BEDROCK GEOLOGY OF THE PELHAM-SHUTESBURY SYNCLINE PELHAM DOME, WEST-CENTRAL MASSACHUSETTS

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ABSTRACT

The Pelham-Shutesbury syncline is situated on the east and southwest flanks of the Pelham gneiss dome in the Bronson Hill anticlinorium of west-central Massachusetts. The cover rocks in the syncline, which overlie the Late Precambrian(?) to Middle Ordovician(?) Fourmile Gneiss of the Pelham dome, consist of various Middle Ordovician through Devonian sedimentary and volcanic units that have been regionally metamorphosed to kyanite-staurolite grade. These units consist of the Middle Ordovician Ammonoosuc Volcanics and Partridge Formation, the Silurian Clough Quartzite, and the Lower Devonian Littleton Formation. Six members have been defined within the Partridge Formation: Basal Quartzite, Lower Schist, Biotite Gneiss, Amphibolite, Felsic Gneiss, and Upper Schist. The Basal Quartzite Member lies along the west limb of the syncline in sharp contact with the Fourmile Gneiss. The Lower and Upper Schist Members consist of rusty-weathering biotite-muscovite-garnet schist, stratigraphically separated by the Amphibolite and Felsic Gneiss Members in the central portion of the syncline. The Biotite Gneiss Member consists of rusty-weathering, coarse-grained biotite-rich gneiss at the base of the formation on the east limb. The Amphibolite Member consists of well layered garnet-pistacite-hornblende amphibolite interpreted as metamorphosed mafic volcanoclastic rocks. The overlying Felsic Gneiss Member is medium- to coarse-grained massive to moderately layered plagioclase-microcline gneiss interpreted as metamorphosed felsic volcanics. The stratigraphy of the syncline is lithically diverse and asymmetric, with a comparatively thick and complete sequence on the west limb and a thinner and less varied sequence on the east limb.

The outcrop pattern of the syncline is shaped like a "J", 27km long and 5km wide, and is largely a product of Acadian (Devonian) deformation. The syncline can be described as a westward-closing, isoclinal recumbent syncline refolded about the southeast-plunging end of the Pelham gneiss dome. The axis of the syncline appears to trend nearly N-S, with a north-plunging hinge on the northeast flank of the dome and a south-plunging hinge on the southwest flank of the dome.

Evidence for three phases of deformation has been found in the area; the first two pertain to the Acadian orogeny and the last to Mesozoic extension. The first phase was characterized by eastward-directed recumbent folding that resulted in the formation of the Pelham-Shutesbury syncline proper. The second phase consisted of the upward doming of the Pelham dome and the resultant formation of a foliation arch and N-S trending mineral lineation. During this phase, the syncline was gently folded about the dome axis, eventually resulting in the present "J"-shaped map pattern. Northward movement of the dome core rocks relative to mantling strata late in this phase caused the formation of the late asymmetric folds that locally deform the mineral lineation. N-S extension parallel to the dome axis and related boudinage constitute another late aspect of the dome phase. Mesozoic brittle fracture and diabase dike emplacement characterized the third phase. The inferred stress system based on the orientations of joints, faults, and diabase dikes produced during this phase had the following approximate principal stress axes: σ_1 -vertical, σ_2 - N65E, horizontal, and σ_3 - N25W, horizontal.

Electron microprobe analyses of minerals in a hornblende-garnet-augite-scapolite assemblage in the Amphibolite Member of the Partridge Formation showed disparate Fe/(Fe + Mg) ratios in coexisting hornblende and augite (.596 and .379, respectively) and an unusually calcic garnet composition ($Alm_{47.7}$ $Gross_{42.0}$ $Pyr_{6.5}$ $Spess_{3.8}$).

INTRODUCTION

Location

The study area is located in west-central Massachusetts between the towns of Wendell and Belchertown, and lies immediately west of the Quabbin Reservoir. This area is included in the Millers Falls, Shutesbury, Quabbin Reservoir, Winsor Dam, and Belchertown 7½-minute quadrangles. It encompasses portions of the townships of Belchertown, Pelham, Shutesbury, and Wendell. Much of the study area lies within the Quabbin Reservation, an extensive watershed preserve that fringes the Quabbin Reservoir. The area has the configuration of a "J"; measuring 27 km on the long axis and 5 km on the short axis.

Topography and Glacial Geology

Numerous small, elongate hills separated by moderately incised stream valleys characterize the topography of the study area. The maximum relief in this region is 707 feet from 525 feet on the shore of the Quabbin Reservoir to 1232 feet on the crest of a hill .6 miles northeast of the town of Shutesbury. A large portion of the area is drained by small streams that flow southeastward into the Quabbin Reservoir. The Quabbin is in turn drained by the Swift River which flows into the Chicopee River, a major tributary of the Connecticut River.

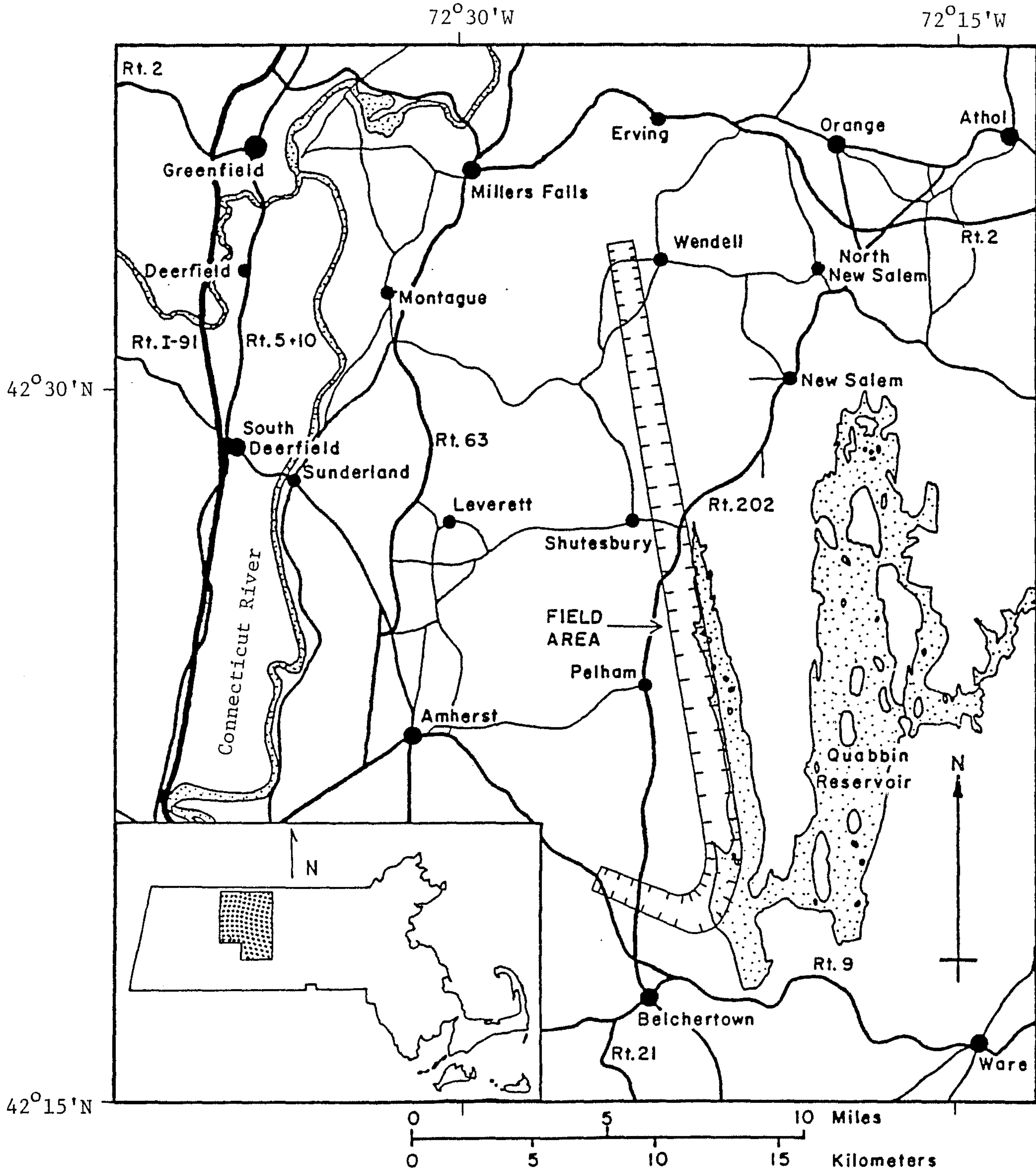


Figure 1. Index map of north-central Massachusetts showing location of study area.

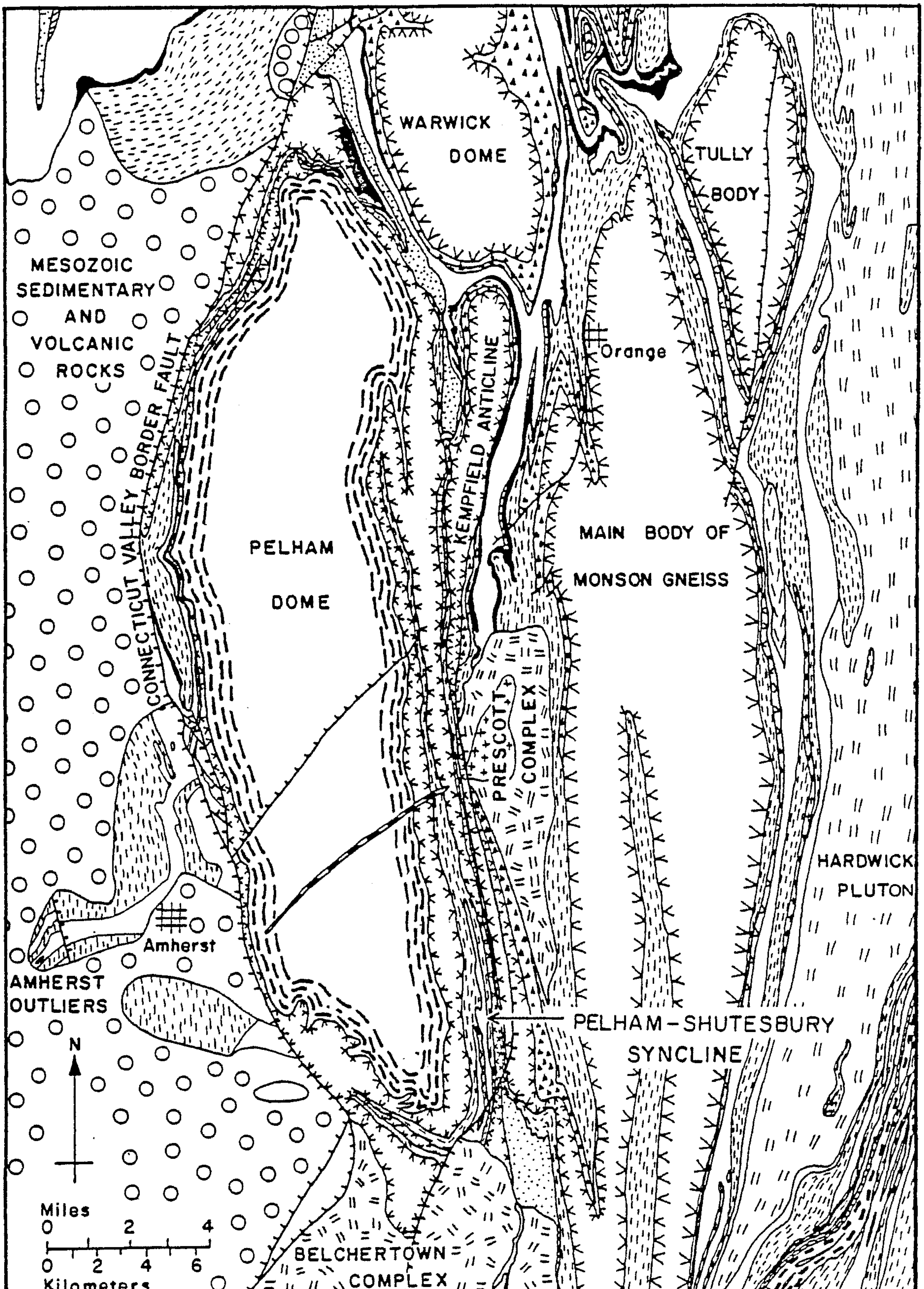
Mixed deciduous and coniferous forests characterize the vegetative cover. Pithy shrubs such as mountain laurel commonly inhabit the north and west slopes of hills.

The study area is veneered by a variety of Pleistocene glacial deposits. Unstratified glacial deposits consist of a compact, clayey till of variable thickness. The northern slopes of hills are commonly covered by thick deposits of this till. Small outwash plains, kame terraces, and a thin aeolian mantle comprise the stratified glacial deposits in the study area. The outwash plains are confined to small stream valleys and are very limited in areal extent. Steep-walled, N-S trending straight valleys atop several hills in the central portion of the study area may represent small glacial spillways. They are characteristically 6-15 meters deep and are occupied by underfit seasonal streams.

The majority of the bedrock outcrop in the area is found: on the southern and western slopes of hills, along the south and southeast facing shoreline of the west arm of the Quabbin Reservoir, and in numerous stream beds. Of particular note is a small island in the Reservoir that affords nearly complete outcrop due to fluctuating reservoir levels and the attendant wave scouring.

Regional Setting

The Pelham-Shutesbury syncline is situated on the eastern and southern flank of the Pelham gneiss dome, central Massachusetts. The Pelham dome lies along a N-S trending chain of mantled gneiss domes that comprise the Bronson Hill anticlinorium, a major stratigraphic-tectonic zone that spans northern and western New Hampshire, central Massachusetts, and cen-


WARWICK
DOME
TULLY
BODY
MESOZOIC
SEDIMENTARY
AND
VOLCANIC
ROCKS
CONNECTICUT VALLEY BORDER FAULT
KEMPFIELD ANTICLINE
Orange
PELHAM
DOME
MAIN BODY OF
MONSON GNEISS
PRESCOTT
COMPLEX
HARDWICK
PLUTON
Amherst
AMHERST
OUTLIERS
PELHAM-SHUTESBURY
SYNCLINE
N
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0 2 4
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BELCHERTOWN
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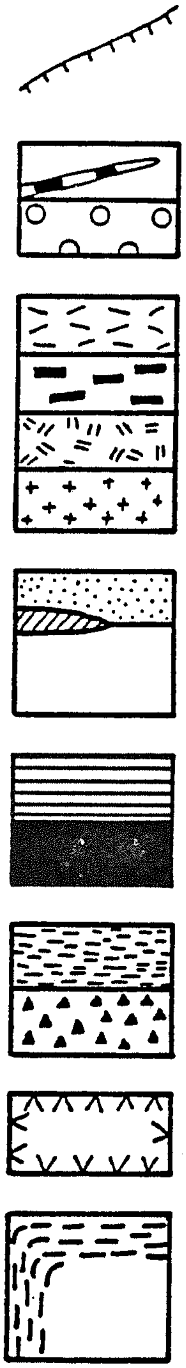


	Mesozoic normal fault, hachures on downthrown side.
Jurassic and Triassic	Diabase dike. Sedimentary rocks and basalts, west of border fault.
Devonian	Foliated granitic gneiss.
	Coys Hill porphyritic granite.
	Granodiorite and quartz diorite.
	Hornblende gabbro and hornblende diorite.
Lower Devonian	Erving and Gile Mountain Formations. Putney Volcanics.
	Littleton Formation.
Silurian	Fitch Formation.
	Clough Quartzite.
Middle Ordovician	Partridge Formation.
	Ammonoosuc Volcanics.
Ordovician or older.	Massive and layered gneisses, including Fourmile Gneiss, Monson Gneiss, Pauchaug Gneiss, and Swanzey Gneiss.
Late Precambrian	Poplar Mountain Gneiss and Quartzite, Mt. Mineral Formation, Pelham Quartzite, and Dry Hill Gneiss.

Figure 2. Generalized regional geologic map of the Bronson Hill anticlinorium in west-central Massachusetts showing the Pelham-Shutesbury syncline on the east and southwest flank of the Pelham dome (Robinson, 1979).

tral Connecticut (Thompson et al., 1968). The rocks of the Bronson Hill anticlinorium consist of pre-Middle Ordovician gneissic basement unconformably overlain by metamorphosed sedimentary and volcanic cover rocks of Middle Ordovician, Silurian, and Lower Devonian age. These rocks were metamorphosed and intensely deformed during the Acadian (Devonian) orogeny, first into a series of west-directed nappes with tens of kilometers of transport (Robinson, 1967a, 1979), then into east-directed backfolds, and finally into gravitationally induced domes of the basement and mantling strata. Accompanying syntectonic plutonism in the Bronson Hill anticlinorium of central Massachussetts included the emplacement of the Prescott and Belchertown plutons.

The Cambrian to Lower Devonian metamorphosed sedimentary and volcanic rocks of the Connecticut Valley-Gaspe synclinorium border the Bronson Hill anticlinorium to the west. This stratigraphic-tectonic zone is characterized by an eastward-dipping homoclinal sequence at its western margin and Acadian gneiss domes and older isoclinal folds in its eastern portion (Rosenfeld, 1968). In central Massachussets and central Connecticut the boundary between the Connecticut Valley-Gaspe synclinorium and the Bronson Hill anticlinorium is obscured by overlying Upper Triassic and Lower Jurassic sedimentary and volcanic rocks that occupy the Connecticut Valley Mesozoic basin. A major border fault separates this Mesozoic basin on the west from rocks of the Bronson Hill anticlinorium on the east.

The Merrimack synclinorium lies immediately to the east of the Bronson Hill anticlinorium. This stratigraphic-tectonic zone consists of Middle Ordovician, Silurian, and Lower Devonian metamorphosed sedimentary and volcanic rocks that have been deformed into a complex series of large amplitude, overturned isoclinal folds (Robinson, 1963, 1967a, and Thompson et al., 1968). The root zones of the nappes of the Bronson Hill anticlinorium are thought to lie within the Merrimack synclinorium (Thompson et al., 1968).

The core rocks of the Pelham dome consist of interlayered gneisses, quartzites, and schists of Late Precambrian to Cambrian or Middle Ordovician age (Robinson, 1963, and Ashenden, 1973). These core rocks are overlain by a mantling sequence of Middle Ordovician, Silurian, and Lower Devonian metamorphosed sedimentary and volcanic rocks. The Pelham-Shutesbury syncline represents a major infold of these cover rocks into the Fourmile Gneiss of the Pelham dome (Robinson, 1967b).

Previous Work

B.K. Emerson first named and described the Pelham-Shutesbury syncline in his geological studies of 1898. In this work, he described several rock types, including: "very coarse, rather rusty, muscovite-biotite gneiss or schist", "hornblendic rocks", and abundant granitic pegmatites. Emerson interpreted the structure of these rocks as an isoclinal syncline overturned to the west and postulated a major longitudinal fault on the east limb.

Balk (1940) compiled a report on the geology of the Quabbin Reservoir area. He noted the presence of two narrow belts of schist in the eastern flank of the Pelham dome; a western belt of quartz-biotite schist, and an eastern belt of kyanite-muscovite schist with conspicuous garnet-rich layers. These two belts of schist were claimed to lie in proximity to each other for a distance of 5 miles along the western edge of the present-day Quabbin Reservoir.

Subsequent reconnaissance and detailed mapping by Robinson (1967b) and Robinson et al. (1973) produced a sound preliminary stratigraphic framework and has better defined the extent of the syncline. Detailed mapping of an island in the west arm of the Quabbin Reservoir (Robinson, 1967b) provided an intriguing glimpse of the stratigraphic and structural complexity of the syncline.

Purpose

The objectives of this study are the compilation of an accurate and detailed bedrock geologic map of the Pelham-Shutesbury syncline, the petrographic characterization of the lithic units of the syncline, and the analysis of structural elements of the syncline. It is hoped that the results will contribute toward a fuller understanding of the complex geologic history of this region.

Field Methods

The bedrock geology of the Pelham-Shutesbury syncline was mapped directly on 7½-minute topographic map bases. Locations in the field were determined with the aid of a Brunton compass and an aneroid altimeter. The altimeter was particularly useful in areas of thick vegetation and smooth topography. Bedrock outcrops were accurately portrayed on one set of topographic bases; a second set of base maps was used for station locations and the recording of geologic contacts. At these field stations, lithologic descriptions, outcrop locations and dimensions, and the attitudes of linear and planar structural features were recorded. Islands and shoreline cliff exposures were examined using a boat provided by the Metropolitan District Commission. The field work of this study spanned the summer and fall of 1979 and 1980.

Acknowledgements

The author is deeply indebted to Peter Robinson for his unswerving and enthusiastic support of this study. He was instrumental in introducing the study area to the author, donating many days to assistance in the field, and providing incisive critical appraisal of all aspects of this project. Leo M. Hall and D.U. Wise are kindly thanked for their careful review of the manuscript. The author's wife, Nancy, provided field-going sustenance and boundless encouragement. Kurt Hollocher served as an able first mate during aquatic field excursions and often shed light on seemingly intractable mineral formulas. John Schumacher graciously advised the author on many petrologic matters. The Metropolitan District Commission-Quabbin permitted access to and provided the author with a master key to limited-access regions of the Reservation. In addition, they lent the author a boat for the purpose of examining the island and remote shoreline outcrops.

Field work for the summer of 1979 and petrographic thin sections were supported by U.S.G.S. grant 04-01-0001-400 to Robinson. The outboard motor used on Quabbin Reservoir was originally purchased in 1966 with the support of N.S.F. grant GA-390 to Robinson. Final manuscript preparation and publication was supported by N.S.F. Grants EAR-7915246 and 8116197 to Robinson.

STRATIGRAPHY

The stratigraphy of the Pelham-Shutesbury syncline can be broadly subdivided into two groups of rocks. A complex sequence of Middle Ordovician to Lower Devonian schists, amphibolites, quartzites, and felsic gneisses comprise the rocks of the syncline proper. These are flanked on either limb by a Late Precambrian(?) to Middle Ordovician(?) felsic gneiss that belongs to the youngest unit in the sequence in the core of the Pelham dome. The contact between gneissic basement and cover rocks outlines the syncline.

The stratigraphy of the cover sequence in the syncline has been correlated with that of the surrounding region. The stratigraphy of the Bronson Hill anticlinorium was first described by Billings (1937, 1956) in northwestern New Hampshire and was subsequently extended southward to Long Island Sound (Moore, 1949; Rodgers et al., 1959; Robinson, 1963, 1967a,b; Thompson et al., 1968; and Dixon and Lundgren, 1968). Four major units of Billing's Bronson Hill anticlinorium stratigraphy are present in the syncline: the Middle Ordovician Ammonoosuc Volcanics and Partridge Formation, the Silurian Clough Quartzite, and the Lower Devonian Littleton Formation. The Partridge Formation is the dominant unit of the syncline and is present along its entire length. The Ammonoosuc Volcanics are only present on the east limb in the central portion of the syncline (east and southeast of the town of Pelham). The Clough Quartzite and the Littleton Formation are exposed in the central region of the syncline in a series of large amplitude isoclinal folds.

A pronounced stratigraphic asymmetry is present in the central region of the syncline where the west limb is dominated by a relatively thick sequence of the Partridge Formation which lies in direct contact with the underlying dome gneiss. The Partridge Formation of the east limb is dramatically thinner and is underlain stratigraphically by the Ammonoosuc Volcanics. In the narrow portions of the syncline near the hinge regions, the stratigraphy of the east limb appears to have been truncated or radically thinned.

The stratigraphy of the core of the Pelham dome was initially established by Ashenden (1973) and subsequently expanded by Robinson et al. (1973). The presently understood stratigraphic framework of these core rocks consists of a layered sequence of felsic gneisses, quartzites, and minor schists and amphibolites. The oldest of these units, the Dry Hill Gneiss (Balk, 1956), has yielded a zircon separate with a Pb_{207}/Pb_{206} age of 565 ± 30 m.y. (Naylor et al., 1973). The age of the youngest gneiss, the Fourmile Gneiss (Ashenden, 1973), is uncertain but constrained to a Late Precambrian to Middle Ordovician age by the underlying Dry Hill Gneiss and the mantling Middle Ordovician cover rocks.

Fourmile Gneiss

The Fourmile Gneiss is the oldest unit mapped within the study area and flanks the cover rocks on both limbs of the syncline. Reconnaissance mapping immediately west of the study area showed that this unit could be divided into a lower yellow-weathering member, quartzite member, and upper gray-weathering member (Robinson et al., 1973). Only the upper gray-weathering member was encountered in the mapping of the study area. The Fourmile Gneiss of the study area differs somewhat from that of the northwest flank of the Pelham dome as described by Ashenden (1973) in

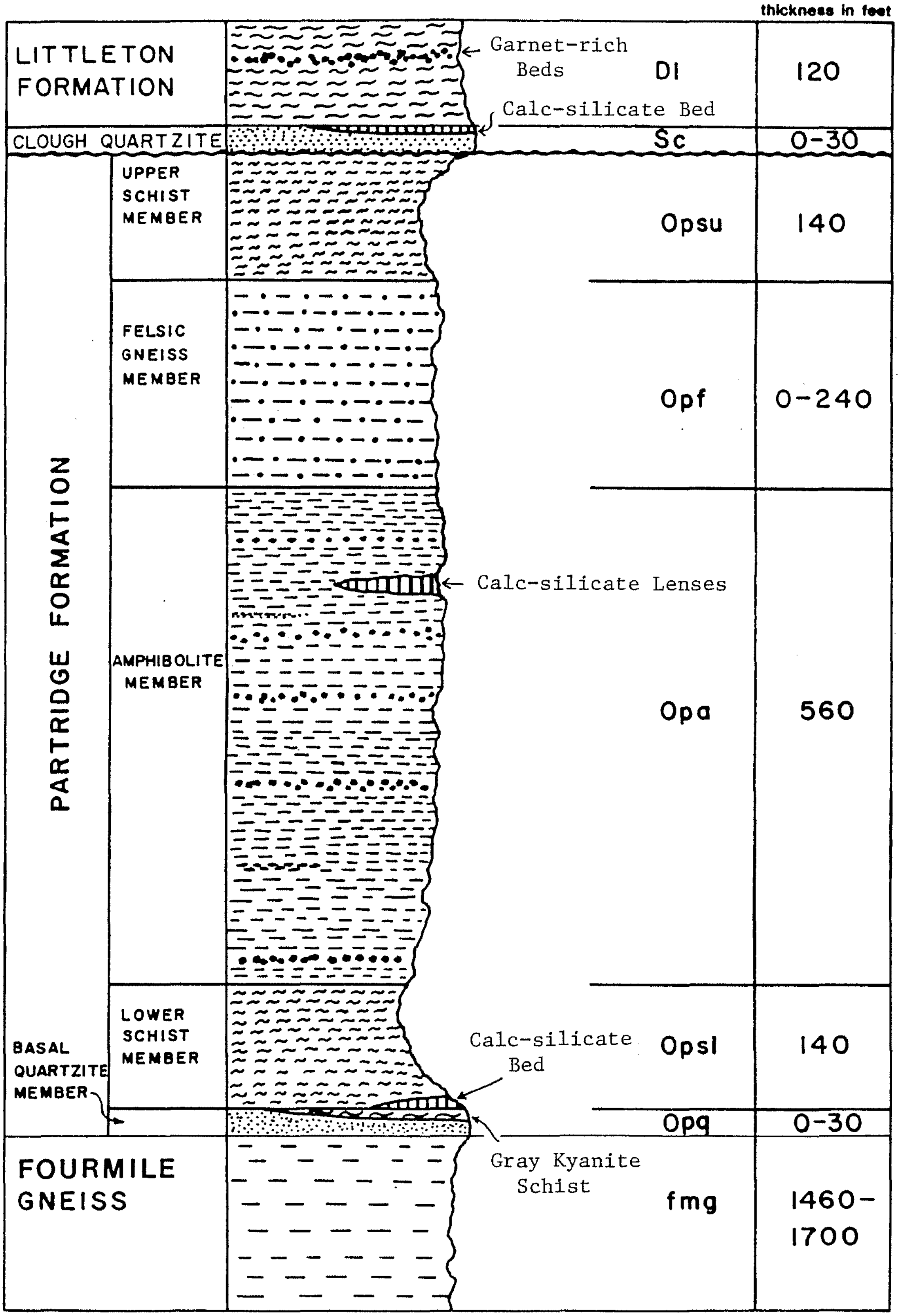


Figure 3. Composite stratigraphic column of the west limb of the Pelham-Shutesbury syncline.

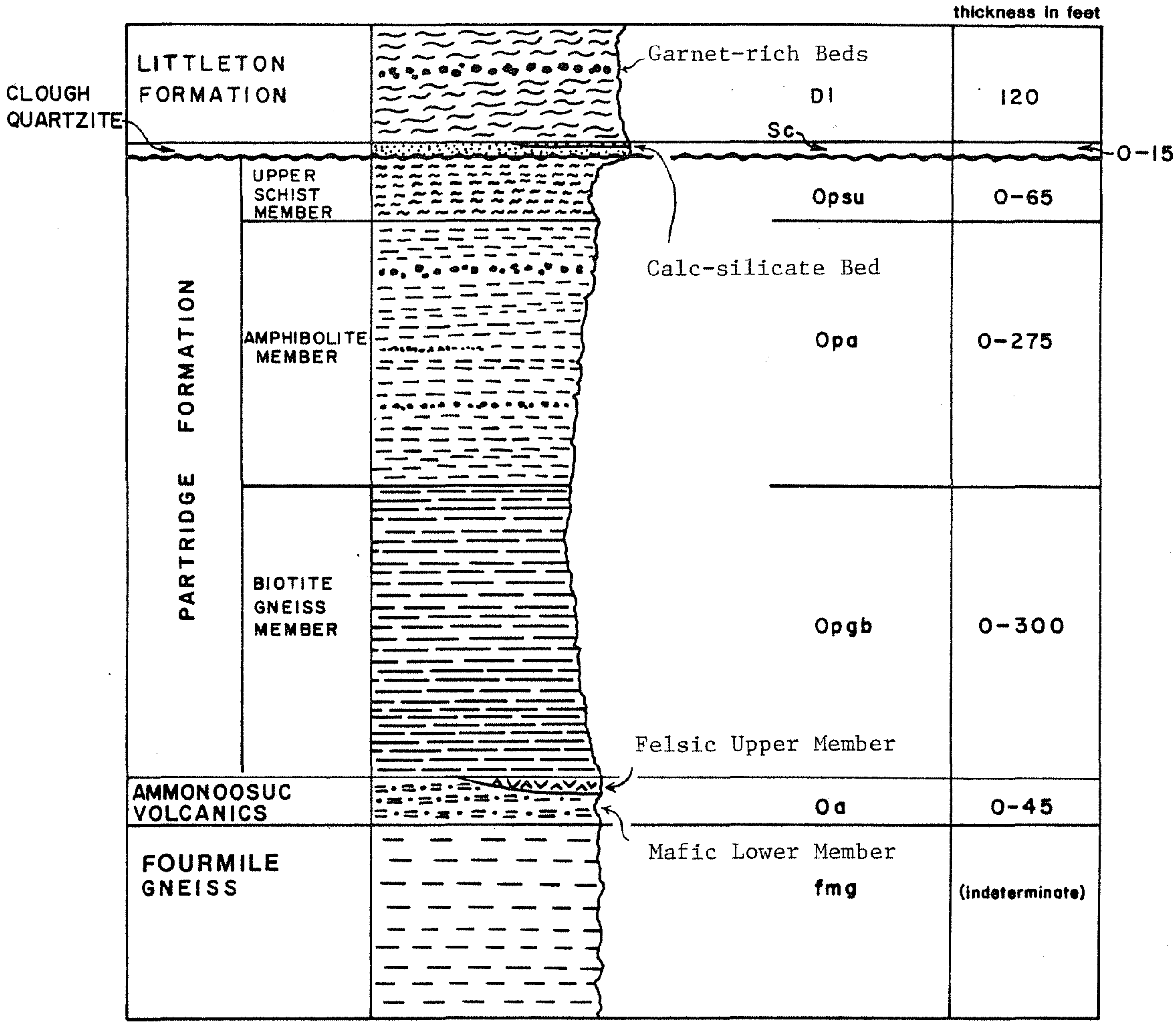


Figure 4. Composite stratigraphic column of the east limb of the Pelham-Shutesbury syncline.

the following respects: the Fourmile Gneiss of the study area is more homogeneous in its appearance (lacking the appreciable amphibolite noted by Ashenden) and is typified by thicker layering. The fact that the Fourmile Gneiss on either limb of the syncline is indistinguishable in the field further underscores its apparent homogeneity.

Lithology. The Fourmile Gneiss is typically a gray-weathering, slabby to massive, biotite-plagioclase-quartz gneiss. The layering in the rock is due to local variations in biotite content. The foliation in the rock is formed by disseminated biotite flakes that are moderately to well oriented.

The mineralogy of the Fourmile Gneiss typically consists of 38-50 percent quartz, 5-48 percent plagioclase (An 10-26), 0-35 percent microcline, 6-8 percent biotite, minor amounts of muscovite, and trace amounts of pistacite, sphene, zircon, and apatite (Table 1). Sample B-89 repre-

List of specimens in Table 1.

J-61 Biotite-feldspar gneiss. Collected by Peter Robinson on W flank of hill 780', N of Atherton Bk.; elevation 720'.

B-66 Granitic gneiss. Model analysis and specimen collection by J. Guthrie. 2000 ft. E of State Highway 9 and 2600 ft. N of Allen St., W of a dirt road in a small quarry.

B-72 Granitic gneiss. Modal analysis and specimen collection by J. Guthrie. 800 ft. N of intersection of Allen St. and U.S. Route 202.

B-94 Biotite-feldspar gneiss. Collected by Robert Balk. N flank of hill 960', 1.5 mi. E of Knights Corner.

B-164 Biotite-feldspar gneiss. Collected by Robert Balk. Road cut on U.S. Route 202, 3400 ft. S of its intersection with Prescott Rd.

B-89 Glassy garnet-muscovite quartzite. Collected by Robert Balk on W flank of hill 971', 1.1 mi. NE of Knights Corner.

Table 1. Estimated modes of specimens from the Fourmile Gneiss.

	Gneiss					Quartzite
	J-61	B-66	B-72	B-94	B-164	B-89
Quartz	50	40	38	50	40	93
Plagioclase	41 An_{10}	31 An_{26}	48 An_{24}	5 An_{16}	48 An_{18}	
Microcline		18	6	36	2	
Muscovite	1	tr	tr	2	3	2
Biotite	8 gb#	7	6	6 gb	6 rb	
Garnet		tr				5
Hornblende			tr		tr	
Pistacite		tr		1	tr	tr
Allanite				tr		tr
Sphene		tr	tr			tr
Zircon	tr	tr	tr	tr	tr	tr
Apatite	tr	tr	tr	tr	tr	tr
Pyrrhotite					tr	
Magnetite					tr	tr
Ilmenite	tr	tr	tr			
Chlorite*	tr +**		tr		1 +	
Calcite					tr	

#Biotite color: gb-greenish brown, rb-reddish brown.

*Secondary mineral.

**Chlorite sign of elongation.

sents a garnet-muscovite quartzite within the Fourmile Gneiss that was collected by Robert Balk.

Quartz and feldspar generally occur as equant, subhedral grains .25-1 mm. in size and lend a medium-grained equigranular texture to this unit. Samples B-94 and J-61 possess biotite with a dark green-brown color in thin sections which may suggest a higher Fe^{+3}/Ti ratio (Hayama, 1959). Minor retrograde Fe-rich chlorite appears to replace biotite in several samples.

Derivation. Ashenden proposed a sedimentary or volcanoclastic origin for the Fourmile Gneiss on the basis of the strong layering and varied composition in the northern portion of the Pelham dome. The Fourmile Gneiss on the eastern flank of the dome possesses more diffuse layering as observed in the field, but exhibits the compositional variability noted by Ashenden to the north. Estimated modes of samples of the gneiss in the study area yield compositions equivalent to the volcanic rocks rhyolite, rhyodacite, dacite, and quartz andesite (Streckeisen, 1967).

Thickness. Thicknesses for the Fourmile Gneiss were calculated on the west limb of the syncline where this unit lies stratigraphically above the Mount Mineral Formation (outside map area, See Robinson et al., 1973) and below the Partridge Formation. This area is characterized by good contact control and an apparent lack of tectonic thickening. The calculated thickness for the Fourmile Gneiss ranges from 1460 to 1700 feet.

Ammonoosuc Volcanics

The Middle Ordovician Ammonoosuc Volcanics (Billings, 1937) represent the oldest cover rock unit in the syncline. It is exposed only on the eastern limb of the syncline where it lies stratigraphically below the Partridge Formation and above the Fourmile Gneiss. Locally, a Silurian unconformity has brought the Lower Devonian Littleton Formation into contact with the Ammonoosuc Volcanics.

Previous mapping of the Ammonoosuc Volcanics in the Bronson Hill anticlinorium has shown there are two members (Robinson, 1963): a mafic lower member composed primarily of hornblende amphibolites (locally accompanied by cummingtonite, gedrite, or anthophyllite-bearing amphibolites) and a felsic upper member characterized by garnet-muscovite-bearing felsic gneisses. It should be emphasized, however, that the Ammonoosuc Volcanics show considerable lithic variability as indicated by the felsic gneisses, garnet quartzites, and marble horizons that are locally present in the mafic lower member and the minor pelitic schists in the felsic upper member. Rb-Sr dating of samples of the Ammonoosuc Volcanics from northwestern New Hampshire yields an age of 440 ± 30 m.y. (Naylor, 1969).

Recent geochemical analyses of the Ammonoosuc Volcanics in north-central Massachusetts has revealed pronounced differences in the chemistries of the mafic lower member and the felsic upper member (Schumacher, 1981). The mafic lower member exhibits chemistries compatible with basalt, basaltic andesite, and dacite protoliths. In addition, these chemistries compare favorably with recent volcanics from the island arc of Tonga. The felsic upper member possesses chemistries compatible with rhyolite and rhyodacite protoliths.

Relatively few exposures of the Ammonoosuc Volcanics were discovered in the course of mapping the study area. The dominant rocks appear to be those associated with the mafic lower member. The very thin and limited exposures of the felsic upper member preclude its depiction as a separate map unit. As a result, the Ammonoosuc Volcanics as mapped include both members.

Lithology. The mafic lower member, not shown separately on Plate 1, of the Ammonoosuc Volcanics is represented by well layered hornblende amphibolites and gedrite-bearing gneisses. These amphibolites have conspicuous garnetiferous layers, gedrite-rich layers, and calc-silicate horizons consisting of coarse diopside and pistacite. Gedrite-bearing gneisses display a variety of textures, ranging from well foliated, medium-grained gneisses to massive, coarse-grained gneisses with prominent radial sprays of gedrite. Gedrite appears to be particularly susceptible to retrograding and is variably pseudomorphed by chlorite.

In its northernmost exposure within the study area, the Ammonoosuc Volcanics consists of a well layered, coarse-grained calc-silicate gneiss overlain by a pyritic amphibolite and a well foliated biotite-gedrite-garnet-plagioclase gneiss. The calc-silicate gneiss consists of 45 percent pistacite, 30 percent diopside, 18 percent scapolite (meionite), 5 percent hornblende, minor amounts of sphene and zircon, and a trace amount of quartz (Table 2). The layering in the rock consists of discontinuous hornblende layers 2-12 mm. thick that are interlayered with pistacite-diopside layers up to 2 cm. thick. Pistacite rims about diopsidic lenses are locally present and suggest a retrograde reaction between hornblende, diopside, and scapolite.

Stratigraphically above this calc-silicate unit is a well foliated gneiss that consists of 30 percent quartz, 25 percent plagioclase (An_{37}), 25 percent biotite, 15 percent gedrite, 4 percent garnet, 1 percent ilmenite, and trace amounts of allanite, zircon, and apatite (Table 2). Biotite grains 1-3 mm. across define a well developed foliation in this rock. Acicular gedrite grains 2-5 mm. long are strongly lineated.

Five miles south of the previously described exposure, the Ammonoosuc Volcanics consist of well layered hornblende-garnet-gedrite amphibolite overlain by a thin felsic gneiss, a well foliated chlorite-gedrite-biotite gneiss, and a coarse-grained gedrite-plagioclase gneiss. The well layered amphibolite has prominent 4 cm. thick garnet layers and coarse chlorite pseudomorphs after gedrite. Stratigraphically above this amphibolite is a thin feldspathic gneiss and a well foliated, medium-grained amphibole gneiss consisting of 30 percent plagioclase (AN_{33}), 25 percent gedrite, 35 percent chlorite, 8 percent biotite, 2 percent pyrrhotite, and trace amounts of garnet, hornblende, allanite, zircon, and ilmenite (Table 2). Intergrowths of chlorite, gedrite, and biotite define the well developed foliation in this rock. Chlorite appears to have partially pseudomorphed gedrite and biotite in this rock.

Overlying this well foliated gneiss is a massive, coarse-grained, rusty-weathering gneiss consisting of 25 percent quartz, 30 percent plagioclase (An_{32}), 40 percent gedrite, minor amounts of biotite, garnet, and ilmenite, and trace amounts of staurolite, allanite, zircon, apatite, pyrrhotite, and rutile (Table 2). The texture of this gneiss is characterized by coarse, radial sprays of gedrite up to 2 cm. long in a granular matrix of quartz and plagioclase. Ilmenite rims were observed about rutile grains in thin section.

In the southernmost shoreline exposures of the Ammonoosuc Volcanics, a gneiss unit with an unusual "agglomeratic" texture consisting of foliated medium-grained felsic lenses in a coarse-grained hornblende gneiss matrix lies stratigraphically above the previously described massive, coarse-grained gedrite gneiss. Stratigraphically above this "agglomeratic" gneiss is a foliated, medium-grained felsic gneiss that may represent the felsic upper member of the Ammonoosuc Volcanics. This felsic gneiss consists of 51 percent quartz, 40 percent plagioclase (AN_{24}), 3 percent biotite, and trace amounts of staurolite, zircon, magnetite, and rutile (Table 2). Sericite occurs in this rock as an alteration product of plagioclase along a joint in the specimen. Small disseminated biotite and chlorite grains define the moderately developed foliation in this rock. Local variations in mica content and thin plagioclase rims about salmon pink garnets were observed in the field.

Contacts. The upper contact of the Ammonoosuc Volcanics is locally exposed in shoreline outcrops within the central portion of the study area. At the southernmost exposure, east of hill 730', the Ammonoosuc Volcanics are seen in sharp, apparently conformable contact with the rusty mica schist

List of specimens in Table 2.

R-53A	Well layered, coarse-grained calc-silicate gneiss. Shoreline outcrop 2400 ft. NNE of confluence of Purgee Bk. and Quabbin Res.
R-54	Well foliated, coarse-grained biotite-gedrite-garnet-plagioclase gneiss. Shoreline outcrop 100 ft. S of R-53A locality.
G-7	Well foliated, fissile, medium-grained chlorite-gedrite-biotite gneiss. Shoreline outcrop 2200 ft. ENE of intersection of Chaffee Bk. and Gate 8 road, Quabbin Res.
N-66	Massive, coarse-grained gedrite-plagioclase gneiss. Shoreline outcrop 1650 ft. SE of confluence of Gulf Bk. and Quabbin Res.
G-9	Foliated, medium-grained biotite-plagioclase-quartz gneiss. 100 ft. S of G-7 locality along shoreline of Quabbin Res.

Table 2. Estimated modes of specimens from the Ammonoosuc Volcanics.

	R-53A	R-54	G-7	N-66	G-9
Quartz	tr	30		25	51
Plagioclase		25 An_{37}	30 An_{33}	30 An_{32}	40 An_{24}
Biotite		25 rb#	8 rb	1 rb	3 gb
Garnet		4	tr	1	
Staurolite				tr	tr
Hornblende	5		tr		
Gedrite		15	25	40	
Diopside	30				
Pistacite	45				
Allanite		tr	tr	tr	
Sphene	1				
Zircon	1	tr	tr	tr	tr
Scapolite	18				
Apatite		tr		tr	
Pyrrhotite			2	tr	
Magnetite					tr
Ilmenite		1	tr	1	
Rutile				tr	tr
Sericite*				tr	5
Chlorite*		tr -**	35 -	2 -	1 ±

#Biotite color: rb-reddish-brown, gb-greenish-brown.

*Secondary mineral.

**Chlorite sign of elongation.

of the Partridge Formation. One mile to the north, the Ammonoosuc Volcanics are observed in contact with the gray mica schist of the Littleton Formation. This unconformable contact relationship might be explained by the presence of an intervening Silurian erosional surface or a fault. No contacts were observed between the Ammonoosuc Volcanics and the Fourmile Gneiss due to the limited extent of the Ammonoosuc Volcanics and to the partial submergence of the east limb of the syncline by the present-day Quabbin Reservoir. A reasonable eastern constraint on this contact can be inferred by projection from the southernmost exposure of the Fourmile Gneiss on the east limb of the syncline.

Derivation. As previously noted, current investigations into the geochemistry of the Ammonoosuc Volcanics (Schumacher, 1981) have suggested an island-arc volcanic or volcanoclastic origin for this formation consisting of an initial extrusion of rocks of basaltic or dacitic composition, followed by the extrusion of rocks of rhyodacitic and rhyolitic composition. Local quartzite, schist, and marble horizons in the Ammonoosuc Volcanics suggest that minor amounts of sedimentary material were incorporated into this volcanic sequence.

Thickness. The lack of an exposed lower contact and the observed fold complications render thickness determinations difficult. An approximate exposed thickness of 45 ft. was calculated for the northernmost exposure of the Ammonoosuc Volcanics where folding appears to be less intense.

Partridge Formation

The Middle Ordovician Partridge Formation constitutes the most areally extensive and lithically diverse formation within the study area. It has been mapped as a continuous unit along both limbs of the syncline with the exception of an isolated exposure on the east limb where the Partridge Formation is absent due to an apparent unconformity.

The Partridge Formation exposed on the west limb displays considerable differences in lithology, stratigraphic thickness, and contact relations from its exposures on the east limb. The rocks of the Partridge Formation on the west limb are thicker and include quartzite, schist, and felsic gneiss units that are absent on the east limb. In addition, the base of the Partridge on the west limb is in contact with the Fourmile Gneiss everywhere, while central exposures on the east limb locally reveal a basal contact with the Ammonoosuc Volcanics.

This study has sought to refine the stratigraphic subdivisions within the Partridge Formation and has defined the following members: Basal Quartzite Member (Opq), Lower Schist Member (Opsl), Biotite Gneiss Member (Opgb), Amphibolite Member (Opa), Felsic Gneiss Member (Opf), and Upper Schist Member (Opsu).

<u>Basal Quartzite Member</u>. This member constitutes the base of the Partridge Formation on the west limb of the syncline. It is fairly consistent in its presence along the central portion of the west limb, where it exhibits local pinch-outs. The Basal Quartzite Member was only observed in one exposure on the east limb of the syncline immediately west of the southern crest of the Pelham dome.

The Basal Quartzite Member is characterized by two lithologies: a gray-weathering, well foliated to glassy, mica-garnet quartzite and an overlying gray-weathering, well foliated kyanite-garnet mica schist. The quartzite is largely composed of quartz, muscovite, biotite, plagioclase, and garnet with trace amounts of tourmaline, apatite, zircon, and ilmenite (Table 3). Muscovite and biotite grains define a moderate to well developed foliation in this rock. The gray schist of the Basal Quartzite Member is characterized by major amounts of quartz, muscovite, biotite, garnet, kyanite, plagioclase, and ilmenite with trace amounts of zircon, apatite, rutile, and graphite (Table 3). This schist exhibits layering on a

Table 3. Estimated modes of specimens from the Basal Quartzite Member of the Partridge Formation.

	M12	H-35	I-81	R-66
Quartz	83	83	40	65
Plagioclase	5		2 An_{25}	
Muscovite	9	12	25	26
Biotite	2 rb#	4 b	20 rb	3 rb
Garnet		1	10	5
Kyanite			2	
Zircon	tr	tr	tr	tr
Tourmaline		tr		
Apatite	tr		tr	tr
Ilmenite	tr	tr	1	1
Rutile				tr
Graphite			tr	tr
Chlorite*	1 +**	tr -		tr +

#Biotite color: rb-reddish-brown, b-brown.

*Secondary mineral.

**Chlorite sign of elongation.

List of specimens in Table 3.

M-12 Glassy muscovite-biotite-garnet quartzite. N shore of Briggs Brook; elevation 585'.

H-35 Muscovite-garnet quartzite with garnets to 6 mm. Collected by Peter Robinson. 900 feet NNE of intersection of Gulf Brook and fire road; elevation 730'.

I-81 Gray kyanite-garnet schist. Collected by Peter Robinson. W side of fire road 800 ft. N of Jennison Rd. on S flank of Locks Hill.

R-66 Gray, well foliated muscovite-biotite-garnet schist. 3200 ft. SSW of intersection of U.S. Route 202 and Prescott Rd.; elevation 860'.

millimeter scale consisting of quartzose layers and micaceous layers. Kyanite occurs in the matrix as coarse, moderately aligned grains up to 3.5 cm. in length. Taken out of their stratigraphic context, these two lithologies of the Basal Quartzite Member could easily be mistaken in the field for similar rocks of the Silurian Clough Quartzite and Devonian Littleton Formation. Given the unequivocal stratigraphic position of the Basal Quartzite Member in contact with the basement gneiss on the west limb, the alternative interpretation assigning it to Siluro-Devonian formations seems improbable.

Lower Schist Member. This member of the Partridge Formation is nearly continuous along the west limb of the syncline. It is present on the east limb in scattered exposures near the hinge regions of the syncline. The Lower Schist Member lies stratigraphically above the Basal Quartzite Member (where present) and the Fourmile Gneiss. The Lower Schist Member is nearly indistinguishable from the Upper Schist Member of the Partridge Formation. The presence of intervening felsic gneisses and amphibolites within the Partridge Formation necessitates the description of these two schist units as separate members.

The Lower Schist Member is characterized by rusty-weathering, well foliated, massive mica schist. This schist is generally medium-grained and typically consists of 10 percent quartz, 20 percent plagioclase (An_{50}), 8-30 percent biotite, 4 percent garnet, 3 percent kyanite, 2 percent tourmaline, and trace amounts of zircon, apatite, and ilmenite (Table 4). Local course, nodular intergrowths of kyanite, quartz, and feldspar up to 10 cm. in diameter have been noted in this member. These kyanites, as well

List of specimens in Table 4.

R-38	Rusty, well foliated biotite-garnet-kyanite-tourmaline schist. W side of fire road paralleling Chaffee Bk; 2000 ft. N of intersection of fire road and Gate 8 road.
N-31	Coarse-grained pistacite-diopside gneiss; SE flank of hill 1021'; N of Atherton Bk. Elevation 840'.
R-30	Coarse-grained, rusty muscovite-biotite schist. 800 ft. ENE of confluence of Purgee Bk. and Quabbin Res.; shoreline exposure.
R-32	Coarse grained, rusty muscovite-biotite schist. 450 ft. N of R-30 along shoreline.
R-41	Gray-weathering muscovite-biotite-garnet schist. W flank of hill 800'; N of Purgee Bk. Elevation 650'.
H-14	Coarse-grained biotite-garnet-magnetite schist. Collected by Peter Robinson. Immediately W of summit 790'; NE of confluence of Purgee Bk. and Quabbin Res.
S-52	Coarse-grained hornblende-garnet horizon in rusty mica schist. Shoreline exposure 1650 ft. SE of confluence of Chaffee Bk. and Quabbin Res.

#Biotite color: rb-reddish brown, gb-greenish brown.

*Secondary mineral.

**Chlorite sign of elongation.

Table 4. Estimated modes of specimens from the Lower Schist Member and the Upper Schist Member of the Partridge Formation.

	Opsl		Opsu				
	R-38	N-31	R-30	R-32	R-41	H-14	S-52
Quartz	10	20	50	31	45	10	15
Plagioclase	20	3	15	10	tr	29	
	An_{50}	An_{39}	An_{32}	An_{31}		An_{10}	
Microcline		30					
Muscovite			20	35	40		
Biotite	60	tr	8	20	10	30	tr
	rb#	b	rb	rb	rb	gb	rb
Garnet	4		2	3	5	20	2
Kyanite	3						
Hornblende		3					69
Diopside		20					
Pistacite		23					
Allanite		tr				1	
Sphene		1					
Zircon	tr	tr	tr	tr	tr	tr	tr
Tourmaline	2		tr				
Apatite	tr			tr	tr	tr	
Pyrrhotite				tr			
Magnetite						10	3
Ilmenite	tr		tr	1	tr		
Rutile							tr
Graphite				tr	tr	tr	
Sericite*			tr	tr	tr		10
Chlorite*	1		5	tr	54		1
	-**		+	±	±		-

as those in the schist matrix are pale gray-blue in contrast to the more deeply hued sky-blue kyanites in the Basal Quartzite Member. A coarse-grained calc-silicate granulite was locally observed in the Lower Schist Member in the north-central portion of the syncline. This calc-silicate rock consists of significant amounts of pistacite, diopside, hornblende, and sphene (Table 4) and is present as a thin lens at the base of the Lower Schist Member.

Biotite Gneiss Member. Scattered exposures along the east limb of the syncline between Atherton Brook and Cobb Brook are of an orange-brown- to black-weathering, fissile biotite-rich gneiss. This gneiss is generally coarse-grained and massive in outcrop appearance, and displays minor variations in biotite content. Abundant coarse grains of biotite define the well developed foliation in this rock and lend it a crumbly, fissile nature.

This gneiss unit merits description as a separate member within the Partridge Formation for the following reasons: it occupies a consistent stratigraphic position within the syncline, and it is lithically distinct from any other unit in the study area. If the symmetry axis of the syncline in this region is assumed to lie within the Amphibolite Member of the Partridge Formation, the Biotite Gneiss Member lies stratigraphically below that unit and above the Four Mile Gneiss on the east limb.

Amphibolite Member. One of the most distinctive and areally extensive units within the study area is the relatively thick sequence of amphibolite within the Partridge Formation. This unit has been mapped along most of the west limb of the syncline. In the narrow northern and southwestern portions of the study area, the Amphibolite Member appears to occupy the structural and stratigraphic center of the syncline.

In the field, this unit is readily identified by its pronounced compositional layering that characteristically consists of alternating mafic and felsic horizons composed of hornblende and plagioclase, respectively. Additional forms of compositional layering are shown by local coarse-grained calc-silicate horizons, garnetiferous horizons, and thin, wispy epidote-rich horizons. In thin section, even more subtle mineralogical layering was observed such as cummingtonite-hornblende layers, discontinuous sphene-ilmenite layers, and hornblende layers with abundant apatite and allanite. The layering in this unit differs in thickness ranging from less than 1 mm. to several centimeters. Some boundaries between adjacent layers are very sharp and others are more diffuse. Locally, a form of graded layering was observed in the field consisting of a plagioclase-rich portion grading into a progressively more hornblendic portion. Structural complications and uncertain extrusive and depositional mechanisms render determinations of "tops" and "bottoms" very tenuous in these graded layers.

The Amphibolite Member is typified by a dark gray-green-weathering, medium- to coarse-grained, well layered amphibolite consisting of 0-21 percent quartz, 12-60 percent plagioclase (An_{23-62}), 0-15 percent garnet, 19-60 percent hornblende, 0-15 percent pistacite, 0-10 percent cummingtonite, and minor to trace amounts of allanite, sphene, zircon, and ilmenite (Table 5). Hornblende in these samples is pleochroic pale tan to blue-green and is tyically moderately to well lineated. Garnet exhibits considerable variation in size and texture, ranging from subhedral grains smaller than 1 mm. to coarse, spongy poikilitic grains up to 6 mm. in dia-

Table 5. Estimated modes of specimens from the Amphibolite Member of the Partridge Formation.

	I-68	J-95	R-11	R-23	R-39	R-39A	R-39B	R-39C	M-45
Quartz	15	21	14	10		20	tr	8	10
Plagioclase	33	30	12	38	50	30	60		
	An_{42}	An_{34}	An_{41}	An_{23}	An_{62}	An_{62}	An_{55}		
Garnet	5		5	1	9	3	15	15	
Hornblende	35	45	60	45	35	30	19	15	4
Cummingtonite	10	3		5					
Tremolite									1
Augite								50	
Pistacite			7		4	15	5	2	84
Allanite	tr			tr		1			
Sphene		tr			2	tr	1	tr	1
Zircon		tr		tr	tr		tr	tr	
Scapolite								10	
Magnetite			2						
Ilmenite	1	1		1	tr		tr		
Apatite	1					1			

List of specimens in Table 5.

I-68 Well bedded, slabby garnet amphibolite. Collected by Peter Robinson. E side of New Boston Rd.; 1400 ft. S of intersection with Mt. Mineral Rd.

J-95 Slabby, well bedded hornblende-cummingtonite-garnet amphibolite. Collected by Peter Robinson. 700 ft. S of confluence of Chaffee Bk. and Quabbin Res. Outcrop presently submerged.

R-11 Finely layered hornblende-epidote-garnet-amphibolite. 1800 ft. SE of summit 1012', N of Atherton Bk. Elevation 730'.

R-23 Medium grained hornblende amphibolite. N bank of Camel Bk. Elevation 700'.

R-39, R-39A,B,C Strongly layered hornblende-garnet-epidote-plagioclase and hornblende-augite-garnet-scapolite amphibolite. 4600 ft. N of confluence of Chaffee Bk. and Quabbin Res.; immediately E of Chaffee Bk.

M-45 Coarse epidote-tremolite calc-silicate bed in hornblende amphibolite. 1.4 mi. E of the town of Pelham on the W side of saddle 760', NE of Purgee Bk.

meter. Where present, cummingtonite is generally intergrown with hornblende and exhibits two sets of fine, green hornblende lamellae. Sphene is a common minor constituent and commonly occurs in thin discontinuous layers, locally rimming ilmenite. Sphene was not observed in any cummingtonite-bearing layers, although the two minerals do occur together in one thin section.

A coarse-grained calc-silicate horizon several centimeters thick was observed in the Amphibolite Member. It consists of abundant, coarse pistacite, fibrous tremolite, sphene, and quartz (Table 5). These calc-silicate horizons are less ductile than the surrounding amphibolite and are commonly boudinaged.

Felsic Gneiss Member. This member of the Partridge Formation is best exposed in a nearly continuous N-S belt 3 mi. long in the central portion of the study area. Other exposures suggest that thin lenses of this unit lie in various stratigraphic positions within the Partridge Formation on the west limb. The most prominent exposures occur stratigraphically above the Amphibolite Member and below the Upper Schist Member.

The Felsic Gneiss Member is typically a light gray, medium- to coarse-grained, massive to moderately layered felsic gneiss consisting of 25-60 percent quartz, 1-31 percent plagioclase (An_{3-27}), 0-52 percent microcline, minor amounts of muscovite and biotite, and trace amounts of garnet, allanite, zircon, apatite, ilmenite and rutile (Table 6). Layering in this rock may represent bedding, and is shown in variations in mica content and thin horizons of fine-grained garnet. Oriented plates of biotite and mus-

List of specimens in Table 6.

B-127 Light gray, quartz-muscovite gneiss. Collected by Robert Balk. SW flank of hill 830', N of confluence of Gulf Bk. and Quabbin Res. Approx. elevation 800'.

B-128 Light gray biotite-feldspar gneiss. Collected by Robert Balk. E facing slope 700 ft. S of junction of Gate 12 road and Quabbin Res.; approx. elevation 600'.

G-51A Layered felsic biotite-muscovite gneiss. Collected by Peter Robinson. S bank of Gulf Bk., 200 ft. W of its confluence with Quabbin Res.

P-71 Light gray, layered biotite-muscovite felsic gneiss. 1000 ft. NNW of confluence of Gulf Bk. and Quabbin Res.

G-51C Rusty, rotten muscovite gneiss. Collected by Peter Robinson. Same exposure as G-51A.

P-73 Very rusty weathering, well foliated muscovite-pyrite-quartz schist. Same exposure as G-51A.

Table 6. Estimated modes of specimens from the Felsic Gneiss Member of the Partridge Formation.

	B-127	B-128	G-51A	P-71	G-51C	P-73
Quartz	57	25	45	60	80	65
Plagioclase	30 An_3	15 An_5	1	31 An_{27}	tr	
Microcline		52	44	4		
Muscovite	6	tr	2	2	20	30
Biotite	tr b#	8 b	7 b	7 rb		tr b
Garnet	tr			tr		
Kyanite						tr
Pistacite	2					
Allanite		tr	tr			
Zircon	tr		tr	tr		tr
Tourmaline			tr			
Apatite	tr	tr	tr	tr	tr	
Pyrite					tr	5
Magnetite	tr					
Ilmenite		tr		tr		
Rutile		tr		tr		
Sericite*	tr	tr	tr			
Chlorite*	5 ±**	tr +	1 -	1 +	tr -	tr -

#Biotite color: rb-reddish brown, b-brown.

*Secondary mineral.

**Chlorite sign of elongation.

covite define a moderately developed foliation.

Exposures near Gulf Bk. reveal an affiliated "white schist" at the base of this member. This schist is very rusty weathering, coarse-grained, and is chiefly composed of quartz and muscovite with trace amounts of biotite, Mg-rich chlorite, kyanite, apatite, and zircon (Table 6). One specimen of this schist contains 5 percent pyrite.

Upper Schist Member. The Upper Schist Member occupies the highest stratigraphic position within the Partridge Formation of the study area. In map pattern, it appears as a folded, N-S trending belt within the central portion of the syncline, commonly lying beneath the Clough Quartzite. These folds appear to have tectonically thickened this unit on the west limb, resulting in an apparent disparity in thickness between west and east limbs.

This unit generally consists of a rusty-weathering, medium- to coarse-grained mica-garnet schist that is undistinguishable from the Lower Schist Member. This schist typically consists of 10-50 percent quartz, 0-29 percent plagioclase (An_{10-32}), 0-40 percent muscovite, 8-30 percent biotite, 2-20 percent garnet, and trace amounts of zircon, apatite, pyrrhotite, ilmenite, and graphite (Table 4). Specimen H-14 was characterized by abundant, fine-grained anhedral garnet, dark green-brown biotite, and coarse, euhedral magnetite.

Contacts. The Partridge Formation overlies the Fourmile Gneiss along the west limb and most of the east limb of the syncline. In the central portion of the east limb, the Partridge Formation locally overlies the Ammonoosuc Volcanics. The prevalent absence of an intervening horizon of Ammonoosuc Volcanics between the Partridge Formation and the Fourmile Gneiss combined with the presence of a basal quartzite along the west limb suggests an unconformity at the base of the Partridge. Several good exposures of this basal contact are present on the west limb; in all cases, the layering in the Fourmile Gneiss appears to be concordant with that in the Basal Quartzite Member.

In the central portion of the study area, the Partridge Formation lies in contact stratigraphically beneath the Clough Quartzite and Littleton Formation. This contact appears concordant in outcrop, but exhibits discordant relationships in map pattern.

Contacts between the various members of the Partridge Formation are generally sharp and concordant in nature. Figures 3 and 4 depict the representative stratigraphy of the various members of the Partridge Formation on the west and east limb respectively.

The Biotite Gneiss Member has the least certain stratigraphic position, lying below the Amphibolite Member and above the Fourmile Gneiss on the east limb.

Derivation. The Partridge Formation of the study area appears to represent a complex sequence of metamorphosed sediments and volcanics. The Basal Quartzite Member probably represents metamorphosed quartz-rich sands and aluminous shales. The Lower and Upper Schist Members were most likely derived from metamorphosed aluminous shales that were deposited in a variably reducing environment with local admixtures of calcareous sediment. The Amphibolite Member probably represents metamorphosed mafic volcanoclastics due to their thinly laminated, well layered nature and apparent basaltic composition. Incorporated carbonate sediments could account for the calcic chemistry of this unit and the local calc-silicate horizons. The

Felsic Gneiss Member may have been derived from metamorphosed volcanic or volcanoclastic rocks of alkali rhyolite, rhyolite, dacite, and quartz-andesite composition (Streckeisen, 1967). The pyritic schist in this unit may represent a metamorphosed sulfidic pelite or altered felsic tuff (Schumacher, 1981).

Thickness. Representative thicknesses for the members of the Partridge Formation in the central portion of the study area are given in Figures 3 and 4. The apparent total east limb thickness as shown in Figure 4 is somewhat misleading because the Amphibolite Member and Biotite Gneiss Member are very discontinuous along this limb. As a result, the actual east limb total thickness of the Partridge Formation is substantially less. The members of the Partridge Formation on the west limb are much more continuous in nature and exhibit more consistent thicknesses. They give an approximate total thickness of 1110 feet.

Clough Quartzite

The Silurian Clough Quartzite is exposed along both west and east limbs in the central portion of the syncline. Its outcrop pattern proved very useful in the course of mapping the study area as it helped delineate several large-amplitude, N-S trending isoclinal folds.

Very detailed mapping of "The Island" in Quabbin Reservoir resulted in the description of three mappable members within this formation (Robinson, 1967b). However, only one of these members proved to be sufficiently thick and lithologically distinct to merit mapping in the remainder of the syncline. This member is the Basal Quartzite Member as mapped on "The

Island"; it typically consists of a gray, coarse-grained, variably micaceous quartzite.

The base of the Clough Quartzite has been interpreted as an unconformity by previous workers elsewhere in the Bronson Hill anticlinorium (Billings, 1937; Robinson, 1963; Naylor, 1969). This unconformity may be shown by the pronounced stratigraphic thinning of Middle Ordovician units on the east limb of the syncline.

Lithology. The Clough Quartzite in the study area is typified by a gray- to buff-weathering, glassy to schistose, variably micaceous quartzite. This quartzite consists of major amounts of quartz and muscovite, minor amounts of biotite, garnet, microcline, and plagioclase, with trace amounts of zircon, apatite, and ilmenite (Table 7). Muscovite and biotite define the weakly to moderately developed foliation present in this rock. Quartz grains are characteristically .5 to 3mm. in diameter and exhibit flattened profiles parallel to foliation. Locally, a very thin, well layered hornblende-epidote-feldspar granulite was observed above the dominant quartzite unit. This probably represents the Upper Calc-Silicate Member as mapped on "The Island". Local conglomeratic facies were also noted on "The Island" (Robinson, pers. comm., 1982).

Derivation. The Clough Quartzite may represent a metamorphosed quartz-rich sandy sediment. The presence of aluminous accessory phases may indicate that some pelitic sediments were incorporated as well. The previously noted calc-silicate unit may represent local thin deposits of calcareous sediment.

Thickness. The Clough Quartzite exhibits variations in thickness within the study area. Where present, it attains a maximum thickness of 30 feet on the west limb and 15 feet on the east limb of the syncline (Figures 3 and 4). The observed variations in thickness may be due to original depositional differences, tectonic thinning, or both of the above.

Littleton Formation

The Devonian Littleton Formation is the youngest stratigraphic unit within the study area. It is exposed in two separate N-S trending belts in the central portion of the syncline. These separate belts were formed by early isoclinal folding during the Acadian orogeny.

The Littleton Formation of the study area typically consists of gray, well layered kyanite-garnet schist, which locally contains staurolite. It is coarser grained and possesses less graphite than the Littleton Formation as it is exposed in the Northfield syncline to the north, the Prescott syncline to the northeast, and the Amherst block to the west.

Detailed mapping on "The Island" delineated three schist members based on subtle mineralogical differences (Robinson, 1967b). In mapping the study area, all three of these members are portrayed as one map unit.

Lithology. The Littleton Formation is characterized by gray- to red-weathering, moderately to well bedded, coarse-grained mica schist. This schist typically consists of 30-59 percent quartz, 0-12 percent plagioclase (An_{24-28}), 15-54 percent muscovite, 0-16 percent biotite, minor amounts of garnet, kyanite, staurolite, and ilmenite, with trace amounts of zircon, apatite, and graphite (Table 7). The bedding generally consists of alternating quartzose and micaceous horizons up to 5 mm. thick. Local beds containing coarse red-brown garnet, coarse sky-blue kyanite, and fine-grained staurolite have been observed. Very coarse grained kyanite up to 4 inches long occurs in veins intergrown with quartz in several outcrops (Robinson, 1967b). Biotite in this formation is typically pleochroic pale yellow-tan to orangish brown.

Stratigraphic variations in the relative abundances of Al, Fe, and Mg are inferred from the presence of adjacent beds of garnet-staurolite schist and garnet-kyanite schist in the Littleton Formation.

Contacts. The Littleton Formation has sharp lower contacts with the Clough Quartzite, the Upper Schist Member of the Partridge Formation, and the Ammonoosuc Volcanics. This contact is concordant at the outcrop scale, but exhibits unconformable relations on a map scale. This unconformity is shown along the east limb of the syncline, where the contact cuts down through the Partridge Formation and brings the Littleton Formation into juxtaposition with the Ammonoosuc Volcanics. The top of the Littleton Formation is not exposed in the study area.

Derivation. The Littleton Formation most likely represents metamorphosed, interlayered aluminous pelites and quartz-rich sands. This derivation is inferred from the aluminous phases that are prevalent in the Littleton Formation and from its well bedded nature. The presence of finely disseminated graphite in the schists of this formation suggests that appreciable organic material was originally incorporated into these pelitic and sandy sediments.

Thickness. The thickness of the Littleton Formation in the study area appears to be accentuated by isoclinal folding. The top of this formation

Table 7. Estimated modes of specimens from the Clough Quartzite and the Littleton Formation.

	Sc		Dl		
	S-69	G-6	B-84	I-11	N-96
Quartz	70	85	59	40	30
Plagioclase		1	12	2	
		An_{38}	An_{24}	An_{28}	
Microcline		10			
Muscovite	20	tr	15	40	54
Biotite	9	3	tr	16	1
	b#	rb	rb	rb	rb
Garnet	2		4	2	2
Kyanite			6		1
Staurolite				tr	1
Allanite		tr			
Sphene		tr	tr		
Zircon	tr	tr		tr	tr
Apatite	tr	tr		tr	tr
Pyrrhotite					tr
Ilmenite	1	tr	1	tr	3
Graphite			tr	tr	tr
Sericite*		1	tr		
Chlorite*	tr	tr	3		8
	+**	+	+		+

#Biotite color: rb-reddish brown, g-brown.

*Secondary mineral.

**Chlorite sign of elongation.

List of specimens in Table 7.

S-69 Gray, foliated biotite-muscovite quartzite. 30 ft. N of shoreline; 1800 ft. SE of confluence of Chaffee Bk. and Quabbin Res.

G-6 Moderately layered muscovite quartzite. Crest of SE facing slope; .5 mi. NE of intersection of Chaffee Bk. and Gate 8 road, Quabbin Res. Elevation 750'.

B-84 Kyanite-muscovite-garnet schist. Collected by Robert Balk approx. 1000 ft. NE of G-6 locality. Approx. elevation 600'.

I-11 Well layered, crenulated muscovite-biotite-garnet schist. SE shore of "The Island", .7 mi. SE of confluence of Chaffee Bk. and Quabbin Res.

N-96 Coarse muscovite-kyanite-staurolite-garnet schist. Shoreline exposure 375 ft. N of Gulf Bk. inlet, Quabbin Res.

is not exposed in the study area; only a minimum thickness can be estimated. The Littleton Formation is at least 120 feet thick in the central portion of the study area.

INTRUSIVE IGNEOUS ROCKS

The intrusive rocks of the study area consist of dikes, sills, and irregular plutons that are presumed to be Devonian and Triassic-Jurassic in age. Age relations of intrusive rocks presumed to be Devonian were established by means of cross-cutting contacts with the country rocks, inclusions of country rocks, the presence of foliation in these intrusives, and by modal mineralogical comparisons with nearby intrusive rocks known to be Devonian. Age relations for intrusive rocks of Triassic-Jurassic age were established from their undeformed nature and cross-cutting relationships with all other rocks of the study area.

Purgee Brook Gneiss

The Purgee Brook Gneiss is best exposed in the central portion of the study area on the west and east flanks of hill 800' immediately northeast of the confluence of Purgee Brook and the Quabbin Reservoir. At this location, it intrudes schists and amphibolites of the Partridge Formation in the form of irregular masses and thin, sill-like apophyses. To the north, along Atherton and Cobb Brook, this gneiss is intruded into amphibolites of the Partridge Formation in the form of a thin (<15 feet thick), discontinuous sill(not depicted in Plate 1 due to limited map width). Three miles south of Purgee Brook and east of Chaffee Brook, it occurs as a series of thin sills intruded into the amphibolites of the Partridge Formation.

Lithology. The Purgee Brook Gneiss is a gray-brown-weathering, coarse-grained, biotite-hornblende tonalite gneiss. The rock possesses an interesting linear fabric consisting of elongate lenses of plagioclase and quartz .5-1.5 cm. long and prominently aligned hornblende and biotite grains. This fabric lends the rock a "pseudo-porphyritic" appearance in hand specimen. A moderately developed foliation is defined by the biotite grains in the rock.

The gneiss is composed of 20 percent quartz, 50 percent plagioclase (An_{36}), 5 percent microcline, 8 percent hornblende, 15 percent biotite, 2 percent pistacite, and trace amounts of allanite, sphene, apatite, and zircon (Table 8). The biotite is dark greenish brown in thin section and the hornblende is bluish green. Euhedral golden yellow allanite grains exhibit a fine, wispy concentric zoning and are commonly rimmed by colorless pistacite.

The estimated modal mineralogy of the Purgee Brook Gneiss was compared to point-counted modal analyses of quartz-diorites from the Belchertown intrusive complex (Guthrie, 1972). Strong similarities in the relative abundances of quartz, plagioclase, microcline, hornblende, and biotite were noted. Additionally, the An content of the plagioclase and the textures of these quartz-diorites as described by Guthrie (1972) are similar to those observed in the Purgee Brook Gneiss. Given these similarities and the unequivocal intrusive nature of the Purgee Brook Gneiss, it seems plausible that it may represent a discontinuous, locally sill-like intrusion of tonalite like that of the Belchertown complex.

Contacts and Thickness. The Purgee Brook Gneiss has sharp, locally discordant contacts with the Partridge Formation. These contacts are extensively folded in several outcrop exposures. Due to the irregular, discordant nature of the outcrop exposure of this unit, thickness calculations have limited usefulness. The sill-like exposure near Chaffee Brook shows a local minimum thickness of 30-50 feet.

Foliated Felsic Sills

Light-gray, medium-grained, foliated biotite quartz-diorite sills have been observed in the schists of the Partridge Formation and Littleton Formation. These sills exhibit post-intrusion deformational features such as: boudinage, mica foliation, asymmetric folds, and crenulated contacts. On this basis, it seems likely that these sills were emplaced prior to the last major phase of Acadian folding.

Lithology. The felsic sills consist of 36 percent quartz, 50 percent plagioclase (An_{38}), 8 percent biotite, 5 percent sericite (secondary), 1 percent magnetite, and trace amounts of muscovite, zircon, apatite, and rutile (Table 8). Disseminated grains of orange-brown biotite define the foliation in this rock. No layering was observed in thin section or hand specimen.

Contacts and thickness. The felsic sills have sharply defined contacts with the surrounding schists of the Partridge Formation and Littleton Formation. Locally, the contacts are folded by asymmetric folds and small amplitude crenulations. The thicknesses of these sills range from 3 inches to 4 feet.

Pegmatite

Pegmatites are the most abundant intrusive igneous rocks within the study area. They are particularly abundant in the central portion of the study area south of Gulf Brook and northeast of Chaffee Brook.

Pegmatites occur as sills, dikes, and irregular masses and are intruded into all pre-Mesozoic units in the study area. Where intruded as sills

List of specimens in Table 8.

152A Diabase dike, 7" thick, striking N60°E, vertical dip. Collected by Peter Robinson. 200 ft. NW of confluence of Cadwell Cr. and Quabbin Res.

S-61B Felsic biotite quartz-diorite sill in Partridge schist. 4" thick. Shoreline exposure 1900 ft. SE of confluence of Chaffee Bk. and Quabbin Res.

R-40 Purgee Brook Gneiss; gray, foliated gneiss. W flank of hill 800', N of confluence of Purgee Brook and Quabbin Res.

Table 8. Estimated modes of intrusive igneous rocks.

	Felsic Sill S-61B	Diabase 152A	Purgee Bk. Gneiss R-40
Quartz	36		20
Plagioclase	50 An_{38}	50 An_{68}	50 An_{36}
Microcline			5
Muscovite	tr		
Biotite	8 rb#		15 gb
Hornblende			8
Augite		40	
Pistacite			2
Allanite			tr
Sphene			tr
Zircon	tr		tr
Apatite	tr	tr	tr
Magnetite	1	7	
Glass (devitrified)		2	
Sericite*	5	tr	tr
Chlorite*	tr -**	1 +	
Calcite*		tr	

#Biotite color: rb-greenish brown, gb-greenish brown.

*Secondary mineral.

**Chlorite sign of elongation.

into schists, they are commonly boudinaged due to differences in competence. Some pegmatites appear to have been emplaced sometime prior to the last phase of Acadian deformation as suggested by local folding of pegmatites, the presence of a weakly developed mica foliation, and boudinage. Other pegmatites appear to be younger by virtue of their undeformed nature. The pegmatites appear to be of granitic composition, with very coarse potassium feldspar the dominant phase. Locally, coarse euhedral tourmaline crystals are present in these pegmatites. They generally occur along the contacts with the country rocks and are oriented such that their long axes are perpendicular to this contact. An exception to the general granitic composition of these pegmatites is observed on "The Island" where a pegmatite contains coarse diopside crystals along a contact with a hornblendite in the Partridge Formation.

Diabase Dikes

Three diabase dikes were mapped in the study area. These dikes strike northeast and possess near-vertical contacts. They are up to 65 feet wide and locally exhibit thin splays into the country rock. The northernmost exposure in Atherton Brook represents the northeastern extension of a major diabase dike that spans the width of the Pelham dome.

These dikes are composed of 50 percent plagioclase (An_{68}), 40 percent augite, 7 percent magnetite, 2 percent devitrified glass, and trace quantities of apatite (Table 8). Secondary chlorite, sericite, and calcite were also noted. Plagioclase crystals are generally euhedral and .2-2 mm. in length. Augite crystals are typically subhedral and .2-.6 mm. in length. This diabase possesses a subophitic texture.

STRUCTURAL GEOLOGY

Generalized Structural History of the Pelham Dome

The Pelham dome was subjected to regional metamorphism and four phases of deformation during the Acadian (Devonian) orogeny, a late-metamorphic phase of folding and faulting, and a period of Mesozoic brittle fracture and dike emplacement (Robinson, 1967a). The current understanding of this structural history is as follows (Robinson, 1967a, 1979; Ashenden, 1973; Onasch, 1973; Laird, 1974):

1.) Early development of major recumbent folds with tens of kilometers of east over west transport. Four major nappes were produced during this phase (Thompson and Rosenfeld, 1979): the Cornish nappe, the Bernardston nappe, the Skitchewaug nappe, and the Fall Mountain nappe (listed in order of ascending structural level). The root zones of these nappes are thought to lie on the east limb of the Bronson Hill anticlinorium.

2.) Development of southeast-directed recumbent folds in the Pelham and Keene domes. This folding involves Late Precambrian to Devonian strata and bears an uncertain age relation to the previously described nappes. Isoclinal synclines with northwest closures, such as the Pelham-Shutesbury syncline, were formed during this phase (Robinson, 1963, 1967a).

3.) Backfolding of the axial surfaces of the early nappes towards the east. This phase of deformation is most pronounced east of the Pelham dome, where the backfolds have amplitudes of several kilometers. An episode of cataclasis associated with this folding has been noted to the east as well (Robinson, 1979).

4.) Formation of gneiss domes via gravitationally induced movement of low density gneissic basement into higher density mantling strata. Accompanying this doming was the development of a pronounced north-trending regional mineral lineation. The emplacement of the Belchertown intrusive complex to the south of the Pelham dome preceded this phase as indicated by its cross cutting relationship with features of phases one and two, and the fact that the intrusive rocks contain the lineation formed during phase four. The development of asymmetric folds accompanied the formation of the Pelham dome. These folds locally deform the mineral lineation of phase four and yield a north-south movement line that is subparallel to this lineation. The rotation sense of these folds suggest that the core of the dome was moving northward relative to the mantling strata.

5.) Late-metamorphic folding and faulting as shown in the retrograde metamorphism of the Prescott syncline to the east of the Pelham dome (Robinson, 1963; Hollocher, 1981).

6.) Brittle fracturing and diabase dike emplacement. This phase was associated with the development of the eastern border fault of the Connecticut Valley during the Triassic and Jurassic.

A high-grade metamorphic event of probable Precambrian age preceded the nappe development of phase one as indicated by the presence of relict sillimanite-orthoclase assemblages in the Mt. Mineral Formation within the core of the Pelham dome (Robinson, Tracy, and Ashwal, 1975). Strata of Lower Devonian age represent the youngest rocks involved in the phase one deformation. The Belchertown intrusive complex (380 m.y., Ashwal et al., 1979) and the Prescott intrusive complex (374 m.y., Naylor, 1970) both postdate phases one and two and are subsequently deformed by phase four doming. These relations provide some age constraints for the Acadian orogeny, which is believed to include phases one through four. The brittle fracture of phase six is Triassic-Jurassic in age.

Phase five is constrained to sometime after dome phase Acadian deformation and prior to Triassic-Jurassic faulting (Robinson, 1963, 1967a; Hollocher, 1981). Recent studies in the Prescott syncline suggest a time of phase five retrograde metamorphism between Lower Mississippian and Lower Permian based in part on post-Acadian erosion rates (Hollocher, 1981).

General Structure of the Pelham-Shutesbury Syncline

The gross structure of the Pelham-Shutesbury syncline can be described as a westward-closing, isoclinal recumbent syncline refolded about the southeast-plunging end of a gneiss dome. The map pattern of the syncline is "J"-shaped, representing a fold interference pattern due to doming superimposed on early isoclinal folding. The axis of the syncline appears to trend nearly due N-S, with a north-plunging hinge near the town of Wendell and a south-plunging hinge near Holland Glen. The axial surface of the syncline appears to be subparallel to the regional foliation in the study area. The internal structure of the syncline is characterized by tight isoclinal map scale folds that have been refolded by late asymmetric map scale and minor folds.

Description of Minor Structural Features

Bedding. Bedding in the study area is shown in a variety of rocks such as quartzites, amphibolites, and pelitic schists. The presence of well defined coarse garnet layers in schists and amphibolites, thin calc-silicate horizons in amphibolites, cyclic layering of quartz and mica in schists, and discrete micaceous layers in quartzites may be indicative of primary bedding. These features are the oldest minor structural features within the study area.

Foliation. The most obvious minor structural feature in the study area is a pervasive regional foliation that is axial planar to phase two and possibly phase one folds. This foliation is typically parallel to bedding with the exception of early isoclinal fold hinges where foliation and bedding are observed in a pronounced angular relationship.

Parallel planar arrays of mica commonly produce this foliation. Acicular amphibole grains have their long axes within the foliation planes.

The shape of the Pelham dome is well described by this pervasive foliation. The prevailing northeast and southwest dips in the study area delineate the eastern and southwestern flanks of the dome respectively.

Mineral Lineation. A prominent north-south trending mineral lineation was commonly observed in the study area. This lineation is typically defined by parallel, elongate grains of biotite, muscovite, hornblende, gedrite, quartz, and kyanite as well as linear quartz-feldspar aggregates in the form of "rods". This lineation generally mimics the trend and plunge of the Pelham dome crest.

Minor folds. Two phases of minor folds were observed in the study area: (1) an early isoclinal fold in bedding, and (2) late asymmetric folds that deform both foliation and bedding. Early isoclinal minor folds are scarce and poorly exposed in the north-central portion of the Pelham dome (Ashenden, 1973; Onasch, 1973; Laird, 1974). This paucity of early minor folds is borne out in the cover rocks of the study area where only one unequivocal fold of this generation was observed.

Late asymmetric minor folds are fairly common in the study area. They deform bedding and foliation, have amplitudes ranging from less than a centimeter to several meters, and refold the one early isoclinal minor fold. The pervasive north-south mineral lineation of the Pelham dome is generally parallel to the axes of these folds. Locally, this lineation undergoes great circle rotation about these folds in the core gneisses of the Pelham dome (Onasch, 1973).

The predominant rotation sense of these folds in the study area suggests an east side-down sense on the east flank of the dome and a south side-down sense on the southwest flank.

<u>Boudinage</u>. Boudinage is a common minor structural feature in the study area. It is characteristically developed in coarse pegmatite sills intruded into schist units where the contrast in competency is pronounced. Locally, this boudinage appears to have been superimposed on pegmatite sills that were previously deformed by late asymmetric folding. Boudinage of calc-silicate horizons within amphibolite units was also observed.

<u>Joints and faults</u>. Two general types of joints were noted: (1) unaltered, planar common joints, and (2) silicified joints that typically weather to ribs of high relief on outcrop surfaces. Both of these joint types possess similar orientations. Planar common joints generally display spacing in the range of .2 to .4 meters and have maximum exposed dimensions of less than 2 meters.

Petrographic examination of the silicified joints reveals zones of alteration parallel to the joint planes that consist of sericitic alteration of feldspar and chloritic alteration of biotite. Thin microscopic shear zones within the joints are typified by granulation in coarse quartz grains, pronounced angular relations with respect to the joint plane, displacement up to .3 mm, and finely recrystallized quartz along these microscopic shear zones.

Faults in the study area are predominantly steeply dipping, northeast trending dip-slip faults that appear to be the youngest minor structural feature. The geometry of offset beds across these faults suggest that they are normal faults. They commonly display slickensides, mullions, and offset all the units in the study area. An older set of shallow-dipping faults appear to be offset by the dip-slip faults. A strike-slip fault on "The Island" with associated silicic breccia and flexural drag in an abutting schist unit bears an uncertain relation to the other faults.

Quartz vein fracture cleavage. A closely spaced fracture cleavage was observed in metamorphic quartz veins. This cleavage generally dips gently to the south. Metamorphic quartz veins were crystallized prior to late asymmetric folding; the age of the subsequent fracture is uncertain.

Basal mylonitic gneiss. Two adjacent outcrops in the central portion of the study area display a thin ductile shear zone at the base of the Partridge Formation on the west limb of the syncline 1.25 miles northeast of the town of Pelham. This zone occurs along the basement-cover rock contact and is typically three to five inches thick. It is characterized by a fine- to medium-grained mylonitic gneiss with quartz and feldspar augen up to 1.5 cm in diameter and a moderately developed mylonitic foliation that is parallel to the regional foliation in adjacent units.

The mylonitic nature of this gneiss is shown in recrystallized shear zones, deformed mica grains, coarse quartz and plagioclase porphyroblasts in a fine-grained quartzo-feldspathic matrix, and paired kink zones in albite twinning within plagioclase grains. These paired kink zones exhibit a consistent angular relation with respect to the external foliation, with one set oriented 81-88° from the external foliation, and the other set oriented 68-79° from the external foliation.

Mylonitization probably occurred at high strain rates during phase three of the Acadian orogeny as noted further east in the Bronson Hill anticlinorium (Robinson, 1967b). The ductility contrast between the basal quartzite of the Partridge Formation and the underlying Four Mile Gneiss may have influenced its development along the basement-cover rock contact.

Structural Subareas

The study area was subdivided into ten structural subareas along the length of the syncline. These subareas were established with the goal of accurate determination of average orientations of linear and planar structural features, changes in the orientations of these features along the length of the syncline, and relations between these structural elements.

Equal area plots of planar structural features (consisting of bedding and foliation) and linear structural features (consisting of fold axes and mineral lineations) were compiled for each subarea and are depicted in Figures 6-10. These plots incorporate measurements from all cover rock units as well as adjacent basement gneiss exposures. Supplemental data from previous unpublished field work (Robinson, 1966-68; Univ. of Mass. Advanced Mapping classes, 1966-67, 1977-78) is incorporated in subareas 1-3, 9, and 10. Subarea 3 represents a compilation of many months of detailed field study of "The Island" by Robinson and students (Robinson, 1967b).

Average strikes and dips of planar features and average trends and plunges of linear features were determined for each subarea and are portrayed in Figure 5. Exceptions to this scheme are as follows: (1) the average linear orientations for subareas 1 and 2 were derived from mineral lineations only, and (2) two average planar values are depicted for subarea 2 which represents the divergent dips on either side of the southeastward plunging crest of the Pelham dome.

General orientation of planar features. Equal area diagrams of planar features in subareas 3-10 reveal a very marked clustering of these features that typically strike N9-22°W and dip 21-61°NE. The strong maxima evident in these plots underscore the isoclinal nature of the syncline as a whole. The dip of planar features appears to undergo a progressive flattening north of subareas 3 and 4 which may indicate a decreased amplitude in the foliation arch in the northeast portion of the Pelham dome.

Planar elements in subareas 3 and 4 form broad east-west girdles consisting of the strong maxima previously noted along with sparse westward dipping measurements. The poles to these girdles appear to be coincident with the dominant mineral lineation and fold axes in these subareas.

The orientation of planar structural features in subarea 2 undergoes a fairly abrupt change with the prevailing northeast dips giving way to southwest dips as one traverses the subarea from east to west.

This difference in orientation is due to the gently plunging southeastern crest of the Pelham dome, about which the syncline is folded. The equal area plot of planar features in this subarea reveals a broad northeast-southwest girdle, the pole to which plunges gently to the southeast. This inferred southeast-plunging dome axis lends credence to previous work (Laird, 1974) which indicated an asymmetric configuration for the Pelham dome, with an eastward dipping axial surface.

Planar features in subarea 1 and the western half of subarea 2 have consistent orientations and strike N44-50°W and dip 32°SW on the average. The isoclinal nature of the syncline is again shown in these plots.

General orientation of linear features. Equal area plots of linear structural features in subareas 5-10 reveal very consistent average orientations, with trends of N1°W-N11°E and plunges of 9-21°N on the average. A marked parallel relation of fold axes to the dominant mineral lineation is evident in these subareas.

The orientations of minor folds present in subarea 4 are different in that they appear to sweep out a broad north-south girdle which is subparallel with the foliation. The linear elements immediately south in subarea 3 ("The Island") contrast sharply with those of subarea 4. A powerful coaxial linear fabric consisting of both fold axes and mineral lineations is evident in this subarea. This fabric trends N11°W and plunges 11°N.

A departure from the coaxiality of fold axes and mineral lineations is observed in subareas 1 and 2 on the southwest flank of the dome. In these subareas, the mineral lineation exhibits a strong clustering that trends S2°W-S5°E and plunges 21°S. The mineral lineation in subarea 2

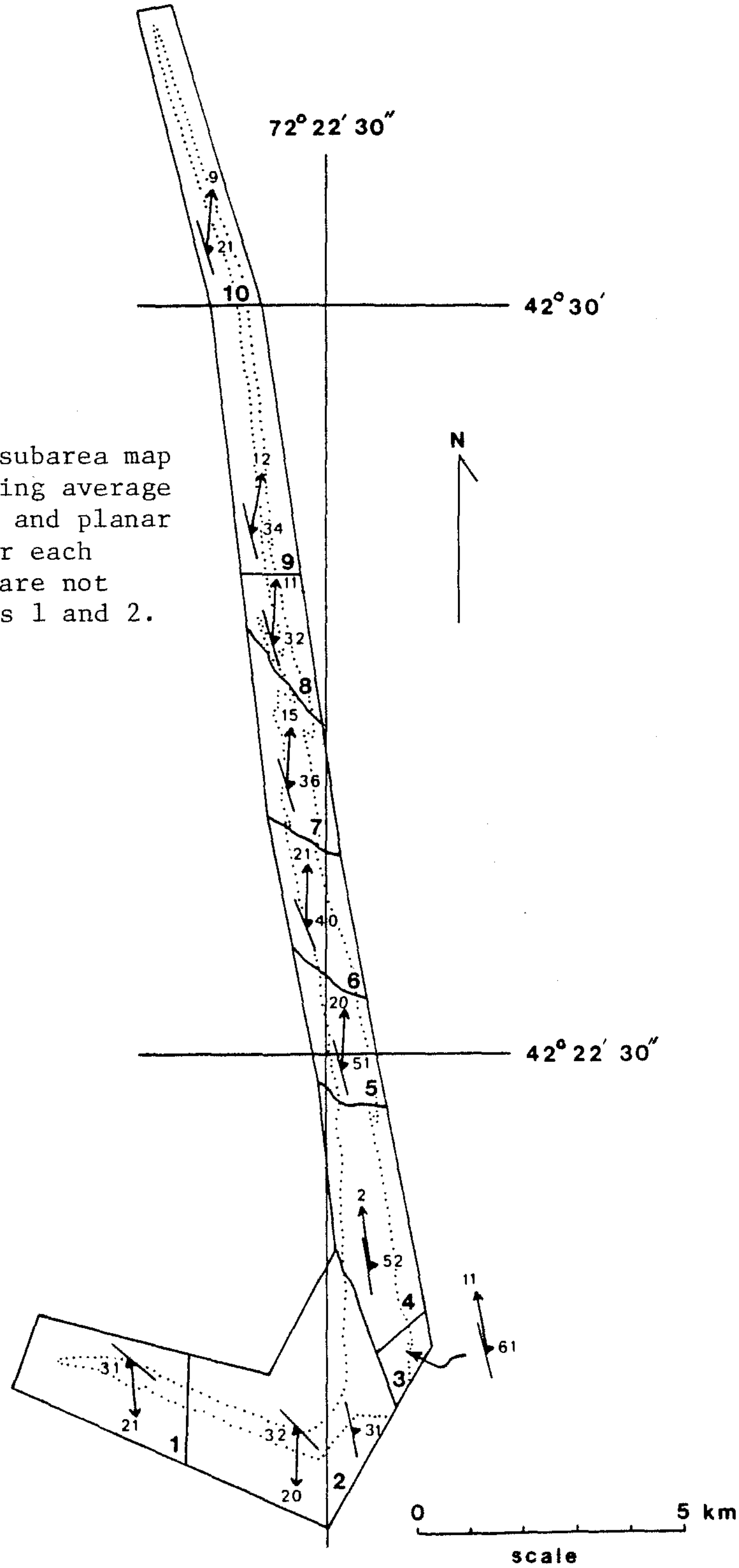


Figure 5. Structural subarea map of the study area showing average orientations of linear and planar structural features for each subarea. Minor folds are not represented in subareas 1 and 2.

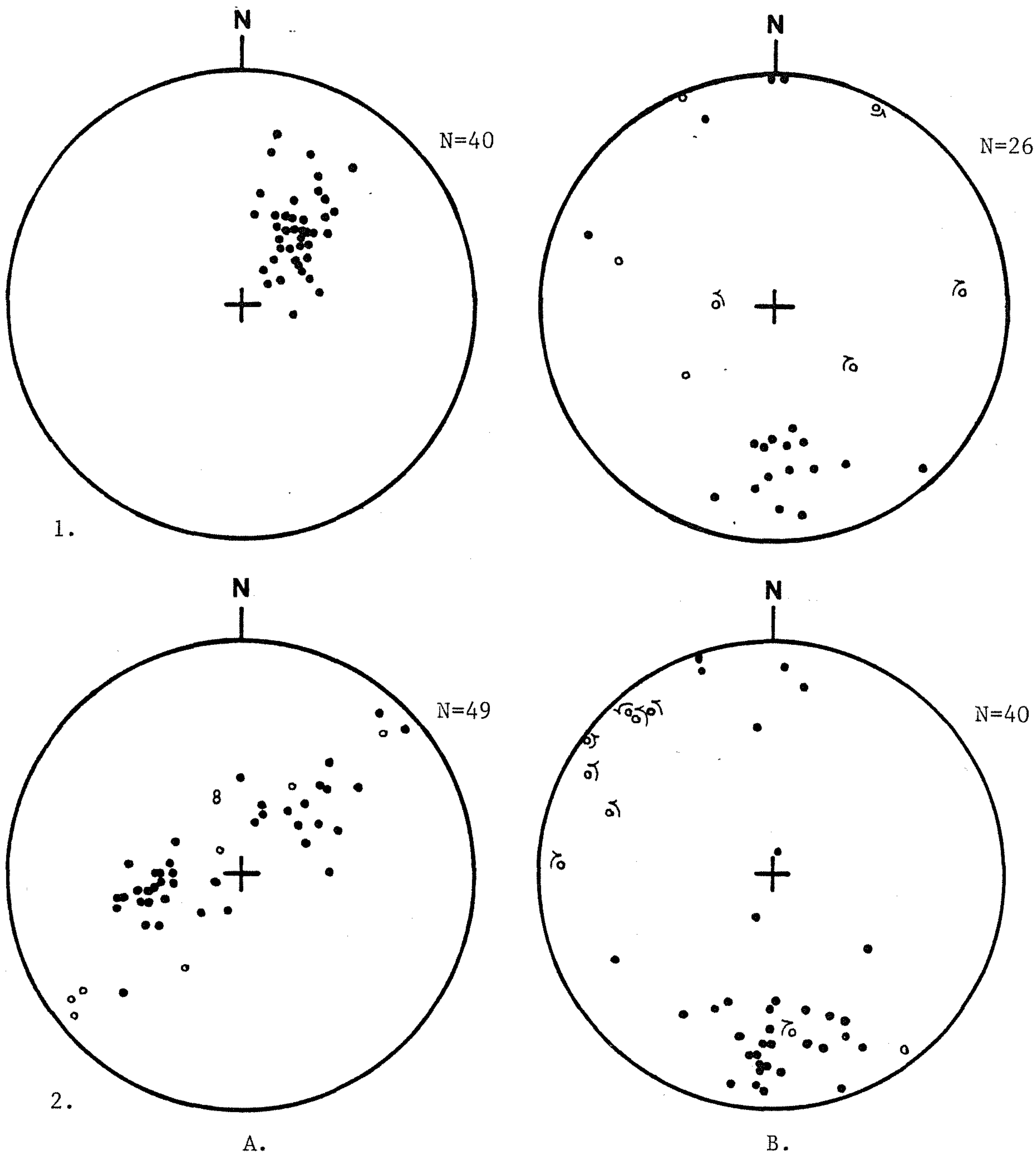


Figure 6. Equal area plots of planar and linear structural features in subareas 1 and 2. A.) • pole to foliation, o pole to bedding. B.) • mineral lineation, minor fold axis and rotation sense.

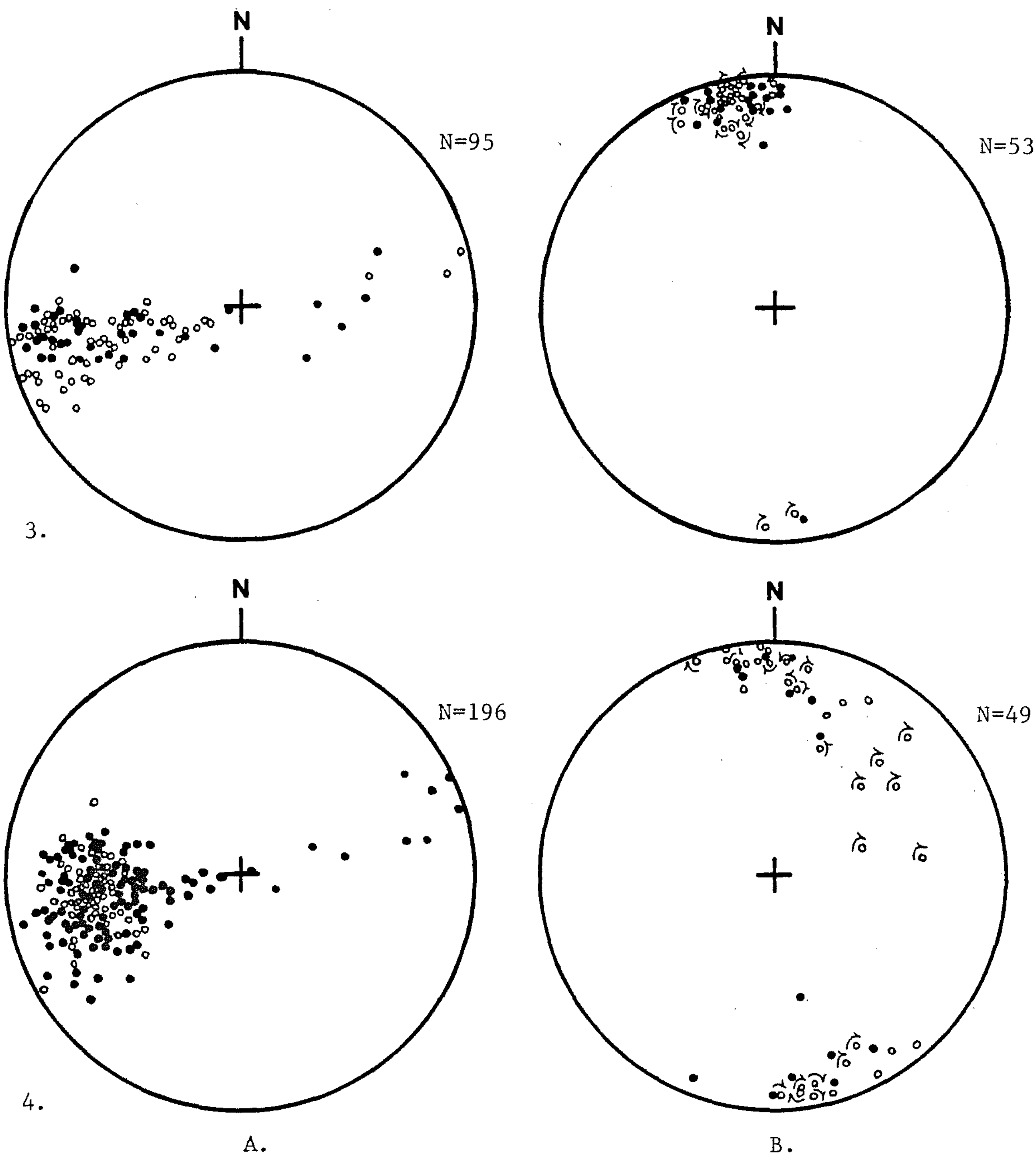


Figure 7. Equal area plots of planar and linear structural features in subareas 3 and 4. A.) • pole to foliation, ○ pole to bedding. B.) • mineral lineation, minor fold axis and rotation sense.

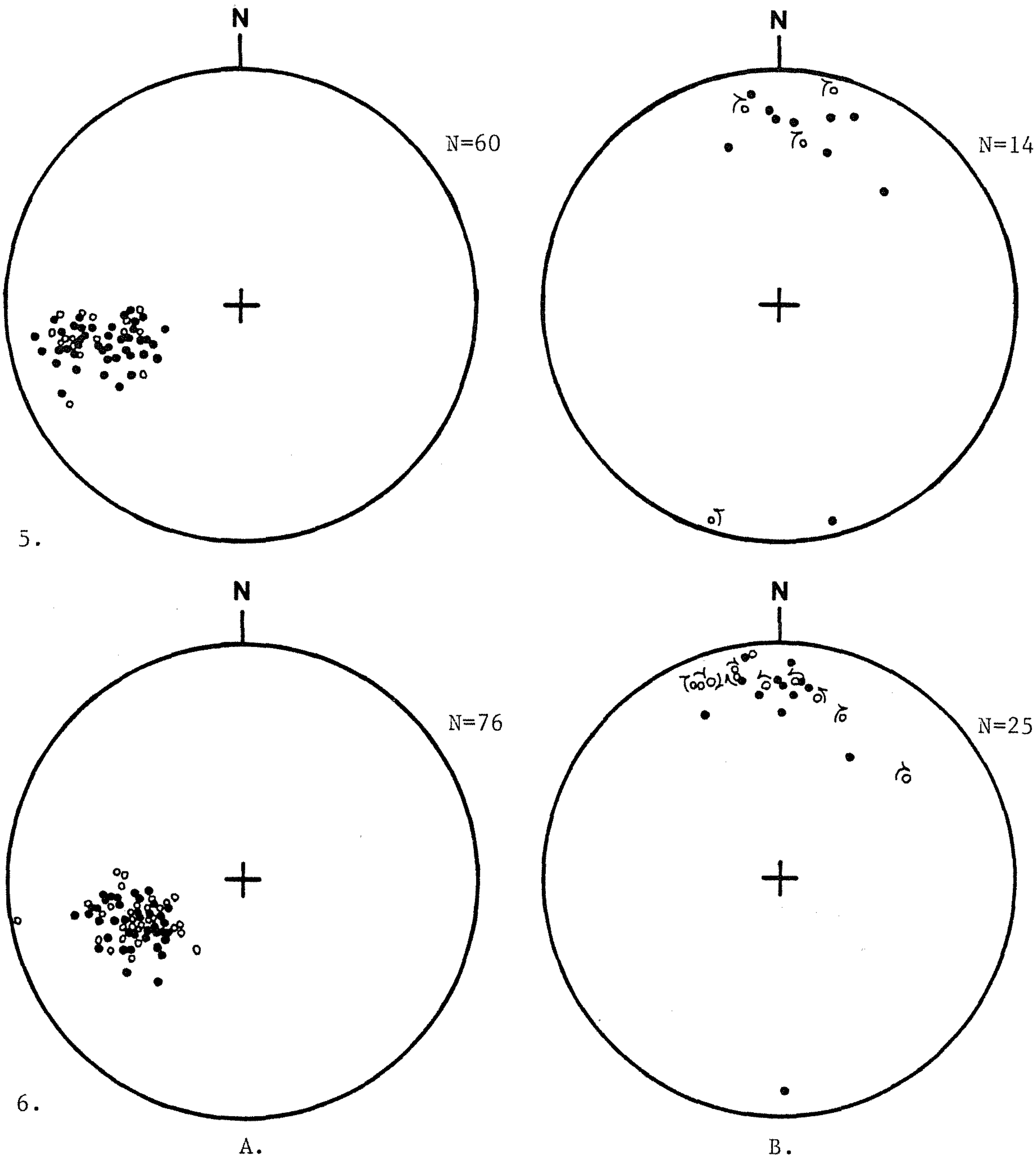


Figure 8. Equal area plots of planar and linear structural features in subareas 5 and 6. A.) • pole to foliation, ∘ pole to bedding. B.) • mineral lineation, ↶∘ minor fold axis and rotation sense.

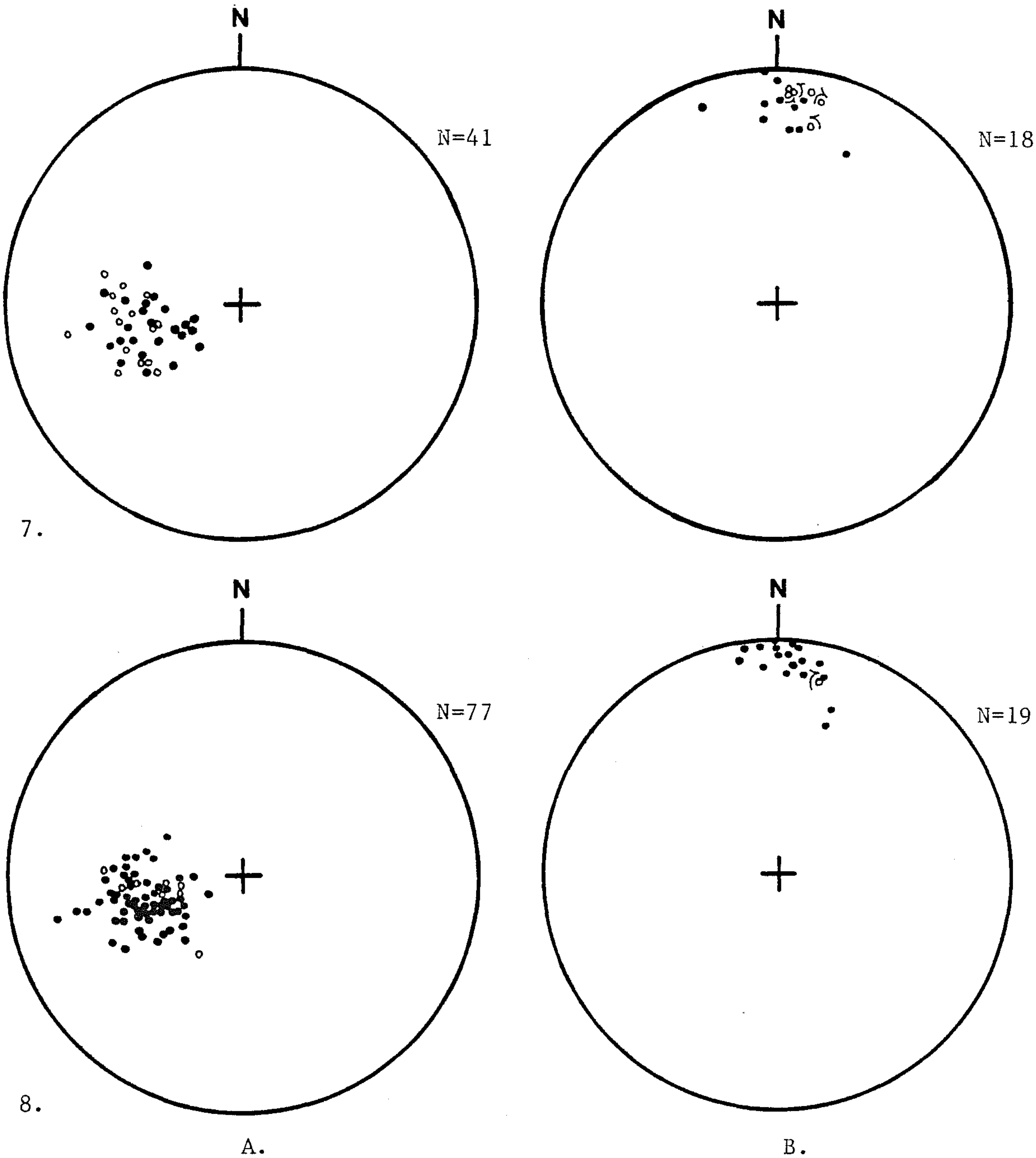


Figure 9. Equal area plots of planar and linear structural features in subareas 7 and 8. A.) • pole to foliation, ∘ pole to bedding. B.) • mineral lineation, ↻ minor fold axis and rotation sense.

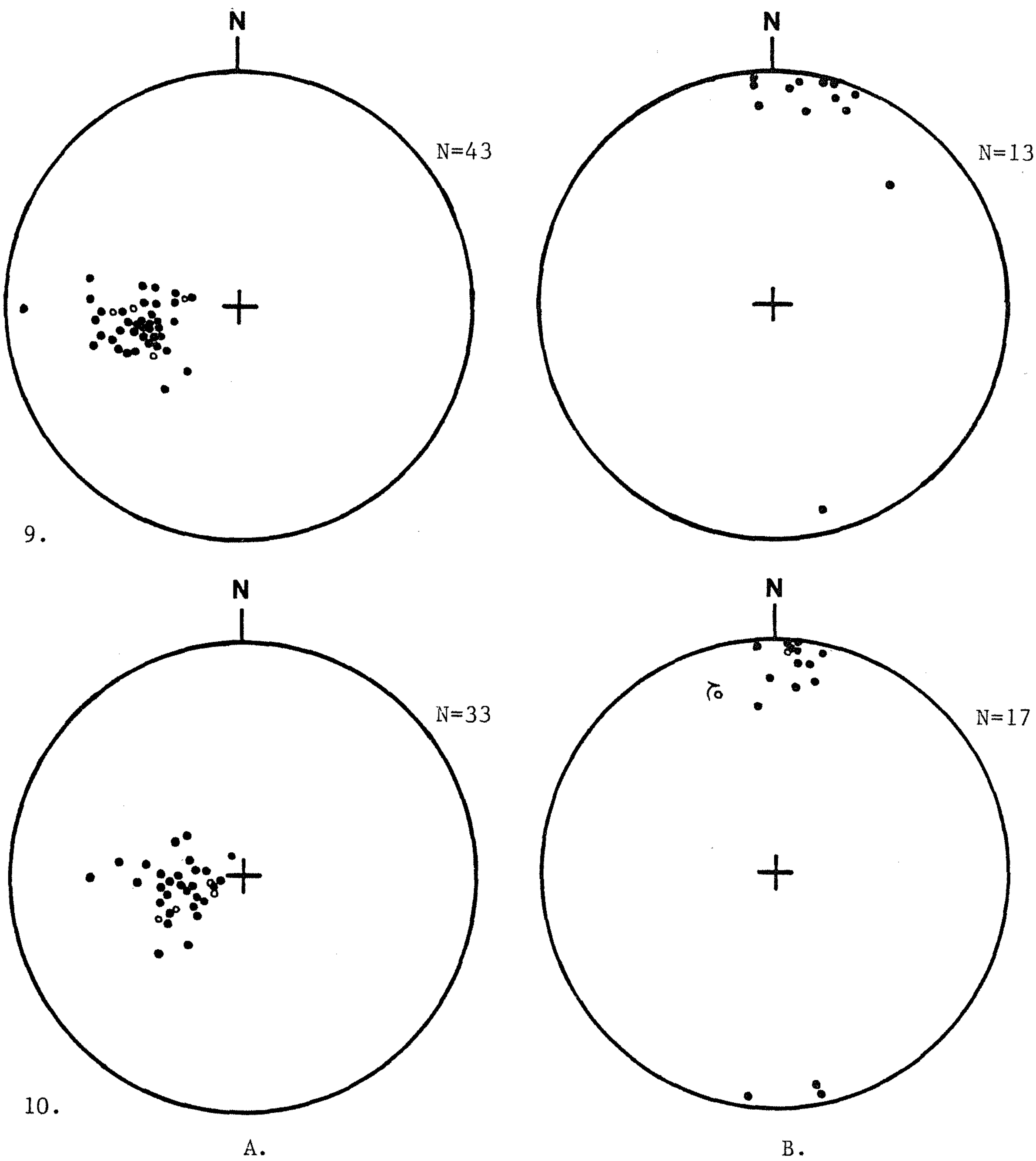


Figure 10. Equal area plots of planar and linear structural features in subareas 9 and 10. A.) • pole to foliation, o pole to bedding. B.) • mineral lineation, ↻o minor fold axis and rotation sense.

does not appear to coincide with the axis of the dome as defined by the girdle of planar structural features in that subarea.

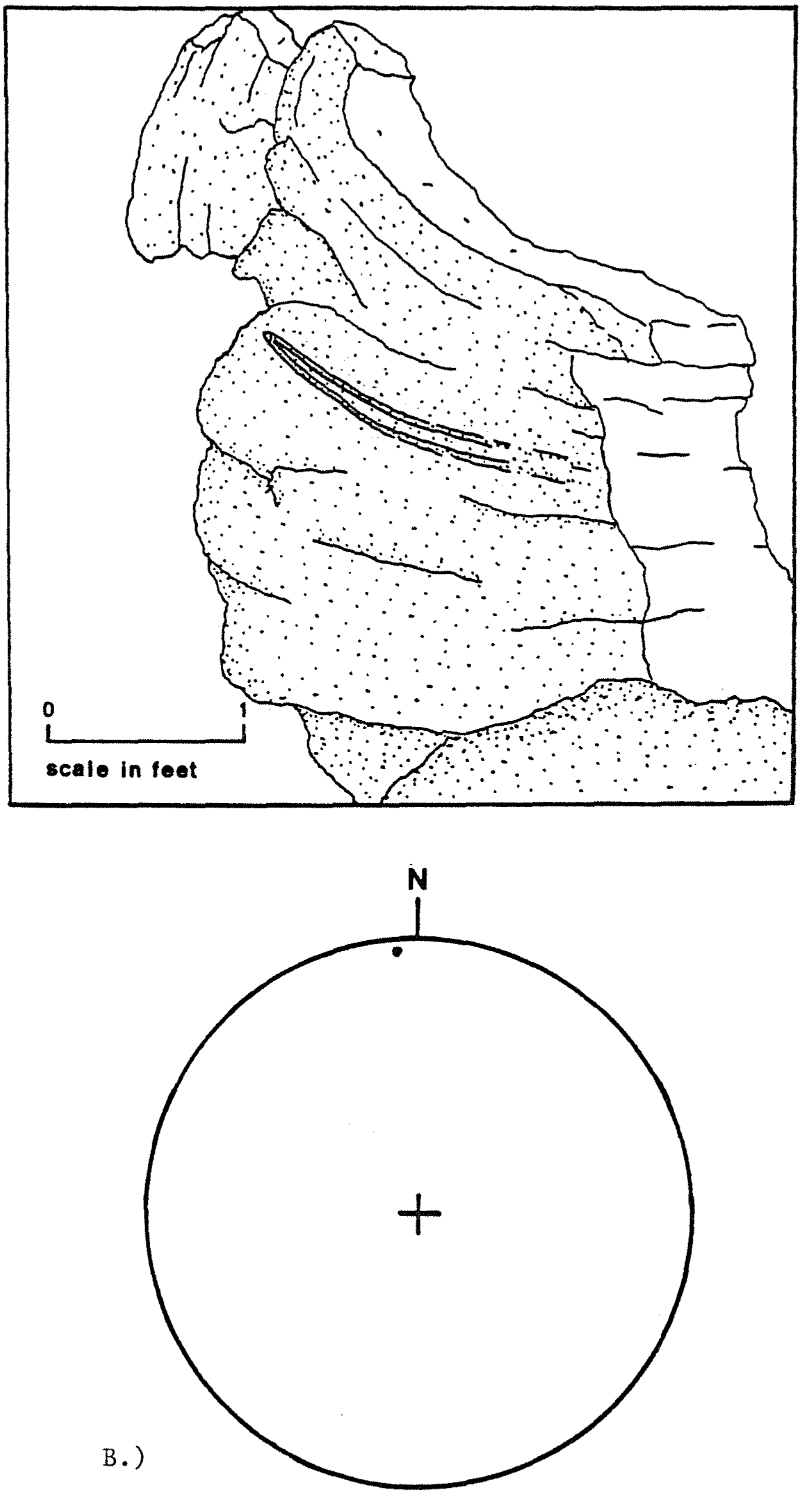
Early Recumbent Folding

Previous work in the northern and central portions of the Pelham dome has revealed a series of northeast-trending recumbent anticlines and synclines with southeast transport directions that involve both the core gneisses of the Pelham dome and the mantling strata (Robinson, 1963, 1967a; Ashenden, 1973; Onasch, 1973; Laird, 1974). The inferred trend and transport direction of these folds and the axial planar relation of the regional foliation to these folds suggest strong similarities to the Pelham-Shutesbury syncline. Of particular interest is the Beers Mountain recumbent syncline (Robinson, 1963; Ashenden, 1973) which represents a deep infold of Middle Ordovician cover rocks into the Pelham dome at a higher structural level.

The episode that produced these folds constitutes the earliest phase of deformation that can be discerned within the study area (phase two as previously described).

Minor folds. Only one minor fold of this phase was identified with certainty in the study area (Figure 11). Its axis trends slightly west of north and has a gentle plunge. This fold is expressed as a tight isoclinal fold in bedding in an outcrop of the Clough Quartzite within the central portion (subarea 4) of the syncline 1800 ft. ESE of the confluence of Chaffee Bk. and the Quabbin Reservoir. Near the hinge of this isoclinal fold, bedding can be observed at a pronounced angle with respect to the foliation, which bears an axial planar relation to this minor fold. It is demonstrably older than the late asymmetric folds as its axial surface is

A.)



B.)

Figure 11.) A.) Outcrop sketch of early isoclinal minor fold in the Clough Quartzite. B.) Equal area plot of hinge line of this fold.

clearly folded about the hinge of one of these later folds with which it is nearly coaxial.

The presence of other related minor folds has been indicated by detailed mapping in the central portion of the study area (subarea 3) on "The Island" (Robinson, 1967b).

Major folds. The most prominent major structural feature of this phase in the study area is the westward closing infold of Paleozoic cover rocks into the gneisses of the Pelham dome that comprises the Pelham-Shutesbury syncline. Detailed mapping has delineated two noses of this syncline, the northern one lying immediately west of the town of Wendell, and the southwestern one lying near Rt. 9 south of Holland Glen in the town of Belchertown. The trend of the syncline axis is not clearly understood, but a tentative axis trending N4°E is inferred by connecting the two noses. The geometry of the dome mandates a northward plunge of the hinge near Wendell, and a southward plunge of the hinge near Holland Glen. This axis has a more northerly trend than the inferred hinge of the Beers Mt. recumbent syncline (Laird, 1974).

The Fourmile Gneiss along the east limb of the syncline could represent the southern continuation of the overturned limb of the nappe in the northern portion of the dome postulated by Ashenden (1973), however, the map pattern of basement gneisses and quartzites northwest of Wendell is not wholly supportive of this interpretation.

Within the central portion of the syncline, the early phase of recumbent folding is shown in north-south trending parallel belts of Silurian-Devonian strata that have been subsequently refolded. The axial surfaces of these isoclinal folds in these rocks appear to be centered in the Littleton Formation in the central portion of the syncline and in the Amphibolite Member of the Partridge Formation near the hinge regions. These early axial surfaces appear to have been extensively deformed during late asymmetric folding. This relation is supported by mapping of "The Island" (Robinson, 1967b) where early isoclines centered about the Littleton Formation appear to be extensively deformed by late asymmetric folds of various amplitudes.

Foliation. The dominant foliation in the Pelham dome area appears to bear an axial planar relation to these early recumbent folds. This relation is shown in the related minor fold previously discussed and in the strong foliation maxima in Figures 6-10. The fact that this foliation is deformed by doming and late asymmetric folding further indicates that it was formed during one of the early phases of deformation. A mylonitic zone is locally present on the west limb of the syncline where the mylonitic foliation appears to be subparallel to the regional foliation in the surrounding rocks. It is probable that this episode of mylonitization postdates phase two on the basis of deformed, reoriented mica grains.

Main Phase of Doming

The second phase of deformation that is observable in the study area consists of the doming of the basement gneisses and mantling strata to form the Pelham dome. This doming is thought to have been gravitationally induced, with the low density core rocks moving upward into the relatively dense mantling strata. This theory is compatible with the gravity low that is centered over the dome (Kick, 1975; Laird, 1974).

Foliation. The formation of the Pelham dome deformed the early recumbent folds and regional foliation into a north-south trending, doubly plunging anticlinal arch. Previous work indicates that the dome morphology includes two distinct culminations in the northern portion and that the dome is somewhat asymmetric (Laird, 1974). The hinge line of the dome is curved as indicated by the southeast-plunging axis at the south end of the dome (defined by the pole to the girdle of planar elements in subarea 2, Figure 6), and the almost due-north trending axis at the north end of the dome (Ashenden, 1973). The upward arching of the Pelham dome gently folded the Pelham-Shutesbury syncline about its southwestern and eastern flanks. Subsequent erosion has produced a "J"-shaped map pattern defined by the periphery of the syncline. This shape represents a fold interference pattern resulting from the doming superimposed on the early recumbent folding.

Lineation. The rocks in many portions of the Pelham dome possess a well developed, north-south trending mineral lineation. In the northern and central portions of the dome, this lineation generally mimics the crest of the dome defined by the arch in regional foliation (Laird, 1974), and plunges gently to the north on the whole. This coincidence of the lineation with the crest of the dome may suggest that it was formed during the main phase of doming. Other evidence suggests that its formation was contemporaneous with the late asymmetric folding (Onasch, 1973). This lineation generally plunges gently to the north in portions of the study area along the east flank of the dome, then heels over abruptly to the southward plunging orientation in subareas 1 and 2 along the southwest flank of the dome. Unlike the north end of the dome, mineral lineation at the south end isn't parallel to the hinge, but plunges south whereas the hinge plunges southeast.

Plutonism. The Belchertown intrusive complex, which lies immediately south of the Pelham dome, was emplaced after early recumbent folding and prior to the main phase of doming (Hall, 1973; Ashwal, 1974, Ashwal et al., 1979). This relation is indicated by the cross-cutting nature of the pluton with respect to early structural features such as the Pelham-Shutesbury syncline, and the presence of foliation and lineation parallel to that in the surrounding country rocks (Hall, 1973; Ashwal, 1974; Ashwal et al., 1979). The Purgee Brook Gneiss of the study area possesses textural and mineralogical similarities to the hornblende-biotite gneisses of the outer zone of the Belchertown complex. Assuming this affinity, this unit may have been intruded prior to doming along foliation in the central portion of the study area as discontinuous sills and irregular masses. The foliated and lineated fabric in this unit may have been imparted during one of the later phases of Acadian deformation. The emplacement of the Purgee Brook Gneiss in the study area preceded the late asymmetric folding, which locally deforms apophyses and contacts of that unit.

Medium-grained felsic sills and early granitic pegmatite sills were intruded into the rocks of the study area sometime prior to late asymmetric folding and after early recumbent folding. The relation of felsic sills to the main phase of doming is uncertain. Pegmatite sills are locally folded by late asymmetric folds and are boudinaged. Their emplacement predates these phases of deformation.

Late Asymmetric Folding

Studies of the northern portion of the Pelham dome by Ashenden (1973) and Onasch (1973) revealed a late set of asymmetric folds that are predominantly found within the core rocks of the dome. These folds in the northern portion of the dome have the following characteristics: (1) they are asymmetric in style, (2) they possess curved hinge lines that lie within their axial planes, (3) they deform the prominent north-south mineral lineation previously described, (4) they have north-trending movement lines that are statistically parallel to this lineation, and (5) they possess rotation senses that suggest a northward movement of the core rocks relative to the mantling strata (Onasch, 1973). Subsequent work elsewhere in the dome (Robinson, Peter, and students of Advanced Mapping class, unpublished field data, 1978-79), including this study, suggests that large scale folds of this generation, as well as related minor folds, are present in the southern and eastern portions of the dome.

Late asymmetric folds in the study area deform features related to early recumbent folding and locally deform the prominent mineral lineation associated with the main phase of doming. Previous studies have postulated that this episode of folding occurred as a late phase in the formation of the Pelham dome (Ashenden, 1973; Onasch, 1973).

Minor folds. Minor folds of this generation are relatively abundant within the study area. These folds can be distinguished from early isoclinal folds in that they deform both bedding and foliation, and are more open in nature. The size and style of late asymmetric minor folds vary considerably, ranging from less than a centimeter to several meters in amplitude, and from rounded, fairly open folds to peaked, tight chevron folds. The variations in style appear to be related to the rocks in which the fold occurs. The more rounded, open folds generally occur in gneisses, and the tighter folds are more prevalent in schists which are less competent.

The axes of late asymmetric minor folds commonly display a consistent orientation in the northern and central portions of the study area, where they trend N11°W-N11°E and plunge 2-21°N on the average. There, the fold axes are parallel to the regional mineral lineation. A departure from the dominant north-plunging orientation of these axes was observed within subarea 4 in the central portion of the study area (Figure 7) where the axes exhibit less constancy, as indicated by several axes that plunge moderately to the southeast and northeast. Minor fold axes of this generation in the southwest portion of the study area display more diverse orientations than elsewhere in the study area (Figure 6). The most prevalent fold axis orientation in this area trends N62°W and plunges 20°NW. The south-plunging regional mineral lineation, which is nearly orthogonal to these fold axes in this area, is clearly deformed about their hinges.

Two axial planar features have been noted in late asymmetric folds in schistose lithologies: 1) A moderate to well developed axial plane cleavage is present in folds in the schists of the Littleton Formation within the central portion of the study area (Figure 12). This cleavage appears to be confined to the hinge regions of these folds and is poorly developed or absent on the limbs. 2) A well developed crenulation cleavage is locally present in schist units in the central portion of the study area. The axes of these crenulations in foliation and bedding are parallel to the late asymmetric folds, to which they bear a parasitic relation. The amplitude of crenulation folds is typically less than one centimeter.

The axial planes of late asymmetric minor folds in the northern and central portions of the study area exhibit fairly consistent orientations, striking N2-16°W and dipping 40-70°NE on the average (Figure 13). This

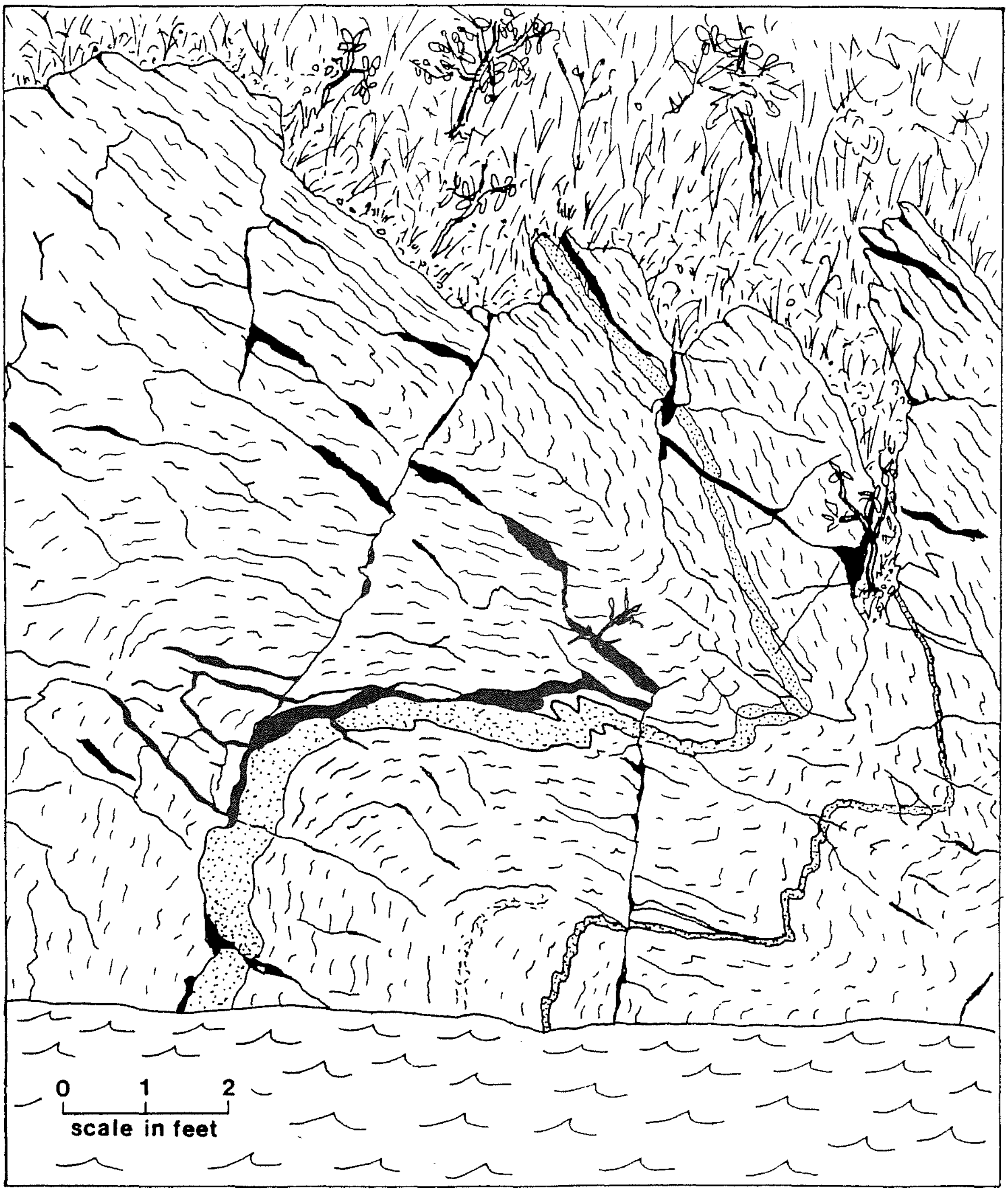


Figure 12. Outcrop sketch of late asymmetric minor fold exposed in the Littleton Formation along the shore of the Quabbin Reservoir. View is towards the northwest. Hinge line of fold plunges to the north (right) suggesting west side-up shear sense.

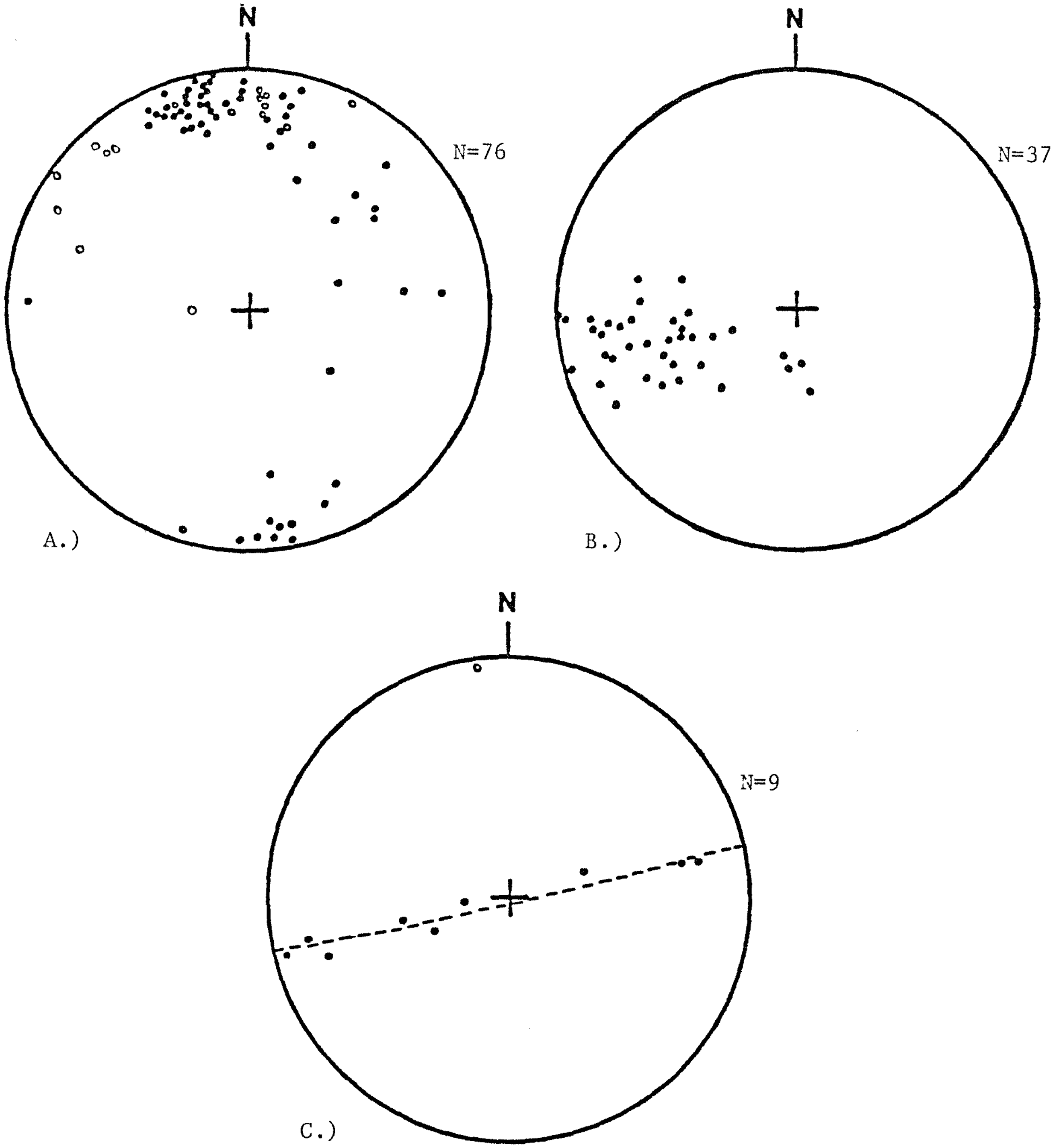


Figure 13. A.) Equal area plot of late asymmetric minor folds from all subareas: • clockwise rotation sense, ∘ counterclockwise rotation sense. B.) Equal area plot of axial planes to late asymmetric minor folds. C.) Equal area pi diagram of poles to foliation about a typical late asymmetric minor fold: • pole to foliation, ---girdle, ∘ minor fold axis.

orientation is subparallel to the dominant attitudes of foliation and bedding in this area. Axial planes to these folds in the southwestern portion of the study area strike nearly east-west and dip gently to the north, reflecting their position on the southwest flank of the dome.

The rotation senses of late asymmetric minor folds in the study area can be generalized as follows:

1) Subarea 1 (southwestern portion of the study area): counterclockwise rotation sense plunging northwest and clockwise rotation sense plunging east.

2) Subarea 2 (southern portion of study area): counterclockwise rotation sense plunging northwest.

3) Subarea 3 ("The Island"): clockwise rotation sense plunging north and south, hence yielding contrasting absolute rotation sense.

4) Subarea 4 (central portion): clockwise rotation sense plunging in many directions, yielding contrasting absolute rotation sense.

5) Subarea 5 (central portion of the study area): clockwise plunging north.

6) Subareas 6 and 7 (central portion of the study area): clockwise and counterclockwise plunging north.

7) Subareas 8-10 (northern portion of the study area): clockwise plunging north.

In subarea 4 (Figure 7), the variable orientations and contrasting rotation senses of late asymmetric minor folds could be interpreted in two ways:

1) The contrasting absolute rotation sense of south-plunging minor folds when compared to north-plunging minor folds could be due to their limb location on folds of a larger scale. For example,

south-plunging minor folds that display clockwise rotation sense might be situated on the short limb of a larger scale fold with a clockwise rotation sense (plunging gently north). Mapping in subarea 4 has not revealed folds of an intermediate scale, however.

2) The hinge lines of late asymmetric minor folds could go through curvatures of nearly 180 degrees within their axial planes, suggesting horizontal slip lines trending N10^{o}W based on a narrow separation of minor fold axes of opposite rotation sense.

Of the above hypotheses, the second better accounts for the girdle-like distribution of minor fold axes in subarea 4 and does not require the presence of intermediate scale folds that have not been documented by detailed mapping. The reasons for the development of this minor fold pattern in subarea 4 are not clear. The syncline reaches its maximum thickness in this subarea, which may have permitted greater than normal variation in minor fold axis orientations.

Major folds. Major map-scale folds of this generation have been noted in the study area and in the core rocks of the south-central portion of the dome. These major folds mimic related minor folds in their general orientation and rotation sense. The pattern of map scale late asymmetric folds in the central and northern portions of the study area would be consistent with axes that plunge gently to the north and axial planes that dip moderately to the northeast, although exact geometric orientations are unknown. The amplitudes of these map scale folds appear to be variable, ranging from tens of meters to over one hundred meters.

Movement line. Five movement line determinations were made in this study based upon the intersections of great circles defined by rotated mineral lineations and the axial planes to late asymmetric folds by which they are deformed mineral lineation and movement line associated with them. Field observations indicate that the mineral lineation undergoes great circle rotations about these fold hinges. Approximations of these great circles were employed in the equal area beta diagrams displayed in Figure 14. Additional data from the hinge regions of the folds might help to better define the great circles in the equal area plots of Figure 14. Beta diagrams A and B depict the approximate movement line for these folds in Beta diagrams A and B depict the approximate movement line for these folds in the central portion of the dome, and beta diagrams C and D depict the approximate movement line for the southern portion of the dome. These plots, in conjunction with the movement lines determined by Onasch (1973) for the northern portion of the dome, suggest a fairly consistent movement line orientation along the entire length of the dome, plunging gently to the north. A tentative slip line suggested by the separation of minor fold axes in subarea 4 possesses a similar orientation.

Figure 15 portrays the movement line defined by a single kyanite crystal that is folded about a late asymmetric fold on "The Island". The resultant movement line is decidedly askew from the other determinations in the Pelham dome and may represent an early east-west mineral lineation subsequently deformed by later folding (Robinson, 1967b).

In the southern portion of the study area, the deviation of the regional mineral lineation from the inferred dome axis might suggest that the late asymmetric folding reoriented a pre-existing lineation that was

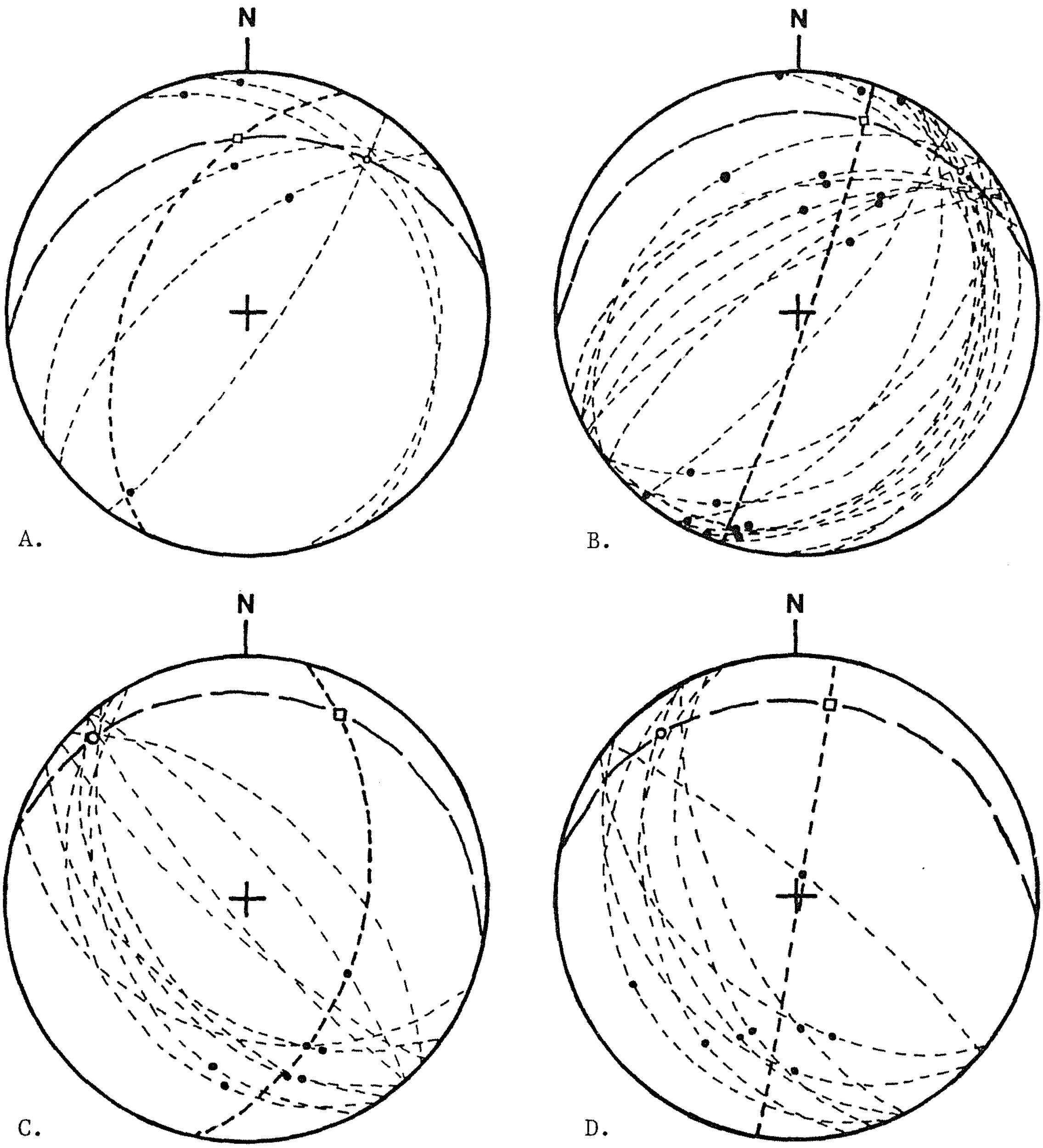


Figure 14. Equal area beta diagrams of late asymmetric minor folds and related movement lines: • mineral lineation, o minor fold axis, □ movement line, - - - trace of great circle containing rotated mineral lineation, - - - trace of foliation and bedding planes, — — trace of axial plane to late asymmetric minor fold. A. and B.) Roadside exposure of Mt. Mineral Formation, Route 202, 3.5 km S of Shutesbury.* C. and D.) Exposure of Fourmile Gneiss, 1.5 km ENE of intersection of Route 202 and Allen St., Belchertown.

*(Robinson, unpublished field data, 1967)

originally parallel with the dome axis or an early isoclinal hinge line. The consistent orientation and parallelism of fold axes and mineral lineations in the central and northern portions of the study area could be the result of a rotation of these features into sub-parallelism with the movement line during late asymmetric folding. The relatively plastic deformation of the cover rocks of the syncline relative to the basement gneisses may have fostered this rotation.

The approximate movement line orientation and dominant rotation sense of late asymmetric folds suggests that they were formed in response to a northward movement of the core rocks relative to the mantling strata. The fact that these folds are pervasive along the entire length of the Pelham dome indicates that this phase of deformation was of greater scope than a localized deformation due to the southward overturning of the Warwick dome (Ashenden, 1973).

Boudinage

The equal area plot of boudin neck lines in the study area displays two clusters: N70°E-S80°E, plunging 20-60°E on the east flank of the dome, and S72°W, plunging 10-40°W on the southwest flank of the dome (Figure 16). Boudinage occurred sometime after late asymmetric folding as indicated by folded felsic sills that were subsequently boudinaged on "The Island". The extension directions in the planes of foliation indicated by the perpendiculars to neck lines are N12°W-S12°E and appear to be controlled by the shape of the dome to some extent. Boudins in the study area differ from those studied in the northern portion of the Pelham dome (Onasch, 1973; Laird, 1974) in two ways: (1) no "mattress structure" was noted in

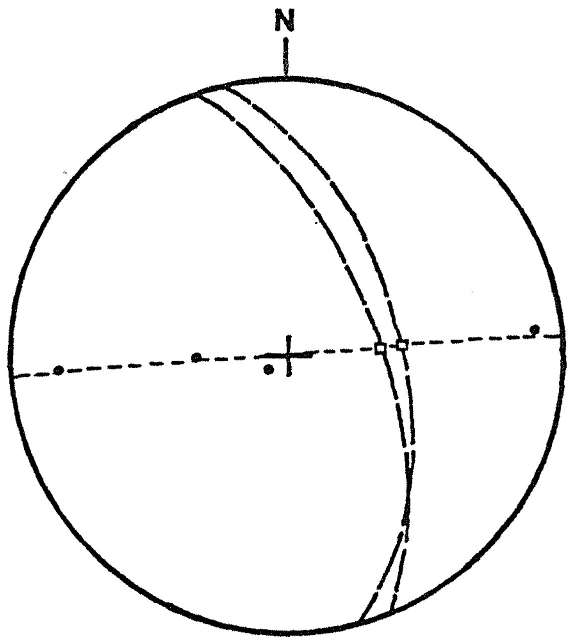


Figure 15. Equal area plot of folded kyanite crystal on "The Island" and associated movement line: • c-axis of kyanite crystal, ▫ movement line, --- trace of great circle containing rotated c-axis, — — trace of axial plane to late asymmetric minor fold (Robinson, unpublished field data, 1967).

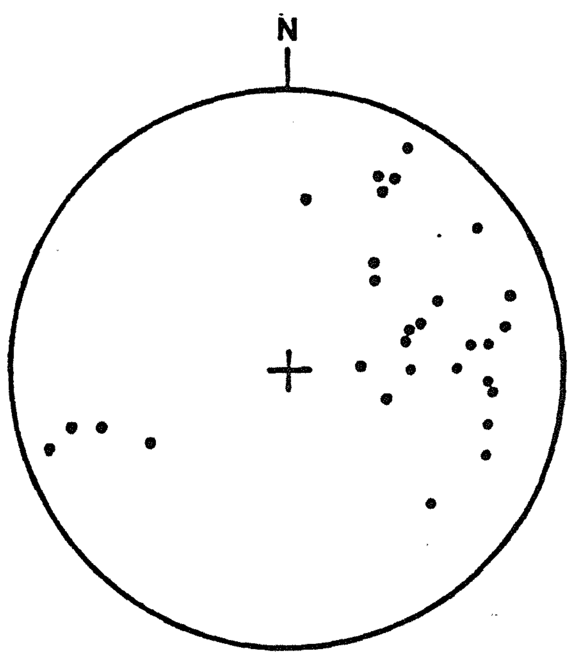


Figure 16. Equal area plot of boudin neck lines.

outcrop or suggested by equal area plot, and (2) jointing does not appear to be related to this period of extension in the study area.

Mesozoic Brittle Fracture

Several minor structural features related to a post-Acadian period of brittle fracture were observed within the study area. These features include a quartz vein fracture cleavage, common joints, silicified joints, dip-slip faults, oblique-slip faults, strike-slip faults, and diabase dikes. The dominant orientation of joints, faults, and dikes compare favorably with the northwest-southeast extensional tectonic models proposed for the Triassic and Jurassic (Chandler, 1979). Age relations between the various brittle elements of the study area are not clearly understood. Common and silicified joints, dip-slip faults, and diabase dikes all display strong maxima that strike northeast and are believed to be of similar Mesozoic age. Shallow-dipping oblique-slip faults are demonstrably older than the more prevalent dip-slip faults.

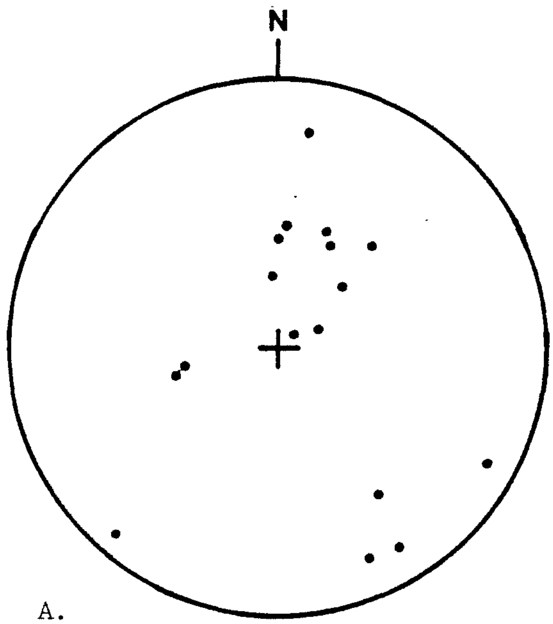
Quartz vein fracture cleavage was developed after the Acadian deformation because its orientation appears to be unrelated to the folding. The equal area plot of quartz vein fracture cleavage in Figure 17 reveals predominant strikes of N42-88°W and dips of 10-40°SW. The age relation of this cleavage to other brittle fracture features is uncertain.

Common joints in the study area display a strong clustering in the equal area plot of Figure 17. These joints strike N64°E on the average and possess near-vertical dips. The orientation of silicified joints is similar to that of common joints. Figure 17 reveals a characteristic strike of N80°E and dip of 70°NW. Basalt dikes in the study area show two distinct orientations (Figure 17), striking N60°E and N22°E. The N22°E trend may correspond to the N30°E regional trend of diabase dikes (May, 1971). The most prominent of these dikes has an average width of 15-20 meters and extends over 9 kilometers from the town of West Pelham to the Quabbin Reservoir 3.5 kilometers southeast of the town of Shutesbury. The "Pelham Dike", as it is informally referred to, strikes N52°E on the average and has a near vertical dip.

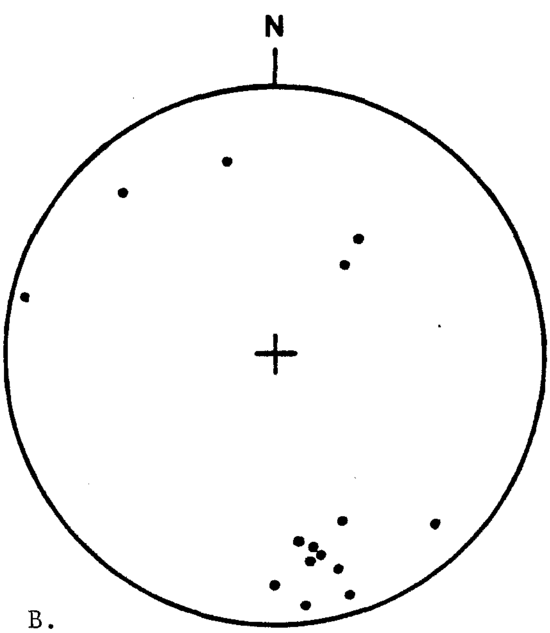
The similar orientations of these brittle features suggest a more or less contemporaneous origin under a northwest-southeast extensional stress system. This system would have the following approximate principal stress axes: σ_1- vertical; σ_2- N65°E, horizontal; and σ_3- N25°W, horizontal.

The dominant faults of the study area strike northeast and are of the dip-slip variety (Figure 18). These faults typically strike N22-54°E and dip steeply to the northwest and southeast. Maxima of rotation axes suggest an approximate σ_2 orientation that is horizontal and trends N24-58°E. Approximate values for σ_3 are N32-66°W; σ_1 is near vertical. σ_2 and σ_3 as indicated by dip-slip faults in the study area differ somewhat from stress orientations derived from Mesozoic dip-slip faults in the Connecticut Valley and areas immediately to the east (Chandler, 1979). There, σ_2 is oriented around N20°E, horizontal, and σ_3 is oriented between N90°W and N60°W. A clockwise rotation of σ_2 and σ_3 principal stress trajectories in the Pelham dome could account for this difference. Dip-slip faulting appears to be related to the previously described jointing and diabase dike intrusion.

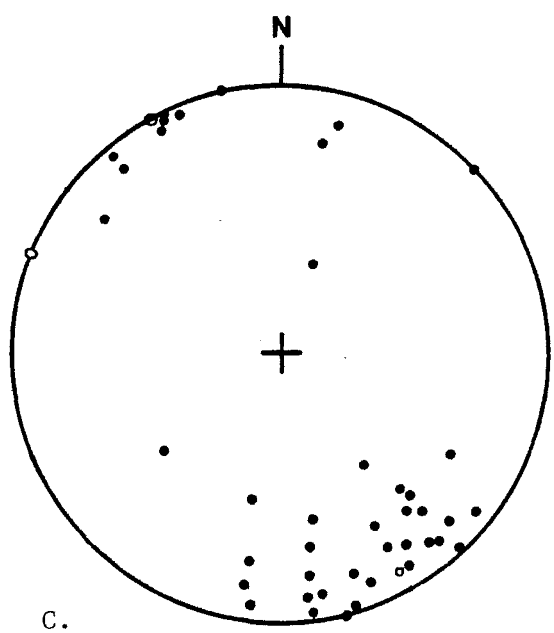
Strike-slip and oblique-slip faults are not so well defined in the study area (Figure 18). An episode of low-angle oblique-slip faulting appears to have preceded the Mesozoic dip-slip faulting. These older faults



A.



B.



C.

Figure 17. A.) Equal area plot of poles to quartz vein fracture cleavage. B.) Equal area plot of poles to silicified joints. C.) Equal area plot of poles to common joints and diabase dikes. • poles to common joints, ∘ poles to diabase dikes.

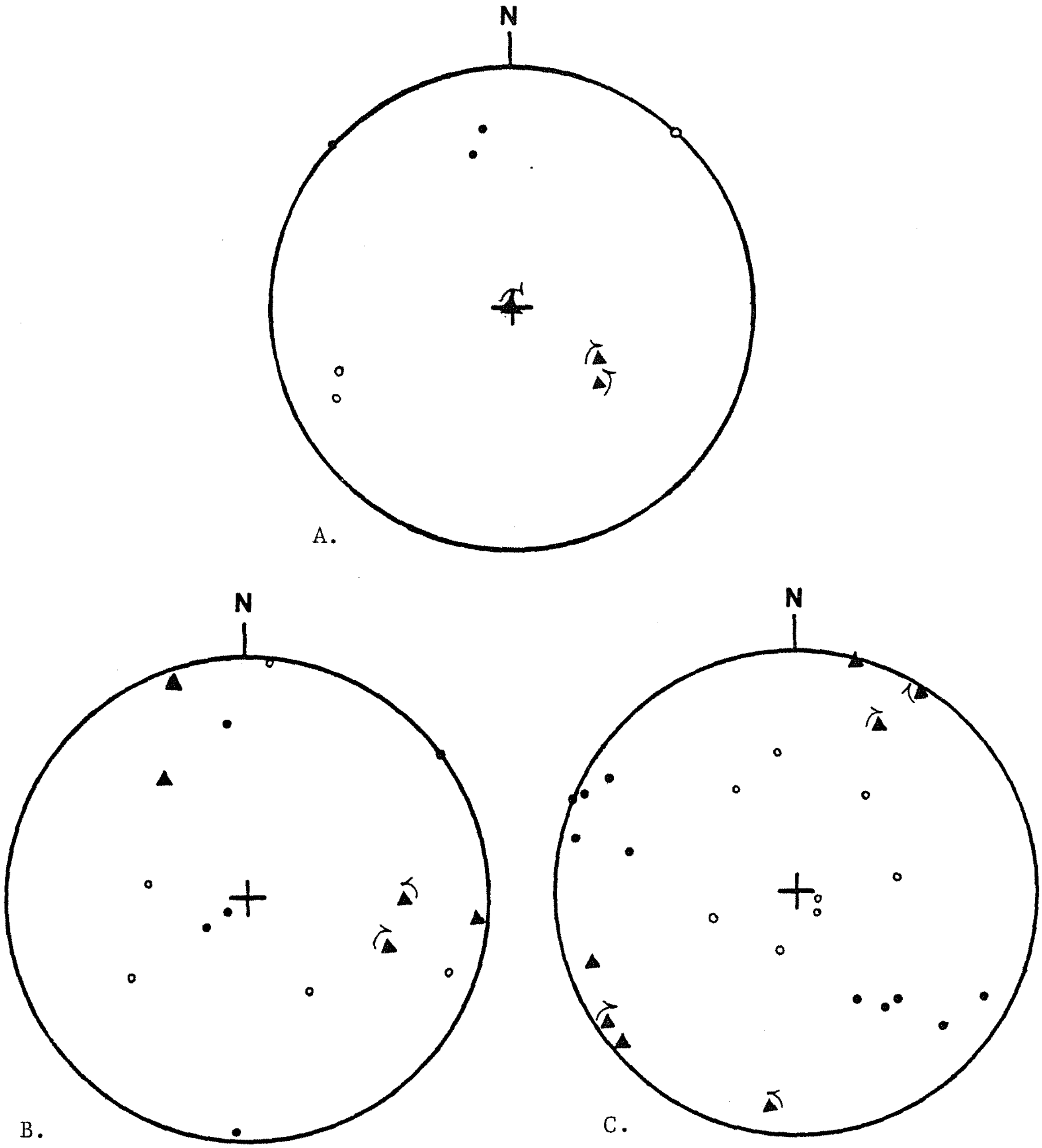


Figure 18. A.) Equal area plot of strike-slip faults. B.) Equal area plot of oblique-slip faults. C.) Equal area plot of dip-slip faults. • pole to fault plane, ○ slickensides, ▲ rotation axis and rotation sense.

dip gently to the northeast and possess rotation axes that trend S80°E and plunge 37°S. Detailed fracture analysis of the Quabbin Reservoir spillway area southeast of the study area revealed a similar set of older shallow-dipping oblique-slip faults (Wise, D.U., and students of Brittle Fracture class, unpublished field data, 1979). These oblique-slip faults are in turn offset by younger dip-slip faults of comparable orientation to those observed in the study area. Stress orientations derived from dip-slip faults in the spillway area are as follows:

σ_1-S15°W, 74°S; σ_2- N41°E, 14°N; and σ_3- N52°W, 8°N.

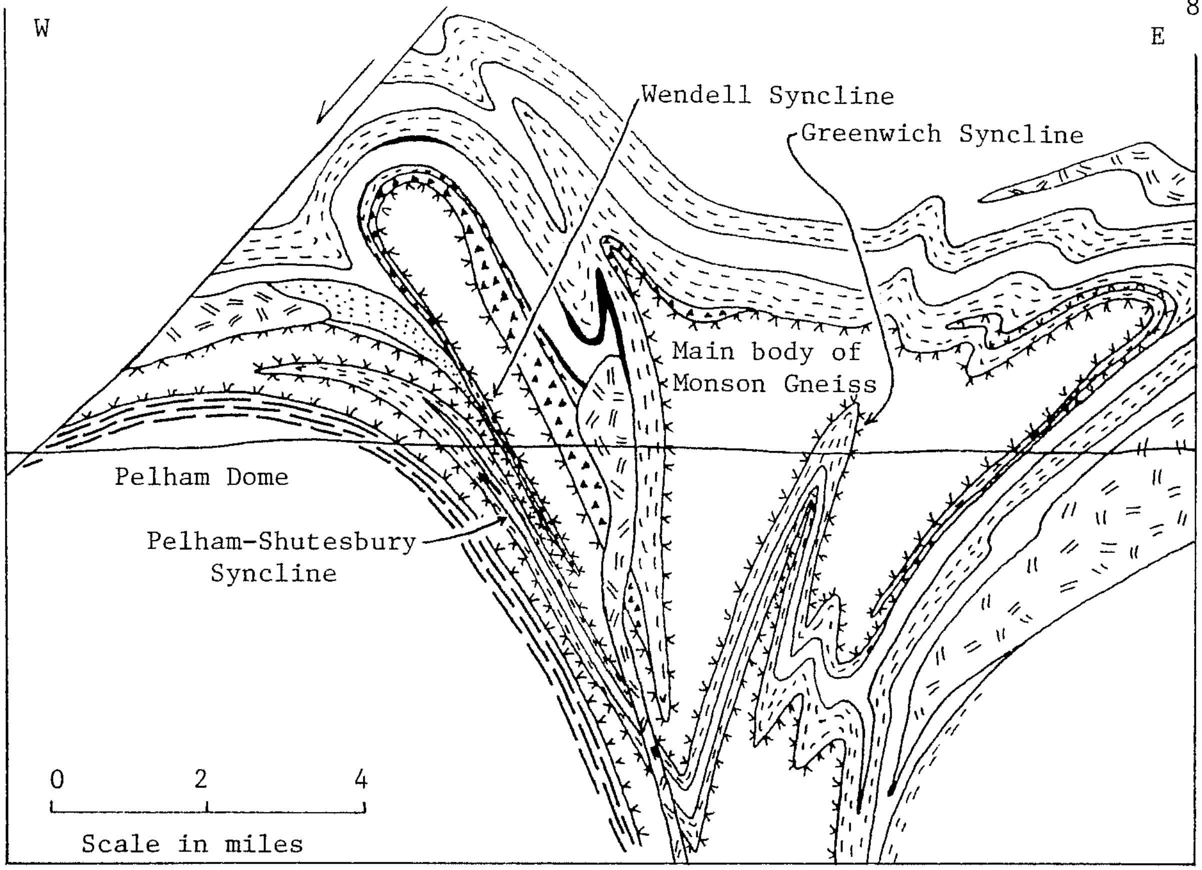
Relationship of the Pelham-Shutesbury Syncline to Adjacent Structural Features

Regional structural studies of the Bronson Hill anticlinorium have delineated several north-south trending belts of Paleozoic cover rocks immediately east of the Pelham-Shutesbury syncline (Robinson, 1967a, b, 1979; Thompson, et al., 1968). Of these cover rock belts, the Wendell syncline is the closest to the study area, lying less than two kilometers to the east on the average. It has been interpreted as a very narrow, isoclinal structure connecting the Northfield syncline to its north with the Great Hill syncline, which extends as far south as Middletown, Connecticut (Robinson, 1967b). The previously cited regional studies have postulated a connection of the Wendell syncline and the Pelham-Shutesbury syncline by way of a buried, north-south trending hinge (Figure 19B). This interpretation has the following to commend it: (1) proximity of the two structures, (2) eastward-opening nature of the Pelham-Shutesbury syncline, and (3) apparent convergence of the axial surfaces of the two synclines. Significant stratigraphic problems are raised by this proposed connection of the two synclines. The Wendell syncline is predominantly composed of amphibolite of the Erving Formation (of Devonian age) and schists of the Partridge Formation. By way of contrast, the structurally deepest exposures of the Pelham-Shutesbury syncline reveal a well developed Silurian-Devonian section consisting of schists and quartzites, and a thick and lithologically diverse Middle Ordovician section. Rapid facies changes and stratigraphic or tectonic attenuations or truncations would have to be invoked under this interpretation.

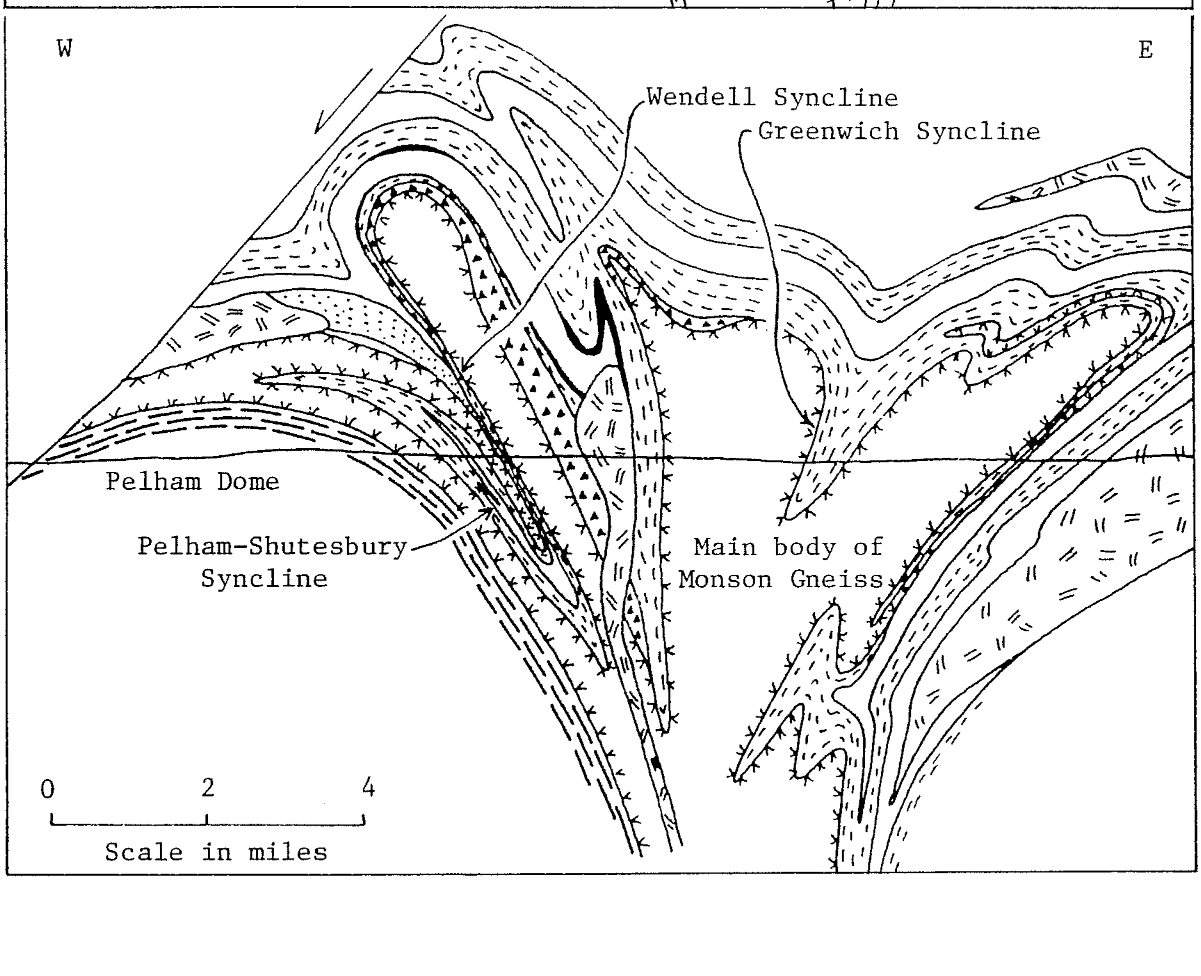
The mafic volcanics of the Partridge Formation in the Greenwich syncline (6-8 kilometers east of the study area) superficially resemble the mafic volcanics in the Partridge of the Pelham-Shutesbury syncline in terms of texture and mineralogy. A connection of these two structural features at depth would alter the understanding of the intervening Monson Gneiss considerably, effectively severing the "main body" from the underlying basement. This interpretation, as in Figure 19A, would also suggest that the stratigraphy of the Pelham-Shutesbury syncline would be an integral part of the stratigraphy of the eastern part of the Bronson Hill anticlinorium rather than the western part as in the interpretation given in Figure 19B.

METAMORPHISM

The rocks of the study area lie entirely within the kyanite-staurolite zone of Acadian regional metamorphism as indicated by the presence of kyanite in pelitic units and rarely in felsic gneisses (Robinson, 1963; Thompson, et al., 1968; Tracy, et al., 1976). Staurolite is locally present in certain pelitic and volcanic units on the east limb of the syncline.


W
E
Wendell Syncline
Greenwich Syncline
Main body of
Monson Gneiss
Pelham Dome
Pelham-Shutesbury
Syncline
0
2
4
Scale in miles

A.


W
E
Wendell Syncline
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Pelham-Shutesbury
Syncline
Main body of
Monson Gneiss
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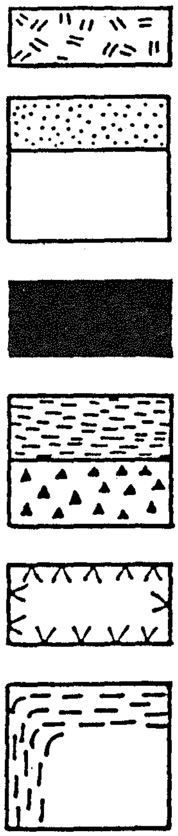
Scale in miles

B.



Devonian	Granodiorite and quartz diorite.
Lower Devonian	Erving Formation. Littleton Formation.
Silurian	Clough Quartzite.
Middle Ordovician	Partridge Formation. Ammonoosuc Volcanics.
Ordovician or older	Massive and layered gneisses, including Fourmile Gneiss, Monson Gneiss, Pauchaug Gneiss, and Swanzey Gneiss.
Late Precambrian	Poplar Mountain Gneiss and Quartzite, Mt. Mineral Formation, Pelham Quartzite, and Dry Hill Gneiss.

Figure 19. Generalized regional cross sections of the Bronson Hill anticlinorium in west-central Massachusetts showing the Pelham-Shutesbury syncline and its relationship to adjacent structural features (modified from Robinson, 1979). A.) Cross section assuming connection with Greenwich syncline. B.) Cross section assuming connection with Wendell syncline.

The study area is flanked by a pronounced increasing metamorphic gradient to the southeast that culminates in a high of sillimanite-orthoclase grade in the south-central portion of the state (Tracy, et al., 1976; Robinson, 1979). The sillimanite isograd lies only two kilometers east of the central portion of the study area. The kyanite to sillimanite transition that occurs here suggests that peak metamorphic pressures were above that of the aluminosilicate triple point. The study of Fe-Mg distribution in coexisting garnet and biotite within the kyanite-staurolite zone in north-central Massachusetts yielded a prograde metamorphic temperature estimate of 580-605°C. The compositions of garnets in equilibrium with quartz and sillimanite suggested a minimum pressure of 5.6-6.2 kbar (Tracy, et al., 1976).

Pelitic Rocks

Kyanite-staurolite mineral assemblages were only observed in the pelitic schists of the Littleton Formation in the study area. Kyanite is commonly present in all pelitic units within the study area, however. The absence of staurolite in the pelitic schists of the Partridge Formation might suggest a more magnesian bulk composition relative to the pelitic schists of the Littleton Formation. Common mineral assemblages (all with graphite and ilmenite) observed in the pelitic rocks of the study area are:

1) quartz-plagioclase-muscovite-biotite-garnet-kyanite
2) quartz-plagioclase-muscovite-biotite-garnet
3) quartz-muscovite-biotite-garnet-kyanite-staurolite

The plagioclase in assemblages 1 and 2 is characteristically oligoclase-andesine. Biotite in pelitic rocks is typically reddish brown in color, which suggests a high Ti/Fe^{3+} ratio (Hayama, 1959).

Calc-Silicate Rocks

Calc-silicate layers have been observed in the Ammonoosuc Volcanics, the Partridge Formation, and the Clough Quartzite. An epidote-diopside-scapolite-hornblende assemblage was noted in the Ammonoosuc Volcanics. Epidote rims about diopside may indicate a retrograde metamorphic reaction in this unit. Epidote-diopside-hornblende-sphene-quartz-plagioclase and epidote-tremolite-sphene-quartz mineral assemblages were observed in calc-silicate horizons within the Partridge Formation.

Felsic Volcanic Rocks

Gneissic lithologies in the study area that have been interpreted as metamorphosed felsic volcanics are characterized by the following mineral assemblage: quartz-plagioclase-microcline-biotite-muscovite. The plagioclase in these rocks is typically albite-oligoclase. Garnet and epidote may be present in trace amounts. Peraluminous bulk compositions are implied by the presence of garnet and muscovite. Biotites in these rocks vary in color from brown to green-brown, suggesting relatively low Ti/Fe^{3+} ratios (Hayama, 1959).

Mafic Volcanic Rocks

Gneissic lithologies in the study area, which have been interpreted as metamorphosed mafic volcanics, display the following mineral assemblages:

1) hornblende-pistacite-garnet-plagioclase-quartz

2) hornblende-cummingtonite-garnet-plagioclase-quartz

3) hornblende-garnet-augite-scapolite

4) gedrite-biotite-garnet-plagioclase-quartz

5) gedrite-biotite-garnet-staurolite-plagioclase-quartz

6) gedrite-anthophyllite-plagioclase-quartz
(J. C. Schumacher, pers. comm., 1982)

Assemblages 1, 2, and 3 are typical of the Amphibolite Member of the Partridge Formation; assemblages 4, 5, and 6 were observed in the Ammonoosuc Volcanics. Sphene and ilmenite are common minor constituents in assemblage 4 in minor to trace amounts. Plagioclase in the above assemblages is characteristically andesine-labradorite.

A study of a hornblende-garnet-augite-scapolite layer in the Amphibolite Member of the Partridge Formation (sample R-39C) was conducted in order to assess the mineral chemistries of coexisting Fe-Mg-bearing phases. Table 9 gives averaged electron microprobe analyses of garnet, augite, and hornblende in oxide weight percent and molecular proportions.

Garnet exhibits various textures, ranging from 1 mm subhedral grains to conspicuous 6 mm anhedral porphyroblasts. The composition of garnet appears to be relatively homogeneous and is characterized by a markedly calcic chemistry: $Alm_{47.7}$ $Gross_{42.0}$ $Pyr_{6.5}$ $Spess_{3.9}$. An eight-cation ferric iron correction does not suggest the presence of Fe^{3+} these garnets.

Hornblende (alumino-ferro-hornblende per Leake, 1978) is typified by 1-3 mm subhedral lineated grains that locally form thin rims about coarse augite grains. Hornblende is optically negative, has a 2V of 70-75°, and displays a strong tan to bluish green pleochroism. Electron microprobe analyses revealed a $Fe^{2+}/(Fe^{2+} + Mg)$ ratio of .596. A ferric iron correc-

Table 9. Electron microprobe analyses of Fe-Mg bearing minerals in a hornblende-augite-garnet-scapolite layer in the Amphibolite Member of the Partridge Formation.

Oxide wt. %	Garnet	Augite	Hornblende
SiO_2	39.59	50.72	44.49
TiO_2	.07	.10	.68
Al_2O_3	21.22	1.48	14.11
Fe_2O_3		2.56	1.41
FeO	21.55	12.41	17.79
MnO	1.69	.30	.20
MgO	1.63	11.42	6.77
CaO	14.79	20.04	10.93
Na_2O		.40	1.79
K_2O			.42
Total	100.54	99.43	98.59
No. of analyses averaged	n = 8	n = 12	n = 5

Formula	Cations per 12ox		4 cations and 6ox*		Cations per 23ox**
Si	3.074	Si	1.943	Si	6.583
	3.074	Al	.057	Al	1.417
			2.000		8.000
Al	1.942				
Ti	.008	Al	.009	Al	1.045
	1.950	Ti	.003	Ti	.076
		Fe^{3+}	.074	Fe^{3+}	.157
Mg	.189	Mg	.652	Mg	1.494
Fe^{2+}	1.399	Fe	.262	Fe^{2+}	2.204
Mn	.111		1.000	Mn	.024
Ca	1.231				5.000
	2.930	Fe^{2+}	.136		
		Mn	.01	Ca	1.735
Total	7.954	Ca	.823	Na	.265
		Na	.03		2.000
			.999		
				Na	.249
		Total	4.000	K	.079
					.328
				Total	15.328

* 4 cation ferric iron corrected.

** Normalized to 13 cations exclusive of Ca, Na, and K; ferric iron corrected.

tion based on 13 cations exclusive of Ca, Na, and K was employed, which yields a maximum reasonable amount of Fe^{3+} (Robinson, pers. comm., 1982).

Augite is characterized by coarse, irregular, subhedral to anhedral grains up to 5 mm in diameter. It displays a faint colorless to pale green pleochroism and is optically positive with a 2V of 40°. Electron microprobe analyses revealed the following composition, which lies in the augite field of the pyroxene quadrilateral (Hess, 1941): $Wo_{42.0}\ En_{33.3}\ Fs_{24.6}$. The $Fe^{2+}/(Fe^{2+} + Mg)$ ratio of augite equals .379.

Textural and chemical relations within this layer may suggest the following reaction, which should proceed to the right with increasing metamorphic grade: hornblende + scapolite = garnet + augite + H_2O + CO_2 + Cl. Figure 20 depicts the phase relations between augite, hornblende, and garnet by means of a scapolite projection. The Fe-Mg partitioning between augite and hornblende is unusual for amphibolites of comparable metamorphic grade in the region (Robinson, pers. comm., 1982).

SUMMARY OF GEOLOGIC HISTORY OF THE PELHAM-SHUTESBURY SYNCLINE

The earliest geologic event that can be discerned within the study area was the period of felsic volcanism sometime from the Late Precambrian to the Middle Ordovician. During this time, the rhyolites and dacites that comprise the Fourmile Gneiss were extruded.

The Middle Ordovician is characterized by island-arc volcanism that produced the basaltic, dacitic, rhyodacitic, and rhyolitic rocks of the Ammonoosuc Volcanics (Schumacher, 1981). Local calcareous layers within these volcanics suggests proximity to a shallow, marine environment condu-

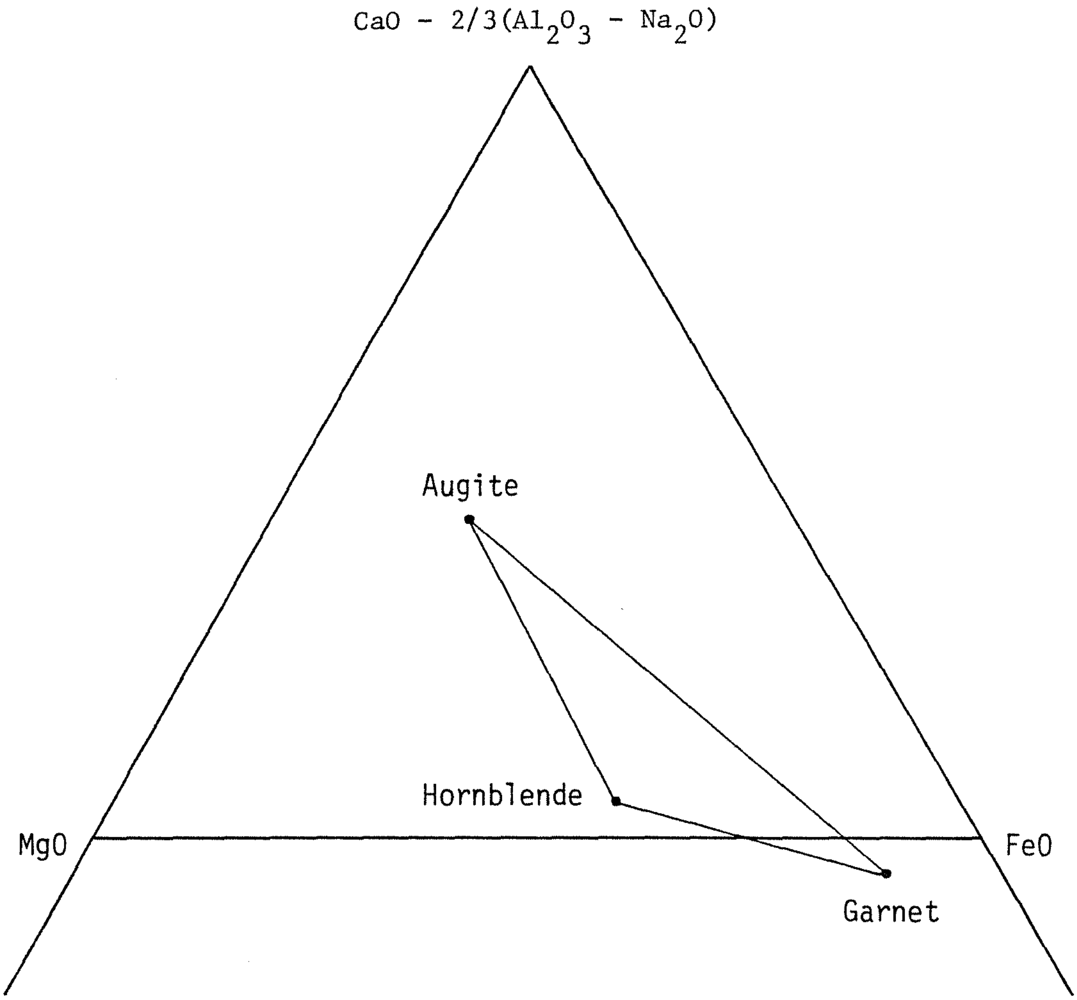


Figure 20. Scapolite projection onto the CFM face of analyzed phases in sample R-39C. Position of the three-phase field augite, hornblende, and garnet according to analyses in Table 9.

cive to the generation of carbonate sediments. Subsequent to this volcanism was the deposition of various terrigenous clastic sediments that comprise the lower portion of the Middle Ordovician Partridge Formation. These sediments consist of quartzose sands and black shales overlain by euxinic black shales. Further bimodal volcanism followed this influx of terrigenous sediments in the form of well bedded basaltic tuffs and more massive rhyolitic volcanics. A second period of euxinic black shale deposition completed the upper portion of the Partridge Formation.

Uplift and erosion of the study area characterized the end of the Ordovician period. Following the development of a widespread erosional surface was the deposition of clean to moderately argillaceous sands that constitute the Clough Quartzite of the study area. A hiatus in terrigenous clastic sedimentation is indicated by the deposition of thin, finely laminated calcareous sediments over the previously described sands.

The Early Devonian in the study area is characterized by the deposition of well bedded, organic-rich shales that comprise the Littleton Formation. Following the deposition of this unit, the rocks of the study area were metamorphosed and intensely deformed during the Acadian orogeny of Early to Middle Devonian time. The earliest structural phase of this orogeny was the development of regional nappes with westward transport directions. Subsequent to this napping was a phase of eastward-directed recumbent folding in the vicinity of the Keene and Pelham domes that resulted in isoclinal, westward closing synclines such as the Pelham-Shutesbury syncline. The subsequent formation of the Pelham dome by gravitationally induced flowage of gneissic basement resulted in further deformation of the Pelham-Shutesbury syncline in the form of a broad arching of the syncline over the dome axis. A late aspect of this phase of doming was the development of asymmetric folds that deform both the gneissic basement and cover rocks of the Pelham dome. The movement line associated with these folds suggests a northward flowage of the core rocks of the dome relative to the mantling strata. A late extensional phase of deformation postdating the asymmetric folding is indicated by the boudinage of relatively competent rocks. Syntectonic plutonism is evident in the emplacement of pegmatite sills, fine-grained felsic sills, and tonalite sills in the study area.

Brittle deformation occurred in Triassic-Jurassic time in the form of northeast-southwest trending extensional features such as joints, normal faults, and diabase dikes.

Pleistocene continental glaciation extensively modified the geomorphic landscape of the study area through erosional deepening of pre-existing valleys and the widespread deposition of till and glaciofluvial sediments.

SUMMARY OF CONCLUSIONS

1) The Pelham-Shutesbury syncline possesses an asymmetric yet coherent internal stratigraphy. Rocks of the west limb are considerably thicker than those on the east limb and are dominated by a diverse sequence of quartzites, pelitic schists, amphibolites, and felsic gneisses that comprise the Middle Ordovician Partridge Formation. The basement-cover rock contact is locally exposed on this limb. This contact is sharp in

nature and is typically defined by the base of the Basal Quartzite Member of the Partridge Formation and the top of the Fourmile Gneiss. The Partridge Formation on the east limb displays considerably less lithologic diversity and is locally underlain by the mafic and felsic gneisses of the Middle Ordovician Ammonoosuc Volcanics. The stratigraphic asymmetry of the syncline may be a function of the original paleogeographic distribution of lithologies and subsequent tectonic attenuation and truncation.

2) The Purgee Brook Gneiss of the study area is a demonstrably post-Middle Ordovician intrusive and is texturally and mineralogically similar to tonalite intrusive gneisses of the Belchertown intrusive complex. It is probable that this unit represents a series of sill-like extensions of the Belchertown complex.

3) Analysis of planar structural features in the study area reveals the following about the goemetry of the Pelham dome: a) the southern hinge line of the dome trends approximately S18°E and plunges 21°S, and b) the foliation on the east flank of the dome undergoes a progressive flattening of dip as one traverses the study area from south to north.

4) Early isoclinal folds (both minor and map scale) are demonstrably older than the late asymmetric folds, by which they are deformed. The pervasive foliation of the study area bears an axial planar relation to these early isoclinal folds.

5) Late asymmetric folds are relatively abundant in the cover rocks of the study area and exhibit considerable variation in size and style. Their axes and axial planes generally display consistent orientations, with the axes subparallel to the regional mineral lineation. Locally, however, this lineation is deformed about the late asymmetric folds and

yields a movement line suggestive of a northward movement of the dome core rocks relative to the mantling strata.

6) A late phase of N-S extension is shown by the boudinage of competent rocks in the study area. The extension direction inferred from these features is subparallel with the dome axis.

7) Brittle fracture elements in the study area such as common joints, silicified joints, diabase dikes, and high-angle normal faults were formed under comparable stress regimes. The inferred principal stress axes have the following approximate orientations: σ_1 - vertical, σ_2 - N65°E, horizontal, and σ_3 - N25°W, horizontal.

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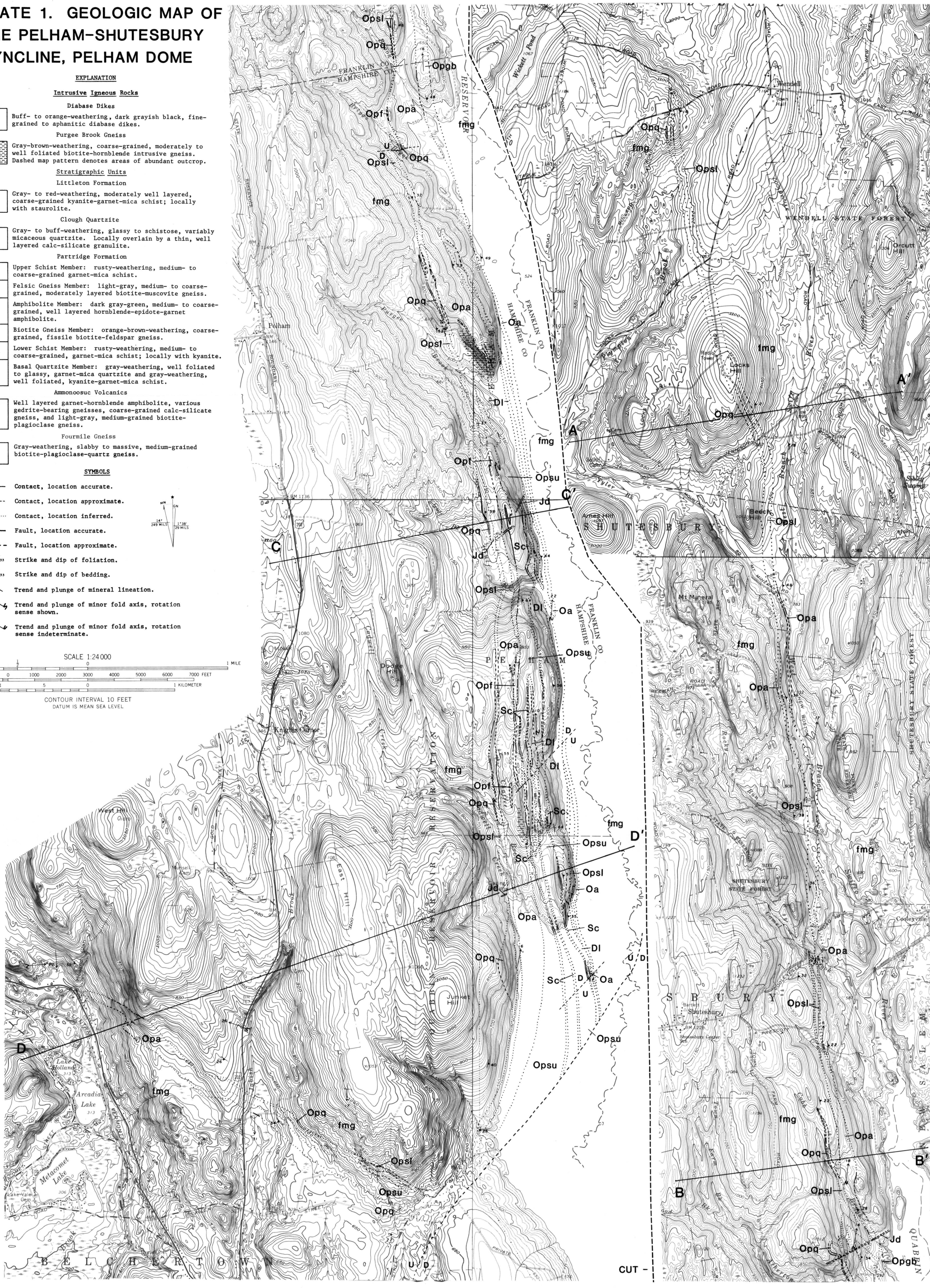
PLATE 1. GEOLOGIC MAP OF THE PELHAM-SHUTESBURY SYNCLINE, PELHAM DOME



EXPLANATION

Intrusive Igneous Rocks

Diabase Dikes

Lower Jurassic — **Jd**: Buff- to orange-weathering, dark grayish black, fine-grained to aphanitic diabase dikes.

Purgee Brook Gneiss

Devonian? — (dashed pattern): Gray-brown-weathering, coarse-grained, moderately to well foliated biotite-hornblende intrusive gneiss. Dashed map pattern denotes areas of abundant outcrop.

Stratigraphic Units

Littleton Formation

Devonian — **Dl**: Gray- to red-weathering, moderately well layered, coarse-grained kyanite-garnet-mica schist; locally with staurolite.

Clough Quartzite

Silurian — **Sc**: Gray- to buff-weathering, glassy to schistose, variably micaceous quartzite. Locally overlain by a thin, well layered calc-silicate granulite.

Partridge Formation

Middle Ordovician:

- **Opsu**: Upper Schist Member: rusty-weathering, medium- to coarse-grained garnet-mica schist.
- **Opf**: Felsic Gneiss Member: light-gray, medium- to coarse-grained, moderately layered biotite-muscovite gneiss.
- **Opa**: Amphibolite Member: dark gray-green, medium- to coarse-grained, well layered hornblende-epidote-garnet amphibolite.
- **Opgb**: Biotite Gneiss Member: orange-brown-weathering, coarse-grained, fissile biotite-feldspar gneiss.
- **Opsl**: Lower Schist Member: rusty-weathering, medium- to coarse-grained, garnet-mica schist; locally with kyanite.
- **Opq**: Basal Quartzite Member: gray-weathering, well foliated to glassy, garnet-mica quartzite and gray-weathering, well foliated, kyanite-garnet-mica schist.

Ammonoosuc Volcanics

- **Oa**: Well layered garnet-hornblende amphibolite, various gedrite-bearing gneisses, coarse-grained calc-silicate gneiss, and light-gray, medium-grained biotite-plagioclase gneiss.

Fourmile Gneiss

Late Precambrian to Ordovician — **fmg**: Gray-weathering, slabby to massive, medium-grained biotite-plagioclase-quartz gneiss.

SYMBOLS

- Contact, location accurate.
- Contact, location approximate.
- Contact, location inferred.
- Fault, location accurate.
- Fault, location approximate.
- 33 Strike and dip of foliation.
- 33 Strike and dip of bedding.
- 12 Trend and plunge of mineral lineation.
- 12 Trend and plunge of minor fold axis, rotation sense shown.
- 12 Trend and plunge of minor fold axis, rotation sense indeterminate.

MN GN 14° 249 MILS 1°38' 29 MILS

SCALE 1:24 000

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

PLATE 2.

MAP OF PLANAR STRUCTURAL FEATURES

EXPLANATION

33 Strike and dip of foliation.

33 Strike and dip of bedding.

MN GN
14° 249 MILS
1°44' 31 MILS

SCALE 1:24 000

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 10 FEET
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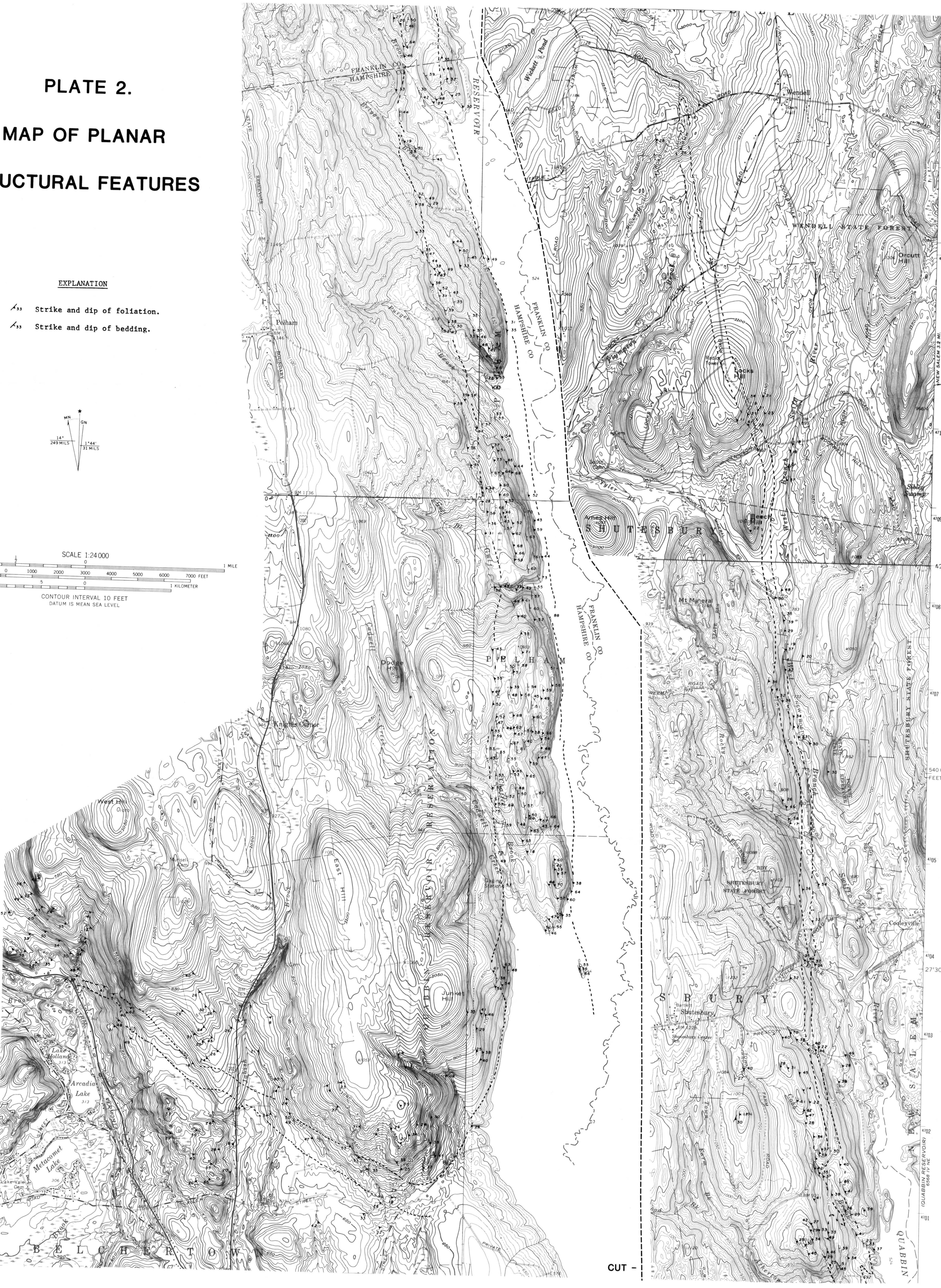

PLATE 3.

MAP OF LINEAR STRUCTURAL FEATURES

EXPLANATION

- Trend and plunge of mineral lineation.
- Trend and plunge of minor fold axis, rotation sense shown.
- Trend and plunge of minor fold axis, rotation sense indeterminate.

MN
GN
14°
249 MILS
1°44'
31 MILS

SCALE 1:24000

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

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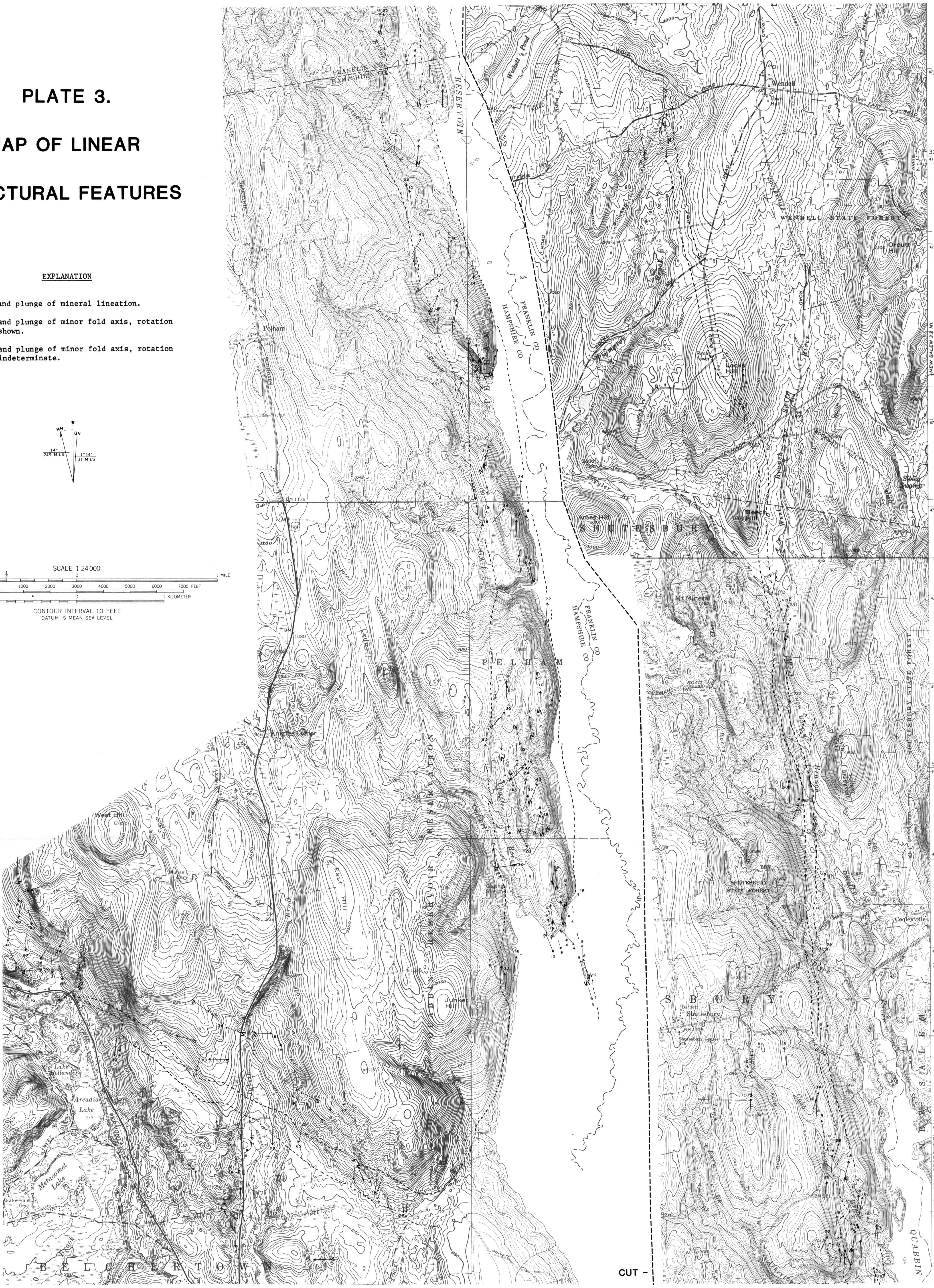

PLATE 4.

OUTCROP MAP

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

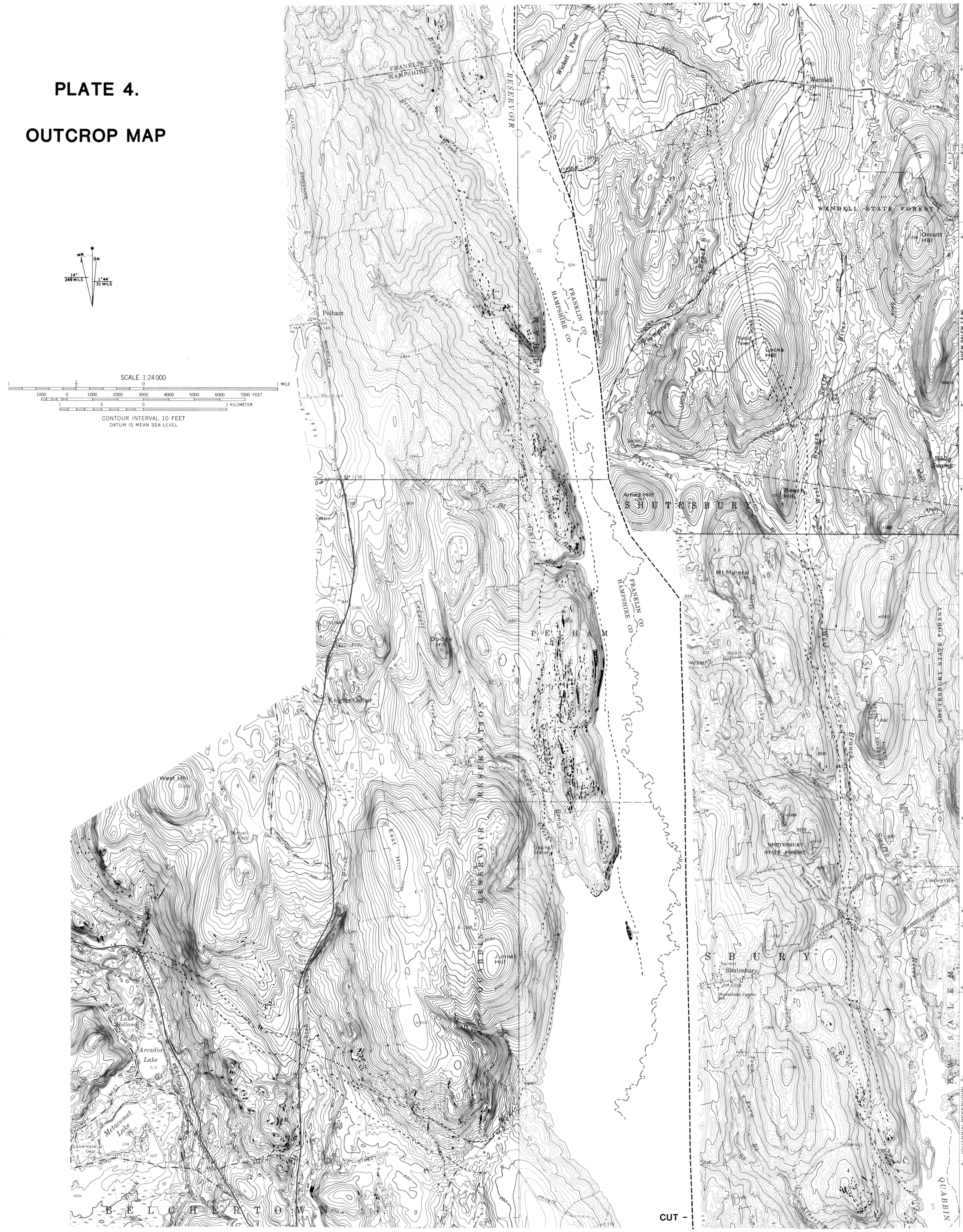

PLATE 5. GEOLOGIC STRUCTURE SECTIONS