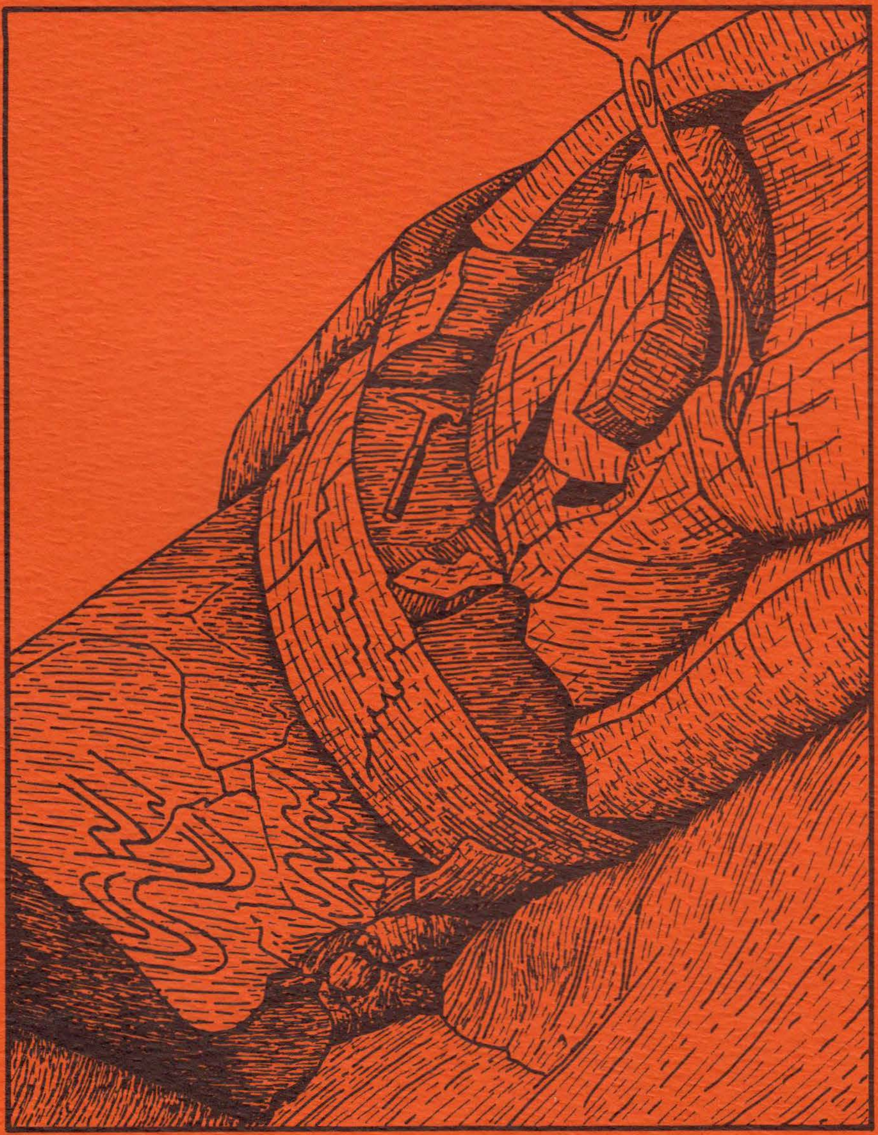
GEOLOGY OF PRE-MESOZOIC BEDROCK OF THE AMHERST AREA, WEST-CENTRAL MASSACHUSETTS

BY RICHARD A. JASAITIS, JR.



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GEOLOGY OF PRE-MESOZOIC BEDROCK

OF THE AMHERST AREA, WEST-CENTRAL MASSACHUSETTS

(M.S. Thesis)

by

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Contribution No. 45

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ABSTRACT

The Amherst area is a structural high of Paleozoic crystalline rocks that separates the Mesozoic Hartford and Deerfield basins of the Connecticut River Valley, west-central Massachusetts. The study area straddles the boundary between the Bronson Hill anticlinorium and the Connecticut Valley synclinorium, both major tectonic features of the Northern Appalachians. Three inliers of Paleozoic metamorphic rocks are present and bordered on the north, west, and south sides by the Mesozoic unconformity and on the east by a major normal fault, the Connecticut Valley border fault, which has a west-side-down displacement of approximately 5 km. These inliers consist of complexly deformed metamorphosed sedimentary rocks that belong to the frontal portions of several Acadian (Devonian) nappes which have been downfaulted into their present positions by displacement on the Connecticut Valley border fault.

The stratigraphic sequence in the Amherst area is similar to that on the Bronson Hill anticlinorium. The oldest unit, the Fourmile Gneiss, is Ordovician or older and consists of biotite-hornblende-feldspar gneiss. It is exposed at the east edge of the area in the footwall of the border fault, and also in small fault-blocks in which footwall rocks are surrounded by the hanging-wall rocks of the Amherst block. All other units in the area are in the hanging-wall of the border fault. The Middle Ordovician Partridge Formation consists of sillimanite-mica schist with variable amounts of garnet

and pyrrhotite. The Silurian Clough Quartzite is thin and discontinuous, consisting of conglomerates with elongate quartz pebbles set in a fine-grained, light-gray matrix of biotite-muscovite schist. The Lower Devonian Littleton Formation is a quartzose, biotite-rich schist with variable amounts of muscovite, garnet, and sillimanite. Within the Fourmile Gneiss is a mottled hornblende quartz diorite intrusive rock, possibly related to the Lower Devonian Belchertown Pluton. All stratigraphic units have been extensively intruded by pegmatites and other granitic rocks.

The structure of the rocks in the Amherst area is the result of the westward transport of Pennine-style nappes followed by three phases of Acadian folding and then Mesozoic faulting. The first phase of folding is shown by northwest-trending mineral lineations. The second phase of folding is represented by widespread minor folds, boudinage, and northeast-trending mineral lineations. The third phase of folding resulted in the open folding of previously formed planar and linear features. The principal Mesozoic faults in the Amherst area are the west-dipping border fault, the apparently later, east-dipping antithetic normal faults in Cushman, and the fault at the north end of Mt. Warner.

The rocks of the Amherst block are in Zone IV of Acadian regional metamorphism characterized by assemblages of sillimanite - muscovite, sillimanite - K-feldspar, and sillimanite - muscovite - K-feldspar, obscured by late metamorphic and Mesozoic retrograde alteration.

INTRODUCTION

Location

The study area is located in west-central Massachusetts in the vicinity of the town of Amherst, and includes parts of four U.S.G.S. 7½-minute quadrangles: the northern portion of the Mt. Holyoke quadrangle, southern and eastern portions of the Mt. Toby quadrangle, the southwestern margin of the Shutesbury quadrangle, and the northwestern corner of the Belchertown quadrangle (Figure 1). The total area is about 60 square kilometers.

Topography and Drainage

The Amherst area lies along the eastern margin of the Connecticut River Valley. The study area has hills trending approximately north-south rising almost 110 meters above their bases. The highest hill in the study area, 202 meters above sea level, is located on the west side of Leverett Pond in the Mt. Toby quadrangle. The lowest elevation, at 30.5 meters is the level of the Connecticut River flowing along the western edge of the study area.

The northern part of the study area is drained by Cushman Brook which flows into Factory Hollow Pond and continues from there as the Mill River, flowing south and west to drain the area north of Mt. Warner and enter the Connecticut River at North Hadley. The east Amherst area is drained by Adams Brook which feeds into the westward flowing Fort River that drains the southern part of the study area and reaches the south-flowing Connecticut River at Hadley.

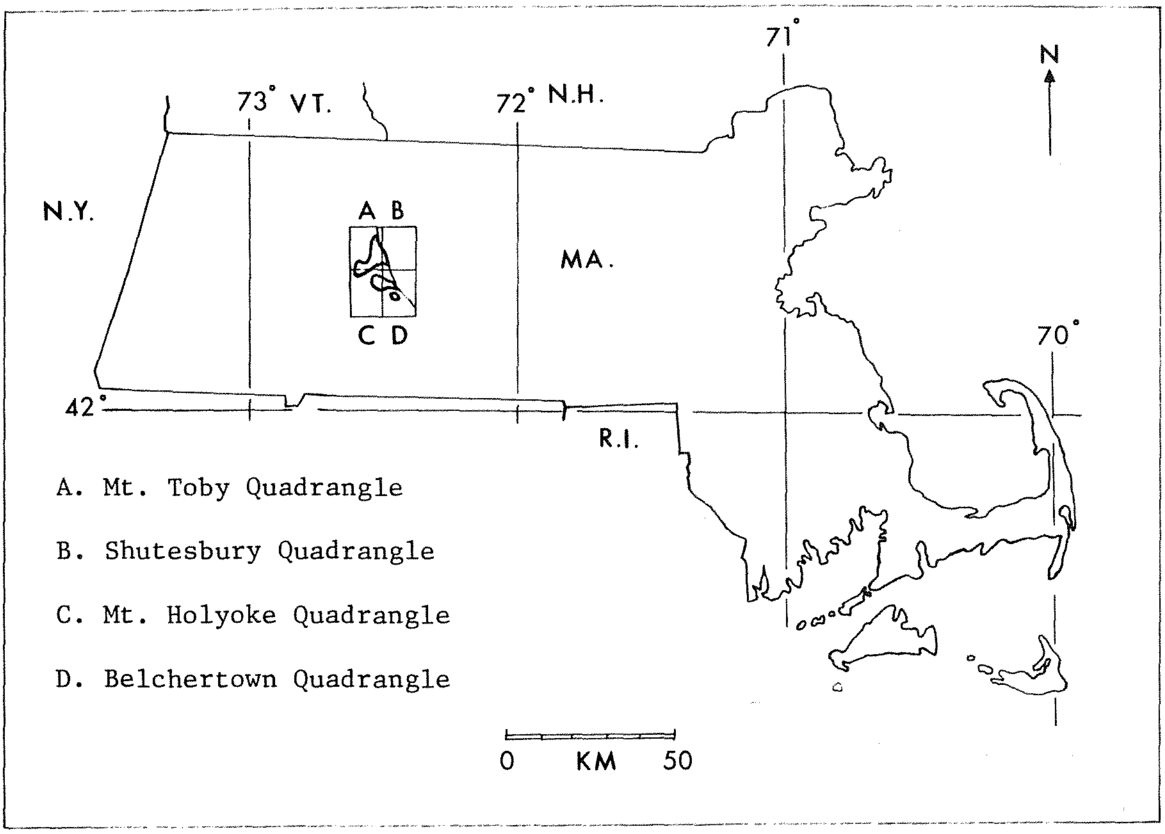


Figure 1. Map of Massachusetts showing quadrangles involved in study with outline of study area superimposed.

Vegetation and Cover

The field area is located in a suburban-rural setting with open fields and forested areas that are covered by mixed coniferous-deciduous growth. The area shows evidence of Pleistocene glacial action with a till veneer and scattered drumlins. Valley floors have been covered by stratified glacial drift and alluvium. Large areas are covered by the post-glacial varved lake sediments of Glacial Lake Hitchcock and by deltaic deposits of sand and gravel deposited from meltwater streams as at the Sunderland and Mt. Warner deltas (Ashley, 1972). Large areas along the western edge of the field area are within the Connecticut River flood plain, which further decreases the likelihood of bedrock exposures. Two exceptions, however, are located northwest of Mt. Warner along the Connecticut River on the east bank. Bedrock exposures are generally more abundant on the south- and east-facing slopes of the larger hills. Exposures of bedrock on the north-facing slopes are poor due to a mantling of glacial till. There are also scattered exposures in stream beds and in road and railroad cuts.

Geologic Setting

The study area is located near the boundary of the Connecticut Valley synclinorium and the Bronson Hill anticlinorium, both major Paleozoic tectonic elements in the Northern Appalachians (Figure 2). The Connecticut Valley border fault, a large west-dipping Mesozoic normal fault, is crudely aligned along the west limb of the Bronson Hill anticlinorium. Movement of this fault is responsible for the creation of a half-graben filled with Mesozoic sediments and volcanics. This Mesozoic basin is divided into two large basins occupying the central portion of Connecticut and west-central Massachusetts, and a tiny northern outlier near the New Hampshire border, the Northfield basin.

The Connecticut Valley synclinorium, which extends from Canada southward through Vermont, Massachusetts, and into Connecticut, contains deformed and metamorphosed sedimentary, volcanic and plutonic rocks of Precambrian, Cambro-Ordovician, and Siluro-Devonian age. At the head of the Deerfield basin near Bernardston, Massachusetts,

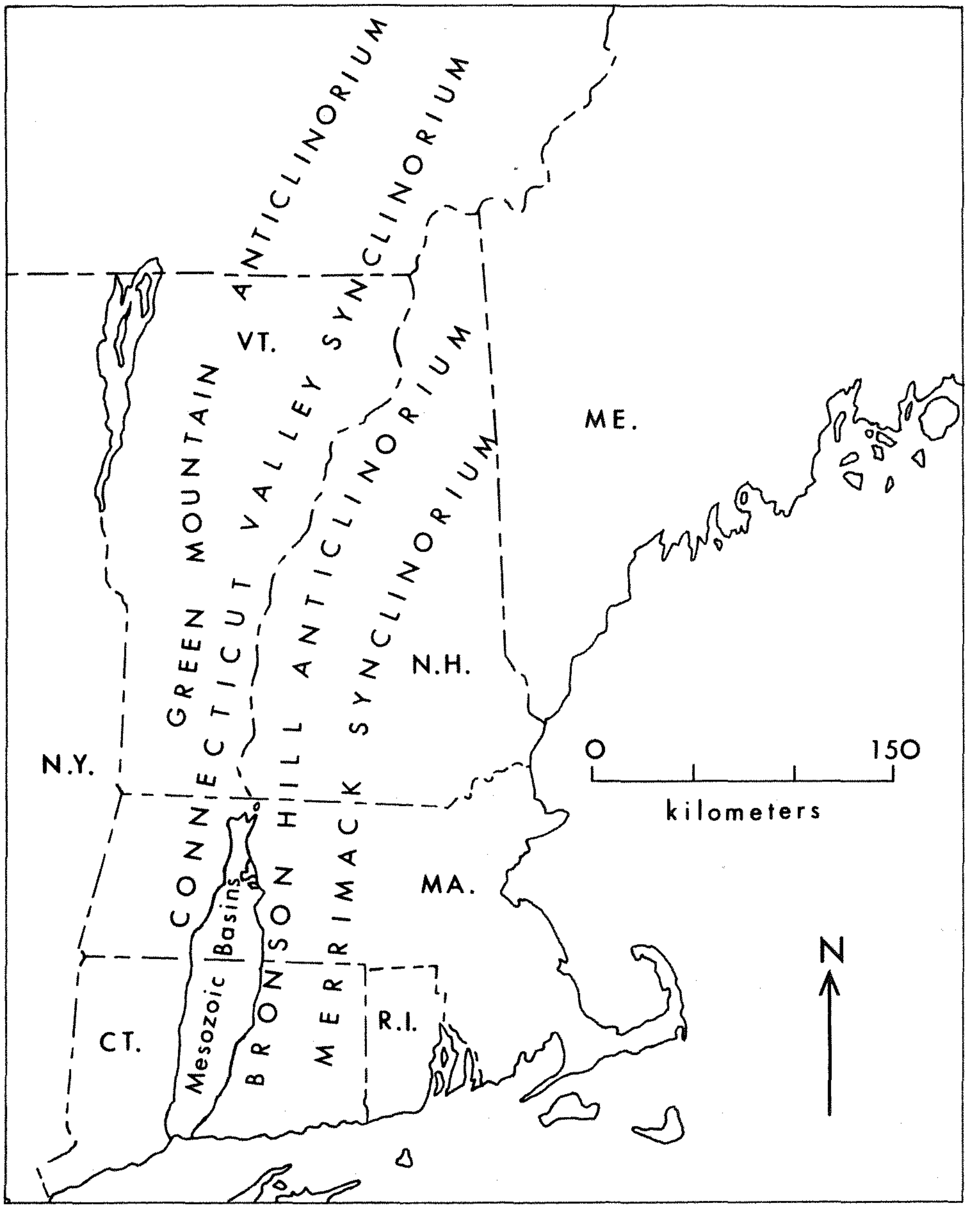


Figure 2. Simplified map of New England showing major tectonic features referred to in text.

Paleozoic schists emerge from beneath Mesozoic cover to reveal an infolded low grade metamorphic core to the synclinorium (Robinson, 1967b). The synclinorium is modified on its western limb by a line of Acadian gneiss domes extending from east-central Vermont into western Connecticut. The Shelburne Falls, Goshen, Woronoco, and Granville domes represent this line of gneiss domes in Massachusetts (Figure 3).

East of the Connecticut Valley synclinorium is the Bronson Hill anticlinorium, actually an irregular chain of domes much entangled with plutons. It consists of approximately 20 en échelon mantled gneiss domes extending from the Maine-New Hampshire border to southern Connecticut. In the Pelham dome, which is adjacent to the study area, dated Late Precambrian gneisses (Naylor et al., 1973) are overlain by gneisses of uncertain age and then by metamorphosed Middle Ordovician, Silurian, and Lower Devonian sedimentary and volcanic rocks (Robinson, 1967b; Thompson et al., 1968). Dome formation was preceded by the formation of large scale regional nappes with east-over-west movement sense, somewhat analogous to the Pennine nappes of the Swiss Alps (Thompson et al., 1968). As a result of the modification of earlier work (Trask and Thompson, 1967; Thompson, Robinson, Clifford, and Trask, 1968), Thompson and Rosenfeld (1979) proposed a regional sequence of four structural levels of nappes. In ascending order they are: the Cornish, Bernardston, Skitchewaug, and Fall Mountain nappes.

Rocks in the Mesozoic sedimentary basin unconformably cover the eastern portion of the Connecticut Valley synclinorium and western edge of the Bronson Hill anticlinorium. The basin is generally regarded as a half-graben (Klein, 1969; Hubert et al., 1978) which formed in response to the stresses active during the rifting of North America from Africa during the formation of the present Atlantic Ocean (May, 1971).

This fault basin was filled during the Late Triassic and Early

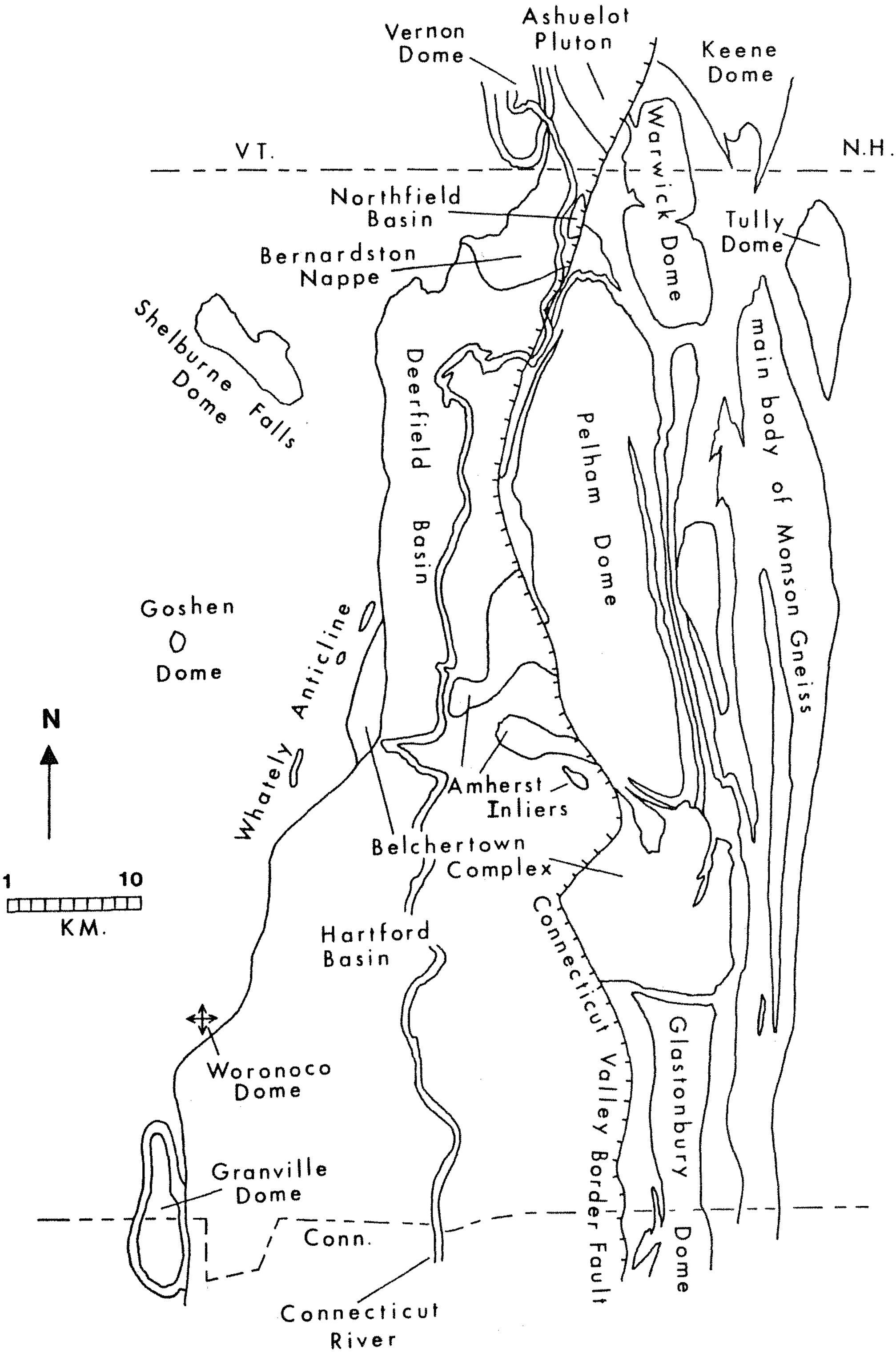


Figure 3. Regional setting of the Amherst inliers.

Jurassic by a 4 km thick sequence of fresh water sedimentary rocks and lava flows and pyroclastics. The larger basin is partially interrupted by an irregular east-west trending arch of Paleozoic basement near Amherst.

The larger southern portion, the Hartford basin, contains Late Triassic- Early Jurassic rocks which have been dated by pollen, spores and fossil fish (Cornet, 1973; Hubert et al., 1978). This basin contains several basaltic units. These volcanic units are the Talcott, Holyoke and Hampden Basalts. The Hartford basin extends southward from Amherst to Long Island Sound, a distance of 140 km, and is approximately 30 km wide. It is bounded on the east by the Connecticut Valley border fault and on the west by an unconformity in places and in other places by east-dipping normal faults of small displacement (Wheeler, 1937; Krynine, 1950).

The northern basin, called the Montague (Emerson, 1917; Goldstein,1976) or Deerfield basin (Chandler, 1978), extends 24 km northward from Amherst to the vicinity of Bernardston, Massachusetts. The Deerfield basin is similarly fault-bounded on the east by the west-dipping border fault. This basin consists of a sequence of Late Triassic to Middle Jurassic sedimentary and volcanic rocks (Hubert et al., 1978) and differs from the southern basin in that it contains only one volcanic unit, the Deerfield Basalt.

The major normal fault, the Connecticut Valley border fault, marks both the present eastern edge of Mesozoic sedimentary rocks in west-central New England and the approximate eastern boundary of the study area. This border fault extends from the area of New Haven, Connecticut, northward, approximately 250 km to northwestern New Hampshire. Vertical displacement on the border fault has been estimated to be 5 km at the Massachusetts-New Hampshire state line (Robinson, 1979).

The study area, referred to as the Amherst block (Chandler, 1978), occupies the irregular east-west trending arch which separates the Hartford and Deerfield basins of the Connecticut River Valley. The Amherst block consists of three inliers of Paleozoic crystalline rock, two of which are bounded on the north, west, and south sides by the Mesozoic unconformity and on the east by the Connecticut Valley border fault (Figure 4). The largest of these inliers extends from Mt. Warner to North Amherst and thence northward to the Village of Long Plain. The second inlier extends from a point 2.4 kilometers southwest of Amherst to the village of South Amherst and eastward to the border fault. The third inlier lies to the southeast of South Amherst, entirely in the subsurface beneath Lawrence Swamp. The exposures consist of Ordovician, Silurian, and Devonian metamorphosed sedimentary rocks with abundant pegmatite and granite intrusions that apparently belong to the frontal portions of several of the west-directed regional nappes, which have been downfaulted into their present position by the Mesozoic vertical slip displacement on the Connecticut Valley border fault.

Purpose of Study

The concerted effort to reappraise the geology of west-central Massachusetts has been underway since the recognition of large scale

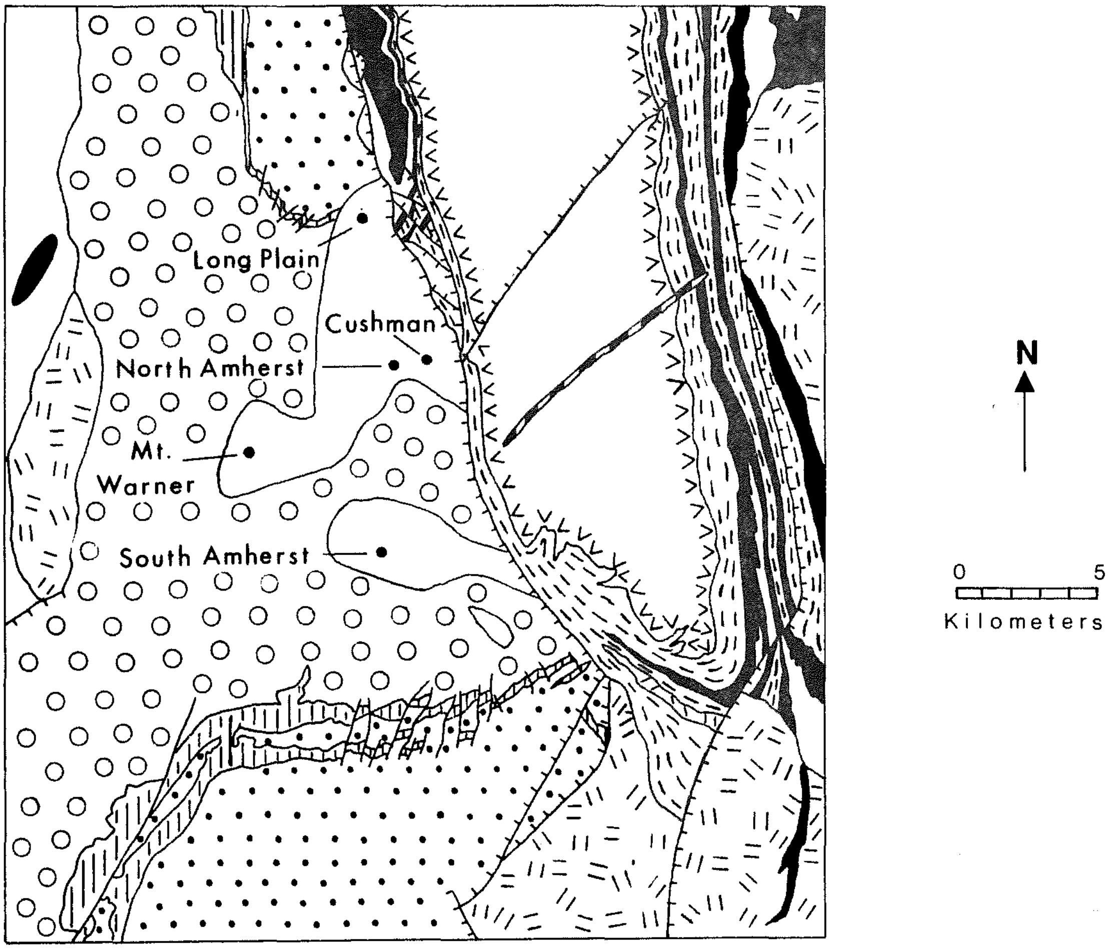


Figure 4. Geologic map of the Connecticut Valley, exclusive of Amherst inliers.

	Intrusive Rocks
Jurassic	Diabase dike
Lower Devonian	Belchertown Intrusive Complex and other syntectonic granitoid intrusions

	Stratified Rocks
Lower Jurassic	Conglomerate, sandstone, and shale Basalt and volcanic tuff
Upper Triassic	Conglomerate, sandstone, and shale
Lower Devonian-Silurian	Clough, Littleton, and Erving Formations
Middle Ordovician	Ammonoosuc Volcanics and Partridge Formation
Ordovician to Upper Precambrian	Fourmile and Monson Gneisses
Upper Precambrian	Dry Hill and Popular Mountain Gneisses and related rocks in core of dome

Normal fault - hachures on downthrown side recumbent folds in New Hampshire (Thompson, 1954) and Massachusetts (Robinson, 1963, 1967a). The primary objective of this study is the subdivision of the schists of the Amherst block in the context of this regional stratigraphic and structural framework. Subsidiary goals are the completion of geologic and outcrop maps, the collection and analysis of pertinent structural data, the construction of interpretive cross-sections, and the petrographic description of representative samples of each major stratigraphic unit.

Previous Work

Edward Hitchcock described the geology of the Amherst area during compilation of the state's first geologic map in 1841. B.K. Emerson examined the area in more detail in 1898 and 1917, proposing a stratigraphy for the area. More recent descriptions of northern Connecticut Valley geology were published by Bain (1931, 1941) who related the Connecticut basins to the general pattern of Mesozoic basins bordering the Atlantic (1954, 1957). Geologic mapping has been done in the Mt. Holyoke quadrangle by Balk (1941), and in the Mt. Toby quadrangle by Willard (1951). This thesis consolidates the unpublished field data gathered during reconnaissance mapping by Robert Pastuszak (1965), Richard Jackson (1973), Hope Davies (1973), Charles Onasch (1973), and William Hart (1979), all working under Professor Peter Robinson's direction. Use was also made of additional field data collected by Robinson in the Belchertown quadrangle, and in the East Pleasant Street area of Amherst during construction of a university heating plant and associated underground pipelines.

Water Wells

The positions of twenty water wells are located on Plate 1 and their logs are reproduced in Appendix 1. The subsurface information these wells provide helps to locate more accurately the contact between Paleozoic crystalline rocks and the Mesozoic sedimentary rocks of the basin.

Field Work

A program of field mapping began in the summer of 1979, and was continued during the summer and fall of 1980, and the spring of 1981. Outcrops were plotted on 7½-minute topographic base maps at a scale of either 1:25,000 or 1:24,000. Map locations were determined with the aid of a pocket aneroid altimeter and a Brunton compass. Planar and linear features were measured with the Brunton compass at numbered stations, and samples were collected for petrographic examination.

Acknowledgments

This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology at the University of Massachusetts, Amherst. The author would like to extend his sincere appreciation to Professor Peter Robinson who suggested the project and served as principle advisor, and to Professors Leo M. Hall and George E. McGill for their advice and critical review of the manuscript. Automobile mileage in the summer of 1979, was provided by a grant from the U.S. Geological Survey, Branch of Eastern Environmental Geology (to Robinson). Expenses of final publication of maps and text were provided by National Science Foundation Grant EAR-81-16197 (to Robinson).

STRATIGRAPHY

The oldest stratigraphic unit in the Amherst area is the pre-Middle Ordovician Fourmile Gneiss. This is exposed locally near North Amherst entirely in the footwall of the Connecticut Valley border fault. The sequence of rocks located in the hanging wall of the border fault is interpreted to consist of a repetition of Middle Ordovician, Silurian, and Lower Devonian strata similar to rocks found on the crest of the Bronson Hill anticlinorium and the western limb of the Merrimack synclinorium (Figure 5).

Since the 1940's, a continuing effort has extended the stratigraphy first defined by Billings (1937) in the Littleton-Moosilauke area of New Hampshire southward along the Bronson Hill anticlinorium towards Massachusetts into progressively more metamorphosed and structurally complex terrane (Moore, 1949; Billings, 1956; Robinson, 1963, 1967a; Thompson et al., 1968). A similar stratigraphic sequence has also been found along the western edge of the Merrimack synclinorium by Field (1975) and Tucker (1977). The stratigraphic sequence defined by Billings consists of Middle Ordovician Ammonoosuc Volcanics and Partridge Formation, Silurian Clough Quartzite and Fitch Formation, and the Lower Devonian Littleton Formation. The subdivision of the rocks of the Amherst block is in the context of this regional stratigraphic framework.

The two major recognized stratigraphic units of the Amherst block are the Middle Ordovician Partridge Formation and the Lower Devonian Littleton Formation. Separation of these units is

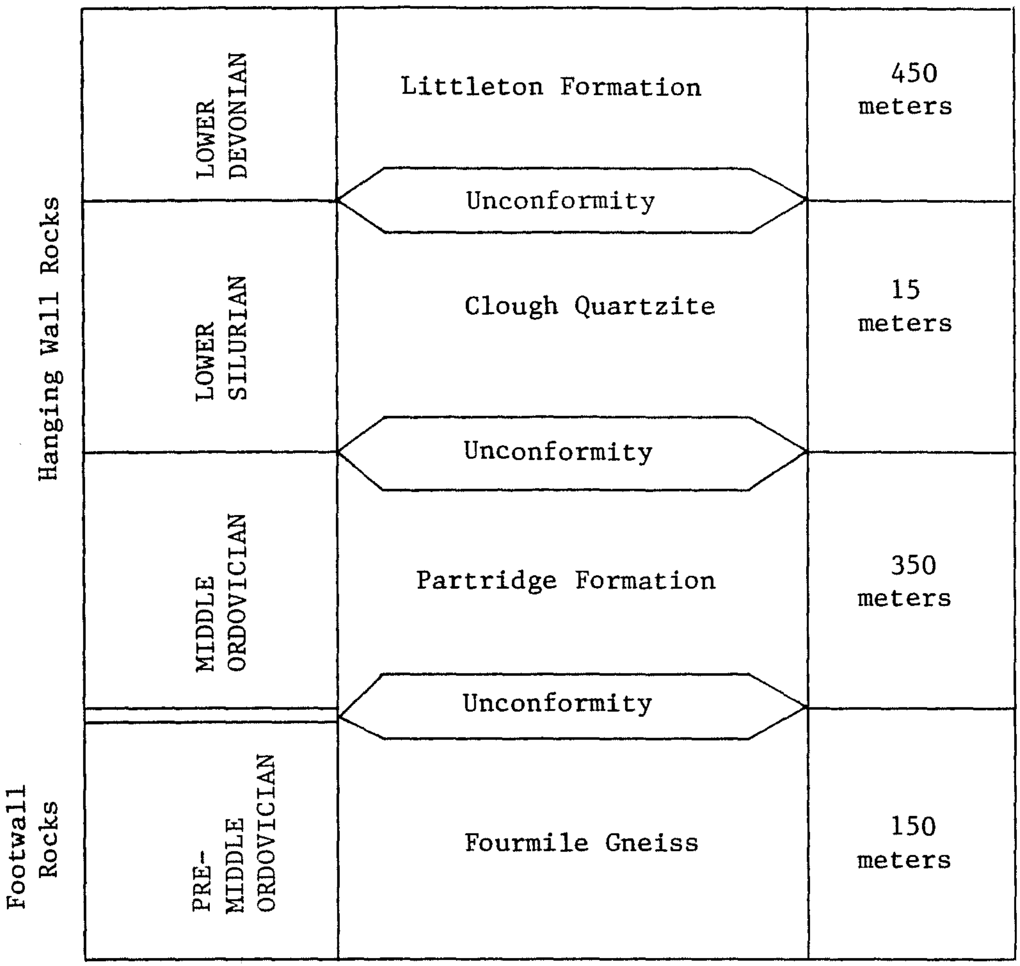


Figure 5. Simplified columnar section of stratigraphic units in the Amherst area, and approximate thicknesses. Hanging wall and footwall designations refer to position with respect to the Connecticut Valley border fault in the Amherst area.

difficult due to their lithic and textural similarities and the paucity of intervening Silurian units. The Silurian Fitch Formation is found to the east in the Bronson Hill anticlinorium and also to the north at Bernardston (Trask and Thompson, 1967), where it consists of calc-silicate granulite and biotite quartz schist. This unit is nowhere known to be present in the Amherst block. The Silurian Clough Quartzite which forms a distinctive marker horizon to the north in the

Bernardston area, consisting largely of quartzite and quartz-pebble conglomerate, is exposed locally only in the northern part of the study area. With the juxtaposition of lithically similar Middle Ordovician and Lower Devonian schist units, the most important criterion for separation of the Partridge and Littleton Formations is the rusty-weathering of the Partridge and the sulfide content which that implies.

The Partridge Formation is here defined to include all red- to rusty-weathering, gray pelitic schists, and the Littleton Formation to include all gray-weathering schists. This criterion for separation of stratigraphic units has been emphasized here and has also been used successfully by Trask and Thompson (1967) to the north in the Bernardston area, and to the east by Robinson (1967a), Field (1975), and Tucker (1977).

Fourmile Gneiss

The Fourmile Gneiss is not in the strictest sense a stratigraphic unit of the Amherst block, but lies on the footwall (east side) of the Connecticut Valley fault. It is the youngest gneiss in the core of the adjacent Pelham dome and is exposed within rocks of the Amherst block due to Mesozoic faulting and later erosion. Thus, it is now exposed in three windows of footwall rocks from the west flank of the dome completely surrounded by hanging wall rocks of the Amherst block (see structure section.)

The name Fourmile Gneiss was first assigned by Ashenden (1973) for its type locality on Fourmile Brook at Northfield Farms, approximately 25.7 kilometers north-northeast of the northern border of the Amherst area. There the unit consists of gray, quartz-feldspar-biotite gneiss and plagioclase gneiss with layers of amphibolite and feldspar-hornblende gneiss. This unit has been traced southward along the western flank of the Pelham dome from Millers Falls (Laird, 1974) into the Leverett area where it appears as a thin belt of layered hornblende gneiss.

In the study area, the Fourmile Gneiss is exposed in three locations in the Cushman and Factory Hollow sections of North Amherst, as well as farther east in the vicinity of Atkins Reservoir on the east side of the main trace of the border fault.

Lithology. The Fourmile Gneiss occurs in three locations in the Cushman section of North Amherst. In the eastern exposure it is composed of two rock types: gray-green, fine-grained gneiss, with undulating layers of hornblende and feldspar approximately 1 to 3 cm thick (samples MT-486A, MT-486B), and felsic gneiss. The southwestern exposure consists of massive, coarse-grained, dark green amphibolite and felsic gneiss. The northwestern exposures of Fourmile Gneiss occur on the east slope of Pulpit Hill. These exposures are composed of hornblende-feldspar gneiss, amphibolite (sample MT-298) and felsic gneiss (samples MT-515, MT-288).

For comparison, samples were also taken from the footwall exposures of Fourmile Gneiss east of the main trace of the border fault near Atkins Reservoir. These exposures consist of coarse-grained amphibolite and, near Adams Brook, south of Shutesbury Road, a fine-grained, well foliated, plagioclase-hornblende gneiss with about 15% of epidote (sample SH-181).

The primary minerals typically contained in the hornblende-bearing members of the Fourmile Gneiss (Table 1) are plagioclase 20-60% (An 24-38), hornblende 30-70%. and epidote 0-15%. Accessory minerals include quartz, biotite, apatite, zircon,diopside, ilmenite, and magnetite. Trace amounts of allanite and tourmaline were also noted as well as secondary muscovite, chlorite, and sericite. Evidence for post-metamorphic readjustment of the mineralogy resulting from cataclasis and hydrothermal alteration is evident in samples SH-181 and MT-486B. Both samples show recrystallized epidotes and hornblende with strained crystals in MT-486B and, in SH-181, veins of mylonitic epidotes exhibiting cross-cutting relationships.

The major minerals contained in the felsic gneiss component of the Fourmile unit are plagioclase 36-38% (An 10-28), quartz 40-45%, and biotite 8-10%. Accessory minerals include garnet, apatite, zircon, magnetite, and ilmenite. Secondary minerals include chlorite, muscovite, and sericite. In spite of all efforts to obtain fresh samples of felsic gneiss, both MT-288 and MT-515 show evidence of heavy alteration. The biotite content of both samples has been largely replaced by chlorite and oxychlorite. The lack of reported orthoclase (MT-288) is in part due to the problems of differentiation among the heavily sericitized feldspars. Extensive evidence of cataclasis is apparent in both samples, with strain-induced twinning of quartz (MT-515) and incipient quartz mylonitization and mylonitic foliation (MT-288).

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

	----Hornblende Gneiss---			Amphibolite	Felsic ----Gneiss----	
	SH-181	MT-486A	MT-486B	MT-298	MT-288	MT-515
Quartz		4		tr	40	45
Plagioclase	21 An 36	46 An 24	44 An 29	15 An 38	36 An 26	38 An 10
Biotite			1	3	10	8
Garnet					1	
Hornblende	40	30	47	70		
Diopside		5	1			
Pistacite	15		3			
Sphene	5	3	2	tr		tr
Allanite	tr					
Apatite	1	1	1	tr	1	1
Zircon	tr	1	1	tr	tr	tr
Tourmaline			tr			
Ilmenite		tr	tr	1	tr	
Magnetite	3	tr	tr	1	tr	tr
# Hematite			tr		tr	tr
* Muscovite					tr	1
* Chlorite	15+		tr+	2+	4-	4-
* Sericite		10	tr	8	8@	3

Plagioclase composition obtained by Michel-Lévy method.

* Denotes secondary minerals: optic sign of chlorite also noted.

Appears as weathering by-product of ilmenite.

@ Several sericitized grains identified as former orthoclase (perthite) due to the presence of albite lamella.

List of Specimens in Table 1.

SH-181	Greenish-gray, fine-grained quartz-feldspar-hornblende gneiss. Located on access road on the west bank of Adams Brook 400 feet below dam in the east-central part of the map area.
MT-486A	Well foliated, greenish-gray, fine-grained biotite-hornblende gneiss with feldspar laminations 5mm thick. Outcrop located 1300 feet east and 450 feet south of the intersection of Henry Street and Pine Street in the central part of the map area.
MT-486B	Greenish-gray, fine-grained, hornblende-feldspar gneiss with irregular thin feldspar laminations. Same location as MT-486A.
MT-298	Massive, dark green hornblende-biotite feldspar amphibolite. Located 650 feet north of Pulpit Hill Road and 450 feet west of railroad tracks in the north-central portion of the map area.
MT-288	Medium-grained well foliated, gray-weathering, felsic gneiss. Sample from outcrop on south side of Pulpit Hill Road on the east slope of Pulpit Hill in the north-central part of the map area.
MT-515	Well foliated, medium-grained biotite felsic gneiss. From outcrop at the 330' contour located 150 feet north of Pulpit Hill Road in the north-central part of the map area.

Derivation. The Fourmile Gneiss is believed to be composed of metamorphosed mixed volcanic rocks. They are prominently layered, suggesting a possible pyroclastic or water-laid origin. Some sills and stocks are also present in the Fourmile. Ashenden (1973) suggests that these rocks were deposited on an early volcanic island arc in pre-Taconian early Ordovician time.

Thickness. The interpretation in cross-section (Plate 2) shows exposures of Fourmile Gneiss in fault-bounded slices and windows revealed by subsequent faulting and erosion in the foot wall of the border fault. As such, no exposure represents the true thickness of the unit.

North of the study area, in Leverett, on the western flank of the Pelham dome, it has been estimated (Laird, 1974) that the Fourmile Gneiss has a thickness of 18-20 meters. The minimum thickness calculated for the Fourmile Gneiss in the Amherst area is based on the eastern-most exposure in the Cushman section. The contacts of the Fourmile Gneiss with adjacent stratigraphic units are not exposed, but assuming that these are coincident with the general foliation, then using an average dip of 30 degrees, an estimated thickness of 150 meters is obtained.

Age. The Fourmile Gneiss is the youngest core gneiss in the Pelham dome and is overlain with probable unconformity by the Middle Ordovician Partridge Formation. The Fourmile Gneiss overlies a coherent older sequence of rocks that includes the Dry Hill Gneiss of probable volcanic derivation which contains dated zircons of Late Precambrian age (Naylor et al., 1973). The age of the

Fourmile is Ordovician or older, possibly Lower Ordovician (Ashenden, 1973).

Partridge Formation

The Partridge Formation occurs in belts which trend north-northeast across the largest of the three Amherst inliers (Plate 1). At Mt. Warner, the lower belt of Partridge schists is exposed at the summit of the southern peak and is inferred to occupy the stream valley sloping to the southwest. The upper belt of Partridge rocks is poorly exposed but is west of Mt. Warner Road. These two belts of Partridge rocks continue onto the main body of Mt. Warner. The lower belt is well exposed along Mt. Warner road where it crosses the saddle and continues up and through the low area on the crest of Mt. Warner and down its eastern flank. The upper belt of Partridge comprises both the base of the western flank of Mt. Warner and its northern end. The Partridge Formation continues through an area of sparse exposure to the vicinity of North Amherst. From North Amherst to the northern border of the study area, exposures of Partridge rock are confined to an area roughly bounded by Route 63 on the west and the Central Vermont Railroad tracks on the east.

In the smaller South Amherst inlier, Partridge exposures are composed of granulitic schists and calc-silicate granulites found in roadcuts along Southeast Street. A single additional exposure of Partridge rock, a rusty schist, is involved in a large pegmatite intrusion 300m north of East Hadley Road, west of Mill Valley helping to locate the western extent of this inlier.

Lithology. The characteristic rock type of the Partridge Formation in the Amherst block is rusty-weathering, sillimanite-mica schist with variable amounts of quartz, plagioclase, and garnet. Subordinate rock types are quartz- and feldspar-rich granulitic schist with considerable biotite, and some muscovite and garnet, and calc-silicate granulite with fine- to medium-grained crystals of garnet and diopside set in a quartz-feldspar groundmass.

The mica schists of the Partridge Formation (Table 2) consist of quartz, plagioclase, biotite, and muscovite as primary constituents with lesser amounts of sillimanite (now retrograded to muscovite), orthoclase, garnet, and pyrrhotite. These schists are fine- to medium-grained and well foliated. Due to the sulfide content, exposures of Partridge schists are highly weathered and in many cases so friable that fresh samples were unobtainable. In spite of severe weathering, outcrops do exist where sillimanite or white aggregates replacing it could actually be identified in hand specimen. On the curve of Mt. Warner Road, in the saddle at Mt. Warner, sillimanite appears as white translucent bundles of crystals 3 to 6mm long set among the mica plates defining the foliation planes. Similarly, sillimanite is also conspicuous in hand specimen at the outcrop in the roadcut on Route 63, located 1.5 kilometers north of the center of North Amherst. In those cases where apparent sillimanite-bearing schists could be obtained for thin sections (MT-377, MT-336A, PMT-54B), it was found that all sillimanite had been replaced by muscovite pseudomorphs.

Additional secondary minerals are noted in other samples as well. Sheet silicates are heavily altered with biotite showing secondary chlorite of both Mg- and Fe-rich varieties. Secondary orthoclase also appears (PMT-55B, MT-336A, MT-258) as lenses arranged parallel to biotite cleavage. Titanium released during biotite transformation to chlorite in two samples (MT-377, MT-258) occurs as rutile needles. In sample MT-336A trace amounts of an unidentified green fibrous mineral were noted replacing plagioclase. In the Mt. Warner area there are schists displaying quartz-rich segregations (samples MT-258, MT-377) arranged parallel to the foliation. These are widely distributed and are believed to be the result of partial melting. Compared to the Littleton Formation, all of the schists of the Partridge Formation are more sulfidic and generally contain more muscovite and less garnet and biotite.

Subordinate granulitic schist and calc-silicate beds appear to be dispersed throughout the section. The granular schists (MH-326B, MT-294A) are rusty-weathering and quartz-rich with significant amounts of pyrrhotite and biotite. These rocks, though there is no mappable distribution, appear to be more common in the northern half of the study area. Calc-silicate rocks (Table 3) appear in nodules and in individual beds 10 to 30cm thick and, where fresh, display a white to light purplish-gray color. These rocks are fine grained, with garnet and diopside crystals 2-3mm in diameter evenly distributed in a matrix of quartz, plagioclase, clinozoisite, sphene, and calcite. In outcrop the weathering out of calcite and garnet crystals has yielded a distinctive "pocketed" appearance. Thin sections of samples MT-71A and MH-334D contain grains of quartz in a

Table 2. Estimated modes of specimens of schists and granulitic schist from the Partridge Formation.

	Schist				Granulitic Schist	
	MT-377	MT-258	PMT-54B	MT-336A	MH-326B	MT-294A
Quartz	53	45	45	35	49	50
Plagioclase	10 An 28	7 An 29	19 An 26	20 An 29	32 An 30	19 ?
Orthoclase	1				2	
Sillimanite	x	x	x	x		x
Garnet	tr		tr		1	tr
Biotite	10	20	15	13	15	15
Muscovite	8¢	20	6¢	15¢	tr¢	6¢
Tourmaline					tr	
Apatite	tr	2	1	1	tr	tr
Zircon	tr	tr	tr	1	1	tr
Graphite	1	1	tr	1	tr	1
Pyrrhotite	1	2	2	1	tr	1
Rutile	tr	tr				
Ilmenite	2	1	2	3	tr	3
# Hematite		1	tr		tr	tr
* Orthoclase		tr	1	2		
* Chlorite	6±	tr-	5-	3-	tr-	tr-
* Sericite	8	1	4	5	tr	5

Plagioclase composition obtained by Michel-Lévy method.

x Former presence of sillimanite inferred due to muscovite pseudomorphs.

¢ Including trace amounts of secondary muscovite.

* Denotes secondary minerals; optic sign of chlorite also noted.

Appears as weathering by-product of sulfides.

? Positive identification hampered due to severe weathering.

List of Specimens in Table 2.

MT-377 Massive, gray, rusty-weathering biotite-rich schist, streaked with quartz-feldspar segregations. Taken from outcrop at the 250' contour on the east flank of Mt. Warner, 3300 feet north and 950 feet west of the intersection of Mt. Warner Road and Breckinridge Road.

MT-258 Well foliated, rusty-weathering, gray biotite-muscovite schist with quartz-feldspar segregations. From the large exposure located at the 180' contour just to the north of the eastward flowing intermittent stream on the east flank of Mt. Warner.

PMT-54B Rusty-weathering, gray biotite-sillimanite schist. From pipeline trench located 100 feet north of the intersection of Eastman Lane and East Pleasant Street in the central part of the map area.

MT-336A Massive, rusty-weathering biotite schist. Sample taken from roadcut on Route 63. .38 miles north of Pulpit Hill intersection in the north-central portion of the map area.

MH-326B Massive, fine-grained, rusty-weathering, biotite-rich granulitic schist. Sample taken from roadcut on Southeast Street at the crest of the hill located south of Hop Brook in the south-central part of the map area.

MT-294A Gray, rusty-weathering, fine-grained biotite-sillimanite granulitic schist with quartz-feldspar laminations. From the outcrop on the pasture side of the driveway south of the home located .55 miles north of the intersection of Route 63 and Pulpit Hill Road in the north-central part of the map area.

Table 3. Estimated modes of specimens of calc-silicate granulite from the Partridge Formation.

	MT-71A	MH-326A	MH-334D
Quartz	35	40	47
Plagioclase	? ?	28 An 64	? ?
Garnet	10	5	5
Muscovite	1¢		
Actinolite			tr
Diopside	5	10	8
Zoisite	2		
Clinozosite			6
Pistacite	?6	3	?tr
Calcite	5	tr	
Sphene	3	3	3
Tourmaline		tr	tr
Apatite	1	2	1
Zircon	1	1	1
Graphite		tr	tr
Ilmenite	2	3	3
#Hematite		tr	
*Sericite	29	5	26

Plagioclase composition obtained by Michel-Lévy method.

¢ Including trace amounts of secondary muscovite.

* Denotes secondary minerals

Appears as weathering by-product of ilmenite.

? Positive identification hampered due to severe weathering.

List of Specimens in Table 3.

MT-71A	Massive, light-gray, fine-grained granulite. From the large exposure located at the bend where Mt. Warner Road crosses Mt. Warner.
MH-326A	Light-gray, fine-grained calc-silicate. Sample taken from roadcut on Southeast Street at the crest of the hill located south of Hop Brook in the south-central part of the map area.
MH-334D	Light-gray, fine-grained diopside-rich calc-silicate. Sample located at the 250' contour 400 feet west and 1150 feet north of the intersection of Station Road and Southeast Street in the south-central part of the map area.

badly weathered calcareous-felsic matrix. Modes for plagioclase and plagioclase composition were unobtainable due to extensive sericitization. Another weathering product of these samples is grouped with pistacite(?) in Table 3. This unidentified mineral is a slightly pleochroic light yellow-green substance whose color is appropriate for pistacite, but which displays traces of a relic pyroxene cleavage and may be a clay mineral alteration of diopside.

Contacts and thickness. Contacts of the Partridge Formation are poorly exposed in the Amherst block with two exceptions. The first is on Mt. Warner Road in the roadcut located on the curve at the saddle of Mt. Warner. This exposure clearly shows the top contact between Partridge and Littleton schists. The other top contact is approached within a meter and is located in the railroad cut just north of Depot Road by the Long Plain Cemetery.

Because no bottom contacts of the Partridge are exposed, only an estimate of the thickness can be obtained. The greatest width of any belt in map pattern is found in the central part of the study area near North Amherst. Assuming an average dip of 25 degrees (Figure 9 and Plate 3), a thickness of at least 700 meters is obtained. Assuming a simple doubling-up due to isoclinal folding, a minimum thickness of 350 meters is obtained.

Derivation. The presence of a significant sulfide content in the Partridge Formation is characteristic of deposition in a closed anoxic basin whose stagnant environment fostered the action of sulfur-reducing bacteria. The calc-silicate beds and concretions of the Partridge Formation are derived from metamorphosed carbonate-rich horizons within the depositional sequence. The schists, granulites, and calc-silicates of the Partridge Formation are derived from marine shales and siltstones originally deposited during a late-collisional relaxation phase of the Taconic orogeny (Robinson, 1979).

Correlation and age. The Partridge Formation has been traced down the axis of the Bronson Hill anticlinorium from the type locality at Partridge Lake, New Hampshire (Billings, 1937), into Massachusetts (Moore, 1949; Robinson, 1963; Trask and Thompson, 1967), and southward along the eastern limb of the anticlinorium (Robinson, 1967a; 1967b) and the western limb of the Merrimack synclinorium (Field, 1975; Tucker, 1977).

The Partridge Formation can be correlated with schists mapped as Partridge Formation on the west limb of the Merrimack synclinorium. The sulfide content and the metamorphic grade suggest a similar origin for both. It has been proposed by Robinson (1979) that the map pattern east of the Bronson Hill anticlinorium suggests that that area may be the root zone of the nappes which are responsible for the repetition of Partridge units on the Amherst block.

The age of the Partridge Formation is best deciphered to the north where rocks are least metamorphosed and fossils are obtainable. It is considered Middle Ordovician based on Zone 13 graptolites found in the Dixville Formation, western Maine (Harwood and Berry, 1967).

Clough Quartzite

The Clough Quartzite is the only Silurian unit mapped in the Amherst block. It has long been recognized (Billings, 1937, 1956) as a useful marker horizon due to its distinctive character. The Clough Quartzite is found in thin lenticular zones at four localities in the northernmost part of the Amherst block. Near the Long Plain Cemetery the Clough occurs in two exposures; one at the 360' contour near the intersection of Route 63 and Long Hill Road, the other south of Depot Road at the base of the east-facing slope of the unnamed 471 foot hill. The remaining two exposures occur near the crest of the hill northeast of the intersection of Amherst Road and Teawaddle Hill Road (Plate 1). These few exposures are significant because they show that the adjacent schists can be divided into Ordovician and Devonian portions.

Lithology. The most distinctive outcrops of the Clough Quartzite are located in the Long Plain area. The exposure near

Long Hill Road (Table 4, sample MT-430) is located 6 meters east of Route 63 and appears as a light-gray, stretched-quartz-pebble conglomerate with pebbles to approximately 15cm in length that are oriented in a matrix of fine-grained, light-gray biotite-muscovite schist. The second Long Plain outcrop, located south of Depot Road (MT-437), is a massive two meter high, eight meter long exposure composed of oriented white stretched quartz pebbles up to 10cm long contained in a white to light-gray felsic matrix. The two exposures of Clough Quartzite located near Teawaddle Hill Road are less characteristic in appearance; they consist of darker, more micaceous gray quartzite and light-gray quartz pebble conglomerate with 10mm long pebbles set in a quartz-mica schist matrix similar in appearance to adjacent quartz-rich Littleton schist outcrops.

Contacts and thickness. The contacts of the Clough Quartzite are nowhere exposed but are approached within a few meters at the two Long Plain exposures. The first is at the outcrop south of Depot Road where the Clough is physically overlain by the stratigraphically older Partridge schist, and the second is near Route 63 and Long Hill Road where the Clough-Littleton contact is overturned. The other exposures of Clough Quartzite have contacts which are not exposed.

The thickness of the Clough Quartzite is reported to vary abruptly along strike to the north. The changes in the thickness may be due to primary stratigraphic differences, tectonic thinning, or large-scale boudinage (Thompson et al., 1968). The calculated thickness of the Clough Quartzite in the Amherst block is based on

Table 4. Estimated modes of specimens of the Clough Quartzite.

	MT-430	MT-437
Quartz	50	60
Plagioclase	10 An 38	15 An 30
Garnet		2
Biotite	10	1
Muscovite	10	4
Apatite	1	tr
Sphene	tr	1
Zircon	1	1
Magnetite	2	1
Ilmenite	1	3
Rutile		tr
Pyrite		tr
# Hematite		tr
* Chlorite	5-	9-
* Sericite	10	3

Plagioclase composition obtained by Michel-Lévy method.

Appears as weathering by-product of Ilmenite.

* Denotes secondary minerals; optic sign of chlorite also noted.

List of Specimens in Table 4.

MT-430 Gray-weathering, fine-grained, well foliated biotite-muscovite schist and quartz-pebble conglomerate. Sample taken from south bank of intermittent stream 100 feet east of Route 63, 600 feet south of the Route 63 Long Hill Road intersection.

MT-437 Light gray, well foliated biotite-muscovite schist and quartz-pebble conglomerate. Outcrop located at the 380' contour, south of the saddle on the east flank of the 471' hill south of Depot Road in the north-central portion of the map area.

the limited exposure near Route 63 south of Long Hill Road and is estimated to be 15 meters.

Derivation. The coarse size of the pebbles or cobbles contained in the Clough indicates a nearby source area. The variable lithology and thickness along strike which has been noted to the north suggests deposition in a shallow water shelf or beach environment.

The rocks of the Clough Quartzite are part of a Silurian eastward-thickening sequence (Robinson, 1979) representing an interlude in New England between the orogenic events that dominated Ordovician and Devonian times.

Correlation and age. The Clough Quartzite has been the lithologic key to unraveling the stratigraphy of the Bronson Hill anticlinorium. The discovery of datable fossils in the quartzites on Skitchewaug Mountain has lead to the recognition of large scale recumbent folding and the reappraisal of the entire style of Acadian deformation in central New England (Thompson, 1954; 1956). The Clough has been traced by Trask and Thompson (1967) from Bernardston, at the head of the Deerfield basin, north and east as a distinctive horizon on the inverted limb of the Bernardston nappe (Thompson and Rosenfeld, 1979). The Clough Quartzite appears, although markedly thinner, on the Amherst block as well. It lies in an inverted position exposed only locally in the northern part of the study area.

The Clough Quartzite contains fossils at a number of localities. The well known locality at Bernardston (Hitchcock, 1841) has fossils in quartzites and marbles in the garnet zone of metamorphism which have been dated (Boucot et al., 1958) as probably late Early Silurian.

Fossils have also been found and similarly dated at Skitchewaug Mountain (Boucot et al., 1958) and even better dated in the sillimanite zone of metamorphism at Croydon Mountain, New Hampshire (Boucot and Thompson, 1963).

Littleton Formation

The schists assigned to the Littleton Formation are exposed in the two larger inliers of the Amherst block (Plate 1). Based on water well data (Appendix 1), they are thought to compose the entire subsurface inlier below Lawrence Swamp.

In the Amherst inlier, near Mt. Warner, the Littleton Formation occurs in two belts trending north-northeast. Both of these belts of Littleton are well exposed around the smaller southern mass of Mt. Warner, and they are also well exposed up the western flank and over the crest and on down the northern and eastern flanks. A belt of Littleton extends northward through an area of poor exposure to the Amherst-North Amherst area. Northward the Littleton is interpreted to occur in that area roughly bounded by the border fault on the east and the Central Vermont Railroad tracks on the west.

In the smaller South Amherst inlier, the Littleton Formation is thought to compose the eastern part based on a few exposures and water wells located near the border fault.

Lithology. The dominant rock type of the Littleton Formation in the Amherst area is gray-weathering, quartz-rich biotite schist which has variable amounts of plagioclase, orthoclase, muscovite, garnet, and sillimanite. Two other rock types of lesser importance are granular schists and calc-silicate granulites. The granular schists contain quartz and plagioclase with lesser amounts of biotite and garnet. Calc-silicate rocks contain garnet and diopside crystals set in a matrix of quartz and plagioclase. The opaque minerals are commonly ilmenite and graphite which account for the gray-weathering character of the Littleton schists.

The mica schists of the Littleton Formation (Table 5) consist of quartz, plagioclase, and biotite as major constituents with lesser amounts of orthoclase, sillimanite, garnet, muscovite, ilmenite, and graphite. These schists are fine- to medium-grained and are very well foliated. Due to the high quartz content and lack of sulfides, as compared to the Partridge Formation, the outcrops generally weather less severely with the exception of those where garnet and sillimanite make up a large percentage of the rock. In samples where the freshest sillimanite-bearing schists were examined (MT-310, MT-422), it was found that the sillimanite had been sericitized but still had retained enough of its physical identity to enable an estimate of its mode to be made. In some samples of sillimanite-bearing schists (MT-267B1, PMT-55B), sillimanite has been entirely replaced by muscovite pseudomorphs. Sample MT-422 appears to contain badly weathered muscovite pseudomorphs as well, but their presence is more uncertain. Heavily sericitized low relief grains marking the presence of primary orthoclase were identified in samples MT-466, PMT-55B, and MT-310. Secondary minerals are noted in these and other samples as well. Variable alteration of the biotite has occurred, with all samples showing some evidence of secondary muscovite and Fe-rich chlorite. The more heavily altered samples (MT-466, MT-310, MT-422) show biotite developing secondary orthoclase as lenses arranged parallel to the biotite cleavage. Titanium released during biotite breakdown to Fe-rich chlorite occurs as acicular rutile in two samples (MT-267B1, MT-310). Also noted in the Mt. Warner area and to the north near Depot Road were exposures of gray schists displaying quartz-feldspar layers (MT-422, MT-267B1) parallel to foliation that were probably formed by partial melting.

Subordinate granular schists and calc-silicate beds appear to be dispersed throughout the section. The granular schists (MT-478B2) are fine grained and quartz-rich with significant amounts of biotite and garnet. The thin section examined also contains muscovite, probably pseudomorphous, after sillimanite. Secondary minerals observed due to biotite alteration are orthoclase as lenses parallel to the cleavage and both Mg- and Fe-rich varieties of chlorite. White to light-gray calc-silicate rocks (Table 6) appear in beds 10.2 to 30.5 cm thick. These rocks are fine-grained with a quartz, plagioclase, epidote, and sphene groundmass and with uniformly distributed garnet crystals 3 mm in diameter. There are variable amounts of diopside and calcite in some specimens. Thin sections of samples MT-75A and MT-275A contain quartz grains in a badly weathered felsic matrix. Due to the degree of sericitization, no plagioclase determination or mode was obtained. Calc-silicate outcrops weather with a distinctive texture due to the removal of garnet and calcite.

Table 5. Estimated modes of specimens of schists and granular schist from the Littleton Formation.

	Schist						Granular Schist
	MT 267B1	MT 466	PMT 55B	MT 310	MT 412	MT 422	MT 478B2
Quartz	24	48	50	32	40	35	41
Plagioclase	35 An 36	3 ?	8 An 34	20 An 39	15 An 28	20 An 28	19 An 42
Orthoclase		1	5	1			1
Sillimanite	x		x	10x	10x	?	?
Garnet	3	5		5	3	3	10
Biotite	tr	20	15	15	20	25	10
Muscovite	7¢	14¢	5¢	tr¢	3¢	10¢	1¢
Apatite	tr	3	3	tr	tr	tr	4
Zircon	1	tr	1	tr	1	1	tr
Ilmenite	2	4	3	4	2	4	3
Rutile	tr		tr				
Graphite	1	1	2	1	tr	1	2
# Hematite				tr	1		tr
* Orthoclase		1		tr		tr	1
* Chlorite	17-	tr-	tr-	2-	2-	1-	1±
* Sericite	10	tr	8	10	3	tr	7

Plagioclase composition obtained by Michel-Lévy method.

x Former presence of sillimanite inferred due to muscovite pseudomorphs.

¢ Including trace amounts of secondary muscovite.

* Denotes secondary minerals, optic sign of chlorite also noted.

Appears as weathering by-product of ilmenite.

? Positive identification hampered due to severe weathering.

List of specimens in Table 5.

MT-267B1	Brown-stained, gray, poorly foliated biotite schist. Outcrop is 200 feet east and 150 feet north of the northernmost water tank located on the western flank of Mt. Warner at the 400' contour.
MT-466	Gray, well foliated biotite-muscovite-garnet schist. Located 1100 feet north and 1000 feet east of the Mt. Warner Road and Stockwell Road intersection at the 280' contour on the west flank of Mt. Warner.
PMT-55B	Massive, gray, well foliated biotite-sillimanite schist with 3 mm pink feldspar phenocrysts. Taken from north side of road, 1950 feet east of the East Pleasant Street and Eastman Lane intersection in the central part of the map area.
MT-310	Massive, light-gray, weakly foliated biotite schist with knots of sillimanite. Located 800 feet upstream on Cushman Brook above the Leverett Road bridge in the north-central portion of the map area.
MT-412	Dark-gray, well foliated biotite-garnet-sillimanite schist. Sample taken from railroad cut 300 feet north of Depot Road in the north-central portion of the map area.
MT-422	Dark-gray, massive quartz-feldspar-rich schist with thin biotite laminations. Sample taken from top of knob located 500 feet due west of house located by the power substation north of Depot Road in the north-central portion of the map area.
MT-478B2	Gray-weathering, fine-grained biotite-garnet granular schist. Taken from outcrop at 250' contour, east flank of Mt. Warner, 1800 feet north and 1400 feet west of the intersection of Mt. Warner Road and Breckinridge Road.

Table 6. Estimated modes of specimens of calc-silicate granulite from the Littleton Formation.

	MT-75A	MT-275A
Quartz	45	31
Plagioclase	? ?	? ?
Garnet	15	5
Biotite	tr	
Diopside		10
Calcite	tr	4
Zoisite	6	
Clinozoisite		10
Sphene	3	5
Apatite	1	2
Zircon	tr	1
Ilmenite	2	1
Graphite	2	1
* Muscovite	1	
* Sericite	25	30

? Plagioclase composition not obtained due to extensive sericite.

* Denotes secondary minerals

List of specimens in Table 6.

MT-75A Gray, fine-grained, massive garnet-rich calc-silicate granulite. Located at the 250' contour, 200 feet due east of the intermittent stream on the north slope of Mt. Warner.

MT-275A Greenish-gray, biotite-rich calc-silicate granulite. Located 1400 feet northwest of the intersection of Maple Street and Mt. Warner Road in the west-central portion of the map area.

Contacts and thickness. The best exposures of Littleton contacts are with the Partridge Formation. These exposures were discussed previously in the contacts and thickness section of the Partridge Formation. Since both the top and bottom contacts of the Littleton Formation are not exposed, only an estimate of the thickness can be obtained. The greatest width of the Littleton Formation in map pattern is found in the northern part of the study area (cross-section A-A', Plate 2). Assuming an average dip of 25 degrees (Figure 8), a thickness of at least 900 meters is obtained. Assuming a simple doubling-up due to folding, this yields a minimum thickness of 450 meters.

Derivation. The abundance of graphite in the rocks of the Littleton Formation suggests deposition under reducing conditions, but the lack of sulfides indicates an absence of sulfur-reducing bacteria. Calc-silicate beds present in the Littleton Formation are metamorphosed carbonate-rich horizons within the depositional sequence.

The schists of the Littleton Formation consist of metamorphosed shales thought to be part of a westward spreading clastic wedge produced at the start of the Acadian orogeny (Robinson, 1979).

Correlation and age. As part of Billings' stratigraphic sequence (1937), the Littleton Formation has been traced southward down the Bronson Hill anticlinorium into Massachusetts. Further work has extended known exposures southward (Robinson, 1967a; 1967b) and eastward into the Merrimack synclinorium (Field, 1975; Tucker, 1977). Though there is no continuity of stratigraphic units, the

Littleton Formation of the Amherst block appears to resemble the exposures of Littleton schists in the proposed root zone of the nappes on the east side of the main body of the Monson Gneiss in the Petersham and Ware areas of Massachusetts.

The Littleton Formation contains Lower Devonian fossils in the Littleton and Whitefield areas of New Hampshire (Billings, 1956; Boucot and Arndt, 1960), and in equivalent rocks in western Maine (Boucot, 1961). These fossils have been dated by Boucot (Boucot and Ardnt, 1960) as being of Onondaga age.

INTRUSIVE ROCKS

Belchertown Hornblende Quartz Diorite

Within the Fourmile Gneiss a coarse mottled hornblende-quartz-plagioclase rock of plutonic aspect has been mapped which may be part of the Lower Devonian Belchertown Intrusive Complex (Robinson, personal communication). This rock type, with abundant hornblende crystals embedded in a felsic matrix, is adjacent to the border fault near Atkins Reservoir and again, poorly exposed, in the Amherst block in the eastern exposure of the Fourmile Gneiss in the Cushman section of North Amherst. Rock similar to this was described by Guthrie (1972) as a hornblende-quartz diorite and has been more recently classified as a tonalite (Ashwal et al., 1979). One important characteristic defining the rock studied by Guthrie is its content of olive-green biotite. This rock is contained as a sill within the Fourmile Gneiss. A similar sill continues northward into the Northfield area where it was sampled by Ashenden (1973) as part of the Fourmile Gneiss at the Northfield Mountain Pumped Storage Hydroelectric Project. Additional work on the Northfield samples by Hodgkins (personal communication, 1980) has confirmed the presence of a similarly colored biotite in these samples. The mode of the sample collected from the large exposure north of Shutesbury Road near Adams Brook is in Table 7. Based on the modal data this sample is classified as quartz diorite (Streckeisen, 1973). Biotite, though lacking in this sample of the Belchertown, is characteristic elsewhere.

Contacts of the sill of the Belchertown Hornblende-Quartz Diorite with the Fourmile Gneiss are not exposed but are approached within several meters at the large outcrop located north of Shutesbury Road. Assumption of an average westerly dip of 40 degrees for the contacts yields an estimated thickness of 60 meters.

The Belchertown Intrusive Complex was defined by Guthrie (1972). The complex was formally renamed the Belchertown Quartz Monzodiorite in 1977 (Leo et al.) on the basis of its dominant composition. The main pluton lies 20 km southeast of Amherst. The Belchertown pluton intrudes rocks as young as the Lower Devonian Erving Formation. The complex truncates structural features formed during the nappe stage of Acadian deformation and, in turn, shows evidence that it was solidified and involved in the dome stage of deformation and metamorphism. Thus intrusion took place during the Acadian orogeny. In addition, a U-Pb age determination based on zircon from the pluton (Ashwal et al., 1979) has yielded an age of 380 ± 5 m.y.

Table 7. Estimated mode of specimen from the hornblende quartz diorite of the Belchertown Complex.

	Quartz	Plagioclase	Hornblende	Apatite	Zircon	Ilmenite	Magnetite	*Muscovite	*Chlorite	*Sericite
SH-148	2	28 An 36	55	1	tr	2	1	tr	1	10

Plagioclase composition obtained by Michel-Lévy method.

* Denotes secondary minerals.

Specimen in Table 7.

SH-148 Massive, gray-green, fine-grained hornblende-feldspar gneiss. Sampled at the 520' contour on the east flank of the 572 foot hill located north of Shutesbury Road, Amherst, near the Amherst-Shutesbury town line in the east-central part of the map area.

Pegmatites and Granitic Rocks

Pegmatites and granitic rocks are the most common rocks exposed on the Amherst block. They increase from 50% of the total outcrop in the south to 75% in the northern part of the study area. They appear to have been intruded as discordant bodies, dikes, and sills into the stratified rocks. They were not mapped separately but are shown on the outcrop map (Plate 5).

The pegmatites are characteristically light-gray to white and coarse to medium grained, with potassium feldspar phenocrysts up to 15 cm long. These pegmatites occur in both foliated and non-foliated bodies. None of the pegmatites was studied in thin section, but they appear to be of granitic composition, containing quartz, plagioclase, and potassium feldspar with both muscovite-free and muscovite-bearing varieties noted. Light-gray to white, fine- to medium-grained granitic dikes and sills were examined (Table 8). Based on the estimated modes of the specimens collected, these rocks are classified as granodiorites.

The ages of pegmatites and other intrusions are not certain. Some pegmatites are foliated parallel to the dominant regional foliation. Some sills are boudinaged. These structural features were formed during the waning phases of the Acadian orogeny and are thought to indicate a Devonian age for the intrusions. Non-foliated pegmatite dikes transecting the regional foliation show that there are also intrusions of a somewhat younger age.

STRUCTURAL GEOLOGY

The structural history of west-central Massachusetts has been dominated by two distinctive deformational episodes. The first was the Devonian deformation and metamorphism of the Acadian orogeny, and the second was the Mesozoic faulting and brittle fracture related to the opening of the present Atlantic Ocean.

In the Amherst area evidence exists for four phases of deformation associated with the Devonian Acadian orogeny. Collectively, these phases correspond to the sequence first proposed by Robinson in the Orange and Quabbin Reservoir areas (1963, 1967b, 1967c), and later modified (Robinson, 1979) to be widely applicable in defining the deformational history in central Massachusetts.

Evidence has also been found for several phases of brittle

Table 8. Estimated modes of specimens of intrusive granodiorites.

	MT-267A	MT-71D	MT-59	MT-75B
Quartz	40	35	50	30
Plagioclase	32 An 36	39 An 30	32 An 28	50 An 33
Orthoclase	14	10	5	7
Biotite	3	5	3	6
Muscovite	4¢	5¢	5¢	1¢
Clinozoisite			tr	
Zoisite				tr
Apatite	1	1	1	1
Sphene				tr
Zircon	tr	tr	tr	tr
Rutile	tr	tr	tr	tr
Magnetite	1	1	1	tr
# Hematite	tr			tr
* Chlorite	2-	2-	2-	tr-
* Sericite	3	2	1	5

Plagioclase composition obtained by Michel-Lévy method.

¢ Including trace amounts of secondary muscovite.

* Denotes secondary minerals, optic sign of chlorite also noted.

Appears as weathering by-product of magnetite.

List of specimens in Table 8.

MT-267A	Grayish-white, fine-grained, massive quartz-feldspar-muscovite granodiorite in an intrusive sill 2 feet thick. Outcrop is 200 feet east and 150 feet north of the northern-most water tank located on the western flank of Mt. Warner at the 400' contour.
MT-71D	Fine-grained, massive, light-gray quartz-feldspar-biotite-muscovite granodiorite. Taken from the large exposure located at the bend where Mt. Warner Road crosses Mt. Warner in the west-central part of the map area.
MT-59	Massive to weakly foliated, medium-grained, porphyritic biotite-muscovite granodiorite. Outcrop located at the 330' contour on the west flank of Mt. Warner.
MT-75B	Fine-grained, massive, light- to medium-gray biotite granodiorite. Located at the 250' contour, 200 feet due east of the intermittent stream on the north slope of Mt. Warner.

deformation during the Mesozoic. Figure 6 (a-d) illustrates in a sequence of cross-sections the development of the nappes in the Amherst block and their Mesozoic dislocation to give the present outcrop pattern.

The first phase of the Acadian deformation, figure 6a, involved major west-directed folding creating a sequence of nappes of regional proportions. In the Amherst area the map pattern (Plate 1) of elongated belts of Ordovician and Devonian rock units and the repetition of these formations is due to this phase of deformation. This is analogous to the nappe stage of folding found in the Orange area (Robinson, 1967b), and in the Ware (Field, 1975) and Barre areas (Tucker, 1977).

The next phase of deformation, the backfold stage of Robinson (1979), consisted of regional backfolding of the nappe axial

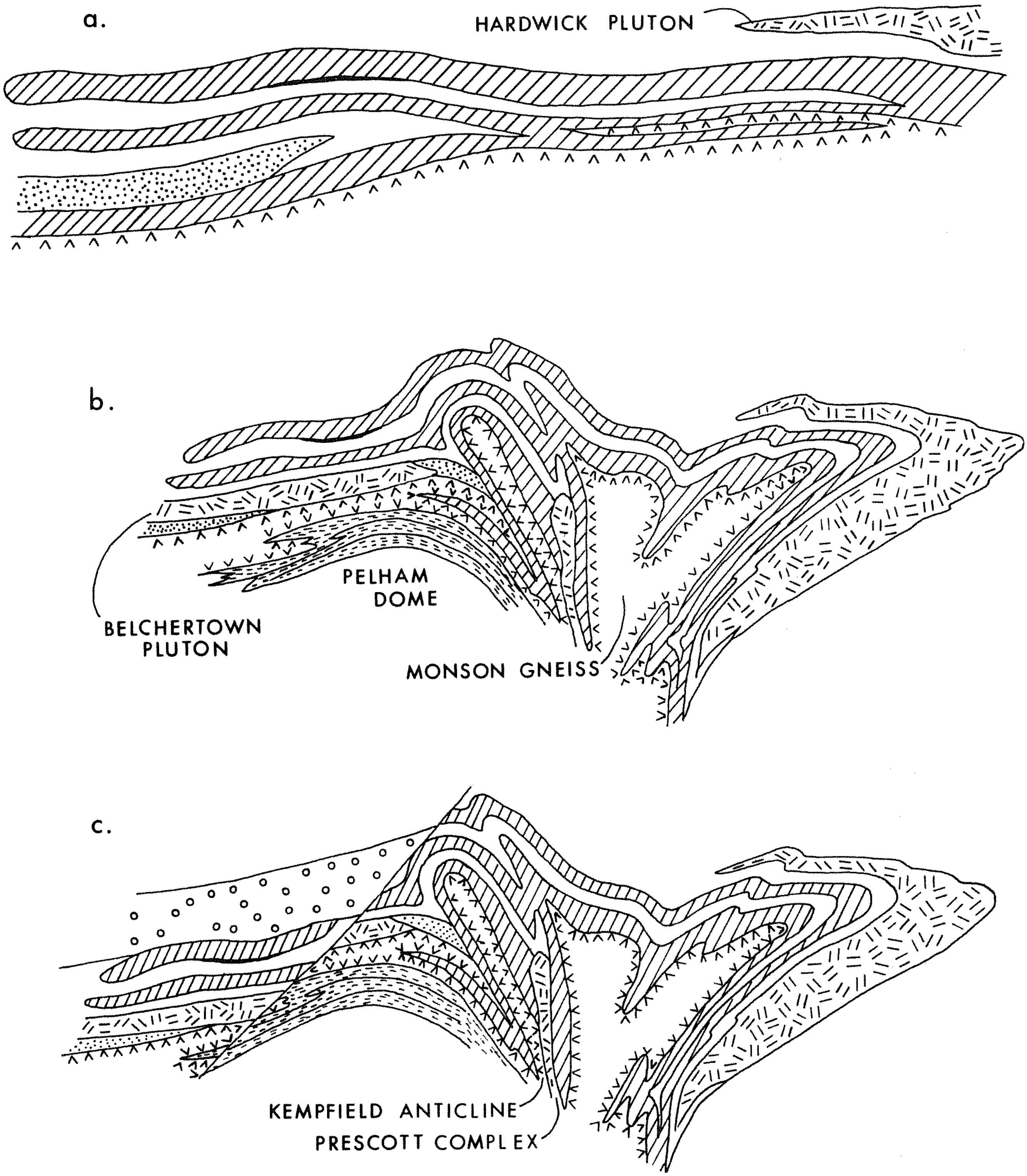
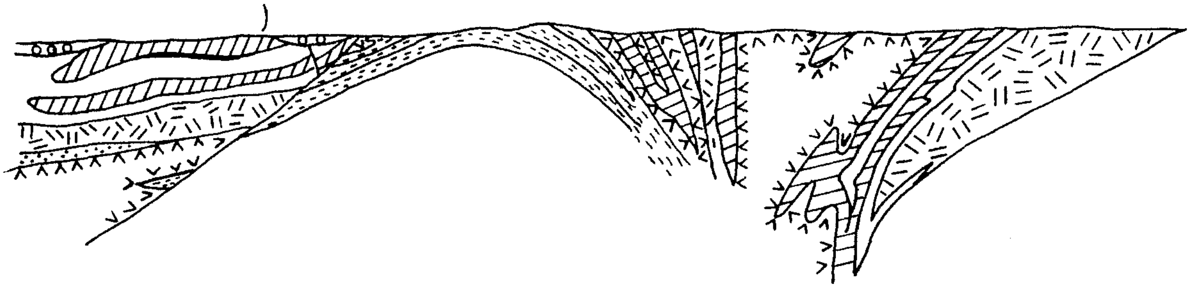


Figure 6. Generalized geologic cross-sections (a-d) showing:
a. Development and emplacement of nappes in the Amherst area.
b. Subsequent refolding.
c. Mesozoic dislocation.
d. Present erosion surface through these features.

d.



LEGEND FOR FIGURES 6 a-d.

Lower Jurassic Upper Triassic	Conglomerate, sandstone, shales of the Sugarloaf Formation
Devonian	Granodiorites, quartz diorites as in the Belchertown and Hardwick plutons and Prescott complex
Lower Devonian	Erving Formation
Lower Devonian	Littleton Formation
Lower Silurian	Clough Quartzite
Middle Ordovician	Ammonoosuc Volcanics and Partridge Formation
Ordovician Precambrian Z?	Monson Gneiss, Fourmile and other related gneisses
Late Precambrian	Popular Mountain and Dry Hill Gneisses as well as Popular Mountain and Pelham Quartzites

surfaces toward the east. Evidence in the Amherst area is inconclusive, but the northwest-trending mineral lineation may have formed in this episode.

The third phase, the dome stage of Robinson (1979), involved the gravitational rise of the gneiss domes, Figure 6b, during their main stage of formation and is represented in the Amherst area by minor folds, boudinage, and northeast-trending mineral lineations. The Belchertown and Prescott Intrusive Complexes came in just before this stage and were deformed during it.

The fourth phase of deformation resulted in later open folding of the previously formed planar features and is most clearly seen in the Mt. Warner area.

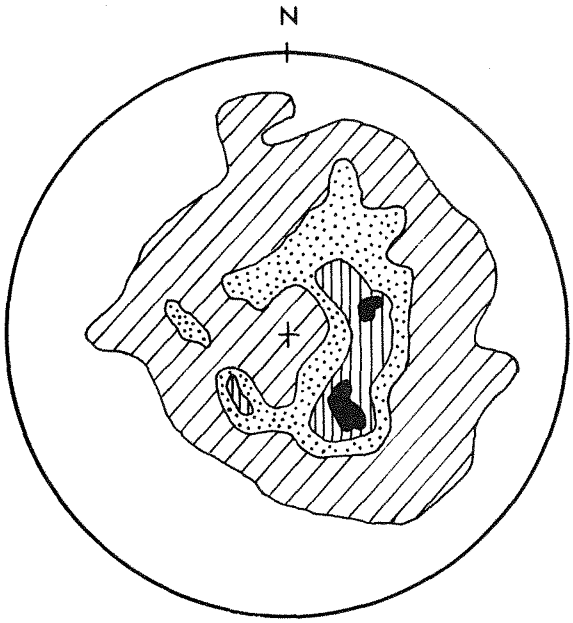
The principal feature reflecting the Mesozoic activity in the Amherst area was the development of the basin-forming Connecticut Valley border fault (Figure 6c), a listric normal fault of major displacement. In the North Amherst area detailed mapping has shown that the border fault itself is cut by two later steep east-dipping normal faults. The resulting geometry and recent erosion has created three windows of footwall rocks of the Pelham dome completely surrounded by hanging wall rocks of the Amherst block (Plate 2, A-A'). Additional subsidiary faults are inferred based on the disruption of the map pattern at the north end of Mt. Warner and in the northern part of the study area near the Long Plain Cemetery. Additional Mesozoic activity included localized occurrences of hydrothermal alteration along the trace of the border fault, and quartz-barite-galena mineralization, as at the Leverett lead mine (Hitchcock, 1841; Wheeler, 1937; Bain, 1941) which is located 0.6 km south of the intersection of Rt. 63 and Long Hill Road.

Nature of Minor Structural Features

Bedding. Evidence of bedding in the schists of the Amherst block is scarce. The contacts between distinctive rock types, which would suggest original bedding, such as calc-silicate horizons in pelitic schists, are here interpreted and measured as representing primary bedding. Everywhere that the attitude of these contacts was measured, it was found to be crudely parallel with the general foliation of the immediate area.

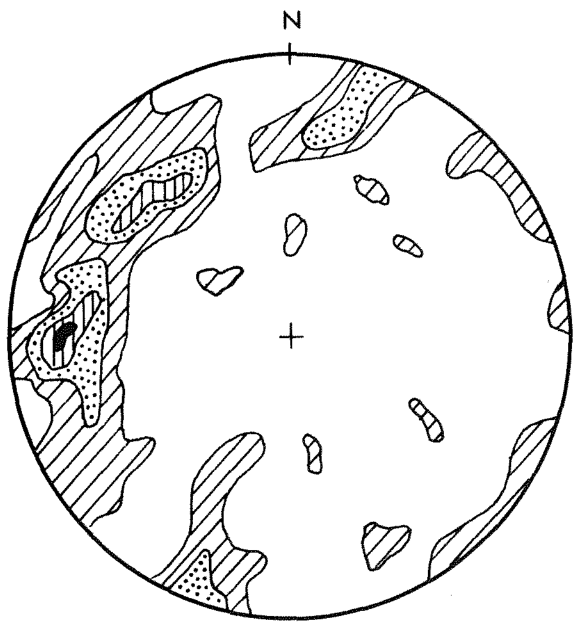
Foliation. Foliation is the dominant planar feature displayed in the outcrops of the Amherst block. In schist it is interpreted to be primarily the result of the tabular arrangement of biotite and muscovite flakes and is also present in massive rocks where a consistent planar attitude in the mineral alignment is displayed.

The dominant foliation in the Amherst area (Plate 3) is believed to be the axial planar foliation which developed subparallel to bedding during the first phase of recumbent folding. A summary diagram for the whole area (Figure 7a) shows the foliation typically dips northwest or southwest with the greatest concentration near N54E 30NW, but there are additional concentrations which reflect the varied attitudes of foliation in the Amherst block. In the northern half of the srudy area, the foliations tend to dip to the southwest, as shown by the N16W 25SW concentration and the general southwest scatter. At Mt. Warner, the smaller N50W 22NE a.



n=294

b.



n=139

Figure 7. Contoured lower hemisphere equal-area diagrams of:
a. Bedding and foliation measured in the Amherst area.
b. Mineral lineations.
Contours 1%, 3%, 5%, 7% per one percent area.

concentration reflects the influence of later stage folding on the normally westward-dipping attitudes.

Mineral lineation. The mineral lineations in the Amherst area (Plate 4) are formed by the long axes of sillimanite crystals, elongated clusters of biotite and muscovite flakes, and the long axes of quartz pebbles in the Clough Quartzite.

The contour diagram summarizing the mineral lineation attitudes in the Amherst block (Figure 7b) shows four dominant orientations. The greatest concentration, at N90W 20W, is due to lineations probably formed during the regional backfold stage and is seen in the northern half of the study area. The second highest concentration of lineations at N45W 30NW is formed by lineations of the same stage which have a different orientation near Mt. Warner. In addition, at Mt. Warner, a later lineation that probably formed during the regional dome stage is responsible for the concentration at N15E 20NE. The fourth grouping at S20W 0-10SW from outcrops in the northern part of the area was probably also formed during the regional dome stage.

Minor folds. Minor folds are fairly common in the Amherst block. They were mostly formed during the later stages of deformation. They are varied in size, deforming both foliation and lineation, with amplitudes ranging from centimeters to meters. The rotation senses of these folds were noted where discernable. The majority of the minor folds are believed to have resulted from deformation associated with the rise of the gneiss domes, and, in general, are coincident with a mineral lineation (Figure 8).

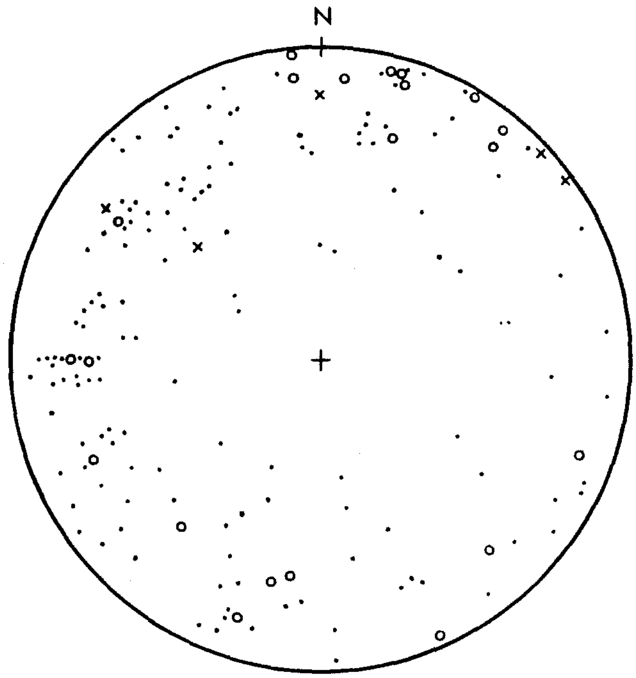


Figure 8. Equal-area lower hemisphere diagram of all 23 fold axes (o) and 139 mineral lineations measured in the Amherst area. Long axes of pebbles in Clough Quartzite indicated with an "x".

Boudinage. Boudins resulted from the plastic deformation of ductile schists about comparatively brittle beds or pegmatite layers. The necklines of the boudinaged layers tend to form normal to fold axes and indicate that the stretching of the paired rock types occurred in a direction parallel to the fold axes. Boudins were found in two outcrops and are plotted in Figure 10 (subareas 9 and 3) with necklines plunging gently to the west.

Pattern of Minor Structural Features

Figure 9 is a reduced-scale map of the Amherst block showing the nine subareas into which the linear and planar structural data has been

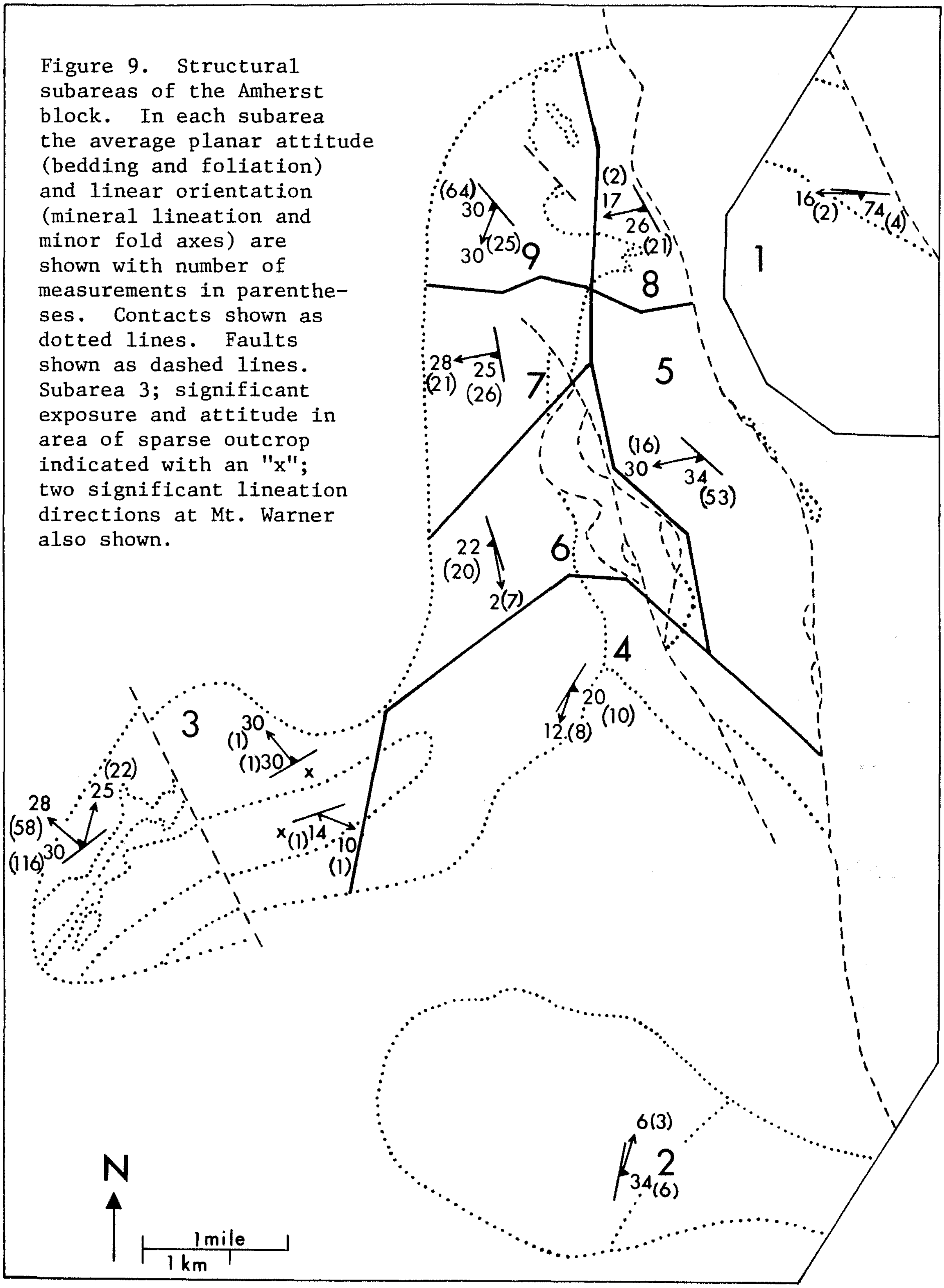


Figure 9. Structural subareas of the Amherst block. In each subarea the average planar attitude (bedding and foliation) and linear orientation (mineral lineation and minor fold axes) are shown with number of measurements in parentheses. Contacts shown as dotted lines. Faults shown as dashed lines. Subarea 3; significant exposure and attitude in area of sparse outcrop indicated with an "x"; two significant lineation directions at Mt. Warner also shown.

Figure 10. Equal-area lower hemisphere diagrams of planar and linear features for the subareas shown in Figure 9. Planar features appear on the left, linear features on the right.

planar

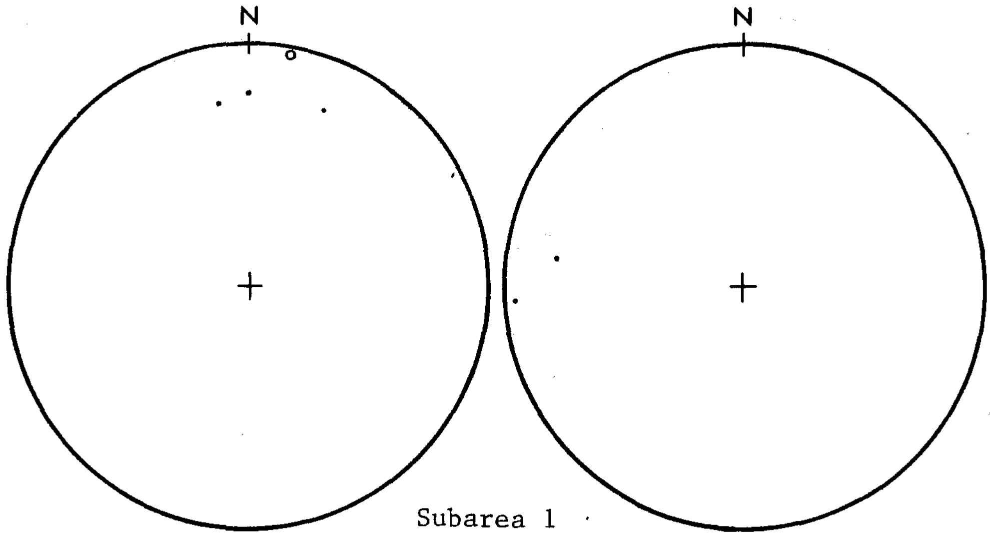
- • poles to foliation
- o poles to bedding

linear

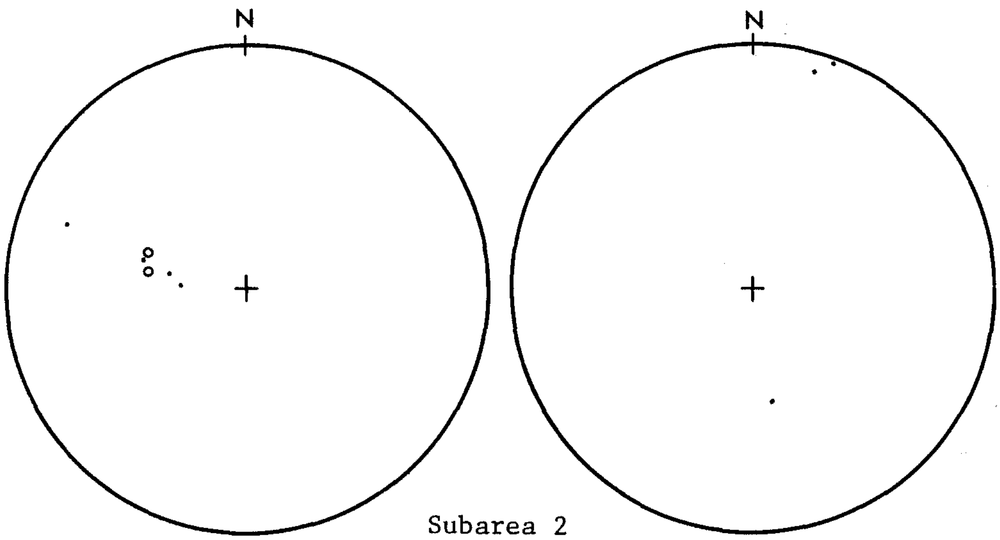
- • mineral lineations
- o minor fold axes
- ● boudin neck lines
- × long axes of deformed quartz pebbles

Number of Measurements:

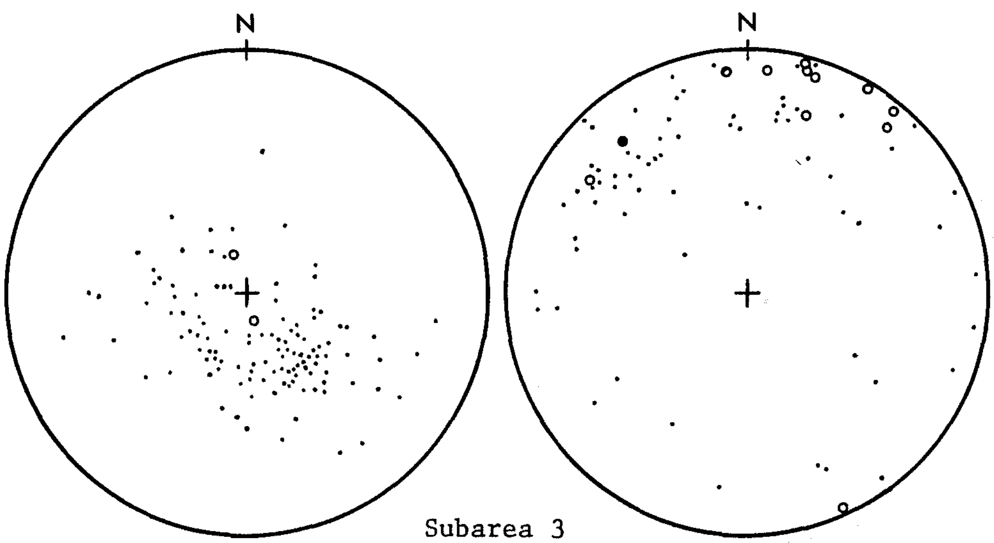
SUBAREA	bedding	foliation	mineral lineation	minor fold axes	boudin neck lines	elongate pebbles
1	1	3	2			
2	2	4	3			
3	2	114	68	11	1	
4	1	9	8			
5		53	15	1		
6		20	4	3		
7		26	18	3		
8		21	1	1		
9		64	21	4	1	5



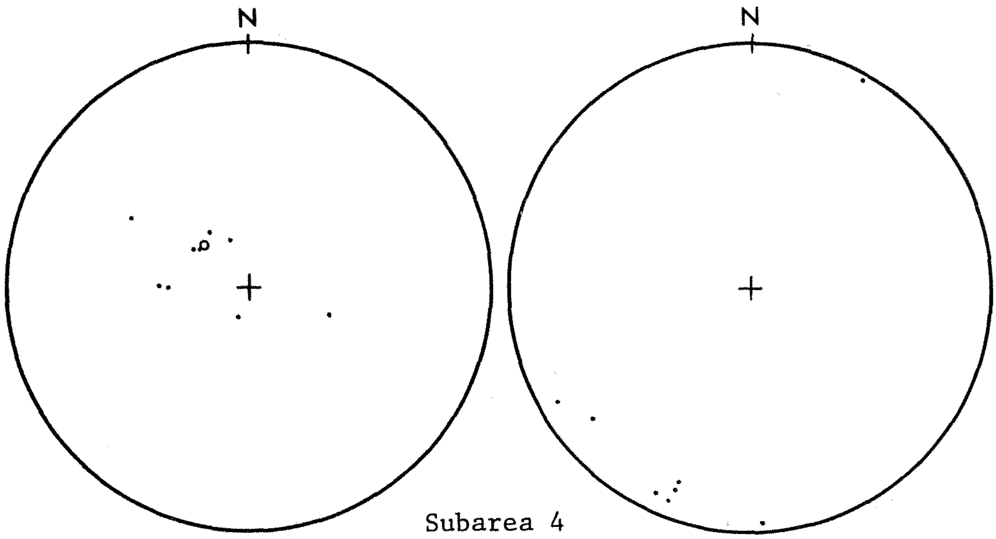
Subarea 1



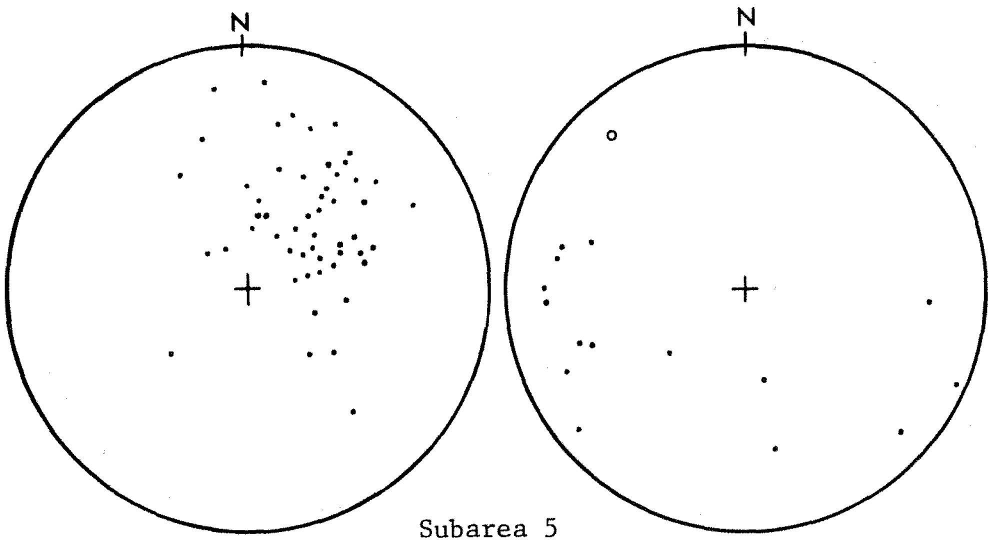
Subarea 2



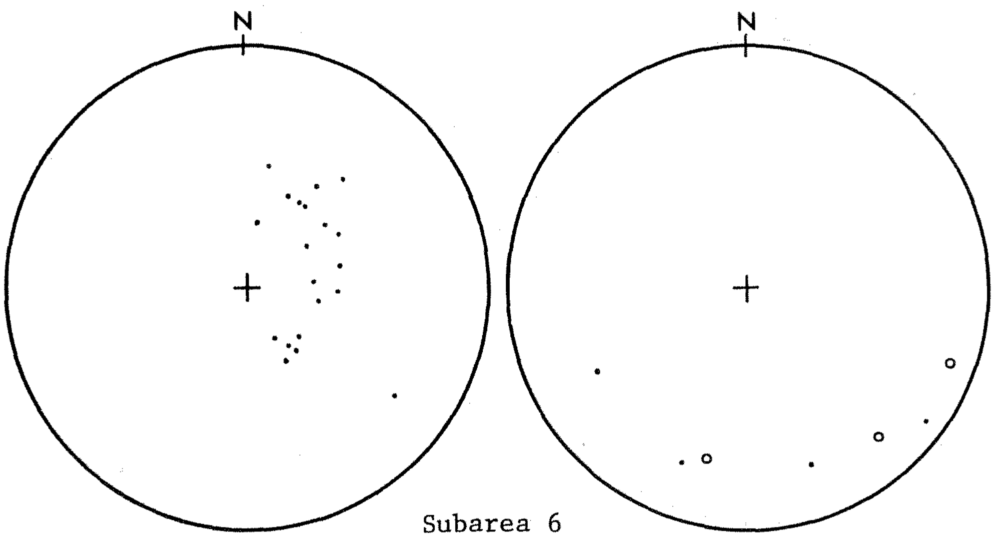
Subarea 3



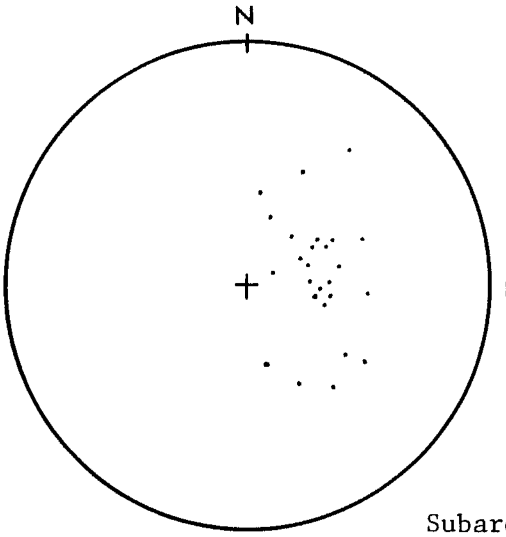
Subarea 4

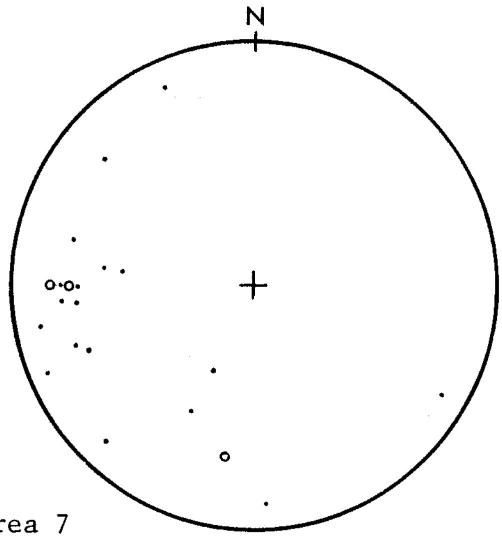


Subarea 5

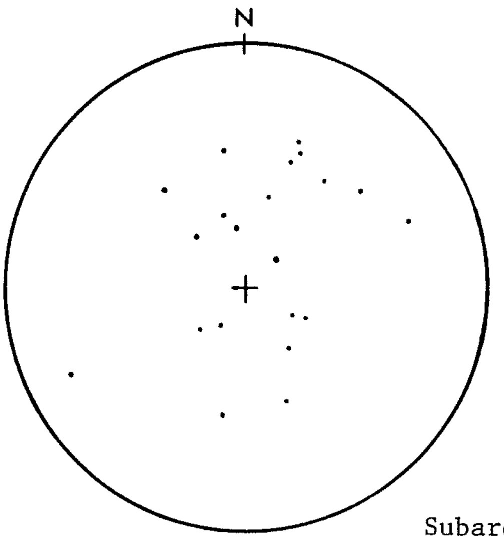


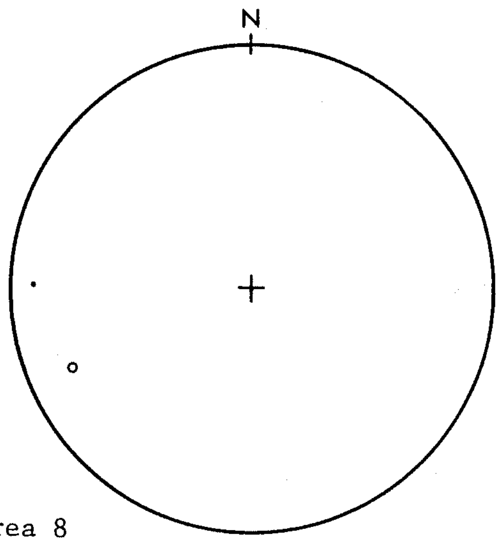
Subarea 6



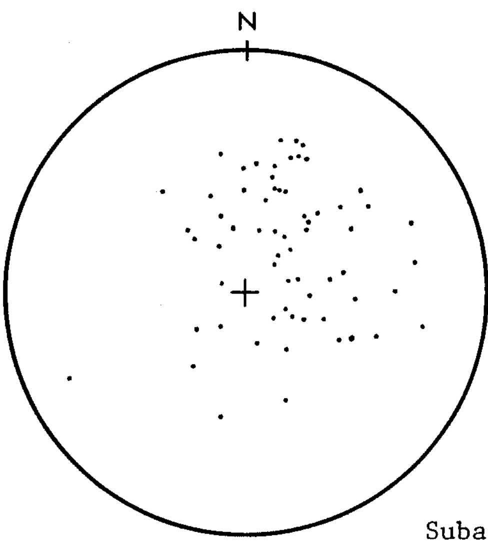


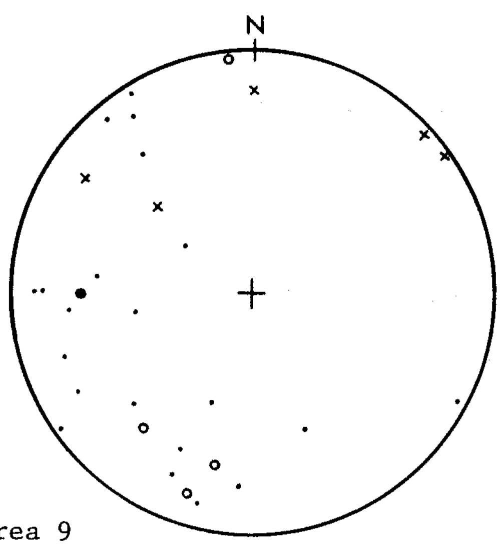
Subarea 7





Subarea 8





Subarea 9

organized. Poles to planar and linear features in each subarea were plotted on lower hemisphere equal-area diagrams and are given in Figure 10. Within each subarea a visual estimate has been made of the mean attitude of the dominant foliation and lineation. Note that in subarea 3 there are strong concentrations of linear features centered approximately sixty degrees apart. Here visual estimates were made to reflect the mean position of each grouping.

The most intriguing feature of these plots in the Amherst area is their notable lack of homogeneity. In comparing the planar plots, this appears to be due in the first place to a general warping of planes from a southeasterly dip at South Amherst, to a northwesterly dip in the vicinity of Mt. Warner, and from there, a change to a southwesterly dip in the northern half of the study area. Second, further complications in the planar pattern at Mt. Warner are due to open folding. A comparison of the plots of mineral lineation attitudes from south to north reveals in the first place a warping of lineations from a predominantly southwesterly plunge in South Amherst and Amherst, to a dominant northwesterly plunge at Mt. Warner, changing again to a west-southwesterly plunge in the northern half of the study area. Second, at Mt. Warner, the lineations form a broad girdle due to the superposition of two generations of lineations, those of an early northwest plunging set and a later northeast plunging set. Third, in most domains there is considerable variability of plunge that ranges through horizontal. Finally, in some areas, linear features have been reoriented by later open folding.

Features of Early Recumbent Folding

The most striking feature of the map pattern of the Amherst area is the repetition of the Littleton and Partridge Formations. This repetition is believed to be due to major early Acadian nappes rooted many kilometers to the east.

In the Mt. Warner area two nappe-stage anticlinal folds cored by the Partridge Formation and two nappe-stage synclinal folds cored by the Littleton Formation have been identified. On the north end of Mt. Warner, this structural sequence has been down-faulted so that only the upper belt of Partridge is now exposed. Apparently the same belt of Partridge is exposed in the vicinity of North Amherst.

As presently understood, the nappe phase of deformation involved westward transport of nappes whose roots lie to the east of the Bronson Hill anticlinorium in the highly attenuated, north-south trending, isoclinal anticlines and synclines of the western part of the Ware area (Thompson et al., 1968; Field, 1975). If the source of the nappes of the Amherst block has been correctly identified, this suggests that the amplitude of the nappes under investigation approaches thirty kilometers. No nappe-stage fold hinges have been found in the Amherst-Mt. Warner area due to the large amplitude of these folds and the poor outcrop in the area.

Detailed mapping in New Hampshire and northernmost Massachusetts has established a regional continuity to the nappe-complex of which the Amherst nappes are a part. North of the Mesozoic basin, an inverted sequence of Paleozoic rocks extends from the Bernardston area northward into the Bellows Falls-Brattleboro areas of New Hampshire and Vermont (Trask, 1964; Thompson et al., 1968), where repetitions of Paleozoic rocks are exposed in two axial depressions along the west flank of the Bronson Hill anticlinorium. A re-interpretetion of the three-dimensional structure of the nappe-complex in this area, undertaken by Thompson and Rosenfeld (1979), has led to the proposal that four structural levels of nappes exist within the complex. In ascending order, they are: the Cornish, Bernardston, Skitchewaug, and Fall Mountain nappes. Evidence of the Cornish nappe exists only north of Bellows Falls, Vermont. In Massachusetts, the lowest of the three members of the nappe complex is the Bernardston nappe which extends southward into the Bernardston-Leyden area where it is unconformably overlain by the Mesozoic rocks of the Deerfield basin (Williams, 1979).

A correlation between high metamorphic grade and tectonic level in the nappe sequence has long been recognized (Thompson and Norton, 1968; Thompson et al., 1968). The positioning of hotter rocks over cooler ones (see metamorphic section) appears to be related to the emplacement of progressively hotter nappes derived from a heated source area to the east. The rocks comprising the Bernardston nappe are largely staurolite grade. Further to the east and north, the nappes above the Bernardston nappe are locally in the sillimanite zone or even in the sillimanite-K-Feldspar zone as at Fall Mountain or above the Ashuelot Pluton southwest of Keene, New Hampshire. The rocks of the Amherst block, being of sillimanite or sillimanite-K-feldspar grade as well, are therefore interpreted to be directly related to the higher nappes to the north and to the sillimanite-K-feldspar grade rocks in the proposed root zone of the Ware area.

Correlating the sequence of nappes in the Amherst block with the recognized sequence refined by Thompson and Rosenfeld, and bearing in mind the further constraints that the metamorphic grade imposes, leads to the conclusion that the Amherst block contains parts of two sillimanite-bearing nappes above the Bernardston nappe. There is presently some question concerning the nomenclature for these nappes, but it seems probable that they belong either to the Skitchewaug and Fall Mountain nappes, or to the Fall Mountain nappe and a still higher nappe.

The formation of the regional foliation is here attributed to the nappe stage of deformation, and the foliation is believed to have formed parallel to axial planes of the nappes.

Features of Regional Backfolding

Based on the map pattern in central Massachusetts Thompson et al. (1968), Field (1975), Tucker (1977), and Robinson (1979) all proposed an episode of eastward backfolding of the previously formed nappe axial surfaces. No major structural evidence for this stage of deformation could be found in the Amherst area, but minor structural features may have formed during this stage.

This deformation was accompanied by the development of a penetrative west- and northwest-trending mineral lineation that is broadly evident over much of central Massachusetts (Tucker, 1977; Robinson, 1979; Robinson et al., 1982). In the Amherst block, the strong concentration of east-west oriented lineations in the northern half of the study area is believed to have formed during this stage, but these lineations are difficult to differentiate from later dome stage lineations, some of which seem to have been rotated to a west-southwest plunge due to still later folding. One particularly clear example on Mt. Warner (Figure 11a) is from an outcrop located 0.35 km southwest from the bend of Mt. Warner Road where it crosses the saddle on Mt. Warner. The view is looking up at this dome stage fold which plunges northeast away from the viewer. The vertical plane to the left of the drawing consists of schist and displays satellitic folds in the hinge area of the fold. The folded surface of the outcrop is formed by a competent granitic layer which displays two generations of lineations. The lower hemisphere equal-area diagram (Figure 11b) shows that the NW-SE trending backfold stage lineations (x) have been folded about a great circle arc nearly perpendicular to the fold axis. The axis of this fold (o) is shown by the intersection of these planes upon which the backfold stage lineations were measured. Associated with this northeast-trending dome stage fold is a northeast-trending dome stage lineation (.). In spite of the fact that few outcrops exist which show unequivocal geometrical relationships between two generations of lineations, a summary diagram (Figure 12) of mineral lineations measured at Mt. Warner shows that two maxima exist at approximately 60 degrees to each other.

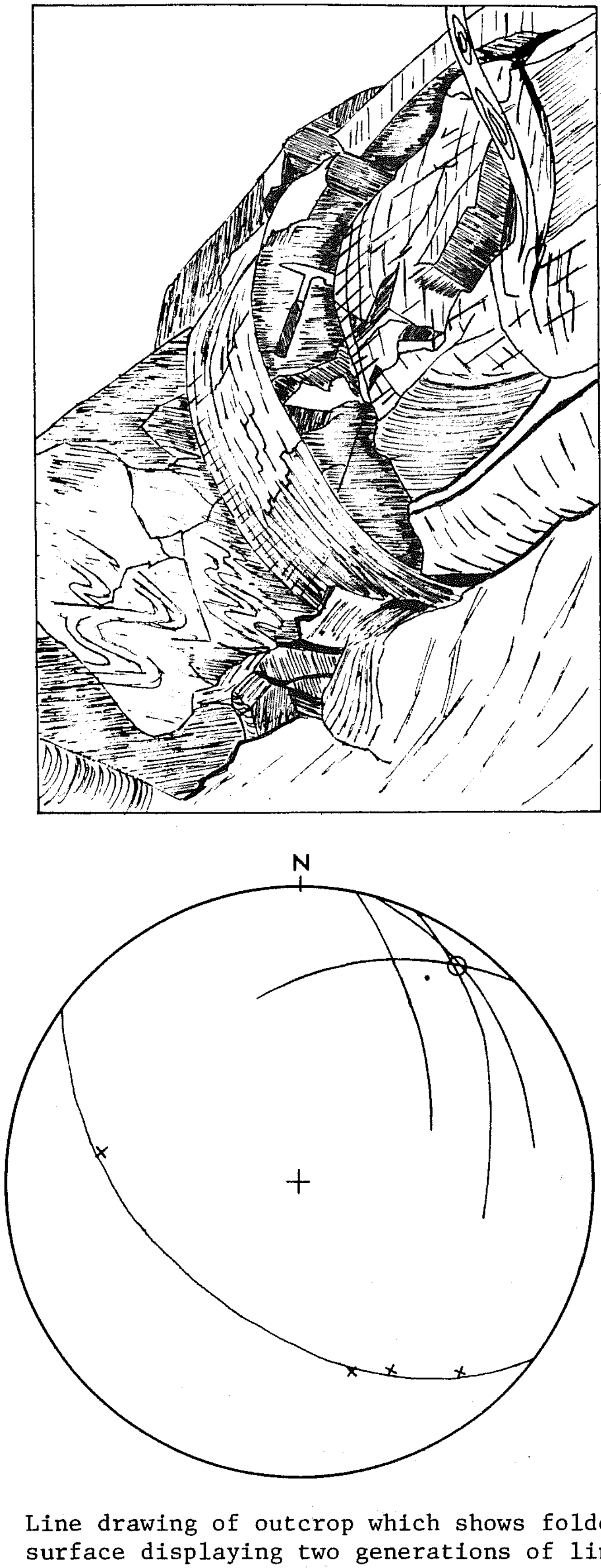


Figure 11. a. Line drawing of outcrop which shows folded surface displaying two generations of lineations.
b. Lower hemisphere equal-area diagram of the folded backfold stage lineations (x) about the dome stage fold (o) with its associated lineations (.).

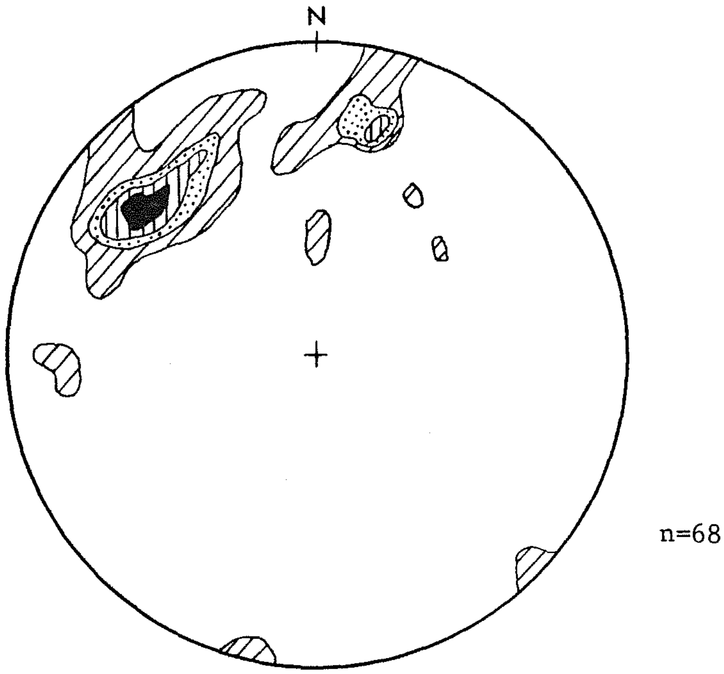


Figure 12. Equal-area lower hemisphere diagram of mineral lineations measured on Mt. Warner. Contours at 3%, 5%, 7%, 9% per one percent area.

Features Related to the Gneiss Dome Stage

The widespread development of minor structural features on the Amherst block is tentatively related to gneiss dome formation in the Bronson Hill anticlinorium. The large majority of minor folds on the Amherst block is attributed to this stage of deformation. They are most commonly found in stratified rocks at outcrop scale. These minor folds (Figure 13) generally trend northeast-southwest, plunging gently to the northeast in the vicinity of Mt. Warner, and gently to the southwest in the northern half of the study area. The scatter of these minor folds is partly attributed to the disruption caused by the later stage faulting in the North Amherst area, but a few of

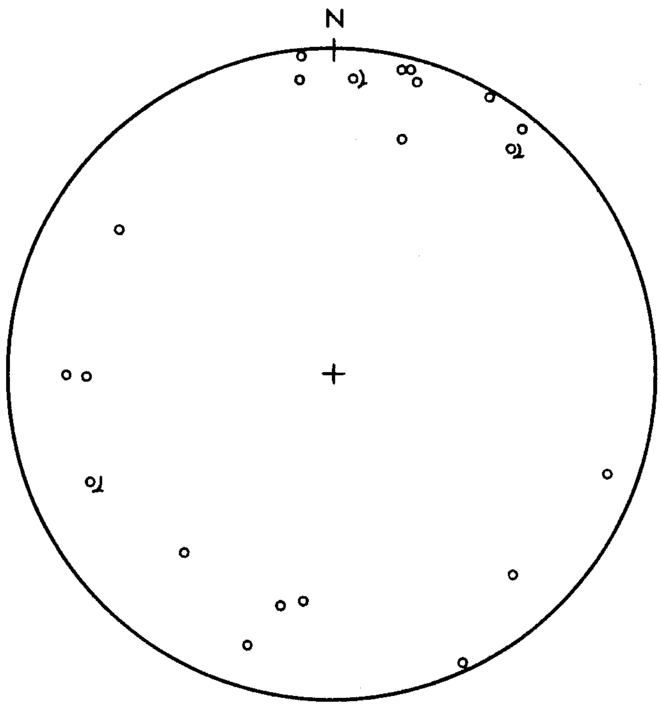


Figure 13. Equal-area lower hemisphere diagram of minor fold axes measured in the Amherst area showing rotation sense where discernable. Most are interpreted as belonging to the dome stage.

the folds may have formed during the earlier phases of deformation. Where discernable in outcrop, the minor folds display a clockwise rotation sense looking down the plunge of the fold.

Minor folds associated with this phase of deformation also affect the map pattern which can be clearly seen on the west side of Mt. Warner. Figure 14a shows a map of Mt. Warner with the axial surfaces of three stages of folds, the first being axial surfaces of nappe stage recumbent isoclinal folds. These have then been modified by dome stage recumbent folds which are north- to northeast-trending, gently plunging folds of which the minor fold in Figure 11 is the best example. The two folds of this stage which were measured in individual outcrops show an average axis direction of a.

b.

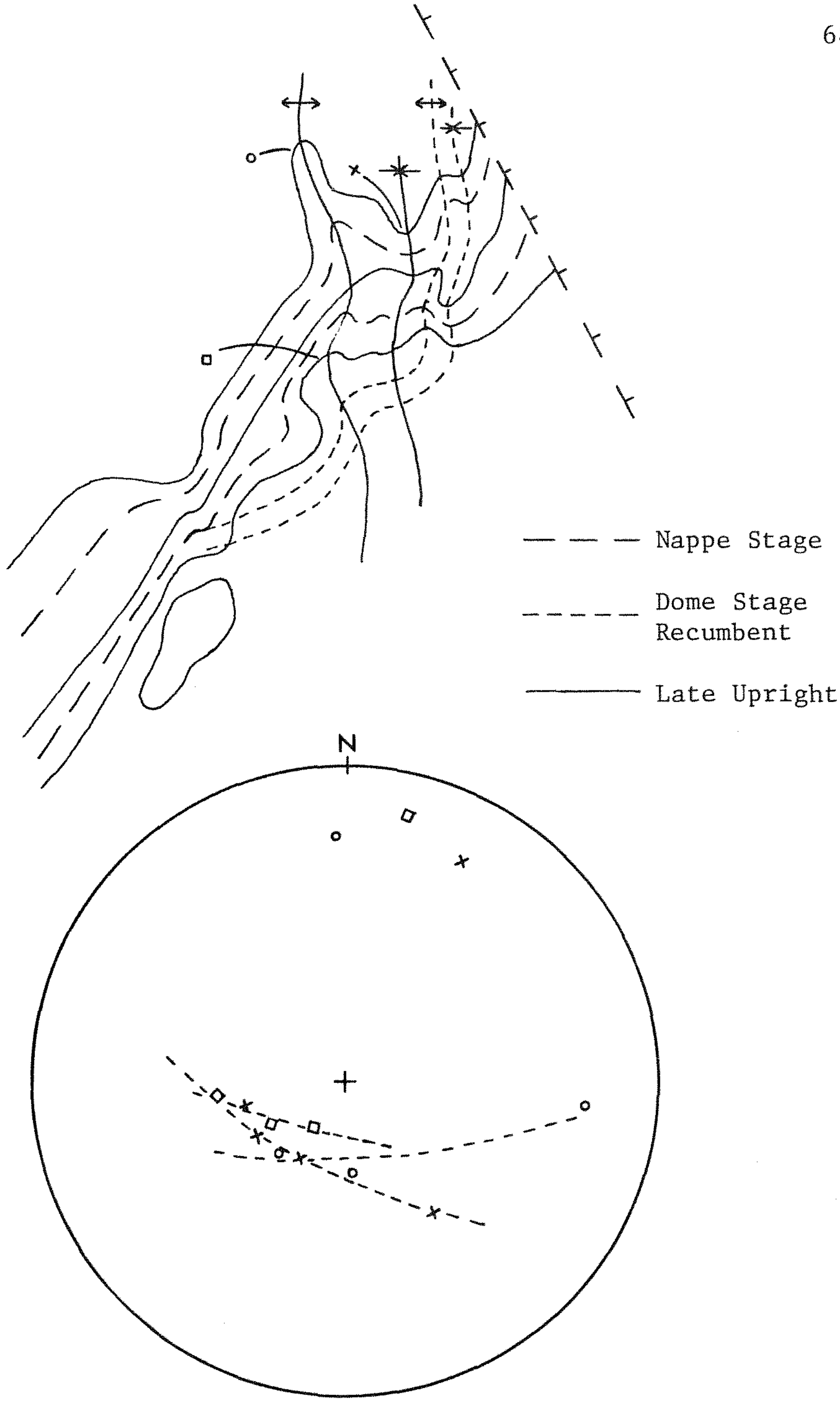


Figure 14. a. Map view of the northwest flank of Mt. Warner showing three generations of axial surfaces.
b. Equal-area lower hemisphere diagram of foliation planes on selected minor folds; poles of these arcs in turn represent axes of late upright folds in the vicinity of the symbols on the map.

N19E 13NE. The third set of folds influencing the map pattern of Mt. Warner is classified as belonging to the next stage of deformation, the late open folding stage.

Mineral lineations defined by the long axes of former sillimanite or mica aggregates are attributable to the dome stage deformation. These lineations are parallel to the northeast-trending minor folds and have been similarly rotated so that those in the northern half of the study area plunge southwest and those in the Mt. Warner area plunge northeast.

Late Open Folding

One example of the structural features classified as late open folds is the third set of folds on Mt. Warner (Figure 14 a and b). These have deformed the previous nappe and dome stage recumbent folds at Mt. Warner and are shown in Figure 14a as late upright folds. Poles to selected foliation planes on these later folds have been plotted in Figure 14b. The poles lie on great circles whose poles in turn represent the fold axes. In general, the late upright folds plunge gently to the north-northeast with an average attitude of N14E 20NE.

The major fold attributable to this phase of deformation on the Amherst block is the Mt. Warner anticline. To determine the trend of the axis of this fold, a mean value was determined for each limb of the anticline in the area of the southern extremity of Mt. Warner and was plotted on an equal-area diagram (Figure 15). The intersection of the planes representing the mean values from the

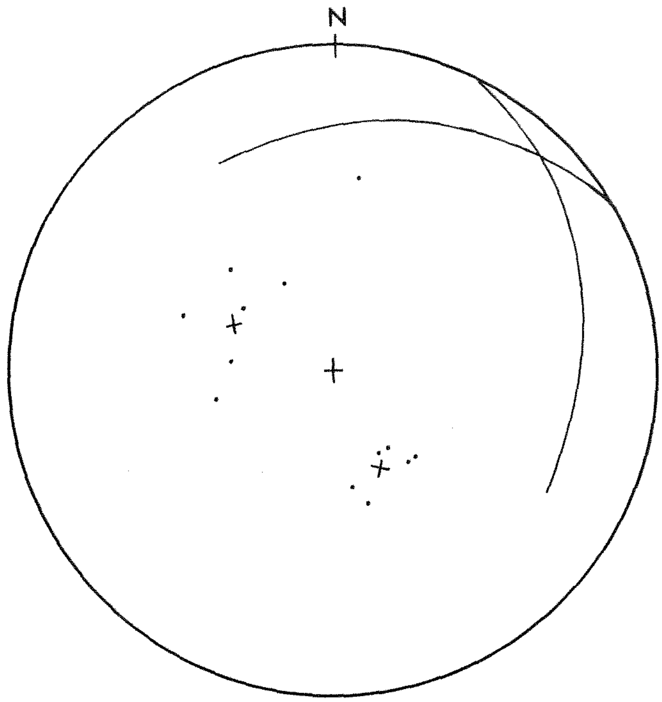


Figure 15. Equal-area lower hemisphere diagram of poles to foliation planes showing average trend and plunge of Mt. Warner anticline. Selected mean values indicated with an "x".

fold limbs show that the attitude of the axis of the Mt. Warner anticline is N44E 10NE. Late open folding also resulted in the rotation of previously formed linear and planar features and is responsible for the warping of attitudes which occurs between the Mt. Warner area and the northern portion of the study area.

Post-Metamorphic Brittle Fractures

Mesozoic structural development involved the growth of the Connecticut Valley border fault and the Connecticut Valley Mesozoic basins (Williams, 1979; Chandler, 1978; Goldstein, 1976; Wise, 1975). This development was primarily responsible for the present distribution and exposure of the pre-Mesozoic rocks on the Amherst block.

Connecticut Valley border fault. The border fault of the Connecticut Valley forms the eastern boundary of the Amherst block. The fault is of Mesozoic age with the initial rifting beginning in the Late Triassic in response to the stresses associated with the initial opening of the present Atlantic Ocean (May, 1971). This continued with the greater amount of displacement and consequent sedimentation in the Jurassic (Hubert et al., 1978).

Estimates of the displacement on the border fault are derived from estimates of the thicknesses of stratigraphic sequences in the Mesozoic basin, displacement of metamorphic isograds, and structural reconstructions based on the displacement of stratigraphic units and plutons in central Massachusetts and adjacent New Hampshire (Robinson, 1966, 1979; Ahmad, 1975). Estimates at the northern border of Massachusetts indicate a west-side-down vertical slip displacement of 5 km. Estimates at the latitude of Springfield, Massachusetts, suggest a vertical displacement of 8 to as much as 12 km.

Surface exposures of the border fault are rare, and the fault's position is commonly inferred from disruptions in the metamorphic grade and structure, change in topography, and locations of silicified zones or localized copper, galena or barite mineralization (Chandler, 1978; Wheeler, 1937). The generally held view is that the border fault is a west-dipping normal fault (Emerson, 1898; Wheeler, 1937, 1939; Willard, 1951; Sanders, 1962; Robinson, 1967a). In the Amherst area, the attitude of the fault plane is partly controlled by the orientation and geometry of the pre-Mesozoic basement anisotrophy (Chandler, 1978). The border fault apparently flattens with depth (i.e. is listric) and marks a gradual transition with depth from brittle to ductile behavior in the crust. To the north of the Amherst block Ashenden's (1973) measurements of multiple fault orientations in the bed of the Connecticut River near French King Bridge suggest the border fault there dips 40 degrees northwest. Similarly, data from diamond drilling east of Mt. Toby in connection with the proposed Montague Nuclear Power Station has yielded an estimated dip of 40 degrees (Northeast Utilities, 1974; Robinson, 1979).

Field work in the Amherst block has more accurately located the trace of the border fault and has shed further light on the fault orientation and mechanics. Detailed mapping on the west flank of Poverty Mountain east of the border fault at the east edge of the map area has revealed a large silicified zone believed to lie parallel to and slightly below the fault plane at that locality. Orientations of cataclastic and mylonitic surfaces from this area were plotted on the lower hemisphere of an equal-area net (Figure 16), and the visual mean of the poles suggests a fault plane orientation of N10W 44SW. In addition, the fault trace has been accurately located on Mt. Boreas due to the direct juxtaposition of downfaulted Littleton Formation against Fourmile Gneiss (Plate 1).

<u>North Amherst faults</u>. Exposures of the Fourmile Gneiss and associated sills related to the Belchertown Complex have been the key to the recognition of the border fault in the Cushman area of North Amherst. Here faulted footwall rock has been brought up to

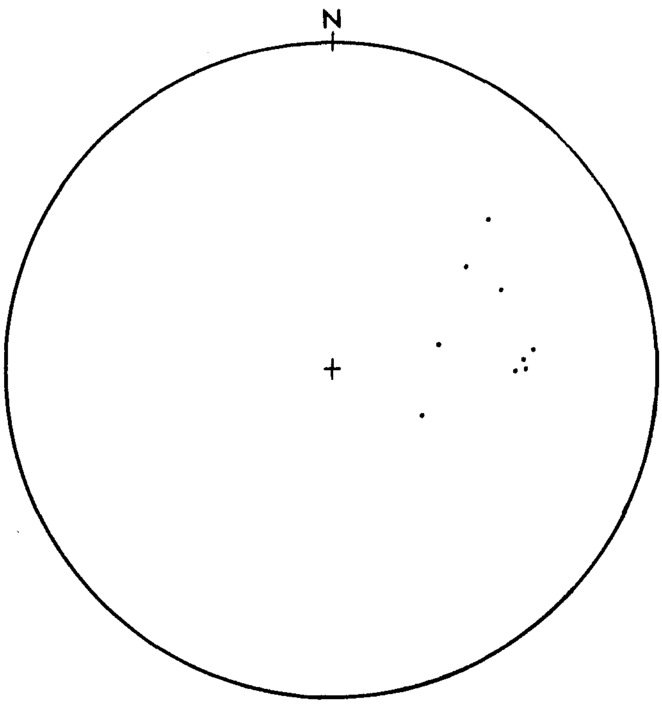


Figure 16. Equal-area lower hemisphere diagram of poles to cataclastic and mylonitic surfaces on Mt. Poverty.

positions where it is exposed west of the main fault trace by antithetic faults that cut across the master fault (Cross-section A-A', Plate 2). Figure 17 shows the faults of the Cushman area and Figure 18 shows the motion history of these faults, which developed in three stages. In the first stage, vertical displacement commenced in the Mesozoic with the initial dislocation and movement along the main border fault (Figure 18a, b). In the second stage, a temporary locking of the border fault sheared a horse from the lower nappe of Ops (Figure 18c). In the third stage east dipping high angle normal faults cut across the older faults (Figure 18d) and erosion produced the present outcrop pattern. Figure 18d shows that the Factory Hollow fault trace is a repetition of the fault that created

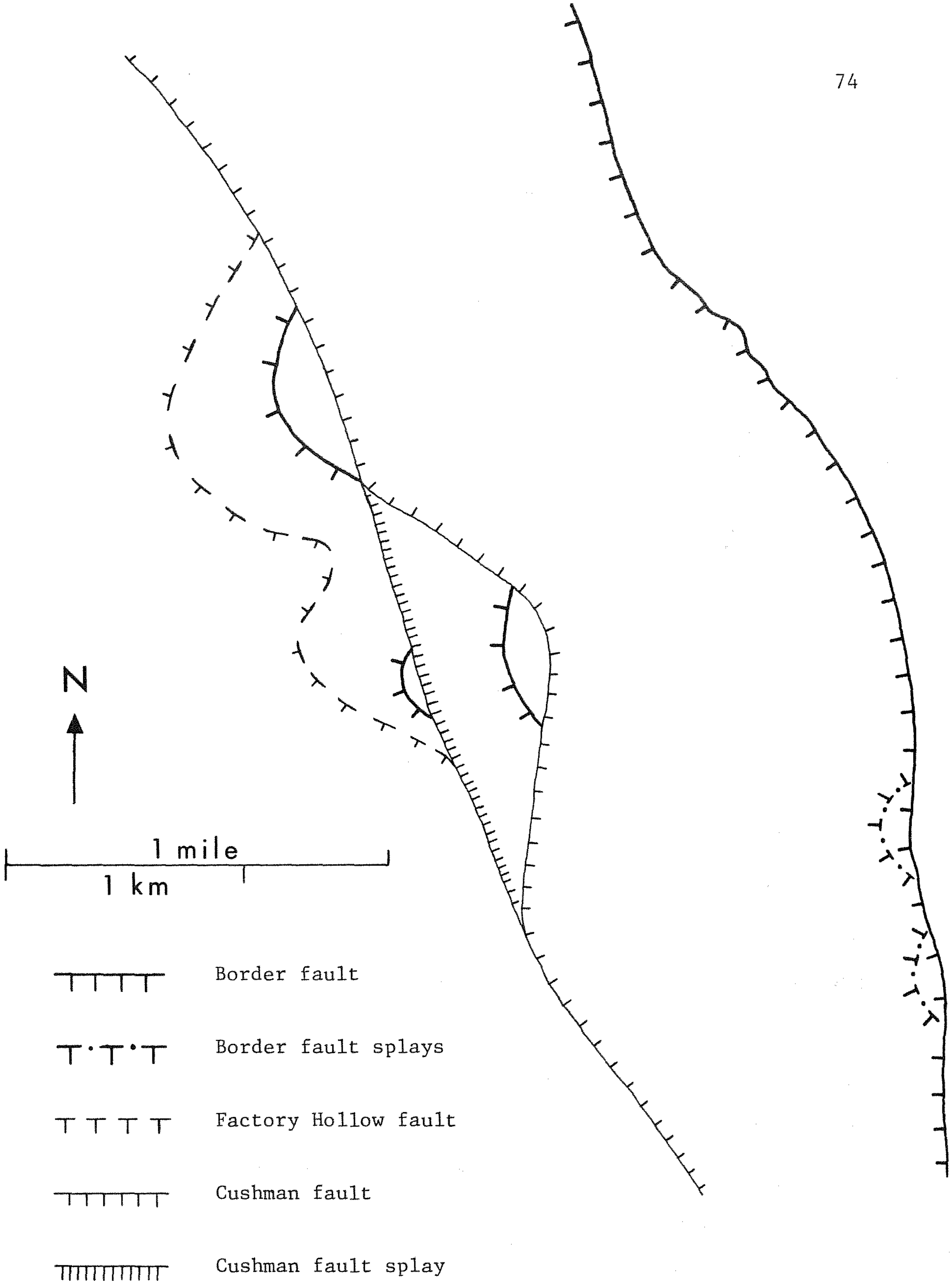


Figure 17. Map showing names and details of normal fault traces near Cushman. Hachures on downthrown side of faults.

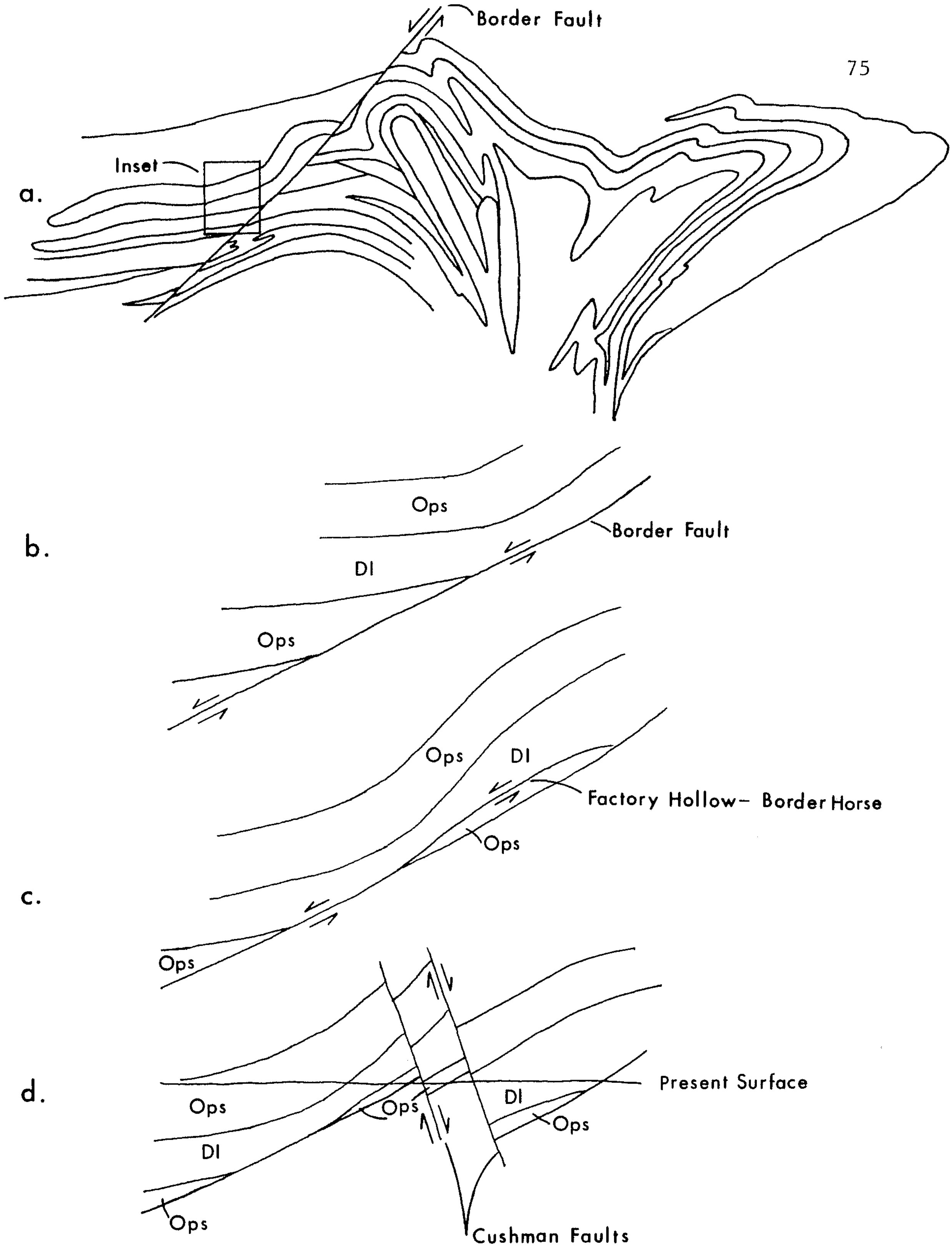


Figure 18. Sequential cross-sections (a-d) showing movement history of the Factory Hollow-Cushman faults.

the border horses. The Cushman fault is the major plane upon which the offset of the border fault occurred, but this splays into two parts in the southern part of the North Amherst area so that the border fault is repeated twice, with two windows of Fourmile Gneiss. Based on cross-section A-A' (Plate 2) the net slip on the Cushman fault is estimated to be 1 km.

Joints. To better understand the fracture history of the Amherst block, joints were plotted and contoured on the lower hemisphere of an equal-area net (Figure 19). It is apparent that several closely aligned trends are recorded in the rocks of the Amherst block. The largest concentrations of joints are steeply dipping to vertical and are oriented at N60E and N78W. Secondary concentrations are at N32E and N54W. Due to the scattered nature and small number of measurements, consolidation of these groupings would reveal a joint set which is broadly oriented at N45E-N65W. A pairing of similar orientations has also been reported by Onasch (1973), Laird (1974), and Goldstein (1976), all working to the north of the study area in the Paleozoic rocks located on the west limb of the Pelham dome. Additionally, Goldstein reports that the Paleozoic basement located to the west of the valley contains similar joint sets at N65E and N75W, and that these directions are generally adhered to as well in the Mesozoic rocks of the Deerfield basin. A similar orientation of joint sets is also reported by Chandler in the Amherst block.

This widespread distribution of similarly aligned joint sets must have formed in response to the stress field active during the early phases of basin formation. In New England, extensional

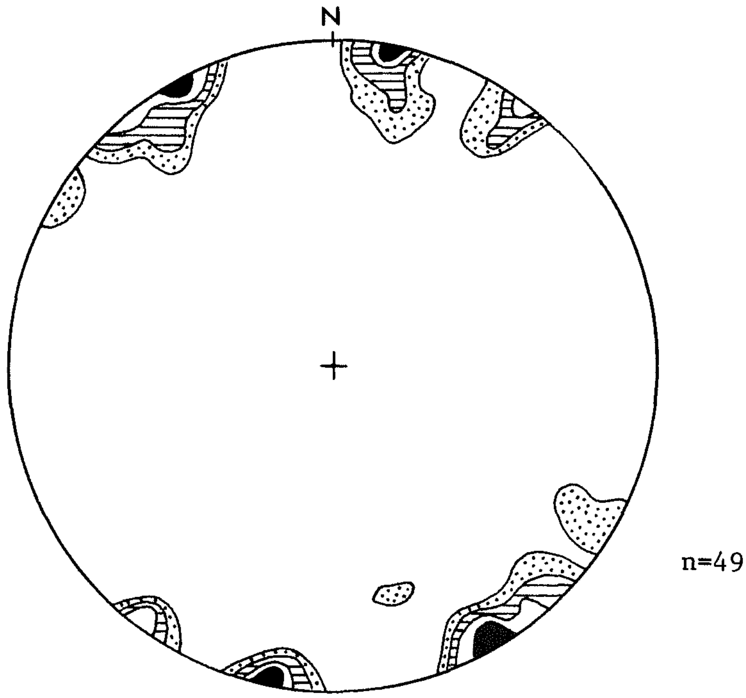


Figure 19. Equal-area lower hemisphere diagram of poles to joints. Contouring is on 4%, 6%, 8%, 10% per one percent area.

structures have been measured with a N30E trend (Wise, 1975), and the widespread distribution of basaltic dikes (May, 1971) with a N30E trend suggest a regional σ_3 orientation of N60W during at least the early part of the Mesozoic. The development of the N60E fracture set in the Amherst block supports the idea that the joint patterns were not directly influenced by this regional stress field, but joint data gathered by the author does agree with the data gathered by other authors.

Subsidiary faults. The locations of subsidiary faults at map scale (Plate 1), were determined by juxtaposition of stratigraphic units, and/or presence of silicification and mylonites. The subsidiary faults at outcrop scale are widely distributed on

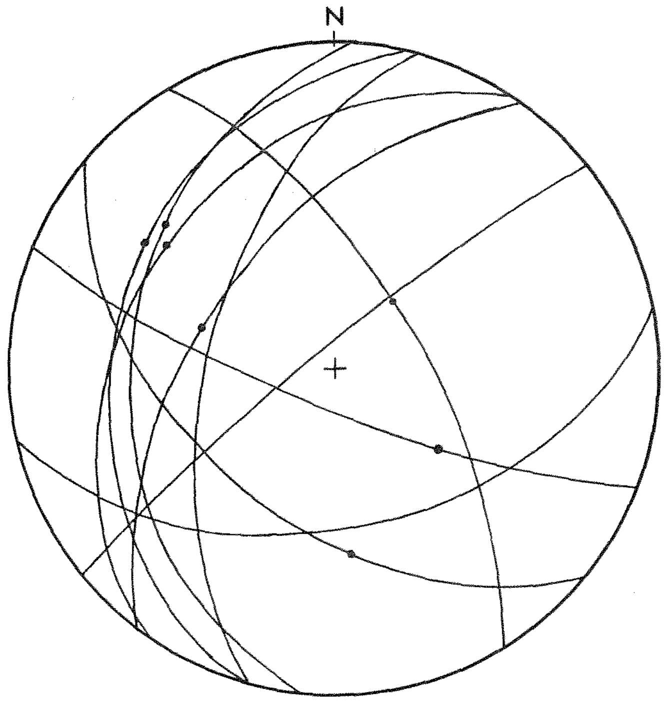


Figure 20. Equal-area lower hemisphere diagram of faults in the Amherst area. Faults shown as planes with slickensides shown on them.

the Amherst block. Five faults from the Mt. Warner area were located, three faults from the Factory Hollow-Mill River area, and two faults from the vicinity of Depot Road in the northern part of the study area. On an equal-area net (Figure 20) these faults show a wide range of orientations, but have a dominant grouping at N22E 45NW. Slickensides show a dip-slip motion with the dominant grouping to the northwest. Two northwest-striking faults show southeast-plunging slickensides indicating oblique slip. The predominantly dip-slip faulting found on the Amherst block yields slickensides which indicate a northwest extension direction of approximately N68W that substantiates the directions derived from fault data by other authors.

METAMORPHISM

The rocks of the Amherst block are dominated by sulfide- and graphite-rich mica schists that show evidence of the beginnings of partial melting. They have been extensively intruded by granodiorites and pegmatites, mainly late in the sequence of regional metamorphism. Sillimanite, commonly appearing as white bundles of needles aligned in the planar fabric of the schists, is widely evident in the outcrops on the Amherst block, but in all examples studied in thin section, the sillimanite had been replaced by white micas. Sillimanite occurs at Mt. Warner in outcrops of Partridge and Littleton schists along Mt. Warner Road. In the central part of the study area, sillimanite occurs in outcrops of Littleton schist at Factory Hollow Pond and along Mill River. It also occurs in Partridge exposures along Route 63 north of North Amherst. In the northern part of the study area, sillimanite occurs in both Littleton and Partridge units in the vicinity of Long Plain along Depot Road.

Examination of thin sections from samples gathered on the Amherst block indicates that sillimanite occurs with muscovite, with K-feldspar, or with both. Such assemblages are characteristic of Zone IV, the sillimanite-muscovite-K-feldspar zone as described in detail by Tracy (1975, 1978) in the Quabbin Reservoir area to the east (Figure 21). Zone IV is transitional from Zone III characterized by sillimanite-muscovite assemblages to Zone V characterized by sillimanite-K-feldspar assemblages completely free of muscovite.

Mineral Assemblages

Pelitic schists. The mineral assemblages found in the pelitic rocks across the Amherst area are listed in Table 9. The locations of critical assemblages are shown in Figure 22. In the majority of schists examined, three main assemblages were recognized; they are quartz-plagioclase-biotite-garnet-sillimanite-muscovite, quartz-plagioclase-biotite-garnet-sillimanite-muscovite-orthoclase, and quartz-plagioclase-biotite-garnet-sillimanite-orthoclase.

The schists appear to have reached a state of textural equilibrium and, within small areas, all phases have been observed to be in contact with each other. Variation in the composition of plagioclase grains was noted, although zoning is sporadic and of small magnitude. Sillimanite occurs in its fibrolitic habit. This fibrolite is intergrown with quartz and it has since been altered to a fine-grained intergrowth of muscovite and quartz. Fibrolite is characteristic of Zones II, III, and, in part, Zone IV, in central Massachusetts (Tracy, 1975).

All the samples examined show evidence of weathering and retrograde metamorphism. In some samples these effects are so extensive that identification of the original mineralogy was difficult. In thin section even the freshest appearing sillimanite was found to have been replaced by secondary white mica. Modal estimates of sillimanite content were based on the abundances of secondary products. Differentiation between plagioclase and orthoclase was complicated by the similarity of relief, extent of sericitization, and lack of twinning. The discrimination between primary and

Metamorphic Zones

- VI — Garnet-cordierite-sillimanite-K-feldspar
- V — Sillimanite-K-feldspar
- IV — Sillimanite-muscovite-K-feldspar
- III — Sillimanite-muscovite
- II — Sillimanite-staurolite
- I_k — Kyanite-staurolite
- I_A — Andalusite-staurolite
- G — Garnet
- B — Biotite
- C — Chlorite

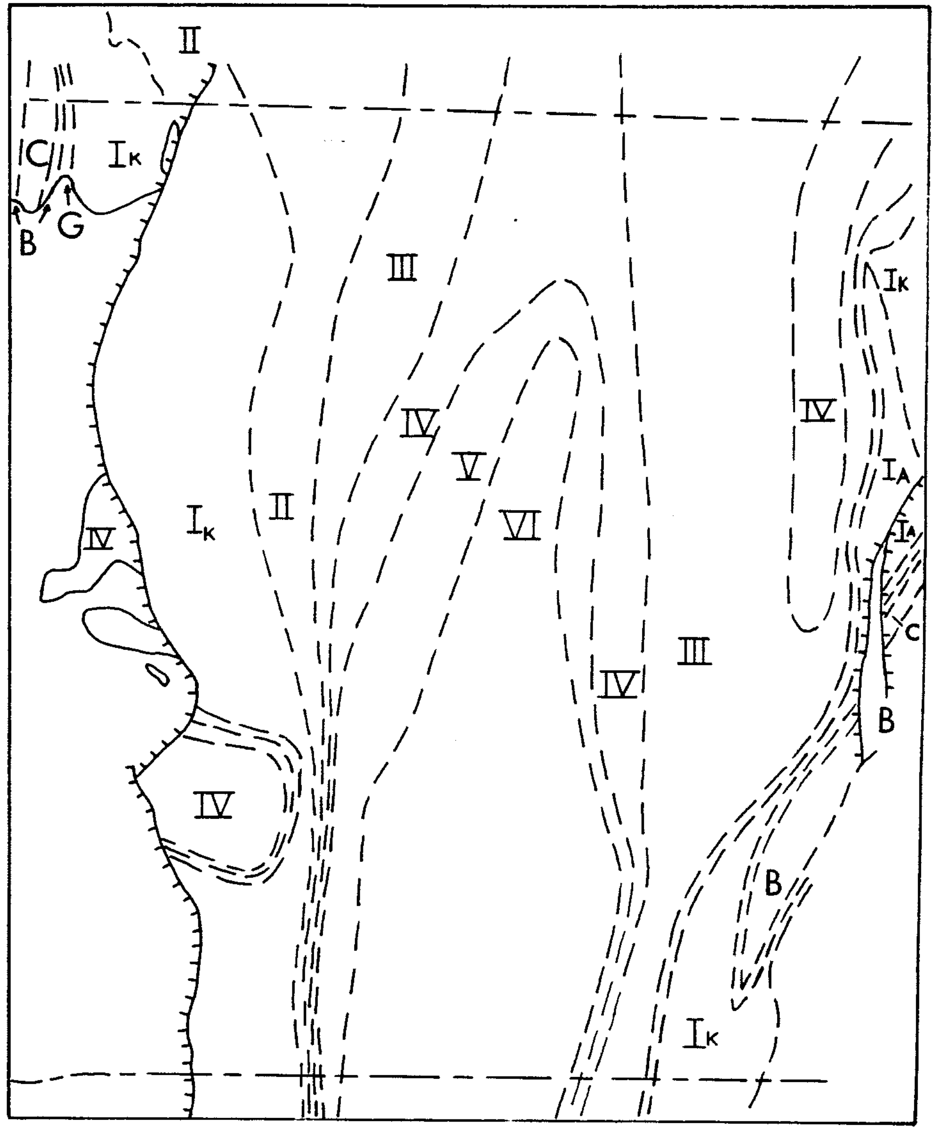


Figure 21. Metamorphic map of central Massachusetts (Robinson et al., 1982).

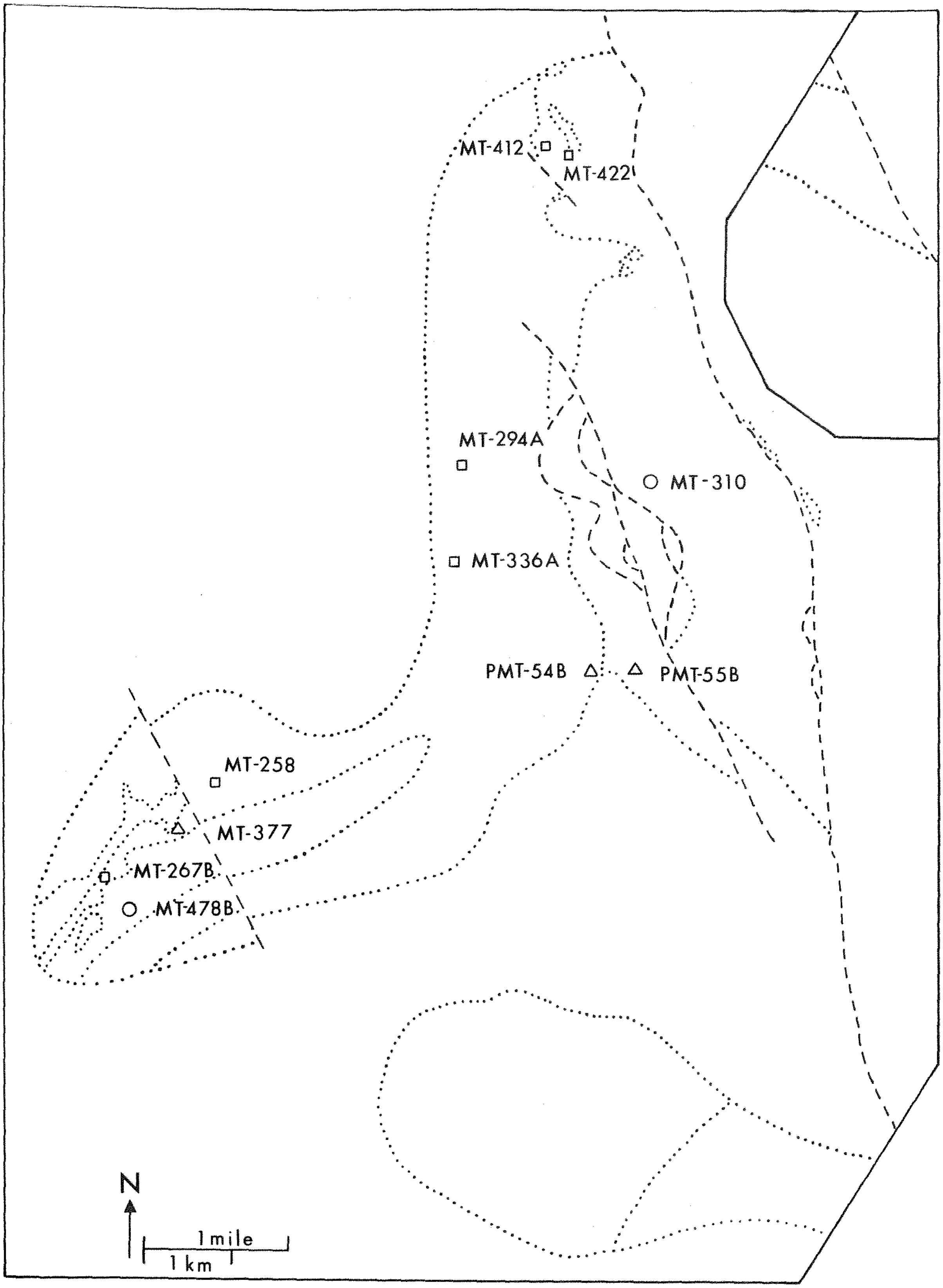


Figure 22. Location map of critical metamorphic assemblages. Symbols as follows:
□ sillimanite-muscovite,
△ sillimanite-muscovite-K-feldspar,
○ sillimanite-K-feldspar.

Table 9. List of mineral assemblages found in pelitic rocks in the Amherst area.

Assemblage No.	Quartz	Plagioclase	Biotite	Garnet	Muscovite	Sillimanite	K-feldspar
1)	x	x	x		x	x	
2)	x	x	x	x	x	x	
3)	x	x	x	x	x		x
4)	x	x	x	x			x
5)	x	x	x		x	x	
6)	x	x	x	x	x	x	x
7)	x	x	x	x		x	x

1) MT-258, MT-336A
2) MT-412, MT-422, MT-267B1, MT-294A
3) MT-466
4) MH-326B
5) PMT-55B
6) MT-377, PMT-54B
7) MT-310, MT-478B2

secondary phases of muscovite, so necessary to characterize properly the metamorphic assemblage, were made using the petrographic criteria developed by Tracy (1975).

The majority of the pelitic schists examined on the Amherst block (Figure 21) have prograde muscovite in a mineral assemblage consisting of quartz-plagioclase-garnet-biotite-muscovite-sillimanite that alone would be typical of Zone III. Schists displaying prograde muscovite co-existing with orthoclase in the assemblage quartz-plagioclase-biotite-garnet-sillimanite-muscovite-orthoclase indicative of Zone IV metamorphism are found in the Amherst-North Amherst area and along the eastern limit of outcrop at Mt. Warner. The assemblage quartz-plagioclase-biotite-garnet-sillimanite-orthoclase that alone would be typical of Zone V is found in sample MT-310, the easternmost sampled outcrop, and also sample MT-478B2 on the east slope of Mt. Warner. These samples have an abundance of low relief sericitized grains marking the past presence of orthoclase, a lack of primary muscovite plates, and replacement pseudomorphs of sericite after sillimanite.

The principal feature of Zone IV metamorphic grade discussed by Tracy (1975, 1978) is the coexistance of mineral assemblages that alone would be typical of Zone III, Zone IV and Zone V metamorphism. These assemblages span the transition from sillimanite-muscovite to sillimanite-orthoclase metamorphic zones. This transition occurs with progressive muscovite dehydration which involves K-Ca-Na continuous reactions. Vatiation in the bulk chemistry of the rocks has a critical effect on the K/Na and Ca/Na ratios, which are the principal variables controlling the muscovite dehydration reaction. Due to the appearance of these three assemblages, the Amherst block is assumed to lie in Zone IV.

Calc-silicate rocks. Calc-silicate rocks in the Amherst area occur as nodules and beds throughout the section, but most commonly in the Partridge Formation. They were sampled near Mt. Warner and in South Amherst. The calc-silicate rocks (Table 10) are characterized by the assemblage quartz-plagioclase-garnet-diopside-sphene with variable amounts of calcite and various epidotes. One sample (MH-334D) contains trace amounts of actinolite. The assemblage quartz-calcite-diopside is a common assemblage in calcareous rocks.

Table 10. List of mineral assemblages in calc-silicate rocks in the Amherst area.

Assemblage No.	Quartz	Plagioclase	Garnet	Sphene	Epidote	Calcite	Diopside	Actinolite
1)	x	x	x	x	x			
2)	x	x	x	x	x	x	x	
3)	x	x	x	x	x		x	x

1) MT-75A
2) MT-275A, MT-71A MH-326A
3) MH-334D

This is indicative of medium- to high-grade amphibolite facies metamorphism.

Structural Geology and Metamorphism

The pattern of metamorphic zones in New Hampshire near the axis of the Bronson Hill anticlinorium has long been recognized (Chapman, 1939; Moore, 1949). The east-dipping inverted metamorphic sequence on the east flank of the anticlinorium was postulated to be due in part to the westward movement of hotter rocks over cooler ones (Chapman, 1953). With the recognition of nappe-style folding in New Hampshire and adjacent Vermont (Thompson, 1954) the mechanism was found to account for the large scale displacement of hotter allochthonous rocks westward over cooler ones. Clear examples are seen in New Hampshire and Vermont at three locations. The first is at Skitchewaug Mountain, Vermont, where staurolite grade rocks are completely surrounded by lower grade rocks. The second is at Fall Mountain, New Hampshire, where sillimanite-orthoclase grade rocks of the Fall Mountain nappe lie above the Bellows Falls pluton which is surrounded by lower grade rocks. The third is near Keene, New Hampshire, where sillimanite-orthoclase grade rocks of the Fall Mountain nappe are located above the Ashuelot pluton. The correlation of high metamorphic grade and high tectonic level in the nappe-complex is well founded(Thompson et al., 1968; Thompson and Rosenfeld, 1979). The Bernardston nappe, which floors the nappe sequence in northern Massachusetts, mainly displays staurolite grade metamorphism, but reaches sillimanite grade near the contact of the Ashuelot pluton (Trask, 1967). Because all rocks on the Amherst block appear to be of at least sillimanite grade, they are assigned to the upper part of the nappe-complex. Additional significance is attached to metamorphic grade because the far-traveled frontal portions of the nappes seem to bear some metamorphic imprint from their source area. The rocks of the Amherst area show widespread evidence of the beginnings of partial melting such as quartz-feldspar segregations. The combination of Zone IV and V metamorphic assemblages, and the suggestion of partial melting in pelitic schists, bears close resemblance to the Quabbin Reservior area studied by Tracy (1975) and other areas on the east side of the Bronson Hill anticlinorium (Field, 1975; Tucker, 1977). Thus, the source of the nappes of the Amherst block, based on lithic similarities and structural reconstructions and supported by the metamorphic similarities, appears to have been to the east of the Bronson Hill anticlinorium in the Petersham and Ware areas of central Massachusetts.

GEOLOGIC HISTORY OF THE AMHERST AREA

The earliest geologic event recognized in the Amherst area was the deposition of the rocks which comprise the Fourmile Gneiss. Ashenden (1973) has suggested that these rocks might have been deposited as volcanic material on a offshore island arc formed during an early phase of the Taconian orogeny. Deposition of clastic material under anaerobic conditions followed, with the accumulation of Middle Ordovician sulfidic shales and siltstones originally deposited during the post-collisional relaxation phase of the Taconian orogeny (Robinson, 1979). The Taconian orogeny was a period of regional metamorphism and deformation of major importance west of the Connecticut Valley. The only evidence for this in the Amherst block is the period of erosion prior to deposition of the Lower Silurian Clough Quartzite. The Silurian rocks represent a quiescent interlude in New England following the Taconian orogeny between the subsidence and deep water sedimentation that dominated Ordovician and Devonian time. Deposition of the Lower Devonian rocks of the Littleton Formation marked the climax of subsidence and sedimentation prior to the Devonian Acadian orogeny.

During the Acadian, multiple regional nappes of Pennine type were emplaced from the east, with compression and sillimanite grade metamorphism. These recumbent folds were then refolded several times, in part during the later rise of the gneiss domes. A waning phase of the Acadian resulted in weak open folding of previously deformed strata.

Mesozoic normal faulting occurred in response to the opening of the present Atlantic Ocean, creating the Connecticut Valley border fault with about 5 km of vertical displacement. Rocks located near the fault were extensively silicified. Accompanying the extensional activity were numerous minor faults and joints. Sedimentation of clastic material from the fault scarp created alluvial fan complexes westward into the valley, locally intertongued with ponded flows of basaltic lava.

The Pleistocene glaciation left its imprint on the geology of the Amherst area. Glacial features include drumlins, eskers, and deposits of till and erratics. Glacial activity produced meltwater streams which left deltaic deposits while feeding glacial Lake Hitchcock as well as varved glacial lake sediments and post-Lake Hitchcock eolian deposits. As a result of crustal rebound and tilting, after the emptying of Lake Hitchcock, the gradient of the Connecticut River has steepened with the resulting straightening of its course and modification of its flood plain.

SUMMARY AND CONCLUSIONS

1) The pre-Mesozoic rocks of the Amherst area are unique in the context of the local geology because they provide a view of a high structural level due to their Mesozoic downfaulting and preservation from erosion.

2) The Middle Ordovician Partridge and Devonian Littleton schists of the Amherst block can be differentiated based on criteria developed by others elsewhere in the Bronson Hill anticlinorium. This differentiation is greatly enhanced by local exposures of Clough Quartzite in the northern part of the study area along the contact between the two formations. The resulting stratigraphic sequence in the Amherst area is similar to that originally proposed by Billings for the Bronson Hill anticlinorium.

3) The rocks of the Amherst area belong to the frontal portions of two west-directed Acadian nappes whose root zone lies some 20 km to the east. Based on lithic comparisons, structural reconstructions, and metamorphic grade, these are believed to have been from a high structural level in the nappe complex. After emplacement, these nappes were affected by three periods of Acadian folding and extensive Mesozoic brittle faulting.

4) Detailed mapping in the North Amherst area has defined more accurately the location of the Mesozoic Connecticut Valley border fault between the Littleton and Partridge Formations of the Amherst block to the west, and the Fourmile Gneiss of the Pelham dome to the east. It has been shown that the border fault has a

gentle west dip from 40 degrees to as low as 20 degrees. The border fault itself was offset by several later steeply east-dipping antithetic normal faults. The resulting geometry of intersecting faults and recent erosion has created three fault-bounded windows of Fourmile Gneiss from the footwall, completely surrounded by hanging wall rocks of the Amherst block.

5) Based on a small number of fault measurements, extensional stresses in the Mesozoic were oriented approximately N68W.

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APPENDIX: WATER WELL LOGS

The information and logs reproduced here were compiled from well drilling data collected by Doug Heath (1979) and William Chandler (1978). The location of the water wells is shown on the geologic map (Plate 1). The subsurface data which these wells provide helps to determine better the geometry of the Mesozoic unconformity around the Amherst block. Additionally, wells 3-78, 7-78, 9-78, and 10-78, reveal another Paleozoic inlier entirely in the subsurface below Lawrence Swamp (Plate 1). This inlier is interpreted to consist of schist of the Devonian Littleton Formation.

The casual descriptions which comprise the drillers' jargon are interpreted as follows:

"redrock"	Mesozoic arkose, shale
"softrock"	till?
"greyrock"	Paleozoic schists
"granite"	felsic gneiss or granite
"white quartz rock"	silicified zone or pegmatite
"hard white rock"	pegmatite
"sedimentary breccia"	Mesozoic conglomerate? or till?
"gneiss"	Paleozoic gneiss
"Triassic"	Mesozoic arkose or shale

Well	Log
A	Sand and gravel 0-45', arkose 45-275', "greyrock" 275-706'.
D	Littleton bedrock at 90'.
131	"Redrock" at 40'.
133	"Redrock" at 80-360', "white quartz rock" at 360".
134	"Redrock" at 140', "hard white rock" at 160'.
149	"Softrock" 56-212', "granite" at 212'.
156	Total depth, 470', "Sedimentary Breccia" to 50', Triassic bedrock from 50' to 330', "gneiss" from 330' to 470'.
157	Bedrock at 233'.
158	"Triassic" at 30', bedrock at 100'.
159	"Triassic" at 50', bedrock at 159'.
410	"Redrock" at 99'.
11-71	"Redrock" at 75'.
3-78	Schist at 141'.
5-78	Sugarloaf arkose at 44'.
6-78	Sugarloaf arkose at 33.5'.
7-78	Schist at 129'.
9-78	Metamorphic rock at 167'.
10-78	Schist with secondary quartzite at 165'.

PLATE I GEOLOGIC MAP OF PRE-MESOZOIC BEDROCK, AMHERST AREA, MASSACHUSETTS

EXPLANATION

INTRUSIVE AND FAULT-RELATED ROCKS

JURASSIC	Jsi	Jsi: Silicified zone
LOWER DEVONIAN	Dbqd	Belchertown Quartz Diorite Gneiss Dbqd: Dark green hornblende crystals evenly dispersed in a white feldspar matrix.

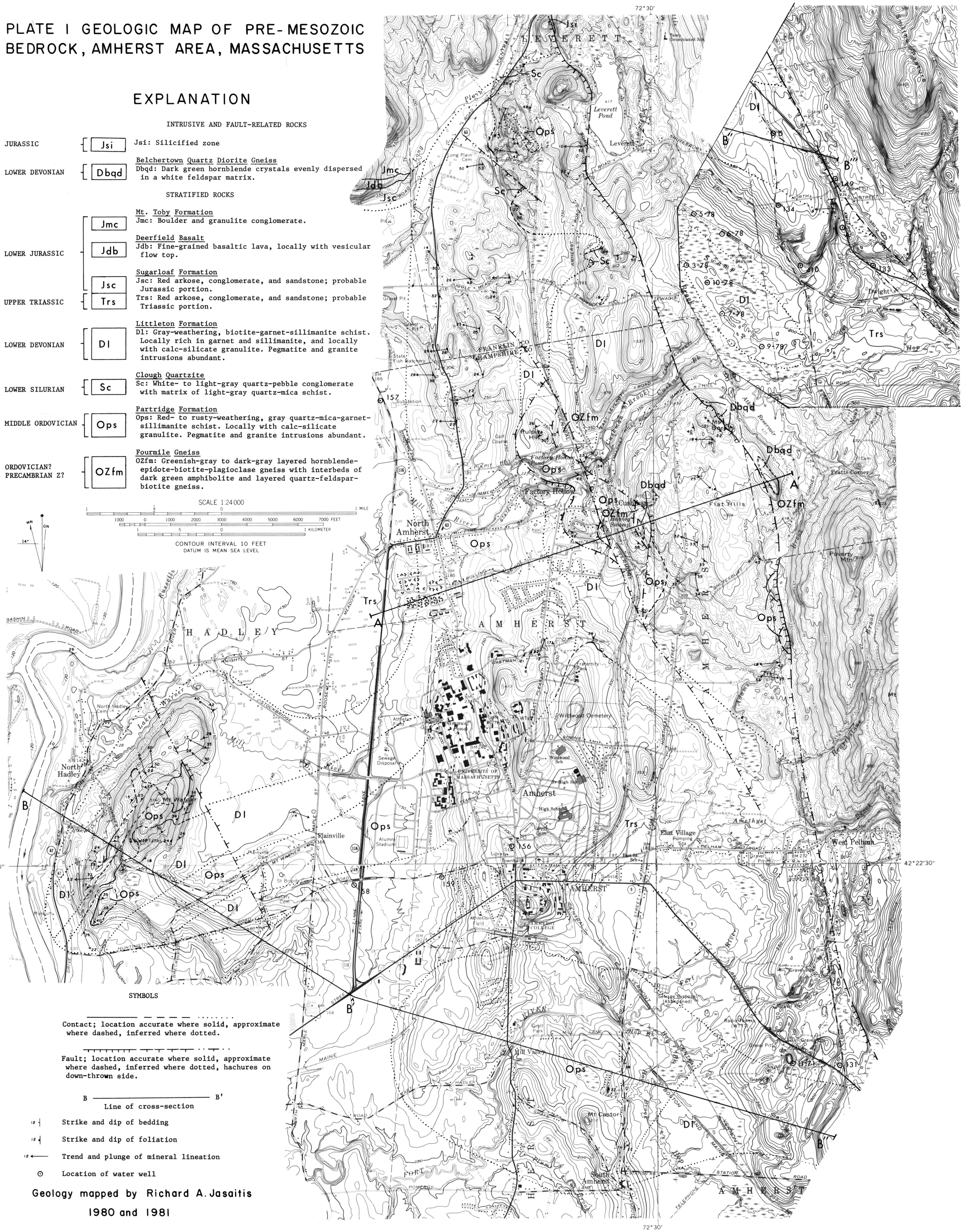
STRATIFIED ROCKS

LOWER JURASSIC	Jmc	Mt. Toby Formation Jmc: Boulder and granulite conglomerate.
	Jdb	Deerfield Basalt Jdb: Fine-grained basaltic lava, locally with vesicular flow top.
	Jsc	Sugarloaf Formation Jsc: Red arkose, conglomerate, and sandstone; probable Jurassic portion.
UPPER TRIASSIC	Trs	Trs: Red arkose, conglomerate, and sandstone; probable Triassic portion.
LOWER DEVONIAN	Dl	Littleton Formation Dl: Gray-weathering, biotite-garnet-sillimanite schist. Locally rich in garnet and sillimanite, and locally with calc-silicate granulite. Pegmatite and granite intrusions abundant.
LOWER SILURIAN	Sc	Clough Quartzite Sc: White- to light-gray quartz-pebble conglomerate with matrix of light-gray quartz-mica schist.
MIDDLE ORDOVICIAN	Ops	Partridge Formation Ops: Red- to rusty-weathering, gray quartz-mica-garnet-sillimanite schist. Locally with calc-silicate granulite. Pegmatite and granite intrusions abundant.
ORDOVICIAN? PRECAMBRIAN Z?	OZfm	Fourmile Gneiss OZfm: Greenish-gray to dark-gray layered hornblende-epidote-biotite-plagioclase gneiss with interbeds of dark green amphibolite and layered quartz-feldspar-biotite gneiss.

SCALE 1:24 000

1 MILE · 1000 0 1000 2000 3000 4000 5000 6000 7000 FEET · 1 KILOMETER

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL



SYMBOLS

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

Fault; location accurate where solid, approximate where dashed, inferred where dotted, hachures on down-thrown side.

B ——— B′ Line of cross-section

12 Strike and dip of bedding

12 Strike and dip of foliation

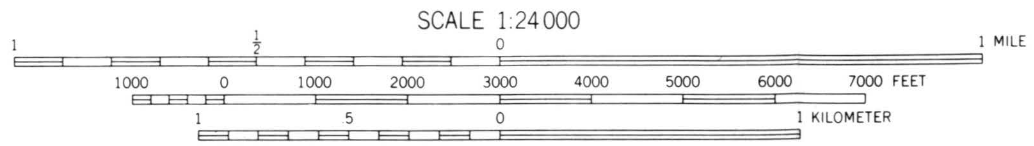
12 ← Trend and plunge of mineral lineation

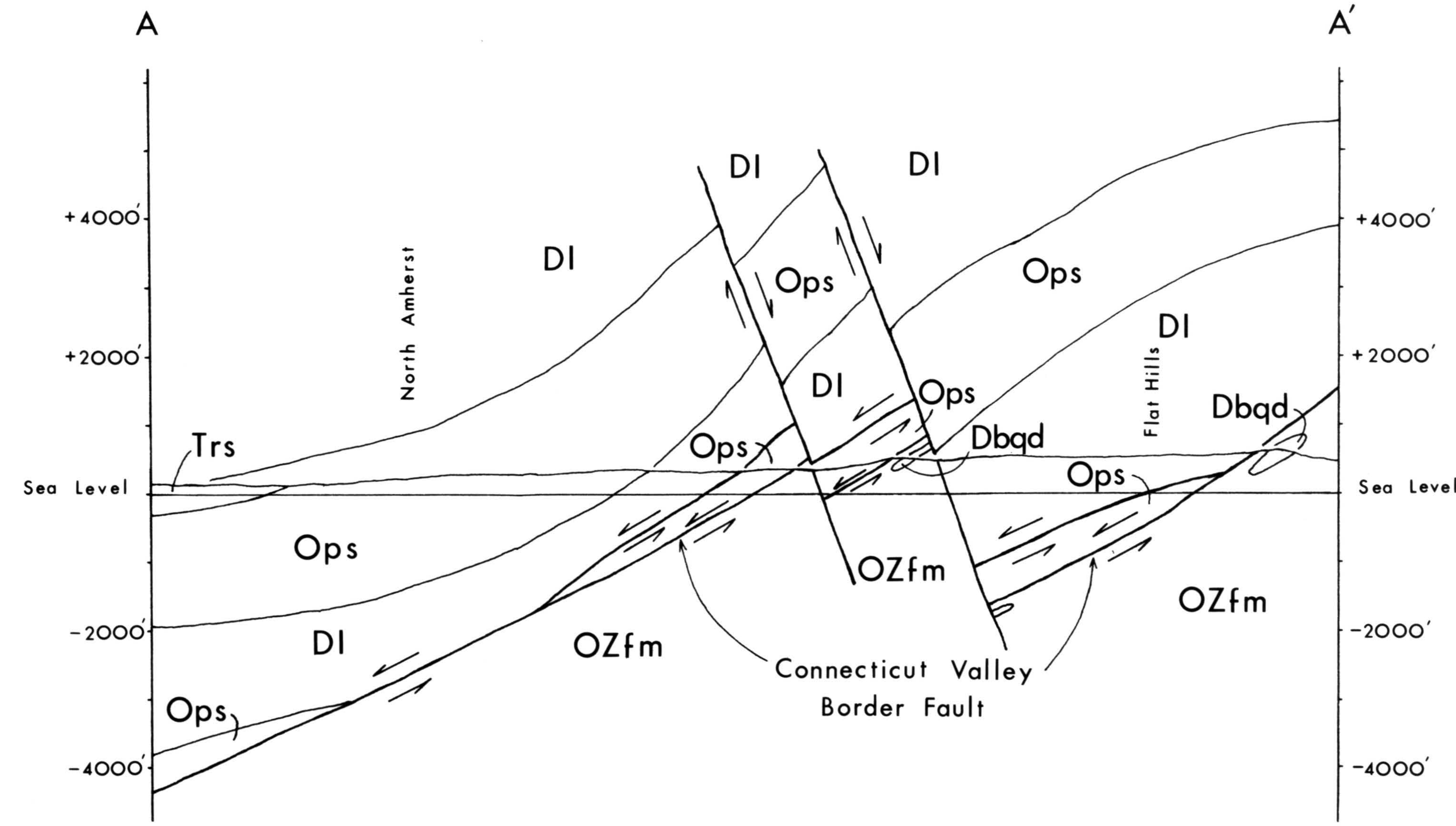
⊙ Location of water well

Geology mapped by Richard A. Jasaitis

1980 and 1981

PLATE 2 GEOLOGIC CROSS-SECTIONS, AMHERST AREA, MASSACHUSETTS





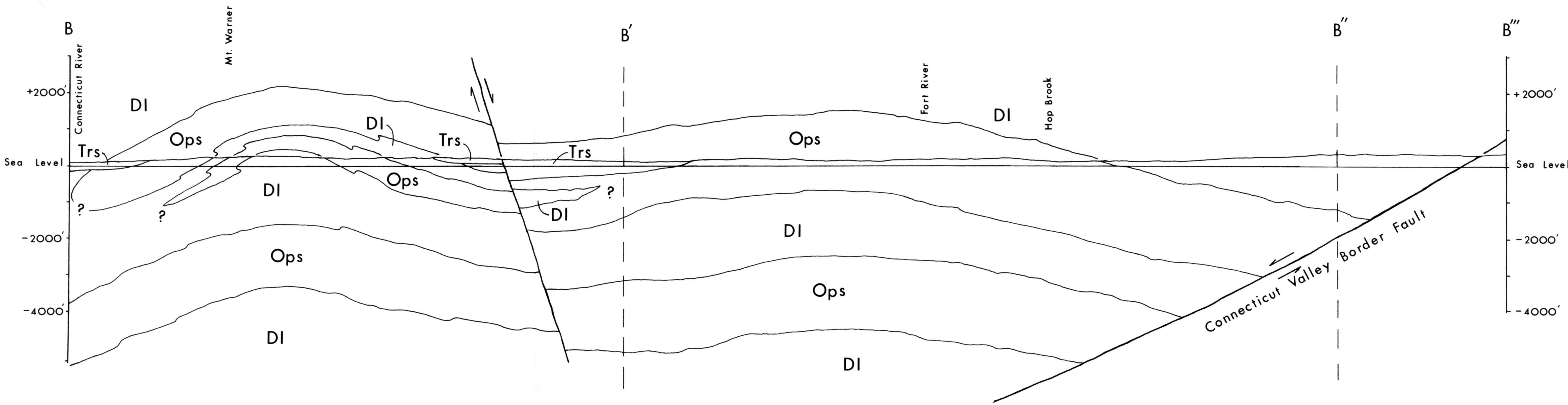


PLATE 3 MAP OF PLANAR STRUCTURAL FEATURES, AMHERST AREA, MASSACHUSETTS

EXPLANATION

12 Strike and dip of bedding.

12 Strike and dip of foliation.

SCALE 1:24000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

PLATE 4 MAP OF LINEAR STRUCTURAL FEATURES, AMHERST AREA, MASSACHUSETTS

PLATE 5 OUTCROP MAP, AMHERST AREA, MASSACHUSETTS

EXPLANATION

Area of bedrock outcrop.

× Temporary bedrock exposures due to construction.

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL