the Ware area, the Wickaboag Pond anticline, contains an ultramafic body, strongly suggesting that the sulfidic schist is Middle Ordovician or older (Field, 1975; Chidester, 1968; Cady, 1969). The Wickaboag Pond anticline has been mapped south of the village of Brimfield by Pomeroy (1973) and Seiders (1976) who assigned such rocks to the Upper Schist Member of the Hamilton Reservoir Formation. The Partridge Formation in the Barre area may also be correlated with the Tatnic Hill Formation of the Merrimack synclinorium (Dixon and Lundgren, 1968b) based on lithologic grounds and similar position in the regional stratigraphic sequence.

Age. The Partridge Formation is considered Middle Ordovician in age (Billings, 1956), most firmly based on Zone 13 graptolites found in western Maine (Harwood and Berry, 1967).

Fitch Formation

Correlation. The outcrop of the Fitch Formation in the Barre area is too small to permit definitive correlation. However, the rock in this exposure is nearly identical to and on strike with extensive exposures of Fitch Formation in the Ragged Hill anticline of the Ware area (Field, 1975). Here the Fitch Formation is a graphite-rich, sulfidic calc-silicate granulite. This belt is generally on strike with the rusty-weathering quartzite of the Littleton Formation in the Mt. Monadnock area (Fowler-Billings, 1949) to the north and the Francestown Member of the Littleton Formation in the Peterborough area, New Hampshire (Greene, 1970). Moreover, all of these rock types are similar to the sulfidic calc-silicate granulite of the Fitch Formation exposed opposite Gee Mill in the Lovewell Mountain quadrangle, New Hampshire (D11 of Heald, 1950; Thompson et al., 1968). Elsewhere in New Hampshire, the Fitch Formation is composed of impure limestones and calcareous slates and at the type locality near Littleton, New Hampshire consists of white calcitic marbles interbedded with light-gray, quartz pebble conglomerates. The Fitch Formation in the Bronson Hill anticlinorium is a mixture of gray-weathering, biotite-plagioclase granulite and calc-silicate granulite. Robinson (1963), in the Orange area, has mapped rusty-weathering, calc-silicate granulite and sulfidic bytownite schist intercalated with diopside-garnet calc-silicate granulite.

<u>Age</u>. The Fitch Formation near Fitch Hill, Littleton, New Hampshire contains corals, crinoids, brachiopods, trilobites and bryozoans previously thought to be of Middle Silurian (Niagaran) age (Billings and Cleaves, 1934). Closer examination by Boucot and Thompson (1963) place the faunal assemblage in the Early-Late Silurian (Early Ludlow).

Paxton Schist

<u>Gray Granulite Member</u>. The Gray Granulite Member of the Paxton Schist in the Barre area is lithically similar to the Oakdale Quartzite

exposed a few miles to the east in the Sterling, Worcester North and Worcester South quadrangles (Hepburn, personal comm., 1976; Grew, 1973). Emerson (1917) has mapped these units across much of central Massachusetts and considered the Oakdale Quartzite to be an eastern, less metamorphosed facies equivalent of the Paxton Schist. Along strike to the northeast, the Oakdale Quartzite resembles the Kittery, Eliot and Berwick Formations of southeast New Hampshire (Billings, 1956; Hussey, 1968). These units can be traced north into central Maine (Hussey, 1968; Osberg et al., 1968) where at lower grade of regional metamorphism the metapelite and metasiltstone of the Mayflower Hill and Waterville Formations contain Late Llandovery (Silurian) graptolites. More specifically, however, these units trace into west-central and northwestern Maine where the Madrid and Fall Brook Formations (Boone, 1973; Ludman and Griffin, 1974) are lithically like the Paxton Gray Granulite Member. The Fall Brook Formation overlies the Late Wenlock to Early Ludlow Parkman Hill Formation and the Late Llandovery to Early Ludlow Sangerville Formation (Ludman and Griffin, 1974) and is older than the Early Devonian Solon Formation (Ludman and Griffin, 1974). Other authors (Field, 1975; Grew, 1973) suggest similar correlations for the Paxton Schist and Oakdale Quartzite in the Ware and Worcester areas respectively.

To the south of the Barre area, the Paxton Schist can be traced into the Hebron Formation of southern Connecticut (Dixon and Lundgren, 1968). Members of the U.S. Geological Survey (Pomeroy, 1973; 1975) have mapped rocks lithically identical to the Paxton Schist south of the Barre area as members of the Hamilton Reservoir, Bigelow Brook and

Southbridge Formations.

White Sulfidic Schist Member. The belt of the White Sulfidic Schist Member of the Paxton Schist mapped in the Barre area is continuous with the western-most belt of Sulfidic White Schist mapped by Field in the Ware area. No other equivalent rock type exists in the immediate area which can be correlated with the White Sulfidic Schist Member of the Paxton Schist. It is similar in weathering characteristics to the Silurian Fitch Formation to the west but is much less calcareous. Of key importance is the lithic similarity of the White Sulfidic Schist Member to the Smalls Falls and Parkman Hill Formations in western and west-central Maine (Boone, 1973; Guidotti et al., 1975; Ludman and Griffin, 1974; Pankiwskyj et al., 1976). In particular, electron probe studies of both the White Schist Member and the Smalls Falls Formation show they have extremely magnesian silicates, high sulfide content, and rutile as the main Ti oxide. The Parkman Hill Formation of west-central Maine contains fossils of Late Wenlock and Early Ludlow age (Ludman and Griffin, 1974).

Gray Graphitic Schist Member. At the present time, the Gray Graphitic Schist Member is thought to rest above the White Sulfidic Schist Member and below the Gray Granulite Member of the Paxton Schist. No unit similar to the Gray Graphitic Schist Member is known to exist in adjacent areas. The Lower Devonian Littleton Formation is lithically somewhat similar to this unit although generally the schist of the Littleton Formation is more quartzose and tends to exhibit better bedding characteristics. The Gray Graphitic Schist Member has not been seen south of the Barre area but to the north it has been mapped as far north as the Winchendon quadrangle. To the east, similar looking rocks are present in the central portion of the Wachusett Mountain quadrangle and Gardner quadrangle.

Littleton Formation

Correlation. The Littleton Formation in the Barre area is lithically identical to that mapped in the Ware area and to some of the Littleton Formation of the Orange area (Robinson, 1963, 1967a). Robinson (1967b and unpublished data) has traced the Littleton Formation east of the North Orange band of Monson Gneiss south from the Orange area to the Ware area. East from this belt, the Littleton Formation is exposed in several isoclinal synclines that have been traced north through the Barre quadrangle and into the southern part of the Templeton quadrangle. Elsewhere in the Merrimack synclinorium the Littleton Formation is lithically similar to the Scotland Schist (Dixon and Lundgren, 1968b; Zartman et al., 1965) exposed in the Merrimack synclinorium in south-central Connecticut. East of the Barre area, cyclically bedded, gray-weathering, quartzose schist very similar to the Littleton Formation occurs on Wachusett Mountain and vicinity, and again on the east side of the Fitchburg Pluton. In the Sterling quadrangle, the "Bee Hill Formation" of Hepburn (personal comm.) has been correlated with the Worcester Phyllite (Grew, 1973) and the Boylston Schist (Emerson, 1917; Grew, 1973) all of which may be varieties of the Littleton Formation. The Littleton Formation probably correlates with Units 3 and 4 of Peck (Peck, 1976) as well as the Holden Formation of Grew (1973).

The Feldspar Gneiss Member and the Cummingtonite-Hornblende Gneiss Member of the Littleton Formation in the Barre area are lithically identical to the Feldspar Gneiss and Orthopyroxene Member of the Littleton Formation in the Ware area (Field, 1975). Field (1975) has suggested that the Feldspar Gneiss may be an unmobilized mass of felsic volcanics, similar to those in central Maine (Smith, 1933). The Cummingtonite-Hornblende Gneiss Member is surely equivalent to the Orthopyroxene Gneiss Member in the Ware area, but regional equivalents are rare. Bilings (1956) has reported rare mafic volcanics in the Littleton Formation of New Hampshire, and early Devonian andesites are known near Presque Isle in northeastern Maine (Boucot et al., 1964).

Age. Brachiopods, crinoid columnals and gastropods have been collected southwest of Littleton, New Hampshire (Billings, 1956; Billings and Cleaves, 1934). Lower Devonian fossils have also been collected in the Littleton Formation northwest of Whitefield, New Hampshire (Boucot and Arndt, 1960). Boucot (Boucot and Arndt, 1960) believes all of these fossils are of Onondaga age.

METAMORPHISM

METAMORPHIC ZONES IN ALUMINOUS SCHIST

The western portion of the Barre area lies well within the sillimanite-orthoclase zone of regional metamorphism as studied by Tracy (1975) and Field (1975) in adjacent areas (Figure 18), and is typified by the assemblage sillimanite-orthoclase-plagioclase-quartz-garnet-biotite. To the east of the Kruse Road syncline the rocks appear to exhibit a trend to lower metamorphic grade, characterized by sillimanite-orthoclase-muscovite-plagioclase-quartz assemblages. Southwest

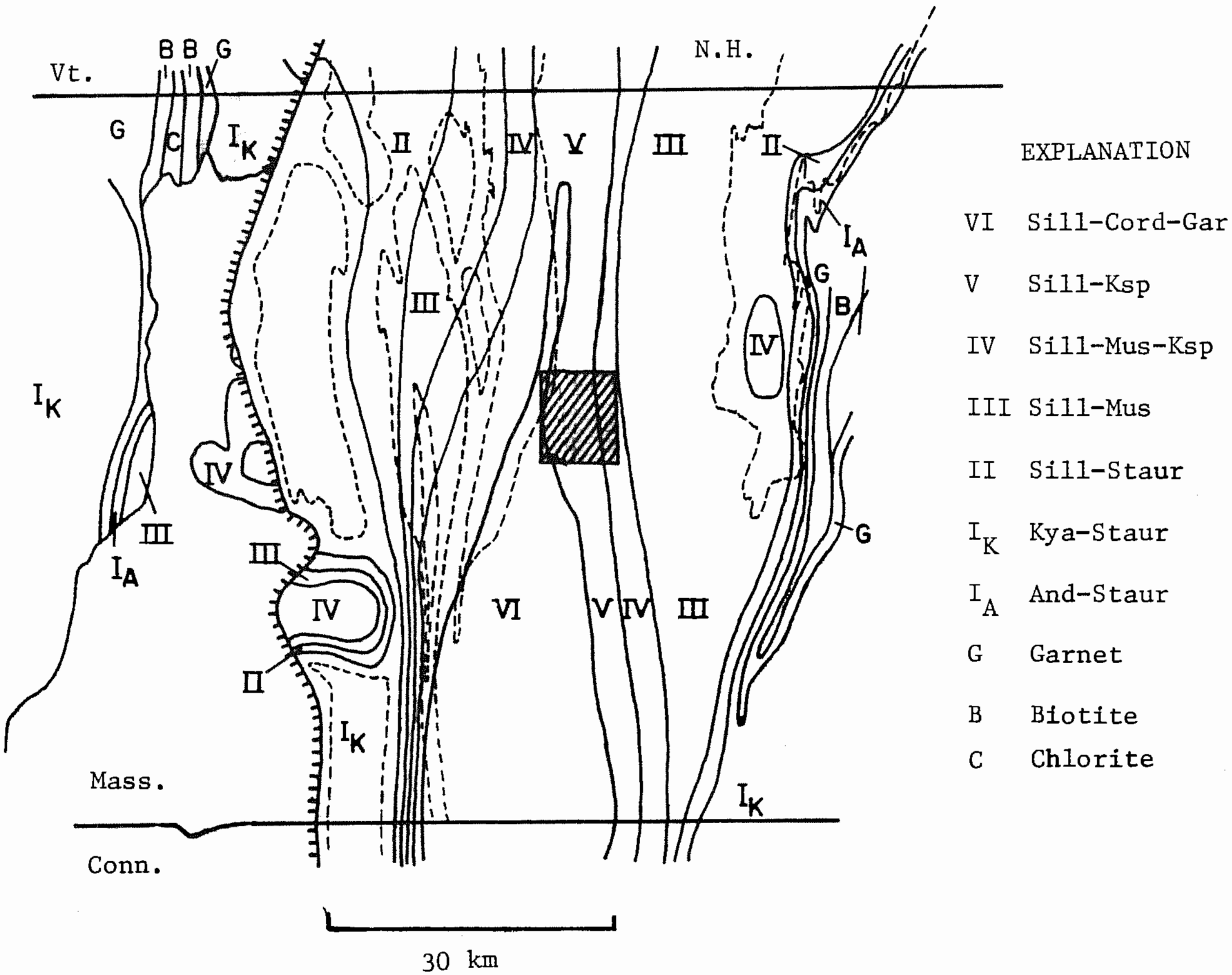


Figure 18. Regional paleozoic metamorphic isograd map of central Massachusetts, southern Vermont, New Hampshire and northern Connecticut (Robinson, unpublished data, 1977).

of the Barre quadrangle, pelitic rocks are typified by the assemblage quartz-orthoclase-plagioclase-sillimanite-garnet-cordierite (Field, 1975) and thus are of somewhat higher metamorphic grade than the western-most rocks in the Barre area. Garnet and cordierite were found in the same thin section west of the Kruse Road syncline (TB-526, TB-434) but are not in contact and thus are not considered to represent a coexisting equilibrium assemblage.

First examination of thin sections east of the Barre area, made from specimens collected during construction of the Quabbin Aqueduct Tunnel (Fahlquist, 1935), indicates that sillimanite-muscovite assemblages are stable at least as far east as the middle of the Sterling quadrangle (Tucker, personal observation). In addition, pelitic schist inclusions in the Fitchburg Pluton contain alkali feldspar (microcline)-sillimanite-muscovite assemblages where sillimanite may replace andalusite. Further to the east however, the regional metamorphic grade drops off very abruptly, resulting in greenschist (biotite-chlorite grade) facies assemblages immediately east of the Fitchburg Pluton (Figure 18).

MINERAL ASSEMBLAGES

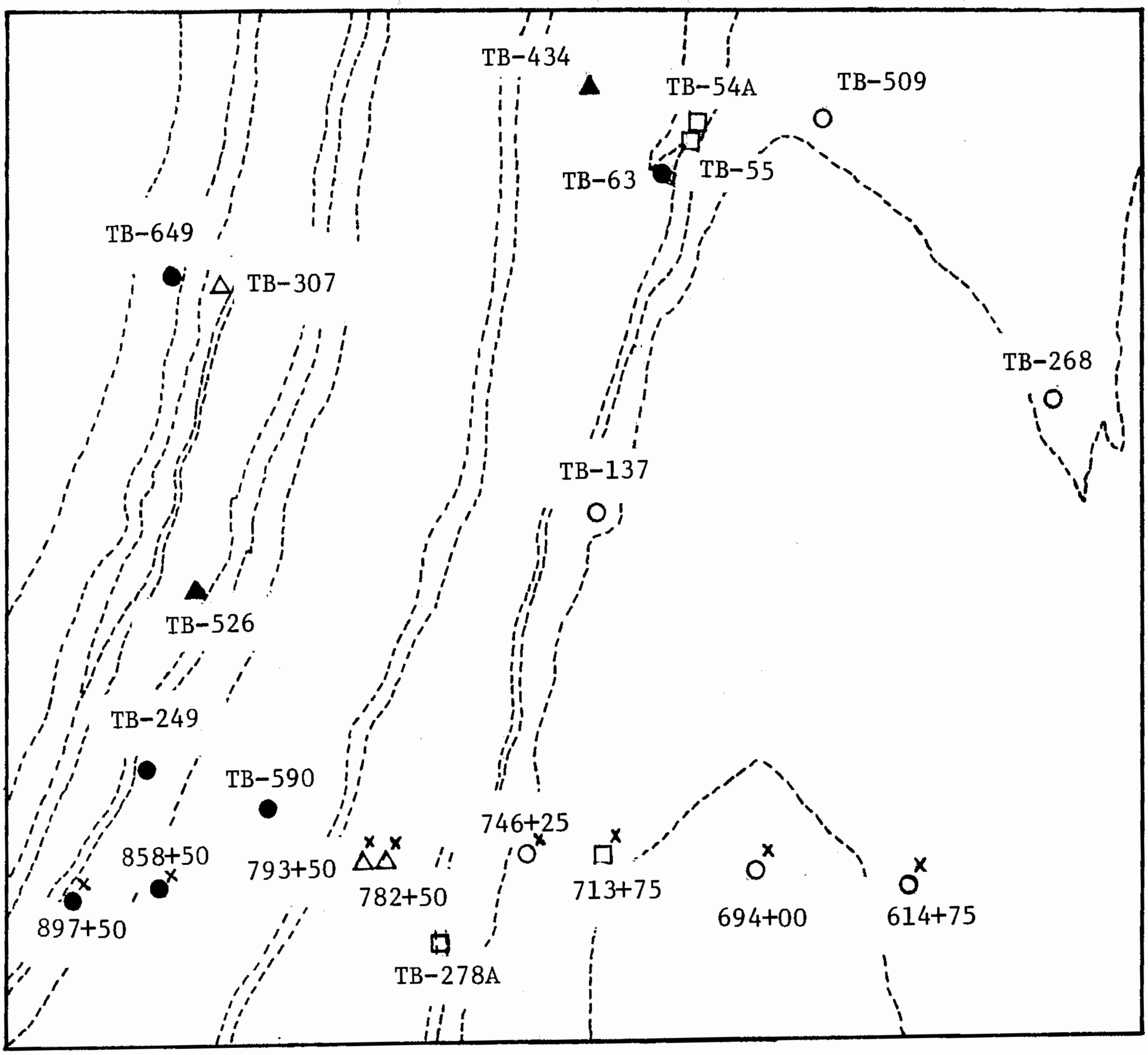
Aluminous Schist

Mineral assemblages in pelitic rocks of the Barre area are listed in Table 12, and are portrayed in Figures 20 and 21.

In the western portion of the Barre area, pelitic schist is characterized by the assemblages quartz-plagioclase-orthoclase-sillimanite-biotite-garnet and quartz-plagioclase-orthoclase-sillimanite-biotite-cordierite (Figure 19). Two thin sections were discovered to contain

	Quartz	Plagioclase	Orthoclase	Muscovite	Biotite	Sillimanite	Garnet	Cordierite
960+00, TB-307 793+50, 782+50	x	x	x		x	x		
TB-542, TB-591 TB-105, TB-590 860+50, 858+50 TB-63, 966+50 965+50, 960+50 TB-649, 928+00 TB-653, TB-332B 897+50, TB-249	x	x	x		x	x	x	
TB-91, 962+00	x	x	x		x		x	
TB-526, TB-434 (disequilibrium)	x	x	x		x	x	x	x
713+75, TB-55 TB-54A, TB-278A,B	x	x	x		x	x		x
TB-268, TB-509 TB-137	x	x	x	x	x	x	x	
TB-146, TB-180	x	x	x	x	x		x	

Table 12. List of mineral assemblages in pelitic rocks of the Barre area.



EXPLANATION

△ Sill-Ksp-Bio

● Sill-Ksp-Bio-Gar

▲ Sill-Ksp-Bio-Gar-Cord

□ Sill-Ksp-Bio-Cord

○ Sill-Ksp-Bio-Gar-Musc

/ Denotes thin section from Quabbin Tunnel

Figure 19. Location map of critical metamorphic assemblages across the Barre area.

garnet and cordierite but garnet and cordierite were not found in mutual contact. East of the Kruse Road syncline, prograde muscovite is stable in the assemblage muscovite-plagioclase-K feldspar-sillimanite-quartz and appears to be involved in continuous reactions involving Ca exchange between muscovite, alkali feldspar and plagioclase (Evans and Guidotti, 1966; Tracy, 1975). For a more detailed discussion on the first appearance of alkali feldspar and last appearance of muscovite in metamorphosed aluminous rocks, the reader is referred to work by Evans and Guidotti (1966), Lundgren (1966), Cheney (1975) and Tracy (1975).

The majority of schists examined in the western portion of the Barre area have the three-phase limiting assemblages biotite-garnet-sillimanite with orthoclase as noted by the X in Figure 20. The two-phase assemblage, biotite-sillimanite, marked X' and the three-phase limiting assemblage, biotite-sillimanite-cordierite marked X'', represents schists with more sulfur-rich bulk compositions that contain more magnesian biotites and even cordierite (Table 15, specimen 713+75).

Element zoning trends in garnets from the Barre area (Figures 22 and 23), are not typical of the sillimanite-garnet-cordierite zone of regional metamorphism in the Ware area as studied by Tracy, Robinson and Thompson (1976). In particular the garnet core compositions studied in the Barre area do not exceed 20.2% pyrope (Table 14) whereas those of the Ware area usually contain about 25% pyrope. Sillimanite-garnet-cordierite zone rocks also have garnets which have a low spessartine component compared to most of those of the Barre area. Further discussion on the significance of zoning trends of garnets across the Barre area is given below.

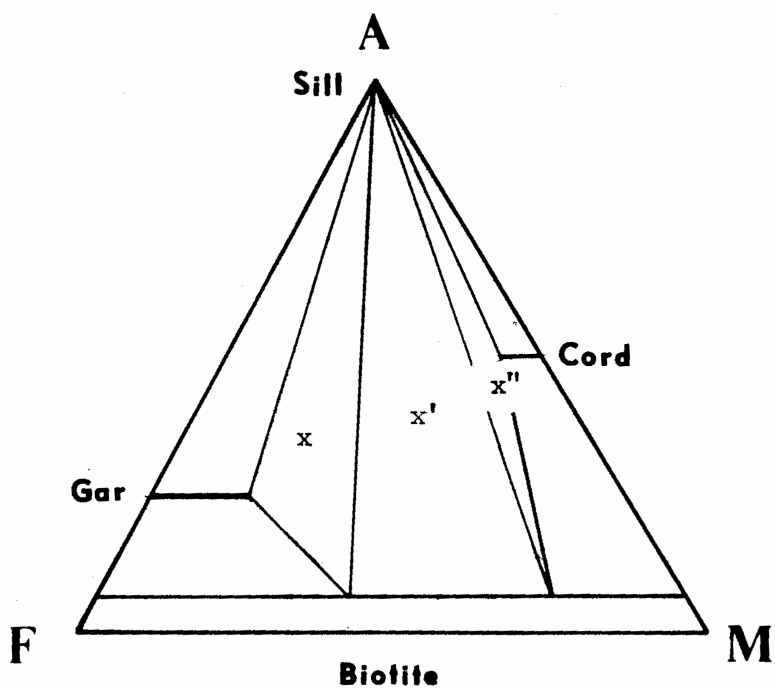


Figure 20. Schematic AFM (Ksp) projection showing the three common assemblages found in the Barre area for bulk compositions x, x' and x".

Calc-Silicate Rocks

Calc-silicate beds and boudins are common in the Barre area. They are most prevalent in the Fitch Formation and the Gray Granulite Member of the Paxton Schist but occur as minor accessory rock types of the Partridge and Littleton Formations. A list of mineral assemblages is presented in Table 13. In addition to the obvious abundance of quartz-plagioclase-diopside-sphene assemblages, many calc-silicate rocks also have actinolite, epidote and scapolite. Calcite, muscovite and quartz were never found in actual contact.

Mafic Igneous Rocks

Mafic igneous rocks in the Barre area are represented by small bodies of amphibolite in the Partridge Formation, the Cummingtonite Gneiss Member of the Littleton Formation and one mafic gneiss lens in the Coys Hill Granite. The assemblages in these rocks are:

1. quartz-plagioclase-biotite-hornblende-cummingtonite-garnet-sphene

2. quartz-plagioclase-biotite-hornblende-cummingtonite

The hornblende in these assemblages is typically pleochroic from light green to dark green, the cummingtonite is pale yellow to colorless. No microprobe analyses have been obtained on the minerals in these rocks, but they appear to be similar to andesine-hornblende-cummingtonite amphibolites studied elsewhere in central Massachusetts, although the association of cummingtonite with sphene is unusual.

	Calcite	Sphene	Labradorite-Bytownite	Orthoclase-(Microcline)	Clino-zoisite	Diopside	Actinolite	Garnet	Scapolite
737+50			x	x					
TB-470		x	x	x		x			
TB-523			x	x		x			
TB-209		x	x	x	x	x			
743+50			x	x	x	x	x		
608+75			x	x	x			x	
TB-276A 745+00 597+00	x	x	x	x	x	x	x		
TB-276B TB-466		x	x	x	x	x	x		
745+00 B	x	x	x	x		x	x	x	
692+50	x	x	x	x	x	x	x	x	x

Table 13. List of mineral assemblages in calc-silicate rocks in the Barre area.

CONDITIONS OF METAMORPHISM

It appears that the rocks studied within the Barre area lie east of the sillimanite-orthoclase-garnet-cordierite zone defined by Tracy et al. (1975) as the highest grade regionally metamorphosed rocks in central Massachusetts and lie astride the transition from the sillimanite-orthoclase-muscovite to the sillimanite-orthoclase zone. Mafic and aluminous assemblages place the Barre area in the amphibolite facies of regional metamorphism (Winkler, 1965).

Electron probe analyses of coexisting minerals from nine aluminous schists collected from the Quabbin Aqueduct across the Barre area are shown in Tables 14 and 15 and plotted in Figures 21, 22, and 23. Like the garnets studied by Hess (1971), Grant and Weiblen (1971), Tracy, Robinson and Thompson (1976), and Robinson and Tracy (1976) retrograde zoning from core to rim is evident, indicating lower temperature reactions involving garnet. Elemental zoning in the garnets is a function of the P-T history of the rock, bulk composition, availability of metamorphic fluids at the time of garnet growth and garnet diffusion rates, as well as the various prograde and retrograde continuous reactions the garnet may have been involved in.

Element distribution paths of zoned garnets in these assemblages (Figures 22 and 23), are consistent with variations found in similar grade rocks studied in the Quabbin Reservoir and Ware areas (Tracy et al., 1976). Using the methods proposed by these authors, the compositions of garnet-biotite pairs have been used to estimate temperatures across the area (Table 16). Applying the compositions of garnet cores,

TABLE 14 . MICROPROBE ANALYSES OF GARNETS.

	928+00		866+00		858+50		746+25		722+00		694+00	
	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim
SiO_2	37.95	37.50	37.13	37.40	36.29	36.42	35.65	36.07	36.54	36.61	36.32	37.14
TiO_2	0	.05	.0	.0	0	0	0	0	0	0	.03	.08
Al_2O_3	21.87	21.61	21.79	21.61	21.34	21.45	21.28	21.04	21.38	21.04	20.26	20.47
Cr_2O_3	.03	.04	.03	.05	.04	.04	0	.02	0	0	0	0
FeO	34.86	37.96	34.79	34.94	34.22	34.55	31.97	32.36	32.26	33.06	32.04	31.73
MnO	.87	1.38	3.92	4.46	3.96	5.19	4.83	5.34	4.48	4.71	4.99	5.59
MgO	5.21	2.22	2.92	2.26	3.12	1.69	3.44	2.40	3.54	2.71	3.71	2.74
CaO	.74	.99	1.03	1.02	1.04	1.04	1.15	1.36	1.12	1.17	1.09	1.09
Total	101.53	101.75	101.61	101.77	100.01	100.38	98.32	99.32	99.35	99.67	98.44	98.84

Formulas based on 12 oxygens

Si	2.973	2.985	2.954	2.978	2.937	2.953	2.924	2.958	2.958	2.968	2.979	3.029
Al	2.019	2.025	2.043	2.027	2.036	2.048	2.055	2.034	2.038	2.042	1.961	1.968
Ti	0.00	.002	.00	.00	.00	.00	.00	.00	.00	.00	.002	.005
Cr	.00	.002	.00	.002	.002	.002	.00	.00	.00	.00	.00	.00
Fe	2.283	2.527	2.314	2.324	2.316	2.341	2.192	2.219	2.183	2.242	2.200	2.165
Mn	.057	.091	.264	.299	.271	.354	.334	.371	.306	.324	.347	.386
Mg	.607	.261	.345	.266	.418	.293	.418	.293	.425	.326	.453	.333
Ca	.060	.084	.086	.086	.088	.090	.101	.118	.095	.100	.096	.095
	3.007	2.963	3.009	2.975	3.050	2.987	3.045	3.001	3.009	2.992	3.096	2.979
Mol % Alm	75.9	85.3	76.9	78.1	75.9	78.4	72.0	73.9	72.5	74.9	71.1	72.7
Mol % Py	20.2	8.8	11.5	8.9	12.3	6.8	13.8	9.8	14.1	10.9	14.6	11.2
Mol % Gr	1.9	2.8	2.8	2.9	2.9	3.0	3.3	3.9	3.2	3.3	3.1	3.2
Mol % Sp	1.9	3.1	8.7	10.1	8.9	11.9	10.9	12.4	10.2	10.8	11.2	13.0

TABLE 15. MICROPROBE ANALYSES OF BIOTITES AND CORDIERITE.

	BIOTITES							CORDIERITE
	928+00	866+00	858+50	746+25	722+00	694+00	713+75	713+75
SiO_2	35.30	35.38	34.57	34.90	34.52	36.85	38.50	49.04
TiO_2	3.97	3.65	3.82	4.02	3.68	3.86	2.17	0.00
Al_2O_3	18.85	19.26	19.53	18.17	19.00	18.49	19.48	33.41
Cr_2O_3	.00	.05	.01	.01	.03	.00	.08	0.00
FeO	20.12	21.36	20.47	19.48	20.13	18.51	8.97	3.10
MnO	.10	.12	.09	.23	.11	.14	.13	.34
MgO	.00	.02	.02	.00	.00	.00	11.30	11.30
Na_2O	.13	.14	.14	.12	.14	.12	.10	.22
K_2O	9.56	9.48	9.61	10.04	9.03	9.65	9.27	.01
	97.07	97.28	96.07	95.64	95.04	96.50	95.40	97.42
Formulas based on 11 oxygens.								18 oxygens
Si	2.666	2.657	2.628	2.663	2.645	2.751	2.761	4.982
Al	1.334	1.343	1.372	1.337	1.355	1.249	1.239	1.018
	4.000	4.000	4.000	4.000	4.000	4.000	4.000	6.000
Al	.333	.361	.377	.396	.361	.379	.408	2.985
Ti	.222	.205	.218	.230	.211	.217	.116	0.000
Cr	.000	.000	.000	.000	.000	.000	.004	0.000
Fe	1.262	1.340	1.301	1.243	1.289	1.156	.538	0.263
Mn	.004	.006	.004	.013	.006	.009	.004	0.029
Mg	.965	.875	.883	.985	.951	.989	1.786	1.712
	2.786	2.787	2.783	2.867	2.818	2.750	2.856	4.989
Ca	.000	.000	.000	.000	.000	.000	.000	.002
Na	.018	.020	.020	.016	.020	.018	.013	.043
K	.914	.908	.930	.977	.881	.919	.848	.000
	.932	.928	.950	.993	.901	.937	.861	.045
X_{Fe}	.567	.605	.596	.558	.575	.539	.231	.133
X_{Mg}	.433	.395	.404	.442	.425	.461	.769	.867

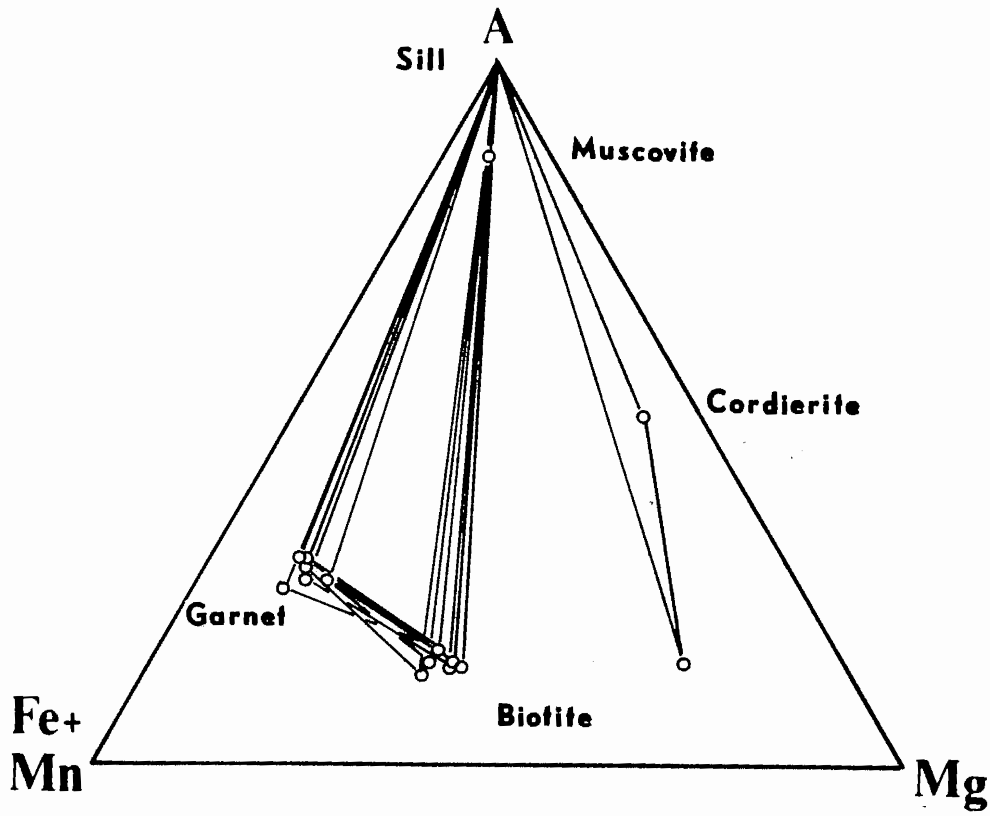


Figure 21. Plotted compositions of mineral assemblages from the Barre area, on AFM (Ksp) projection. Note that analysed assemblages fall into two bulk compositions garnet-biotite-sillimanite ± muscovite and cordierite-biotite-sillimanite. Also note the plotted position of analysed muscovite.

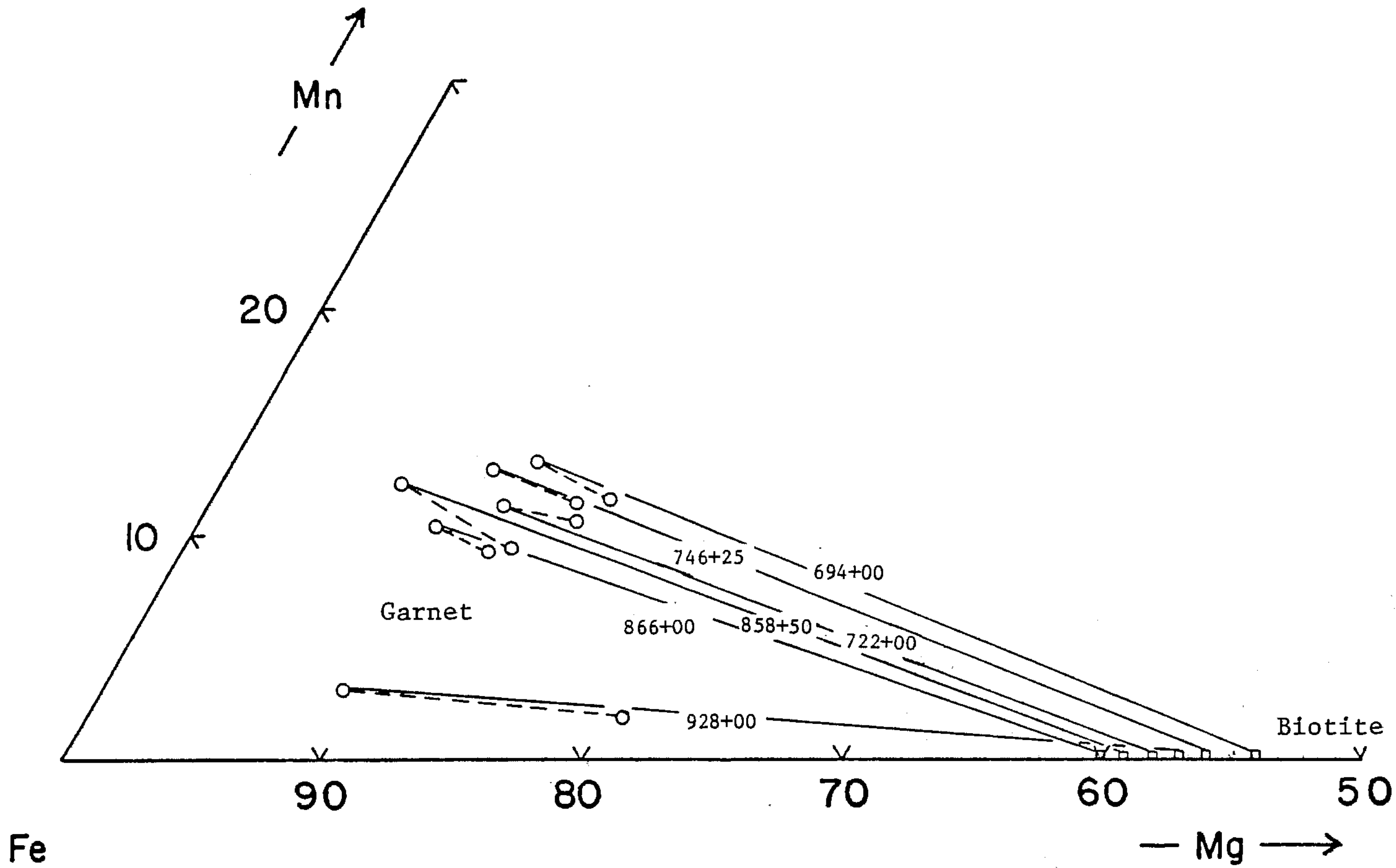


Figure 22. Projection of sillimanite-biotite-garnet three phase triangles from sillimanite onto the base of A-Fe-Mg-Mn tetrahedron. Plot is designed to show the range of spessartine component in garnets in equilibrium with biotite. Solid lines connect garnet rims to biotites, fine dashed lines tie garnet rims to garnet cores.

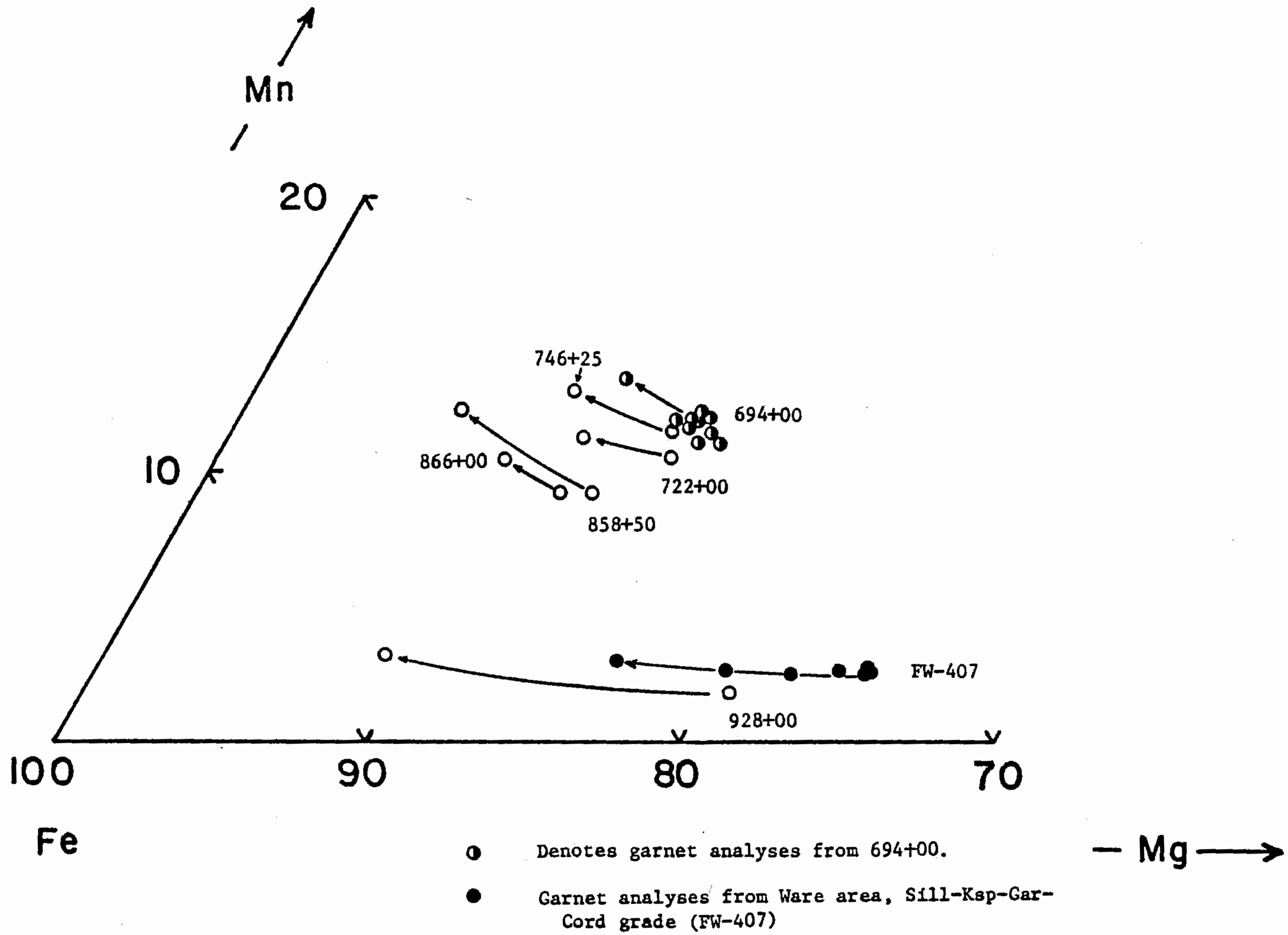


Figure 23. Plot of analysed garnet cores and garnet rims in biotite-sillimanite-garnet assemblages, shown in ternary Fe-Mg-Mn system. Arrows connect garnet cores to rims.

Table 16. GARNET-BIOTITE Fe-Mg FRACTIONATION AND ESTIMATED TEMPERATURES AND PRESSURES.

Sample		X_{Fe}	X_{Mg}	K_D Gar-Bio Mg-Fe	ln K_D	T C	Minimum P kbar
928+00	Gar core	.79	.21	2.84	1.04	780	5.8
	Gar rim	.91	.09	7.63	2.03	490	
	Biotite	.57	.43				
866+00	Gar core	.87	.13	4.46	1.49	620	5.1
	Gar rim	.90	.10	6.00	1.79	550	
	Biotite	.60	.40				
858+50	Gar core	.86	.14	4.26	1.45	640	5.2
	Gar rim	.92	.08	7.99	2.07	480	
	Biotite	.59	.41				
746+25	Gar core	.84	.14	4.13	1.41	655	5.3
	Gar rim	.88	.12	5.76	1.75	555	
	Biotite	.56	.44				
722+00	Gar core	.84	.16	3.80	1.33	670	5.3
	Gar rim	.87	.13	4.84	1.57	600	
	Biotite	.58	.42				
694+00	Gar core	.83	.17	4.15	1.42	650	5.5
	Gar rim	.86	.14	5.23	1.65	585	
	Biotite	.54	.46				

corrected for grossular content, to the ternary Fe-Mg-Mn diagram of Tracy and others (1976, Figure 6, p. 720) and assuming an average temperature of 650°C, minimum pressures are estimated to have been 5.1 kb to 5.8 kb. These pressures and temperatures, as expected, lie within the field of sillimanite stability as determined in various experimental work (Richardson et al., 1969; Newton, 1966; Holdaway, 1971).

GEOLOGIC HISTORY OF THE AREA

The earliest recognizable geologic event in the Barre area is the deposition of the sulfidic shales and silts of the Partridge Formation in Middle Ordovician time. Early in the depositional history of the Partridge Formation, thin basaltic flows or mafic volcanic ashes were laid down that are now recognized as amphibolite lenses in the lower parts of the formation.

Firm evidence for an orogenic episode in the later part of the Ordovician is lacking in the Barre area, but numerous authors (see Pavlides et al., 1968) have noted the effect of such an episode throughout much of New England and the northern Appalachians. It is likely that part of the Taconic orogeny was going on in surrounding areas and it probably resulted in limited deposition or erosion in Late Ordovician time in the Barre area.

In the Silurian, the western portion of the Barre area was a zone of limited deposition, recorded by thin and discontinuous calcareous silts and clastics deposited in a reducing environment (Fitch Formation). To the east, however, lay a deeper marine basin which extended for some distance. The sediments collected in this basin, now mapped as the Paxton Schist, range in composition from impure quartzites and sulfide-rich shales at the base, through organic-rich shales and silts to calcareous silts and pelites at the top. An eastern source is implied for these sediments, possibly the Siluro-Devonian Newburyport Volcanic Complex (Shride, 1976).

Following the Silurian, Lower Devonian sediments were laid down as a thick and widespread sequence of cyclically bedded quartzose shales and sands (Littleton Formation). The graded-bedded nature of this formation and its widespread areal extent imply rhythmic deposition on a large, deep water shelf or in a basin. Felsic and mafic volcanic lavas, and tuffs were deposited locally in the section.

At the onset of the Acadian (Devonian) orogeny, the most intense orogenic episode recognized in the area, large sheet-like plutonic masses, the Hardwick Quartz Diorite and the Coys Hill Granite, were intruded into Devonian rocks in the uppermost parts of the stratigraphic section. Subordinate binary and biotite granites were also implaced. These rocks and the enclosing sediments were then intensely deformed and metamorphosed reaching their peak of metamorphism at temperatures around 650 C° and at pressures of at least 5.5 kbars. The earliest stage of folding in the study area was marked by east over west recumbent folding under the influence of compressional forces and/or gravity, probably from an already heated source area. The axial surfaces of these nappes were subsequently backfolded to the east. Occurences of cataclastic textures cross-cutting these structures indicate that the rocks in the Barre area were sufficiently dehydrated to undergo solid state inter-grain crushing at high strain rates. Continued east-west compression resulted in asymmetrical folds with shallow, west-dipping axial surfaces. The last deformation in the Barre area was an episode of rather weak, broad open folding.

Permian events, (Allegheny), which affected the K/Ar ages through much of New England (Zartman et al., 1970) as well as localized retrograde metamorphism are well known in central Massachusetts, and may have slightly affected the rocks in the Barre area. Mesozoic tectonics are seen at a limited scale, in the form of Jurassic diabase dikes with a N60E trend, and as extensional joints and faults.

Pleistocene glaciation left its impact on the landscape, resulting in deposition of till and numerous erratics throughout the area. Meltwater deposits are common in the Barre area typically seen as fluvioglacial drift in valleys, discontinuous eskers or as kame terrace deposits.

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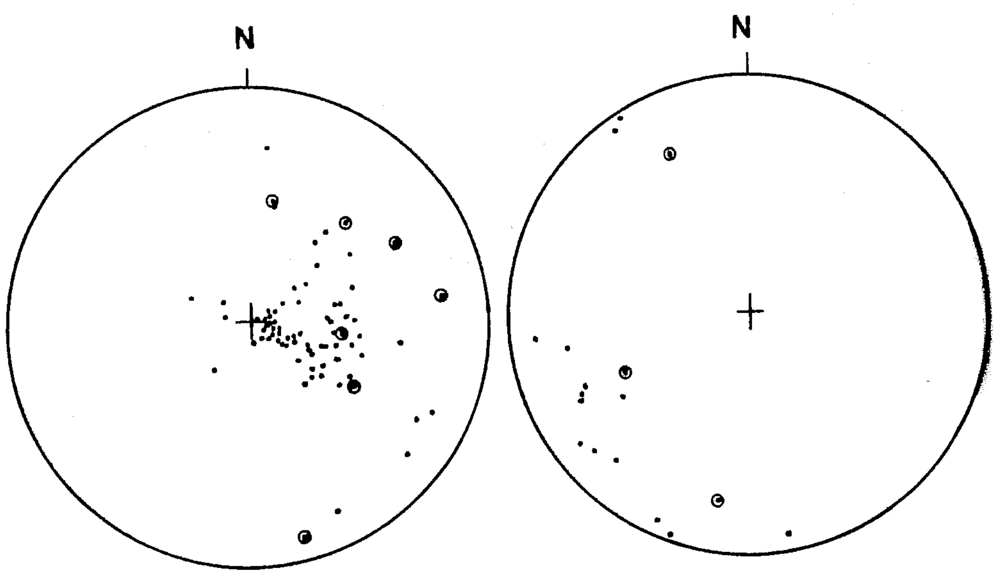
APPENDIX

This appendix contains 28 equal-area, lower hemisphere plots from 14 sectors of poles to bedding (⊙) and foliation (on the left) and fold axes (⊙) and mineral lineations (on the right). The location of each of the sectors is shown in Figure 9.

Poles to bedding (⊙) and foliation (·) | Minor fold axes (⊙) Mineral lineations (·)



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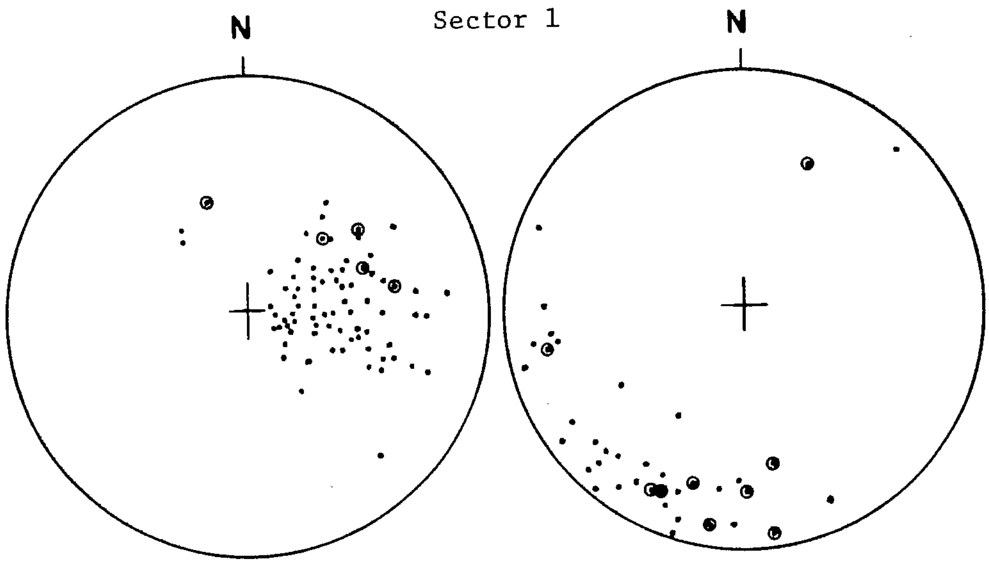

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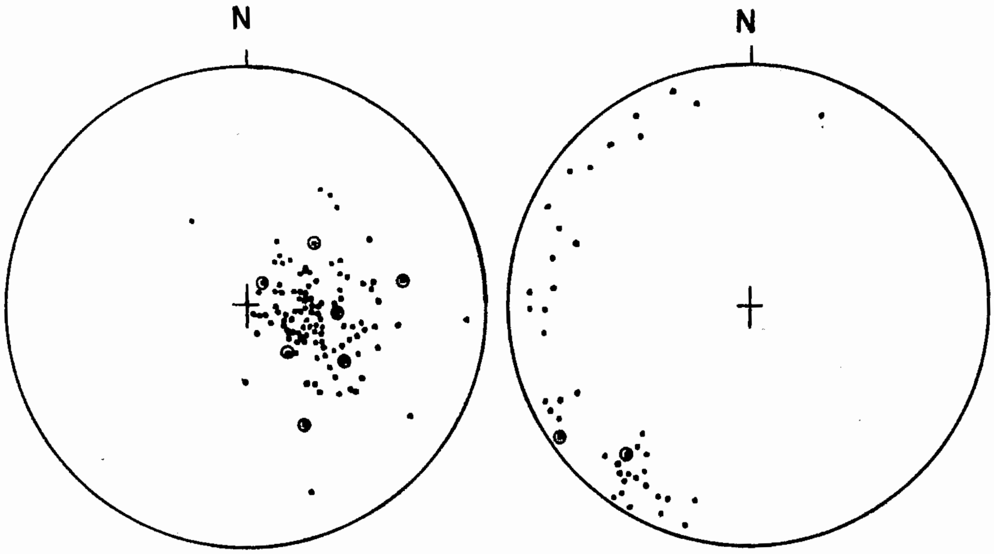

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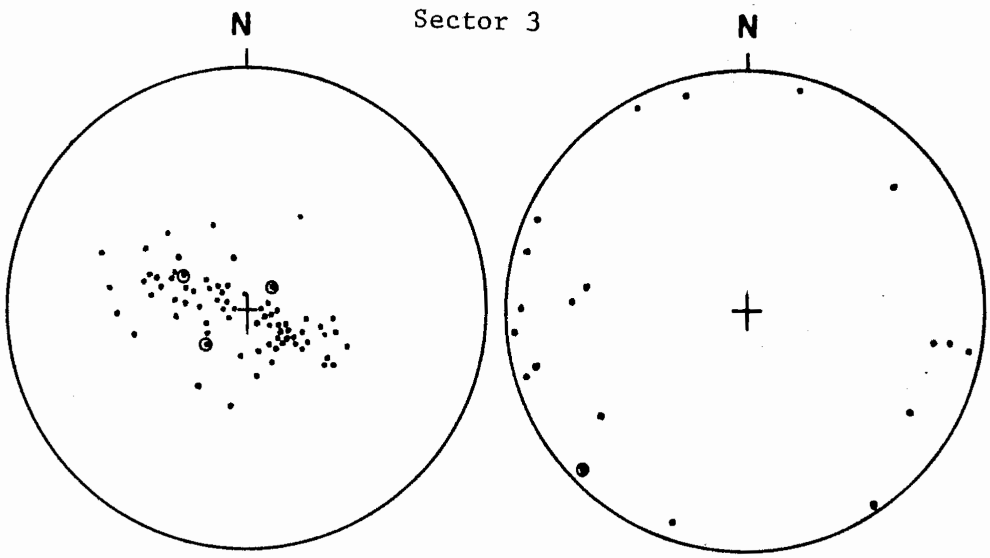

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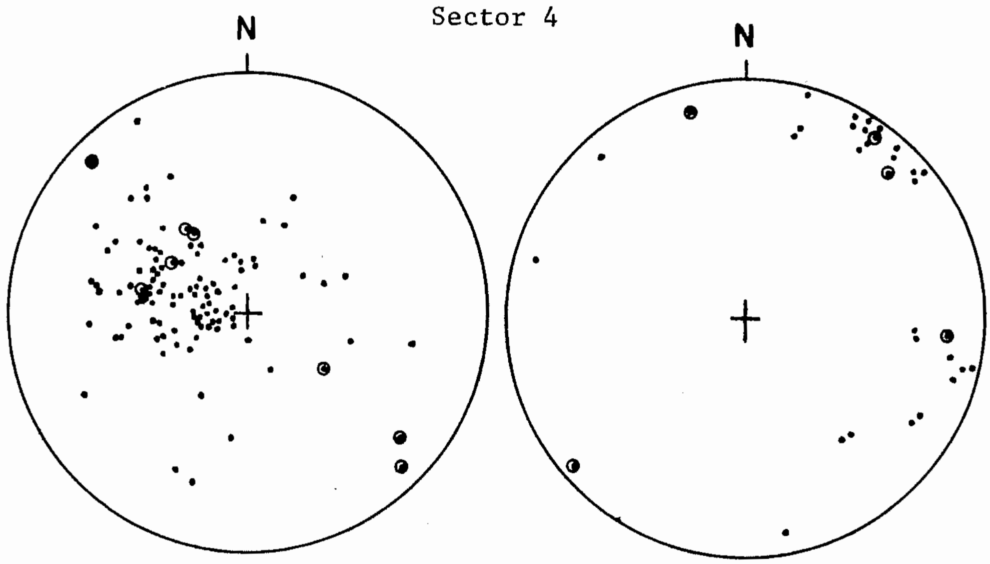

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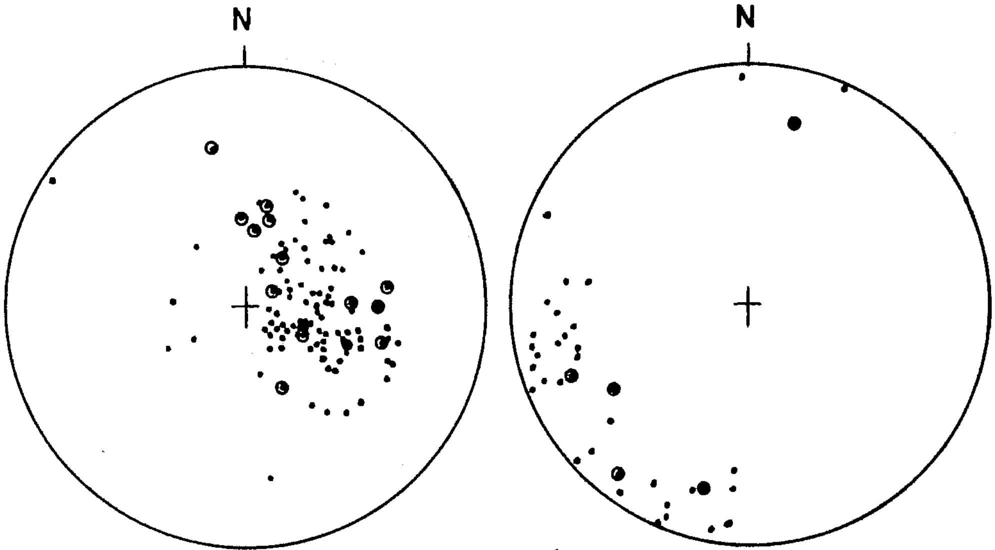

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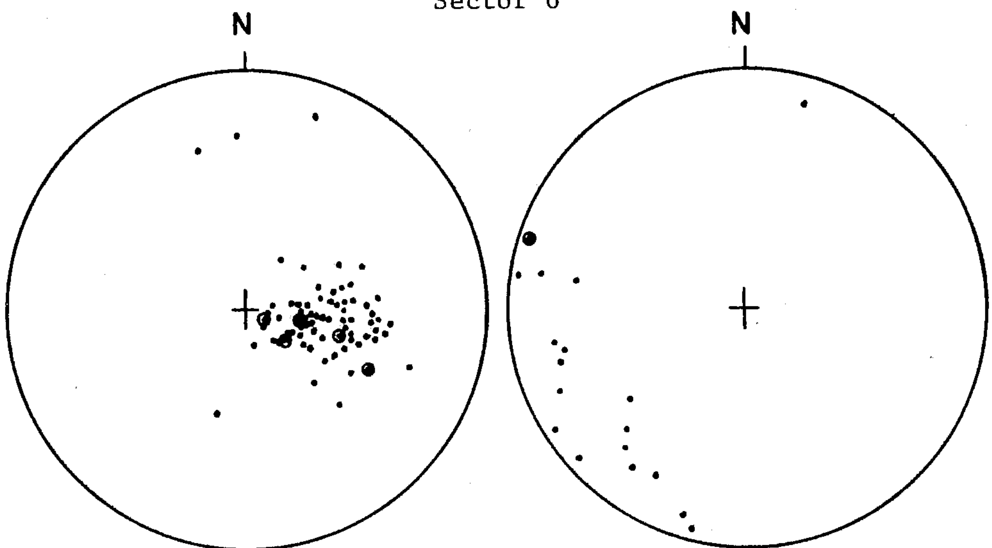

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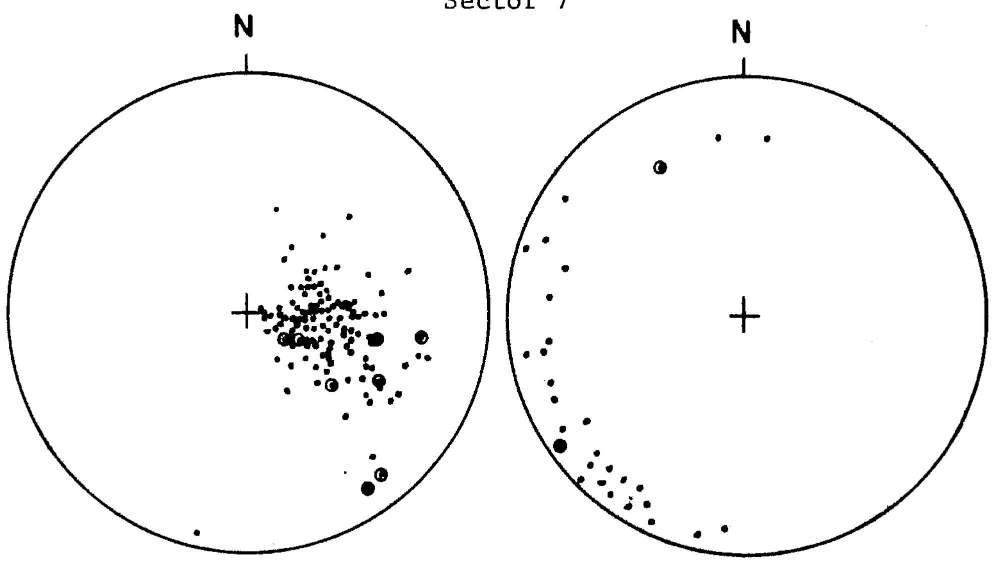

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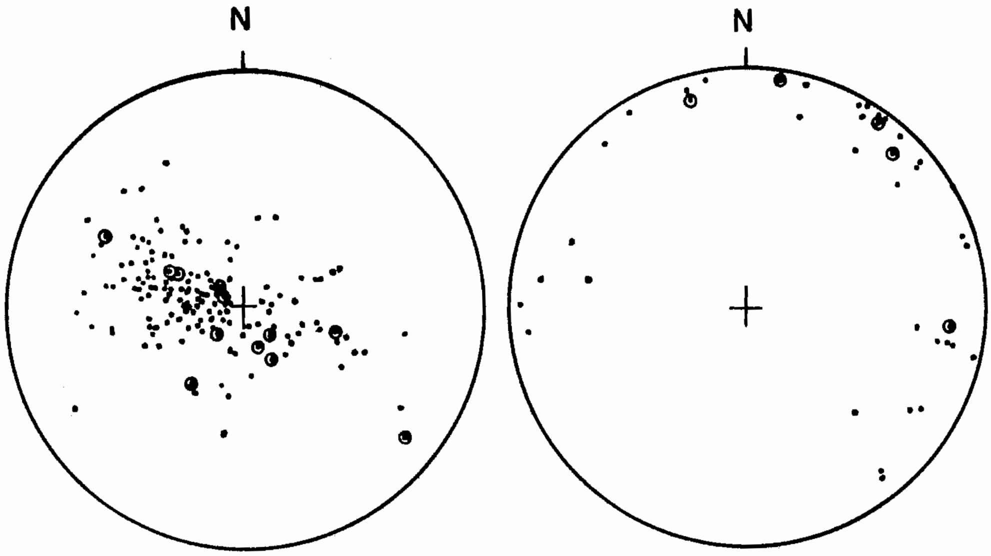
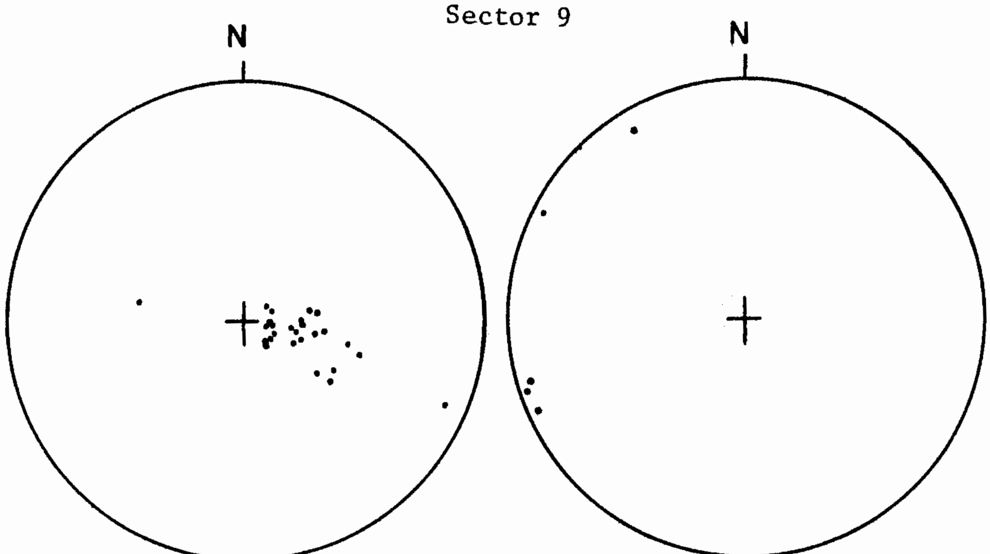


Sector 9



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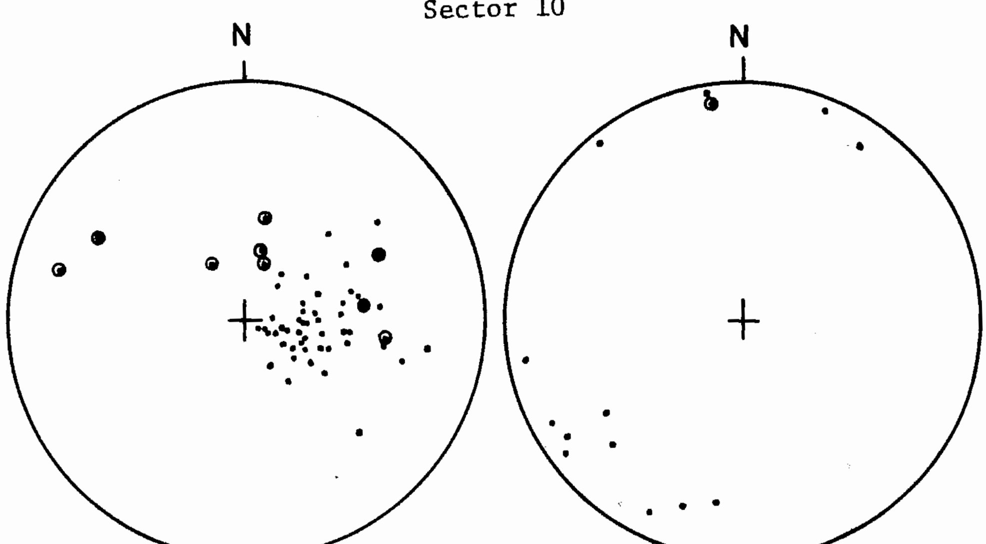

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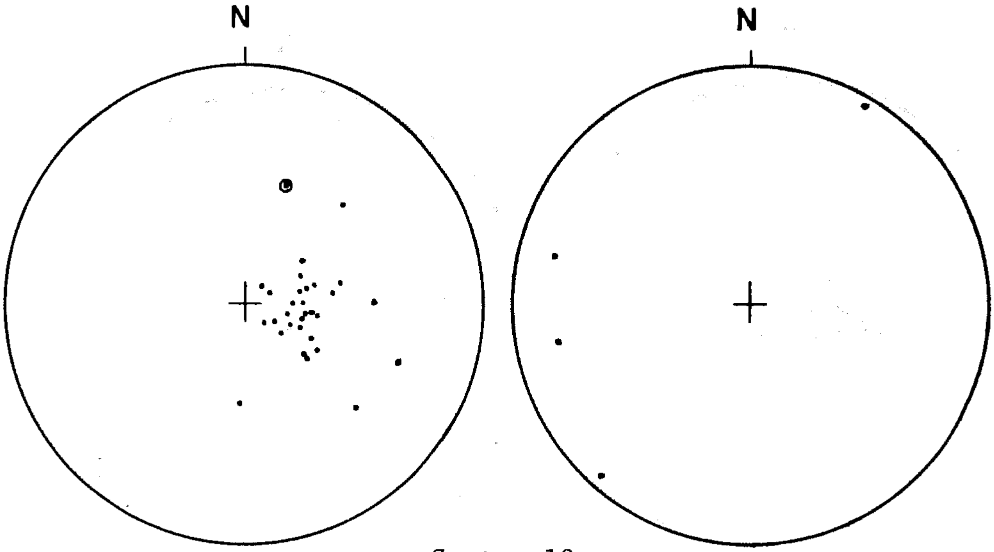

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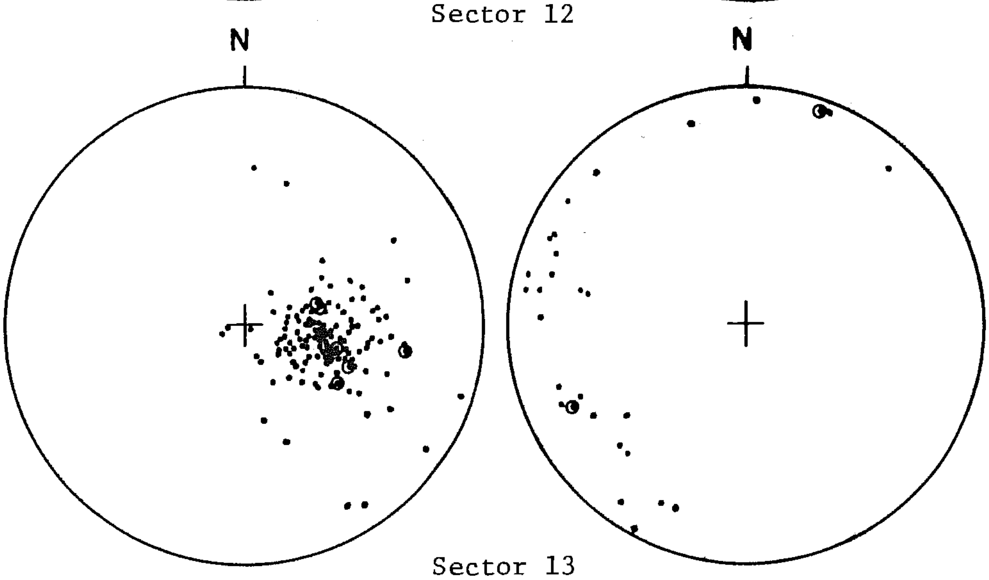

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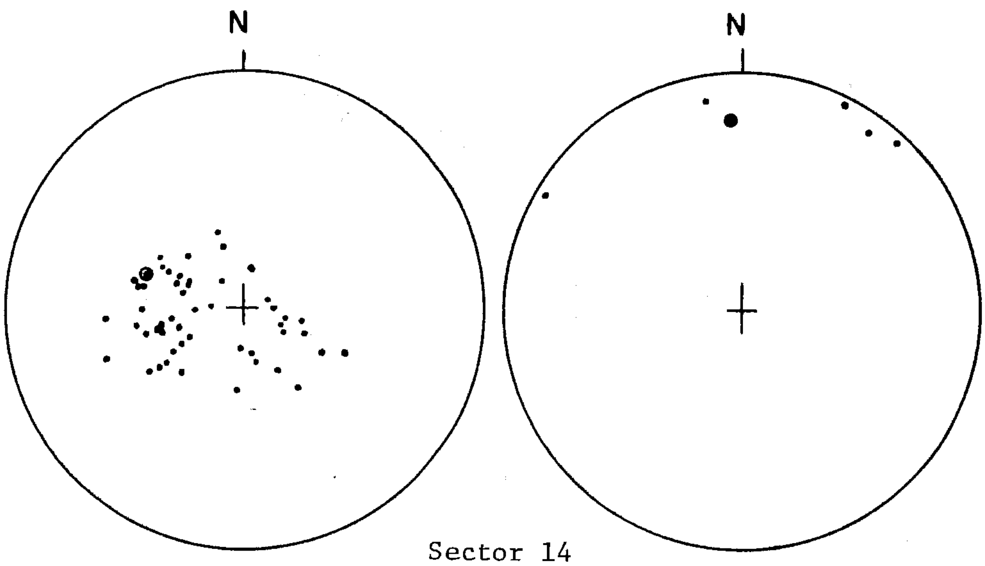


Sector 14

PLATE I BEDROCK GEOLOGIC MAP, BARRE AREA, CENTRAL MASSACHUSETTS

EXPLANATION

INTRUSIVE IGNEOUS ROCKS

Jurassic

Jd

Diabase dike
Jd: Fine-grained augite-plagioclase diabase.

Devonian?

h

Hardwick Quartz Diorite
h: Strongly foliated, medium-grained, biotite quartz diorite with minor amounts of biotite granite and biotite granodiorite gneiss.

ch

Coys Hill Granite
ch: Well foliated, massive quartz monzonite and biotite granite gneiss. Typically porphyritic with microcline phenocrysts up to 2 inches across in matrix of quartz, plagioclase, biotite, garnet and rarely sillimanite.

gg

Gneiss of Pleasant Brook
gg: Well foliated, light-colored, medium-grained biotite-garnet-quartz-plagioclase-orthoclase gneiss.

STRATIFIED ROCKS

Lower Devonian

Dlo **Dl** **Dlf**

Littleton Formation
Dl: Gray Schist Member: Gray-weathering, biotite-garnet-sillimanite-orthoclase schist, commonly in beds 2-5 inches thick, locally exhibits graded bedding.
Dlf: Feldspathic Gneiss Member: Quartz-feldspar gneiss with minor amounts of biotite. Small 1/8 inch pink garnets are characteristic.
Dlo: Cummingtonite Gneiss Member: Dark brown, medium-grained cummingtonite-hornblende-plagioclase gneiss.

Silurian

Sp **Spg** **Spw**

Paxton Schist
Sp: Gray Granulite Member: Medium-grained, gray- to purple-weathering, biotite-quartz-labradorite granulite and rusty-weathering quartz-andesine-biotite-sillimanite schist. Calc-silicate beds consisting of actinolite-diopside-clinozoisite-sphene and labradorite are also present.
Spg: Gray Graphitic Schist Member: Gray-weathering, graphite-biotite-sillimanite-muscovite-garnet schist. Conspicuous quartz-feldspar pods and segregations are found throughout the unit.
Spw: White Sulfidic Schist Member: Quartz-orthoclase - Mg-rich cordierite - Mg-rich biotite-sillimanite-rutile schist and feldspathic quartzite.

Sf

Fitch Formation
Sf: Sulfidic graphitic quartz-labradorite-diopside-sphene granulite.

Middle Ordovician

Ops **Opa**

Partridge Formation
Ops: Sulfidic, biotite-garnet-orthoclase-sillimanite ± muscovite schist and slabby-weathering, quartz-plagioclase-biotite-garnet granular schist. Thin biotite-diopside-quartz-plagioclase calc-silicate beds are common throughout the section.
Opa: Rare lenses of cummingtonite-hornblende-biotite amphibolites are found in the lower parts of the formation.

Contact; location accurate where solid, approximate where dashed, inferred where dotted.

A ——— A' Line of cross-section

22 Strike and dip of bedding, dot shows stratigraphic top.

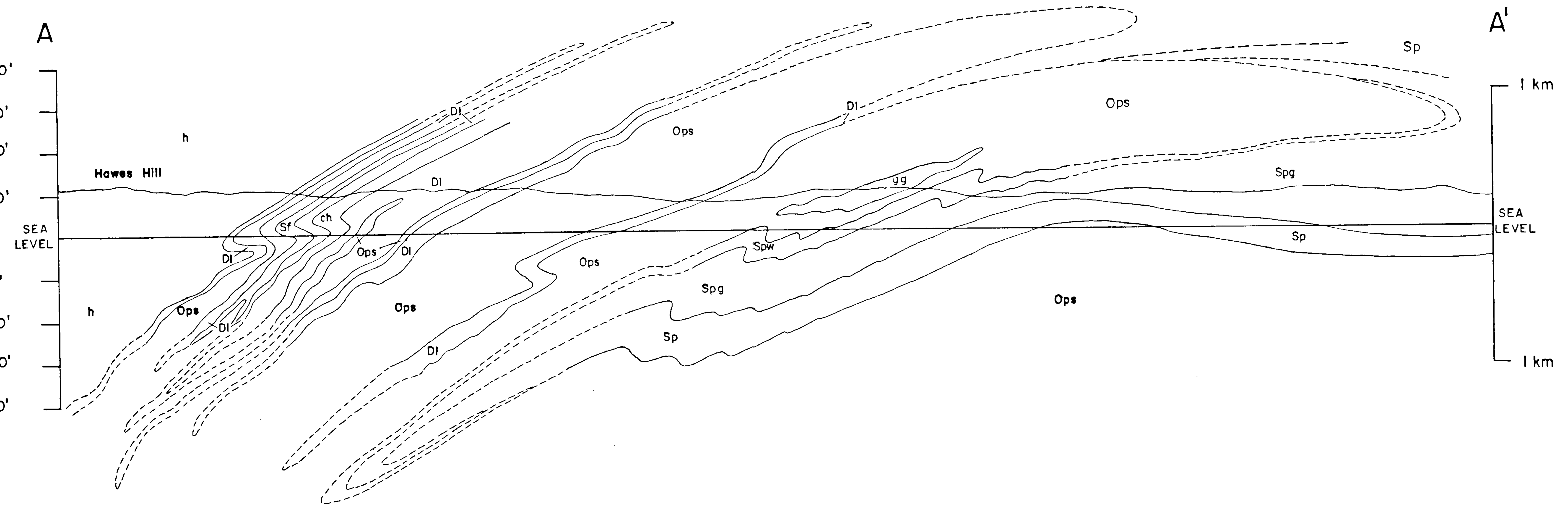
22 Strike and dip of foliation.

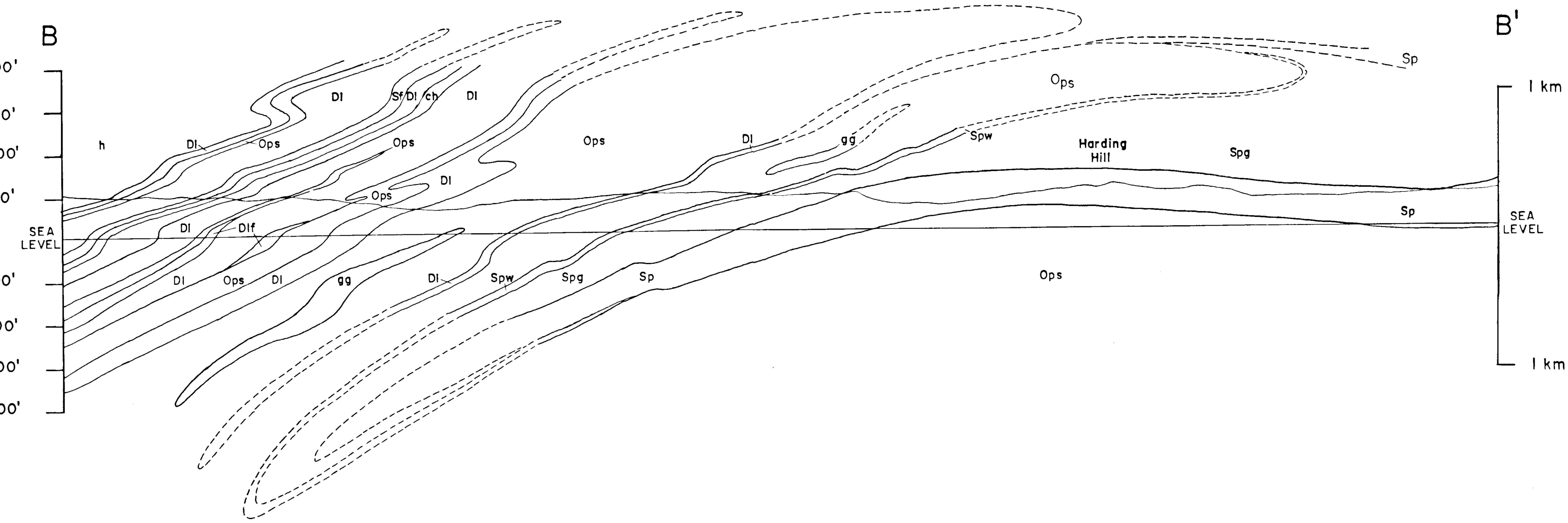
22 Strike and dip of foliation measured in Quabbin Aqueduct Tunnel (Fahlquist, 1935).

10 Trend and plunge of lineation.

Geology mapped by Robert D. Tucker
1975 and 1976

PLATE 2 GEOLOGIC CROSS-SECTIONS, BARRE AREA





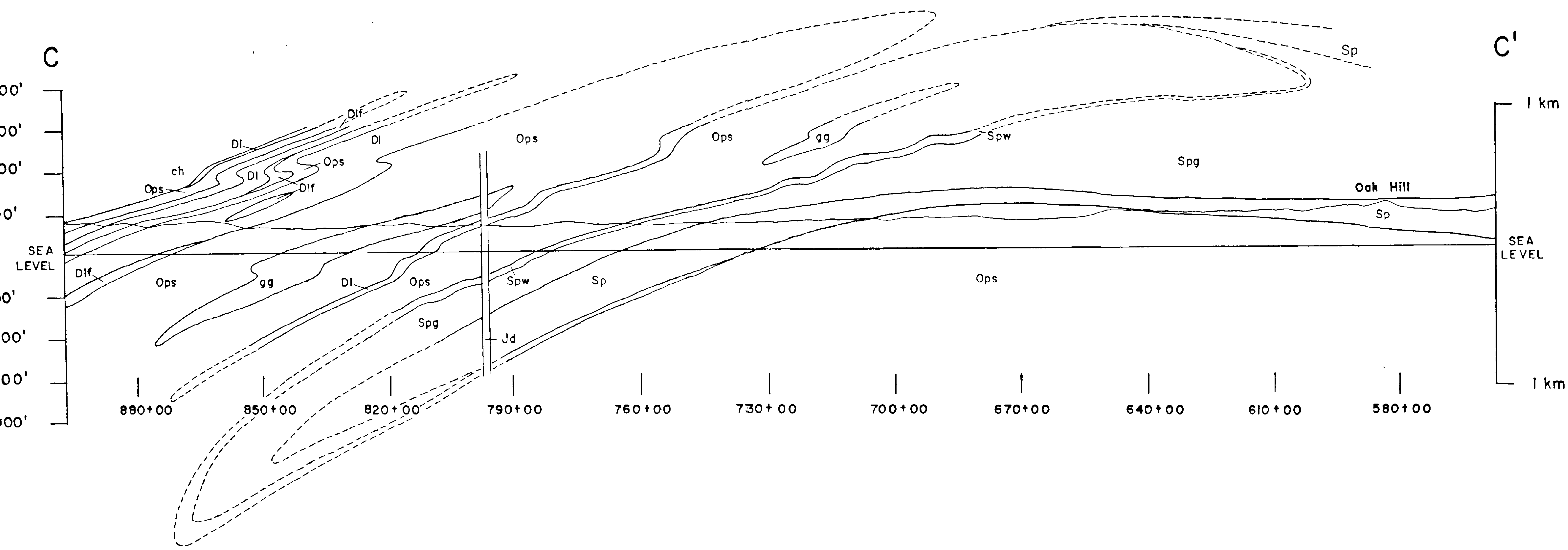
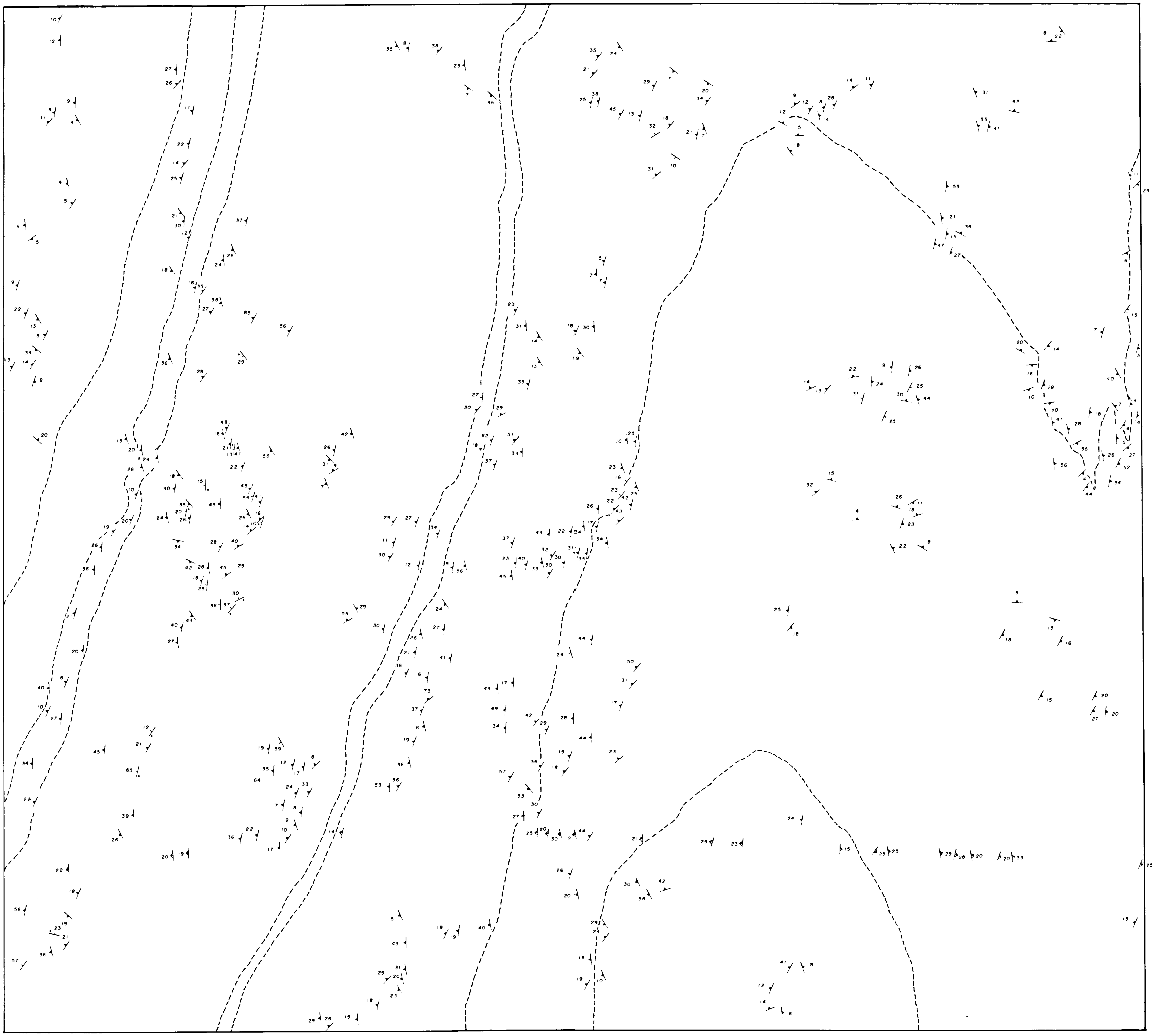


PLATE 3 MAP OF PLANAR STRUCTURAL FEATURES, BARRE AREA



EXPLANATION

42 Strike and dip of bedding. Dot indicates stratigraphic tops.

42 Strike and dip of dominant metamorphic foliation.

42 Strike and dip of metamorphic foliation based on subsurface measurement in Quabbin Tunnel (Fahlquist,1935).

Selected geologic contacts.

PLATE 4 MAP OF LINEAR STRUCTURAL FEATURES, BARRE AREA

EXPLANATION

Trend and plunge of mineral lineation.

Trend and plunge of Phase 2A mineral lineation.

Trend and plunge of axis of minor fold, showing movement sense.

Selected geologic contact.

PLATE 5 OUTCROP MAP, BARRE AREA

(WARE) 6568 I SW

SCALE 1:24 000

1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 KILOMETER

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

UTM GRID AND 1969 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

14½° 258 MILS
1°59' 35 MILS

QUADRANGLE LOCATION

(PAXTON) 6668 IV SW

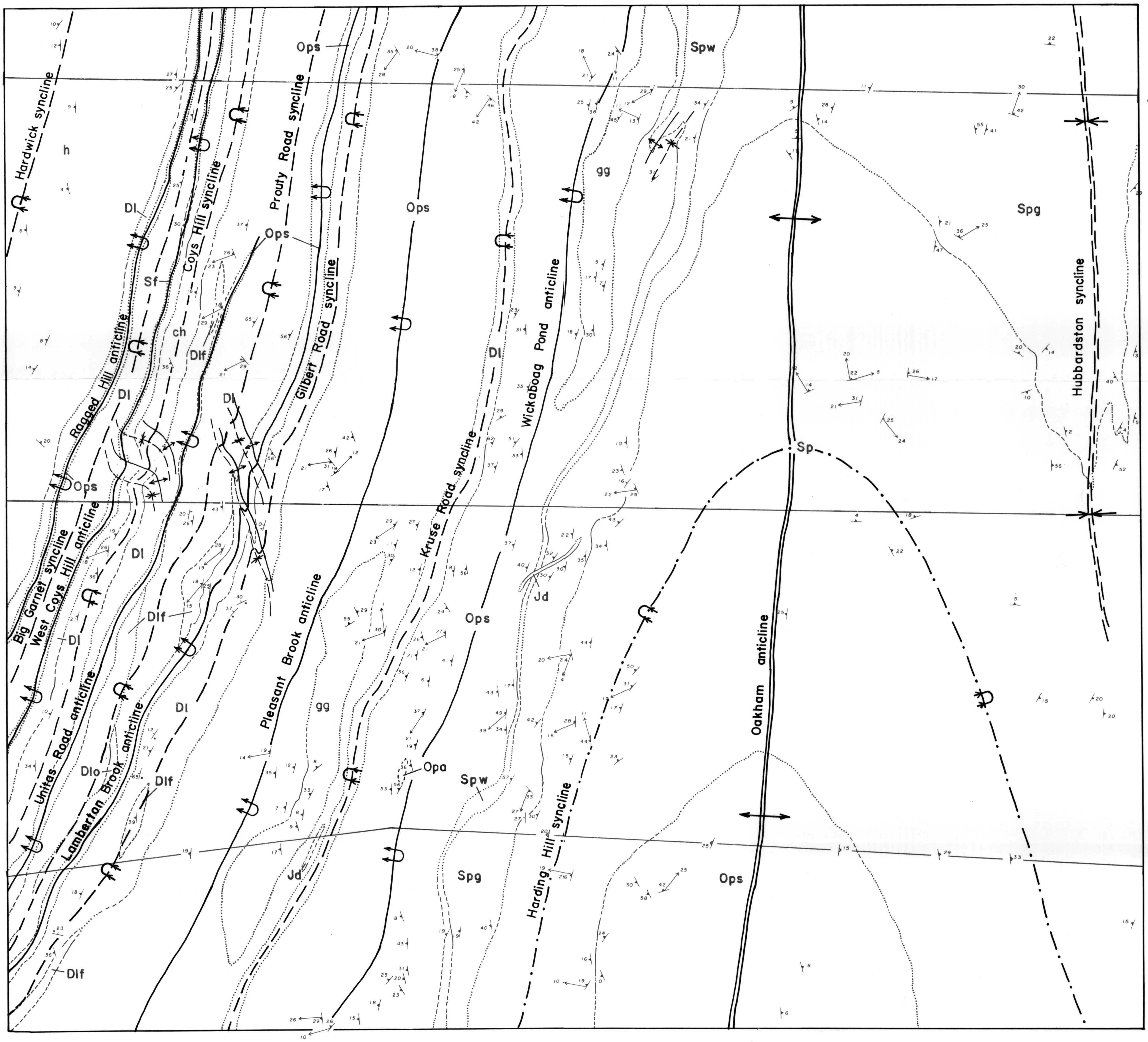
ROAD CLASSIFICATION

Secondary highway, all weather, hard surface
Light-duty road, all weather, improved surface
Unimproved road, fair or dry weather
State Route

EXPLANATION

Area of bedrock outcrop

PLATE 6 MAP OF AXIAL SURFACES, BARRE AREA



EXPLANATION

Major early isoclinal folds
anticline
syncline

Phase 2A recumbent fold
syncline

Southwest-trending "main stage" folds
anticline
syncline

Late open folds
anticline
syncline