United States Department of the Interior

Geological Survey

Bedrock Geology of the Nashua River Area, Massachusetts - New Hampshire

By Gilpin Rile Robinson, Jr.

Open-File Report
81-593

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. This report was originally submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in geology at Harvard University, Cambridge Mass., March 1979.

1981

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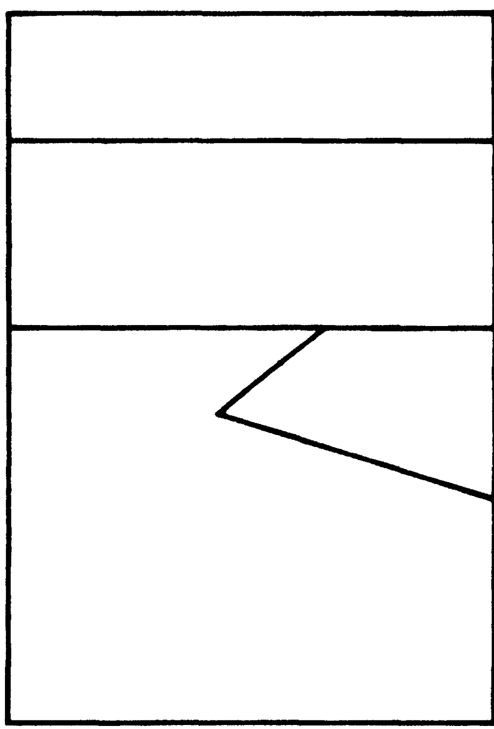
The Paleozoic stratigraphic section has been strongly deformed by two Acadian events which preceded the latest Devonian granites in the Fitchburg Pluton (380 m.y.). The oldest deformation event (D1) produced northeast-trending tight isoclinal folds (F1) coincident with the regional metamorphism and the development of the dominant regional schistosity (S1). Event D1 is likely correlative with the recognized deformation which produced the westward-facing isoclinal and recumbent folds in the western Merrimack Synclinorium and Bronson Hill Anticlinorium of Vermont and Massachusetts.

Deformation D2 produced subhorizontal, northeast-trending, chevron folds (F2) overturned to the east, and eastward-directed thrusts accompanied by the development of secondary fracture cleavage

Figure 1.
PROPOSED STRATIGRAPHIC SECTION

Stratigraphic Column



Unit	Predominant Lithology
ALUMINOUS SCHIST	Graded bedded pelite, pelite, and lustrous mica schist.
OAKDALE FM. AND MERRIMACK FM.	Calcareous siltstone and quartzofeldspathic granofels, subordinate biotite schist.
TOWER HILL QUARTZITE	Quartzite and conglomerate interbedded with gray-black carbonaceous pelite.
WORCESTER FM.	Gray-black cyclically bedded carbonaceous pelite and graywacke. Local calcareous lenses.

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Deformation D2 produced subhorizontal, northeast-trending, chevron folds (F2) overturned to the east, and eastward-directed thrusts accompanied by the development of secondary fracture cleavage and schistosity (S2). Event D2 is likely correlative with the thrusting and deformation associated with the Honey Hill-Lake Char thrust system in the Merrimack Synclinorium in Connecticut, although the intensity of deformation appears to have diminished to the northeast.

Gentle upright open folds (F3) locally deform S2 schistosity and postdate D2. Northeast-trending high-angle faults and subordinate northwest-trending faults (D4) truncate the previous structural fabrics, metamorphic isograds, and lithologic units. Adjacent to the faults are zones of intense chevron folding (F4), schistosity development (S4), and hydrothermal alteration and retrograde metamorphism. The high-angle faulting was apparently initiated during the Late Devonian to Pennsylvanian, creating the localized Pennsylvanian basins filled with terrestrial conglomeratic and pelitic sedimentary rocks in the Worcester and Harvard, Massachusetts, areas. The Late Devonian to Pennsylvanian age of northeast-trending fault initiation is supported by the intrusion of granites into portions of the faults in the Manchester, N.H., area (280 to 275 m.y. radiometric age on granite) and Rochester, N.H., area (333 m.y. radiometric age on granite) (Hussey and Newberg, 1978, Geol. Soc. Amer. Abs. with Prog., v. 10, no. 2, p. 48). These northeast-trending faults were reactivated in the Mesozoic and deformed the Pennsylvanian basins and intrusive rocks.

Displacement on the Wekepeke Fault system, as indicated by drag folds, was primarily dip slip, with the eastern block downthrown. A component of right-lateral strike-slip motion is indicated by locally well-developed slip cleavage. Local defomation is intense and complex, with multiple periods of mylonitization evident.

Metamorphic grade in the map area varies from chlorite zone to staurolite-kyanite zone of regional metamorphism and locally sillimanite zone in the vicinity of plutonic intrusive rocks. Metamorphic isograds generally parallel the northeast structural trend of the rock units, with metamorphic grade increasing to both the east and west from a metamorphic low (chlorite-biotite zones) located east of the Wekepeke Fault.

East of the Wekepeke Fault, pelitic metasedimentary rocks contain andalusite, which constrains the pressure during metamorphism to be below the aluminosilicate triple point (3.8 kb.: Holdaway, 1971, Am. Jour. Sci., v. 271, p. 97-131). Devonian granite intrusive rocks in this area contain primary muscovite. The stability of muscovite in the granite melt constrains the pressure during crystallization to be greater than the pressure at the intersection of the muscovite + quartz breakdown curve with the granite minimum liquidus under water-saturated conditions. Experimental determinations place the intersection pressure at about 3.4 kb. (Chatterjee and Johannes, 1974, Contrib. Mineral. Petrol., v. 48, p. 89-114; Tuttle and Bowen, 1958, Geol. Soc. Amer. Memoir 74). Estimates of pressure at the time of Devonian metamorphism range from 3.5 to 3.8 kilobars.

Rocks west of the Wekepeke Fault zone are in the kaynite-staurolite to andalusite-staurolite zone. Pelitic schists along the eastern border of the Fitchburg Pluton in the Fitchburg and Sterling quadrangles contain andalusite, which constrains pressure during metamorphism to be below 3.8 kilobars. Devonian granite intrusive rocks in the Fitchburg Pluton contain primary muscovite, which constrains the minimum pressure to be above approximately 3.4 kilobars. One occurrence of pelitic schist containing kyanite in the Townsend quadrangle gives an estimated metamorphism equilibration temperature of 470° to 550°C using garnet-biotite Fe-Mg K_D geothermometers. The existence of stable kyanite in this temperature range constrains the minimum pressure to lie above 3.5 kilobars. Estimates of conditions during the Devonian metamorphism are: P = 3.5 to 3.8 kilobars, T = 470° to 510°C.

A Pennsylvanian or younger metamorphism of at least biotite grade has affected the small outliers of Pennsylvania rocks in the Worcester and Harvard, Massachusetts, areas.

Average uplift rates following the Acadian orogeny can be estimated in the Nashua River area. Pennsylvanian sedimentary rocks in the Worcester area contain cobbles of the muscovite-bearing granite (380 m.y.) at Millstone Hill. In the 60 to 100 m.y. following the Acadian orogeny, average uplift and erosion rates were 0.1 to 0.16 mm/yr in the Worcester area, while erosion rates of 0.034 mm/yr are more typical as a regional average. The periods of rapid average uplift and erosion (0.1 to 0.16 mm/yr) probably reflect periods of active faulting.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the support and encouragement of my Ph.D. advisory committee at Harvard University: J.B. Thompson, Jr., J. Haller, and J.F. Hays. Special appreciation is due Professor Thompson for his guidance in the field and for the time spent in improving this manuscript. J. Haller, R. Siever, J.F. Hays, and J. Binstock also read this thesis in its early form and made many helpful comments.

I wish to thank E. Zen, R. Goldsmith, E.L. Boudette, J. Peper, J. Aleinikoff, M. Pease, C. Hepburn, J. Peck, R. Gore, P. Robinson, and R. Tucker for informative discussions regarding the geology of New England and for showing the writer the geology in various parts of New England. They provided stimulating discussions and pleasant company while on joint field trips and visiting me in the field. E.L. Boudette, U.S. Geological Survey, provided supervision during my first summer of field work. Special appreciation is given to S.L. Russell who introduced the writer to the stratigraphic complexities in the area and provided field assistance during my first summer of work. A. Barrett and L. Mutti also provided excellent field assistance during portions of field seasons.

I wish to thank A. Knoll and J. Repetski who processed rock samples for microfossil analysis, and W. Kirk who provided a zircon concentrate from a rock sample which was analyzed by J. Aleinikoff.

I extend my appreciation to numerous friends, graduate students, and colleagues whose support, encouragement, and insight helped make this thesis possible.

Portions of the field work for this thesis were financially supported by the U.S. Geological Survey cooperative program with the Commonwealth of Massachusetts and special funds of the Department of Geological Sciences, Harvard University.

CHAPTER 1. INTRODUCTION

The Nashua River area, a lowland area located in northeast-central Massachusetts approximately 35 miles northwest of Boston, covers portions of the Ashby, Ayer, Clinton, Fitchburg, Hudson, Nashua South, Pepperell, Shrewsbury, Shirley, Sterling, Townsend, and Worcester North 7-1/2' quadrangle sheets. This report is a supplement to U.S. Geological Survey Miscellaneous Field Studies Map MF-957 (Robinson, 1978) which covers the Pepperell, Shirley, Townsend quadrangles and part of the Ayer quadrangle. Reference to information in MF-957 occurs throughout this report. Reference to localities in the text refer to localities listed in MF-957. Information about other locations in the Nashua River area is derived from reconnaissance work by the writer and from detailed mapping and research by other workers.

The Nashua River area spans a portion of a northeast-trending belt of low-grade metamorphic rocks (chlorite-biotite zone) which is sharply bounded by plutonic rocks and metamorphic rocks of higher grade on both the east and west (Thompson and Norton, 1968, p. 320, Fig. 24-1). The configuration of alternating high-grade and low-grade belts in metamorphic terranes is not uncommon. In the southern Appalachians, some linear belts of low-grade rocks sharply bounded by high-grade rocks, such as the Brevard Zone, have been described as retrograde mylonite zones (Reed and Bryant, 1964). Although regional faulting may explain some of the metamorphic variation within the Nashua River area, sedimentary features, such as cross-bedding and graded bedding, preserved in the low-grade belt indicate that the low metamorphic grade is not due to retrograde metamorphism associated with mylonitization.

GEOMORPHOLOGY AND SURFICIAL GEOLOGY

The geomorphology of the Nashua River area reflects the variation in metamorphic grade of the underlying bedrock. The low-grade belt central to the area occupies a triangular topographic lowland that drains northward into the Merrimack River in New Hampshire. Exposure of the low-grade metamorphic sedimentary rocks in the central lowland area is poor, in contrast with the fair bedrock exposure in the surrounding upland areas of plutonic and higher-grade metamorphic rocks.

The lowland area is the site of Glacial Lake Nashua (Jahns, 1953; Koteff, 1970, 1974; Koteff and Volckmann, 1973), whose Pleistocene deposits cover much of the area. These Pleistocene deposits are complex due to periods of intermittent ice stagnation and the general northward drainage pattern (see Koteff and Volckmann, 1973, for a map of the surficial geology of the Pepperell quadrangle). Extensive areas of Pleistocene lake-bottom sediments and deltas are preserved in the lowland area.

PREVIOUS WORK

Reports on the geology of Massachusetts and New Hampshire by C.T. Jackson (1844), Edward Hitchcock (1832, 1835, 1838, 1841), and Charles Hitchcock (1877) described the geology of the Nashua River area and vicinity. Burbank (1876) and Crosby (1876, 1880) studied the geology of the Nashua River area, and Crosby (1877) prepared a geological map of eastern Massachusetts (scale: 1:316,800), including the Nashua River area. Tilton (1896) mapped and described the geology in the vicinity of Nashua, N.H. Emerson (1917) prepared the Geologic Map of Massachusetts and Rhode Island (scale: 1:250,000). The U.S. Geological Survey is currently preparing a revised geologic map of Massachusetts (scale: 1:250,000).

The area south of the Nashua River has been studied in relation to dam and aqueduct construction projects. The geology of the Quabbin Aqueduct has been described by Callaghan (1931), Fahlquist (1936), and Larsen and Morris (1933). Crosby (1899) described the geology of the Wachusett Reservoir and Aqueduct. Billings (unpublished) and Skehan (1968) studied the geology of the Wachusett-Marlboro Tunnel. The Worcester Coal Mine has received considerable geological study (summarized by Grew et al., 1970) because it is the only fossil locality in this area of southeastern New England.

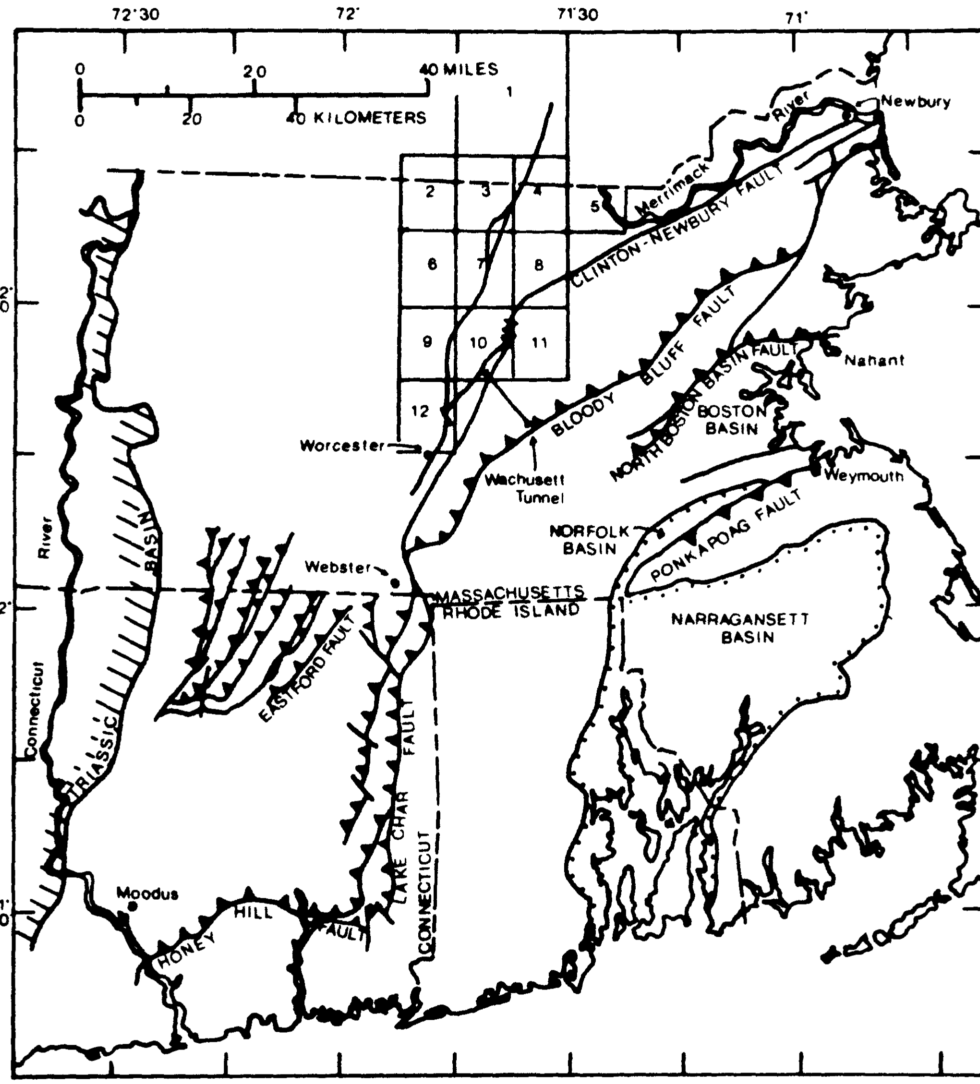
Since 1950, considerable work has been undertaken in and around the Nashua River area. Reference to these works will be made throughout the thesis. Figure 2 gives quadrangle locations, areas studied by various geologists, and bibliographic references to published work.

REGIONAL SETTING

Much of New England is underlain by deformed, metamorphosed, and intruded sedimentary rocks of Cambrian to Devonian age unconformably overlying Precambrian basement of two distinct ages. Basement rocks having a 900 to 1,000 m.y. radiometric age (Grenville) are

Figure 2. Index Map

1. Milford, N.H. 15 minute quadrangle
   Aleinikoff (1978)
2. Massachusetts portion of the Ashby, Mass. - N.H. $7\frac{1}{2}$ minute quadrangle
   Peper and Wilson (1978)
3. Townsend, Mass. - N.H. $7\frac{1}{2}$ minute quadrangle
   Robinson (1978)
4. Pepperell, Mass. - N.H. $7\frac{1}{2}$ minute quadrangle
   Robinson (1978)
5. Massachusetts portion of the Nashua South, Mass. - N.H. $7\frac{1}{2}$ minute quadrangle
   Jahns and others (1959)
6. Fitchburg, Mass. $7\frac{1}{2}$ minute quadrangle
   Peper and Wilson (1978)
7. Shirley, Mass. $7\frac{1}{2}$ minute quadrangle
   Robinson (1978)
8. Ayer, Mass. $7\frac{1}{2}$ minute quadrangle
   Jahns and others (1959)
   Gore (1976a)
   Robinson (1978)
9. Sterling, Mass. $7\frac{1}{2}$ minute quadrangle
   Hepburn (unpublished)
10. Clinton, Mass. $7\frac{1}{2}$ minute quadrangle
    Peck (1975, 1976)
11. Hudson, Mass. $7\frac{1}{2}$ minute quadrangle
    Hansen (1956)
12. Worcester North, Mass. $7\frac{1}{2}$ minute quadrangle
    Grew (1970)
    Hepburn (1976)



Thrust fault or high-angle reverse fault-- Sawteeth on upper plate

High-angle fault or dip of fault surface not known

Border of Triassic and Jurassic basins

Border of Narragansett and Norfolk basins

FIGURE 2

confined west of the Connecticut Valley and exposed in the Berkshire Hills, Green Mountains, and the Adirondack Mountains as well as Canada. Basement rocks with a 550 to 650 m.y. radiometric age (Avalonian) are exposed in southeastern Newfoundland, coastal New Brunswick, and southeastern Massachusetts, although an exposure of Avalonian-age gneiss occurs farther west in the core of the Pelham Dome in Massachusetts (Naylor, 1975).

Between these two zones of contrasting basement types, the Appalachian Mountains in New England are divided into alternating northeast-trending anticlinoria and synclinoria of complexly deformed and metamorphosed Paleozoic sedimentary, volcanic, and plutonic rocks (Zen, 1968b, pp. 1-3; see Fig. 3 of this report).

The Merrimack Synclinorium, east of the Bronson Hill Anticlinorium, was defined by Billings (1956, p. 114) in New Hampshire as a northeast-trending synclinal basin underlain by rocks of the Lower Devonian Littleton Formation, but subsequent study has shown that the area is not a simple synclinorium, but consists instead of a complex sequence of isoclinally folded and multiply deformed Lower to Middle Paleozoic rocks.

The rocks in the Merrimack Synclinorium in Massachusetts, New Hampshire, and Connecticut are not fossiliferous, but they are lithologically similar to, and in certain cases can be traced into, fossiliferous rocks in the Merrimack Synclinorium in Maine and the Bronson Hill Anticlinorium in New Hampshire. Rocks underlying the Merrimack Synclinorium in Maine range in age from Ordovician to Devonian and consist of volcanic sedimentary rocks, and pelites and calcareous

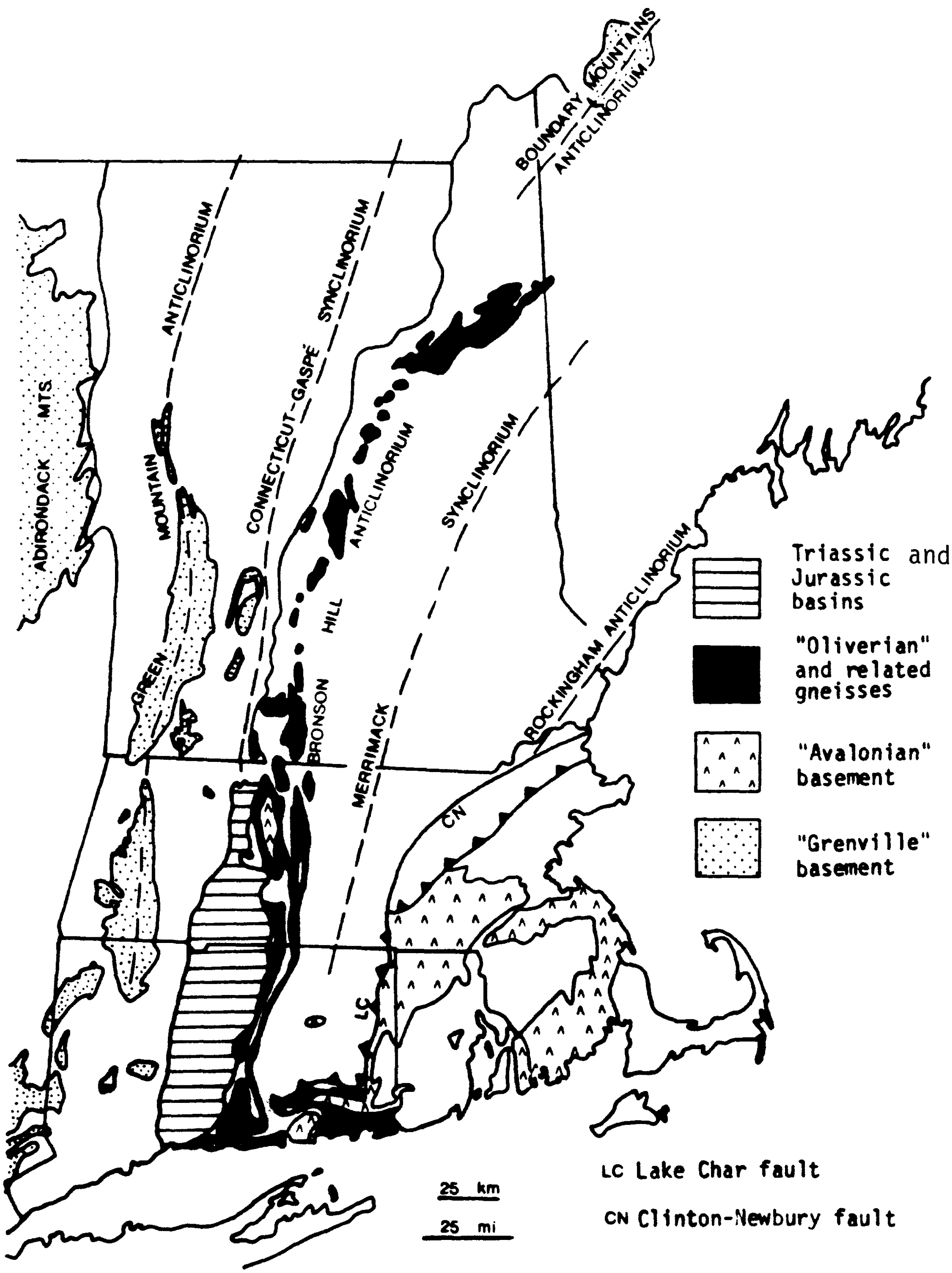


FIGURE 3

Major structural elements of New England siltstones of deep marine or turbidite affinity (Osberg et al., 1968; Hussey, 1968; Berry, 1968; Boucot, 1968; Ludman, 1976; Ludman and Griffin, 1974; Pankiwskyj et al., 1976).

Three orogenic events are recognized in New England. The Taconic orogeny, marking the emplacement of the Taconic allochthon and plutonism in the Bronson Hill Anticlinorium, developed a systematic pattern of diastrophism, uplift, and erosion in New England (Pavlides et al., 1968). Initial Taconic deformation began in Trenton time (Graptolite Zone 12 - 13) with the initiation of high-angle faulting in the Normanskill sea and development of wildflysch conglomerates in the Normanskill shales, and extensive gravity slides and thrusts (Zen, 1968a). The Taconic orogeny may mark the time of juxtaposition of the contrasting Grenville and Avalonian basement types in New England, since Ordovician (Graptolite Zone 12 - 13) volcanic rocks and schists (Ammonoosuc Volcanics, Partridge Formation, Hawley Formation) are the oldest units that can be correlated across the zone of basement convergence along the Connecticut River (Peter Robinson, 1978, p. 82). Pavlides et al. (1968) have identified a linear series of belts in which Taconic unconformities generally change laterally into disconformities and ultimately into apparently conformable sequences. The Taconic unconformity lacks a strong discordance in the western Merrimack Synclinorium and may not be present in the eastern Merrimack Synclinorium (Pavlides et al., 1968; Peter Robinson, 1978; Boone et al., 1970, pp. 5-6).

This relatively thin Silurian and Devonian section in the Bronson Hill Anticlinorium and western Merrimack Synclinorium, overlying the

Taconic unconformity and a basal conglomerate (Clough Quartzite) versus a thick Silurian and Devonian section in the eastern Merrimack Synclinorium with no evidence of the Taconic unconformity implies the Bronson Hill "anticline" and Merrimack "syncline" were structural features by at least the Late Ordovician to Silurian.

The Middle Devonian Acadian orogeny was apparently responsible for much of the deformation and metamorphism in New England. Acadian deformation in the central Merrimack Synclinorium includes westward-transported isoclinal folds of extreme elongation followed by eastward-transported backfolding and subhorizontal thrusting (Peter Robinson, 1978; Dixon and Lundgren, 1968; Peper et al., 1975). Strongly folded and metamorphosed Silurian and Devonian sediments are intruded by syntectonic to posttectonic Devonian peraluminous granites and calcalkaline diorites and granodiorites. Posttectonic peraluminous granites in the Nashua River area have been dated at 380 to 410 m.y. (granite at Millstone Hill, Worcester, Mass., 380 ± 13 m.y.; granite at Malden Hill, Fitchburg, Mass., 410 ± 12 m.y.: Rb-Sr whole rock ages, Zartman and Naylor, in press).

The Late Pennsylvanian, Early Permian Alleghanian orogeny strongly affected the Pennsylvanian basin in Rhode Island and surrounding areas, but its effect elsewhere in New England is not fully known. Grew (1970, 1973) has shown that Carboniferous rocks of limited extent exist in the Worcester area, and that all rocks of a demonstrable Carboniferous age have unconformable or fault contacts with adjacent pre-Carboniferous rocks. The Pennsylvanian sedimentary rocks in the Worcester area have been metamorphosed to at least biotite grade, and some of these sedimentary rocks contain prograde garnet with an unknown spessartine content. Pelites and conglomerates of Pennsylvanian age that unconformably overlie the Ayer Granite (424 ± 6 m.y. Pb/U age on zircons: Zartman and Naylor, in press) at Harvard, Mass., (Thompson and Robinson, 1976 are in the biotite zone. Pelites associated with the Pennsylvanian conglomeratic sedimentary rocks contain chloritoid (Thompson and Robinson, 1976), which is consistent with biotite zone metamorphism. K-Ar isotopic ages of micas from intrusive and metasedimentary rocks in southeastern New England are Permian (230 to 330 m.y.) and may represent either post-Acadian orogeny cooling ages (Zartman et al., 1970) or re-equilibration of isotopic ages during an Alleghânian metamorphism (Grew, 1970, pp. 254-256). The recent discovery of extensive areas of granite with a 275 to 280 m.y. age (Pb/U age on zircons: Aleinikoff, 1978) in the Milford, N.H., area lends support to the hypothesis of an Alleghanian metamorphism in this area.

Major faults cause some difficulty in determining regional stratigraphic correlations in the Nashua River area. The zones of closely spaced isograds that bound the low-grade trough in the Nashua River area (Thompson and Norton, 1968, Fig. 24-1) are generally localized along post-metamorphic faults and actually indicate discontinuities in metamorphic grade.

The map area in MF-957 is bisected by a high-angle fault zone that coincides with the northwestern metamorphic discontinuity bounding the low-grade belt. Novotny (1961) recognized the regional significance of this fault. Rodgers (1970) postulated continuity of this fault with the Flint Hill

Fault in the Mt. Pawtuckaway quadrangle, N.H. (Freedman, 1950), and extrapolated the fault into the Casco Bay area of Maine. It was named the Wekepeke Fault in the Clinton quadrangle, Massachusetts (Peck, 1975), and this name is used here.

The southeast boundary of the Nashua River area coincides with the trace of the Clinton-Newbury Fault (Skehan, 1968; Essex Fault of Castle et al., 1976). The Clinton-Newbury Fault is a regionally prominent break separating terranes of different metamorphic grade, structural trend, and lithology. The Clinton-Newbury Fault forms a metamorphic discontinuity between chlorite to actinolite zone siltstones and quartzofeldspathic rocks to the west and andalusite to sillimanite zone schists and gneisses to the east.

CHAPTER 2. LITHOLOGY AND STRATIGRAPHY

Since major faults divide the map area and complicate lithologic correlation, the stratified rocks in the Nashua River area are best discussed as three belts of different metamorphic grade separated by the northeast-trending Wekepeke and Clinton-Newbury Faults. Paleozoic rock types in the map area lack fossils. Each continuous strike belt of rock type is named and described separately, even though correlations may exist between units. Figure 4 shows the distribution of rock types in the Nashua River area.

ROCKS EAST OF THE CLINTON-NEWBURY FAULT ZONE

East of the Clinton-Newbury Fault is a terrane of stratified quartzofeldspathic gneiss and migmatite with subordinate interbedded amphibolites, impure marbles, and pelitic schists generally exposed in the sillimanite to second sillimanite zones of metamorphism. The quartzofeldspathic gneiss and subordinate amphibolite, marble, and schist comprise the Nashoba Formation of Hansen (1956). Along its western margin the Nashoba Formation is bordered by a poorly bedded rusty- to gray-weathering schist (Tadmuck Brook Schist of Bell and Alvord, 1976). The nature of the contact between the Nashoba Formation and the Tadmuck Brook Schist is poorly known, but is thought to be either a fault or an unconformity (Alvord _et al._, 1976, p. 327). The Tadmuck Brook Schist ranges in metamorphic grade from the chloritoid to sillimanite zones.

Figure 4.
LITHOTYPE BELTS IN THE NASHUA RIVER AREA

IG	Intrusive Plutonic Rock.

LITHOLOGY EAST OF CLINTON-NEWBURY FAULT ZONE

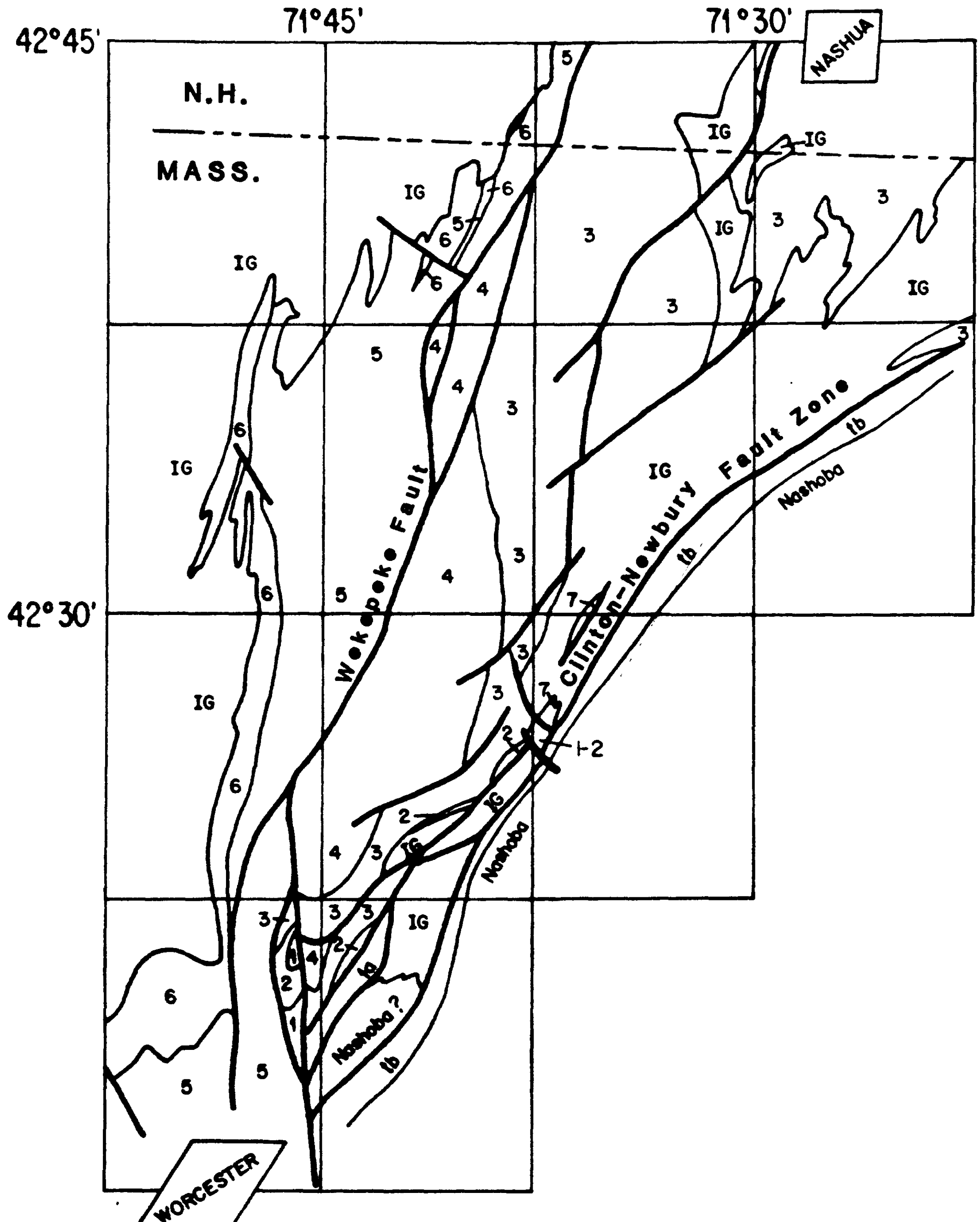
tb	Rusty and Grey Weathering Pelitic Schist.
Nashoba	Quartzofeldspathic Gneiss. Minor Amphibolite and Marble.

LITHOLOGY WEST OF CLINTON-NEWBURY FAULT ZONE
(No Stratigraphic Significance Implied by Order)

7	Terrestrial Conglomerate and Pelitic Sediments.

6	Graded Bedded Pelite, Pelite, and Lustrous Mica Schist.
5	Quartzofeldspathic Granofels.
4	Cyclically Bedded Graphitic Pelite and Graywacke. Minor Calcareous Lenses.
3	Calcareous Siltstone and Quartzofeldspathic Granofels.
2	Quartzite and Conglomerate Interbedded with Minor Pelite.
1	Graphitic Pelite, and Graphitic Pelite Interbedded with Minor Clean Quartzite.
1a	Massive Bedded, Slightly Sulfidic Pelite.

Figure 4.
LITHOTYPE BELTS IN THE NASHUA RIVER AREA

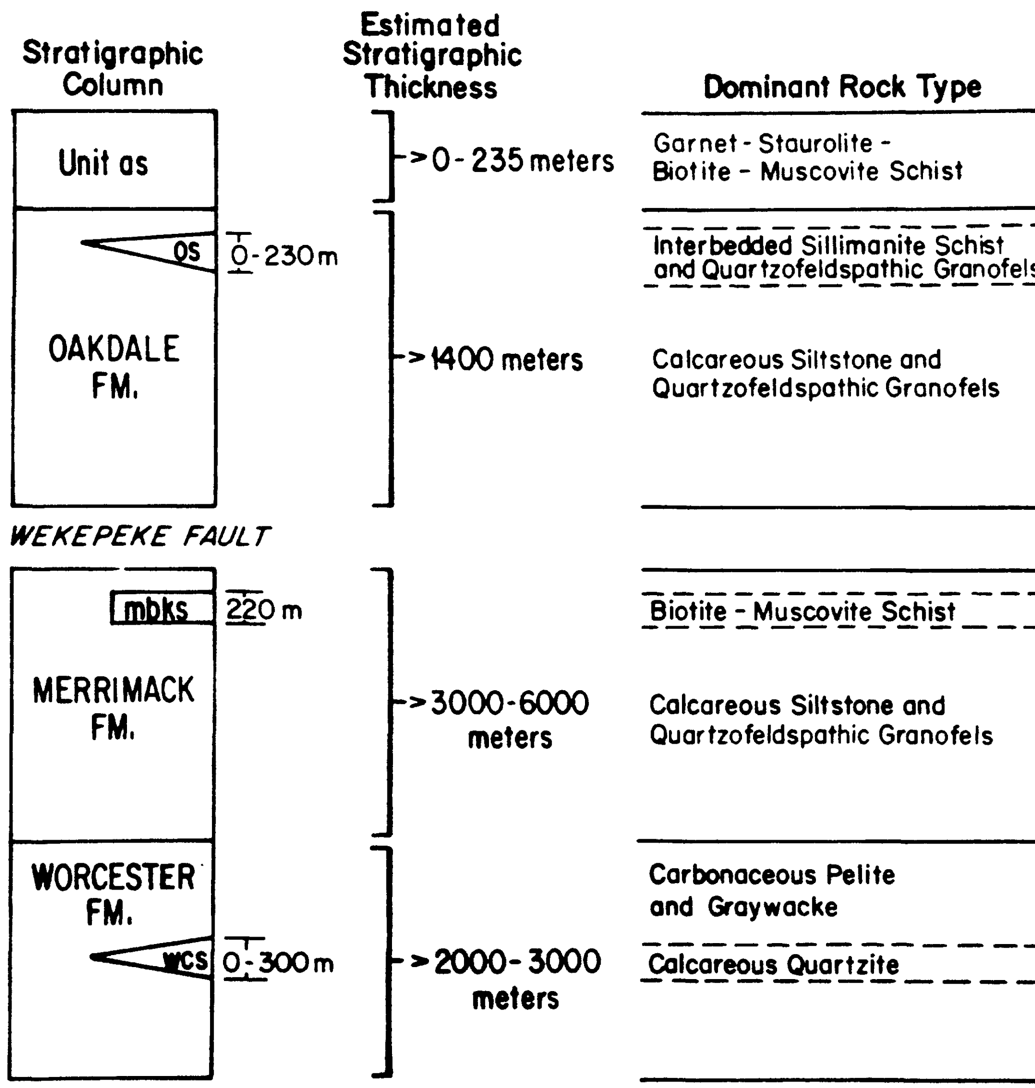


ROCKS IN THE NASHUA RIVER AREA

The stratified rocks east of the Wekepeke Fault and west of the Clinton-Newbury Fault consist of a lower unit of metamorphosed graphitic pelites and graywackes (Worcester Formation) overlain by calcareous siltstones (Merrimack Formation). Estimated stratigraphic thicknesses are shown in Figure 5. The stratigraphic facing has been determined in the Shirley quadrangle (locality 6) where graded and cross-laminated beds in the Worcester Formation underlie beds in the Merrimack Formation. Lenses of clean quartzite and conglomeratic sediments are interbedded with graphitic pelite along the southern and eastern portions of the belt (Tower Hill Quartzite of Grew, 1970). Topping evidence generally is poorly exposed along the contact with the adjacent siltstone unit, but it is generally believed that the siltstone unit overlies the quartzite (Grew, 1970; Peck, 1976). In the Worcester and Harvard, Mass., areas, small outliers of Pennsylvanian pelitic and conglomeratic sedimentary rocks occur, isolated by faults and an unconformity from the underlying Paleozoic rocks. The Worcester Coal Mine, the source of Pennsylvanian fossils in the Worcester area, occurs in one of these fault-bounded blocks of Pennsylvanian rock (Grew, 1970).

The rock units are exposed in the low to intermediate zones of regional metamorphism. The metamorphic isograds approximately parallel the boundaries between rock units. The metamorphic grade increases to both the east and west from a metamorphic low (chlorite zone) located east of the Wekepeke Fault and west of the Nashua River in the Pepperell and Shirley quadrangles.

Figure 5.
ESTIMATED STRATIGRAPHIC THICKNESS



The stratified rocks located west of the Wekepeke Fault and east of the intrusive Fitchburg Pluton consist of a lower unit of metamorphosed calcareous siltstones (Oakdale Formation) and an overlying unit of mica schist (Aluminous Schist). The stratigraphic facing is not known in the Shirley or Townsend quadrangles, but can be inferred from the Fitchburg quadrangle, where staurolite-garnet-andalusite/sillimanite schists (unit DSgs of Peper and Wilson, 1978), locally preserving relict graded bedding, overlie quartzofeldspathic rocks of the Oakdale Formation. The band of Aluminous Schist (unit as) in the Townsend quadrangle is not continuous with the band of DSgs in the Fitchburg quadrangle, but is lithologically identical to portions of unit DSgs. Unit as in the Townsend quadrangle is structurally interpreted as a synclinal infold in the Oakdale Formation. Both the schist and granofels units are exposed in the staurolite-kyanite/andalusite (actinolite) zone of regional metamorphism.

The lithologic units are described in the following section in ascending age according to the preferred stratigraphic model for the area. Rock types are described under each section in order of decreasing abundance in the formation. The term "granofels"[1] is used to describe fine-grained rocks composed largely of equidimensional minerals with a granular texture.

The protolith of the metasedimentary rocks has been inferred from the bulk composition, relict sedimentary textures, and bedding characteristics of the lithologic units.

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[1] Goldsmith, R., 1959, Granofels: A new metamorphic rock name, Jour. Geol., Vol. 67, #1, pp. 109-110.

WORCESTER FORMATION

Nomenclature, Historical Background, and Distribution

The name "Worcester" was first used by Emerson (1890, p. 560; 1898, p. 17) to refer to an extensive belt of argillite, phyllite, and chiastolite-bearing mica schist in Worcester and neighboring areas. The formation was described in detail as the Worcester Phyllite by Perry and Emerson (1903) and Emerson (1917), and assigned a Carboniferous age on the basis of plant fossils found in coal-bearing beds at the Worcester "coal mine" (White, 1912). The Pennsylvanian age of the coal-bearing rocks has been recently confirmed by Grew *et al.* (1970). However, Grew (1970, 1973, 1976) has shown that the "coal mine" strata containing the fossils are actually separated by faults and an unconformity from the rest of the pelitic rocks that Emerson called Worcester Phyllite.

Hansen (1956), mapping in the Hudson area, changed the name to Worcester Formation and redefined the unit to include other rock types in addition to phyllite. The belt of Hansen's Worcester Formation in the Hudson quadrangle is now thought to be unrelated to the main belt of Worcester Phyllite as mapped by Emerson and is separated from it by a fault zone (Skehan, 1968; Peck, 1976; Gore, 1976b).

The Worcester Formation is redefined as the slate, phyllite, and granofels coinciding approximately with Emerson's belt of Worcester Phyllite extending from the Worcester area northward into the towns of Clinton, Shirley, and Leominster, excluding the fossiliferous strata and related rocks of Pennsylvanian age at Worcester and neighboring areas. The Worcester Formation, thus defined, is equivalent to units 3 and 4 of Peck (1976) and the eastern belt of Grew's Holden Formation (1970) (unit De of Grew, 1973).

In the late 1700's to early 1800's, the rock was quarried for roofing slates and tombstones in Lancaster and Leominster, and is presently quarried for road aggregate in Lunenburg.

Lithologic Description

The Worcester Formation consists dominantly of interbedded dark-gray carbonaceous slate and granofels. A gray calcareous quartzite (unit wcs) occupies an unknown stratigraphic position in the formation and comprises a small portion of the unit. Slate and granofels beds typically alternate, although local repetitive sequences of individual slate beds and granofels beds occur. The beds range in thickness from a few centimeters to a meter, are typically thinly laminated, and sometimes show grading or cross-lamination. In general, the granofels consists of a fine-grained matrix of quartz and mica with an average grain size of 0.01 to 0.1 mm; however, massive bedded granofels layers typically contain 0.1 to 0.5 mm-diameter detrital grains of quartz and plagioclase imbedded in the fine-grained matrix. In local areas, granofels containing 1.0 to 2.5 mm detrital grains of quartz, feldspar, or slate fragments in a pelitic matrix occurs. Where conformable, contacts with the overlying Merrimack Formation are gradational over a thickness of a few meters to tens of meters. The lower contact of the Worcester Formation is not exposed, since the Worcester Formation is truncated along its western border by the Wekepeke Fault.

In the map area (MF-957, Robinson, 1978), the Worcester Formation is exposed in the chlorite to andalusite metamorphic zones. The andalusite-zone rocks show retrograde alteration, as indicated by partial replacement of garnet by chlorite, and partial or complete replacement of andalusite by muscovite and margarite micas.

The thickness of the Worcester Formation is difficult to determine, since the unit is intensely folded on a small scale and truncated by a fault along its entire exposure in the Nashua River area. In the Clinton quadrangle, Peck (1976, p. 244, Fig. 2, units 3 and 4) estimated the thickness between 3050 and 4270 meters. In the Worcester area, Grew (1970, p. 157, his Holden Formation) estimated the thickness to be greater than 3000 meters.

The stratified slate and micaceous granofels of the Worcester Formation are the metamorphosed equivalents of interbedded marine muds and fine-grained graywackes.

Slate, phyllite, and granofels member (wspg)

Interbedded gray carbonaceous slate, phyllite, and granofels comprise the dominant member of the Worcester Formation. The thickness of individual beds ranges from 0.5 to over 10 cm but typically is 2 to 7 cm. Beds are generally thinly laminated, and some granofels and pelite beds show grading or cross-lamination (Plate 1a; c). The lamination and sedimentary features are defined by thin bands of carbonaceous dust. Repetitive sequences of alternating homogeneous slate and granofels are typical; however, zones of alternating granofels and pelite with

Plate 1. Worcester Formation

Photo location on following page: a, lower left corner; b, upper left corner; c, lower right corner; d, upper right corner.

a. Cyclically bedded micaceous sandstone and pelite in the Worcester Formation. Locality 19, Shirley quadrangle.

b. Penecontemporaneous slump folds overturned to the southeast in a micaceous quartzite layer in the Worcester Formation. Locality 19, Shirley quadrangle.

c. Truncated cross-bedding in the Worcester Formation. View is easterly on a subhorizontal surface. Sedimentary topping direction is to the east. Locality 5, Shirley quadrangle.

d. Randomly oriented crystals of andalusite in the Worcester Formation. Locality 19, Shirley quadrangle.

graded bedding are distributed throughout the unit. Thin graphite-rich seams and beds are common. Fine-grained quartz, 0.01 to 0.1 mm in diameter, typically comprises the matrix in granofels layers. Massive bedded quartzwacke, sandstone, and granofels layers typically contain detrital grains of quartz and feldspar 0.1 to 0.5 mm in size. The detrital quartz grains are typically rounded to subangular and show straight to slightly undulose extinction. Large detrital quartz grains generally consist of polygranular aggregates with straight to crenulated grain boundaries. Detrital feldspar grains consist predominantly of plagioclase fragments, which in some cases show albite twinning and some alteration. Detrital grains of potassium feldspar typically contain numerous plates of illite or muscovite as an alteration product. Detrital grains of polygranular quartz and feldspar occur in some coarse-grained layers. The upper portion of this member in the Clinton quadrangle contains a thinly bedded granule conglomerate with feldspar, quartz, and slate fragments in a pelite matrix. This granule conglomerate is discontinuous along strike and disappears to the northeast. The rock weathers light gray to buff, with some rusty spots from oxidation of pyrite.

Slate and phyllite comprise 70 to 75 percent of the member, with the remaining 25 to 30 percent being carbonaceous granofels and micaceous quartzite. This member is exposed primarily at chlorite and biotite grades of metamorphism. The pelite layers are composed mostly of muscovite, chlorite, and quartz, with occasional porphyroblasts of biotite, magnetite, or garnet. The granofels layers contain quartz, chlorite, muscovite, plagioclase, and occasional biotite.

Slate, granofels, and sandstone member (wsgs)

Interbedded dark-gray carbonaceous slate, granofels, and micaceous sandstone comprise a unit distinguished from member wspg by the presence of thicker bedding and more abundant sandstone layers and lenses.

Fifty-five to sixty-five percent of the member is pelite and the remaining thirty-five to forty-five percent comprises granofels and sandstone.

The unit consists of alternating or graded couplets of granofels, sandstone, and quartzwacke at base and pelite at top. Parallel lamination and cross-lamination, defined largely by carbonaceous dust, are common in the coarser grained beds. Some massive sand layers contain overturned ripple marks or slump folds (Plate 1b). Beds are generally massive, with a typical thickness of 5 to 15 cm, although occasionally they are as thick as one meter.

The granofels layers are composed primarily of quartz, chlorite, muscovite, plagioclase, and biotite. The pelitic layers contain garnet porphyroblasts 2 to 3 mm in diameter and randomly oriented andalusite (chiastolite) porphyroblasts in a matrix of muscovite, chlorite, and quartz. One mm chlorite and/or biotite porphyroblasts are intergrown with the fine-grained muscovite, chlorite, and quartz in the matrix. The andalusite porphyroblasts average 3 to 4 cm in length and 0.5 cm in diameter, although locally grow as large as 10 cm long and 1.5 cm in diameter (Plate 1d). The garnet porphyroblasts are partially or completely replaced by chlorite and the andalusite porphyroblasts by muscovite or an intergrowth of muscovite and margarite. Ilmenite laths in the matrix are partially altered to leucoxene.

The contact between members wsgs and wspg is poorly exposed in the map area, but is reported to be gradational in the Clinton quadrangle (Peck, 1977, p. 247).

Calcareous sandstone and micaceous quartzite member (wcs)

Interbedded light-gray, fine-grained, calcareous, micaceous quartzite and quartz-rich schist comprise a small member in the Worcester Formation located in the Townsend quadrangle. Beds range from 2 to 20 cm thick and consist of massive quartzite alternating with thinly bedded micaceous quartzite. The quartzite consists primarily of fine-grained quartz, muscovite, calcite, and some plagioclase and chlorite, and has a blocky fracture.

This member is structurally situated as either a plunging antiformal infold or a stratigraphic lens in member wspg. The western contact of member wcs with wspg appears conformable and is gradational over a few meters. Member wspg adjacent to wcs along the western border becomes uncharacteristically coarse-grained and quartz-rich for a few tens of meters prior to the contact.

The estimated thickness of unit wcs ranges from 0 to 300 meters.

MERRIMACK FORMATION

Nomenclature, Historical Background, and Distribution

The term Merrimack was used by Hitchcock (1877, pp. 621-625, Vol. 2) for the rocks along the Merrimack River in Lowell and Lawrence that strike into Kittery, York, and Eliot, Maine. Hitchcock (1877, Plate XXIII, Fig. 98) included the rocks in the Nashua River area in his Merrimack unit.

Emerson (1917, p. 59) noted the lithologic similarity between his Oakdale Quartzite and his Merrimack Quartzite, but preserved the name Merrimack for the quartz schist in the Lowell area, since this belt of rock was far removed from the main strike belt of his Oakdale. Work by Jahns et al. (1959) in the Westford-Tyngsboro area has extended Emerson's Merrimack Quartzite along strike into the vicinity of the Nashua River area.

Billings (1956) called the entire group of rocks from Nashua, New Hampshire, to southeastern Maine the Merrimack Group, containing subdivisions of the Kittery, Eliot, and Berwick Formations in Maine (Hussey, 1962). This report proposes to use the name Merrimack Formation to describe this group of rocks in the Nashua River area, since the Kittery, Eliot, and Berwick subdivisions cannot be made with any certainty in Massachusetts or southeastern New Hampshire.

The Merrimack Formation, as defined in this report, comprises the metamorphosed calcareous siltstones east of the Wekepeke Fault (Peck, 1976) and includes unit 2 of Peck (1976), the eastern belt of Grew's Oakdale (1970) (unit DSd of Grew, 1973), and a portion of

Emerson's Oakdale Quartzite and Schists and Gneisses of Undetermined Age. Portions of the Merrimack and Oakdale Formations may be equivalent, but they cannot be correlated member by member.

Lithologic Description

The Merrimack Formation consists of metamorphosed interbedded calcareous siltstones, micaceous siltstones, and calcareous phyllites, with rare noncalcareous phyllite and quartzite beds.

The metamorphic grade of the Merrimack Formation varies from chlorite to actinolite zone. In the chlorite and biotite zones, the formation consists of interbedded siltstones and phyllites that weather dull brown. In the actinolite zone, the lithology consists of stratified fine-grained quartzofeldspathic granofels.

The beds range in thickness from a few centimeters to two meters and are uniformly thinly laminated. The typical grain size ranges from 0.01 to 0.35 mm, although rare coarser grained quartzites contain detrital grains of quartz and feldspar 0.1 to 0.7 mm in size, and a lens of graywacke with granules of quartz, feldspar, and shale fragments in a siltstone matrix occurs just north of the Pepperell quadrangle.

The Merrimack Formation is generally poorly exposed. In the chlorite and biotite zones, it weathers quickly to a brown soil containing numerous chips of siltstone. One roadside outcrop present in 1967 (Koteff and Volkmann, 1973) had decayed into a jumble of soil and fragments by 1975 (Koteff, 1975, personal commun.) The best exposures of the formation are found on the flanks of ridges supported by igneous rocks and the hills bordering the flood plain of the Nashua River.

The contact of the Merrimack Formation with the underlying Worcester Formation is gradational over a few meters to a few tens of meters. The contact has been drawn where carbonaceous phyllites of the Worcester Formation disappear and dark-green chlorite-rich calcareous phyllites in the Merrimack Formation appear. Near the contact between the Worcester and Merrimack Formations, dark-green phyllites in the Merrimack are abundant, but they become less prevalent elsewhere in the section.

Poor exposure, intense fold deformation (including isoclinal folds of extreme attenuation), and fault truncation make the thickness of the Merrimack Formation impossible to measure with any accuracy. Peck (1977, p. 244, Fig. 2, unit 2) estimated a thickness between 1220 to 2130 meters; however, his estimate is hampered by similar uncertainties. In the Nashua River area, the Merrimack is estimated to be more than 3000 to 4000 meters thick.

Micaceous calcareous siltstone member (ms)

This member consists of interbedded, thinly laminated siltstones and phyllites. Beds average 1 to 8 cm thick, although occasional beds reach 2 meters. The average grain size varies between 0.01 to 0.3 mm in diameter; however, locally beds containing detrital grains of quartz and plagioclase up to 0.6 mm in diameter occur. Rare lenses and layers of coarser grained (0.02 to 0.85 mm diameter) quartzites are distributed in the unit, particularly near the contact with member mqfg. Siltstone lenses containing monomict rip-up fragments of siltstone occur in a few localities (Shirley quadrangle, locality 12; Worcester North quadrangle, north shore of Wachusett Reservoir). A lens of graywacke containing granules of quartz, feldspar, and siltstone fragments in a siltstone matrix occurs just north of the Pepperell quadrangle. The quartz granules are typically rounded to subrounded and show undulose extinction. The smaller fragments are generally single grains of quartz, while the larger fragments consist of multigranular aggregates with straight to slightly crenulated grain boundaries and slight undulose extinction in each grain. The detrital grains of feldspar are generally rounded to subangular. Plagioclase is the dominant detrital feldspar, and detrital grains typically show albite twinning and some alteration. Rounded to subrounded fragments of myrmekite and polygranular aggregates of quartz and feldspar with straight grain boundaries also occur as detrital grains. Siltstone fragments are lensoidal and are distinguished from the silt matrix by a color difference.

In the biotite and chlorite zones of metamorphism, the member consists of light-gray to light-tan micaceous calcareous siltstone interbedded with gray micaceous phyllite and dark green-gray chlorite-rich phyllite. Approximately 65 percent of the unit is siltstone and 35 percent phyllite. The siltstones are composed mostly of quartz, muscovite, ankerite (sometimes calcite), chlorite, and detrital plagioclase. Thin brown laminae and spots of altered ankerite are evident on weathered surfaces. The phyllites contain muscovite, chlorite, ankerite or calcite, quartz, and some plagioclase. In the biotite zone, the siltstones begin to develop an interlocking grain texture and gain a blocky fracture. Biotite does not become abundant in most layers until the actinolite zone.

In the actinolite zone, the rock becomes a stratified, fine-grained, quartzofeldspathic granofels with a reddish or greenish tinge on fresh surfaces. The granofels is primarily composed of fine-grained (0.02 to 0.4 mm diameter) quartz, plagioclase, biotite, and actinolite or muscovite and garnet. Compositional layering is defined by differing modal proportions of biotite and plagioclase, and layers are typically separated by a thin muscovite or biotite film. Thin lamination, defined at this metamorphic grade primarily by biotite, persists but is not as pronounced as at lower grade. Less than 50 percent of the granofels at this grade contains disseminated actinolitic hornblende, and muscovite-bearing assemblages are common.

Quartzofeldspathic granofels member (mqfg)

Stratified quartzofeldspathic granofels, generally in the biotite to actinolite zones of metamorphism, comprises member mqfg. Beds are thinly laminated and average 3 to 10 cm in thickness, occasionally as much as 2 meters thick, and are defined by variation in mineral abundance between layers. The granofels consists mostly of fine-grained (0.02 to 0.6 mm diameter) quartz, plagioclase, and biotite.

In the chlorite and biotite zone, the granofels consists of thinly laminated gray-green calcareous siltstone with a blocky fracture. Beds are defined primarily by thin micaceous layers along bedding contacts. The granofels is composed primarily of quartz, plagioclase, carbonate, and minor amounts of muscovite, chlorite, or biotite.

In the actinolite zone, the granofels coarsens, develops an interlocking grain texture, and begins to lose some of the thin lamination. Here it consists mostly of quartz, plagioclase, biotite, and actinolite. Approximately 80 percent of the layers contain amphibole. Muscovite-bearing assemblages are rare.

The stratigraphic contact with member ms is gradational over a few tens of meters and has been placed in the chlorite and biotite zones of metamorphism where massively bedded (greater than 6-cm thick) siltstones and quartzites lacking a phyllitic parting become more than 50 percent of the exposed rock type. Lenses and beds of massively bedded calcareous sandstone and quartzite, occasionally exhibiting graded bedding, occur near the contact. A few distinctive thin layers of biotite-rich schist also occur near the contact.

The stratigraphic contact with members mbks and mps is not exposed.

Biotite-knot schist member (mbks)

Member mbks consists of a thinly laminated, massively bedded quartz-rich schist with distinctive 1-mm knots of biotite. The schist is composed primarily of fine-grained muscovite, quartz, biotite, and plagioclase. Bedding on an outcrop scale generally is not apparent. Fresh exposures of this rock have a blocky fracture atypical of schistose rocks.

The stratigraphic contact of member mbks with the surrounding quartzofeldspathic granofels member mqfg is not exposed, but is thought to be gradational because of the increasing frequency of thin schistose beds in the granofels member near the contact. The thickness of member mbks has been estimated at 220 meters (Fig. 5) in the map area (MF-957, Robinson, 1978).

Rusty weathering schist member (mps)

The rusty weathering, pyrrhotite-bearing schist of member mps is an enigmatic unit in the Merrimack Formation. In thin section the schist contains thin seams of fine-grained mica that form the dominant schistosity in the rock, cutting across a coarser grained, randomly oriented, aggregate of muscovite, quartz, and plagioclase. The intergrown muscovite, quartz, and plagioclase show vermicular textures in what may have been larger plagioclase grains. In outcrop, the schist appears foliated, and in some areas mica-rich foliation planes regularly spaced through the schist give it a banded appearance.

The schist contains sporadic, apparently isolated, blocks of granite and biotite-bearing quartzofeldspathic granofels typical of the granofels members in the Merrimack Formation. Feldspar in the granite blocks generally is partially altered to mica. Pyrrhotite is present in the schist in small amounts and occurs in some granite blocks.

This member is generally on strike with member mbks, but is separated from it by an intrusive body of Diorite and Monzonite and a fault truncation. Member mps is interpreted to be a sheared and hydrothermally altered equivalent of member mbks, which also contains a few exotic fragments of the adjacent granofels and granite units. The contact between mbks and the Chelmsford Granite is believed to be a fault, but field evidence does not rule out an intrusive contact.

OAKDALE FORMATION

Nomenclature, Historical Background, and Distribution

Emerson (1917, p. 61) first used the name Oakdale Quartzite to refer to fine-grained quartzites containing biotite or actinolite exposed near the village of Oakdale in West Boylston, Mass. Previously Emerson (1898, p. 17) had referred to the formation as the Worcester Quartzite and Perry and Emerson (1903) had described it in detail.

Grew (1970) changed the name to Oakdale Formation and redefined the Oakdale to include not only the Oakdale Quartzite of Emerson (1917) but also portions of the Paxton Quartz Schist of Emerson (Paxton Schist of Perry and Emerson, 1903) and subordinate pelitic schists.

In this report the Oakdale Formation is redefined to include the metamorphosed calcareous siltstones west of the Wekepeke and Pine Hill Faults (Peck, 1976; Grew, 1970; Castle _et al._, 1976) and coincides with the western Oakdale belt of Grew (1970) on strike northeast of the Oakdale type-locality of Emerson. The Oakdale Formation, thus defined, includes unit 5 of Peck (1976), but excludes the eastern belt of Oakdale of Grew (1970) (unit DSd of Grew, 1973) on strike with unit 2 of Peck (1976).

Lithologic Description

The Oakdale Formation in the Nashua River area consists of stratified quartzofeldspathic granofels with a few micaceous schist beds generally in the staurolite-kyanite zone of regional metamorphism. The quartzofeldspathic rocks are the metamorphosed equivalents of interbedded calcareous siltstones and phyllites found in the chlorite and biotite zone along strike to the south in the Worcester North quadrangle (Grew, 1970; Hepburn, 1976). The Oakdale Formation is similar, although not identical, in composition and bedding style to the previously described Merrimack Formation, and they may be equivalent. In the vicinity of the Fitchburg Pluton, the Oakdale Formation becomes a coarse-grained quartzofeldspathic gneiss.

The thickness of the Oakdale Formation is difficult to determine since the unit is intensely folded and is truncated by a fault along its eastern border. In this area the thickness is estimated as greater than 1400 meters (Fig. 5).

Quartzofeldspathic granofels member (oqfg)

Member oqfg, typical of the Oakdale Formation as a whole, consists of stratified quartzofeldspathic granofels. Beds average 2 to 12 cm in thickness, although occasionally are up to 1 meter wide. The bedding is expressed primarily by differing modal proportions of quartz, plagioclase, biotite, and muscovite or actinolite assemblages which comprise the granofels layers. The beds often show a thin lamination defined by biotite. The average grain size of quartz and feldspar varies between 0.02 to 0.7 mm. When fresh, the granofels has a red-brown to greenish color, caused primarily by disseminated red-brown biotite, and chlorite grown along tiny fractures. When weathered, the granofels develops a dull chocolate red-brown color and a "salt-and-pepper" appearance. Rare thin schist beds composed of muscovite, quartz, and biotite with occasional garnet porphyroblasts occur. Thin, light-colored calcareous beds, composed of coarse-grained plagioclase, quartz, amphibole, and in some cases calcite, help to define bedding. The calc-silicate layers comprise less than one percent of the member. Actinolitic hornblende generally is not as common in the granofels as in the Merrimack Formation, and less than 50 percent of the granofels contains hornblende.

Locally abundant thin calcareous veins composed of plagioclase, quartz, and, in many cases, hornblende and calcite both parallel and crosscut the compositional layering. The granofels layers sometimes show boudinage, with boudin necks filled with quartz, quartz-carbonate, or quartz-plagioclase segregations.

With increasing metamorphic grade toward the Fitchburg Pluton, the granofels becomes coarser grained with the concomitant loss of fine lamination. Locally the granofels becomes a coarse-grained quartzofeldspathic gneiss adjacent to and as inclusions in the granitic rocks of the Fitchburg Pluton.

Schist and granofels member (os)

Interbedded micaceous granofels, micaceous schist, and quartzofeldspathic granofels make up member os, a relatively minor subdivision of the Oakdale Formation. Member os is exposed in the sillimanite zone adjacent to the Fitchburg Pluton.

Beds range from 2 to 10 cm thick and consist of approximately 50 percent schist and micaceous granofels layers and 50 percent quartzofeldspathic granofels layers. The schist and micaceous granofels layers are composed of quartz, biotite, plagioclase, and muscovite, with sillimanite and garnet usually present. Sprays of fibrolitic sillimanite are intergrown with biotite and muscovite. The quartzofeldspathic granofels is composed of quartz, plagioclase, biotite, and amphibole.

The stratigraphic position of member os in the Oakdale Formation is unclear. Contacts of member os with member oqfg are not exposed, but are believed to be gradational. The estimated stratigraphic thickness of member os ranges between 0 and 230 meters (Fig. 5).

Cataclastic rocks and altered rocks

Cataclastic rocks and altered rocks of the Oakdale Formation occur in the vicinity of the Wekepeke Fault in the Shirley and Townsend quadrangles and are particularly well exposed in two quarries near the fault in the Shirley quadrangle (localities 7 and 18). The nomenclature of Higgins (1971) is followed in the description of the cataclastic rocks.

Mylonite and Protomylonite

Mylonite occurs as black bands of aphanitic rock 1 mm to 6 mm wide that are regularly spaced through the rock adjacent to the fault zone. The mylonites consist of angular to rounded quartz grains 0.01 to 1.0 mm in diameter distributed throughout a fine-grained recrystallized matrix of chlorite, epidote, quartz, and muscovite. Quartz grains show undulose extinction and are typically recrystallized to multigranular aggregates with granulated grain boundaries. Quartz is commonly replaced by chlorite and epidote along grain boundaries. Large porphyroblasts of quartz typically have trails of granulated quartz oriented parallel to fluxion bands. Fluxion structure is visible both macroscopically and microscopically. Some mylonites appear to have the capacity to flow and fill what appear to be tension gashes oriented at a high angle to the principal shear direction (Plate 3c).

Protomylonite occurs as black anastomosing bands 1 cm to 2 m wide containing visible fragments (2 mm to 10 cm diameter) of crushed quartz vein, altered rock, and mylonite. Textures and mineralogy are similar to those described for the mylonites. Mineral assemblages in the mylonites and protomylonites include

quartz + chlorite + epidote + muscovite ± calcite .

Altered Rock

In areas adjacent to zones of intense cataclasis related to the Wekepeke Fault, belts of Oakdale Formation showing textures and mineral assemblages indicative of retrograde alteration are common.

The rocks are thinly laminated and besides local brecciation show little evidence of cataclastic textures. The altered rocks consist of a granular aggregate of quartz surrounded by an intergrowth of epidote, chlorite, calcite, and muscovite. Most plagioclase feldspar shows alteration. Mineral assemblages include

quartz + chlorite + epidote + calcite ± muscovite ± albite ± magnetite ± pyrite .

ALUMINOUS SCHIST

Definition, Historical Background, and Distribution

The band of rock designated Aluminous Schist is located in the Townsend quadrangle situated near the eastern border of the Fitchburg Pluton. This rock was mapped by Emerson (1917) as Brimfield Schist, although it is not rusty weathering and lacks the general character of the unit as described by Emerson.

The band of Aluminous Schist in the Townsend quadrangle is not laterally continuous with, but is lithologically similar to, portions of the band of schist and phyllite along the southeastern border of the Fitchburg Pluton in the Fitchburg, Sterling, and Worcester North quadrangles mapped by Emerson (1917) as Worcester Phyllite and Boylston Schist, and by Grew (1970) as the western belt of his Holden Formation. Graded bedding preserved in the schist along the contact between the schist and the Oakdale Formation in the Fitchburg quadrangle (Peper and Wilson, 1978) demonstrates that the schist belt overlies the Oakdale Formation.

Lithologic Description

Unit as is composed of lustrous mica schist with rare quartzofeldspathic layers. Bedding is difficult to recognize except where quartzofeldspathic layers are interbedded with the schist. In the adjacent Fitchburg quadrangle the schist equivalent to unit as also contains gray graded-bedded pelite (unit DSgs of Peper and Wilson, 1978).

The schist is composed of a coarse-grained aggregate of muscovite, quartz, biotite, and plagioclase, commonly containing 3 to 5 mm-long staurolite and garnet porphyroblasts. Rare beds contain kyanite porphyroblasts. Garnets show a slight rotation highlighted by inclusions. Staurolites show an inner core with slightly rotated inclusion trails surrounded by an inclusion-free outer rim. At localities adjacent to the Fitchburg Pluton, fibrolitic sillimanite is sometimes intergrown with biotite and muscovite.

The estimated thickness of unit as in the map area is 0 to 235 meters (Fig. 5).

275-280-M.Y.-OLD GRANITE IN THE MILFORD-MASON, N.H., AREA

Nomenclature and Distribution

Aleinikoff (1978) has defined a granite with a 275-280 m.y. age in the Milford-Mason, N.H., area by U-Pb-Th zircon radiometric age determinations. At present this granite is unnamed and in this report will be designated "275-280 m.y. granite." Reconnaissance work by the writer and Aleinikoff indicates that intrusive bodies of the 275-280 m.y. granite are likely to occur in the Nashua River area; however, no occurrences of this granite are shown in MF-957 since the isotopic date postdated publication of the MF. It is now believed that most of the Fitchburg Granite unit Dfg in the Townsend Quadrangle is actually the 275-280 m.y. granite.

In the Milford, N.H., area the granite occurs as dikes and sills, and as small to moderate-sized plutons. Intrusive contacts are reported to be sharp (Aleinikoff, 1978, p. 60).

Lithologic Description

The 275-280 m.y. granite consists of a light-gray, unfoliated to indistinctly foliated, fine- to medium-grained granite composed of quartz, microcline, oligoclase, and biotite with minor amounts of primary muscovite. Biotite is generally present in amounts between 5 and 7 percent and muscovite is present around 1 percent. Accessory minerals include apatite and magnetite. Local pegmatitic segregations occur.

Radiometric Age

A $^{207}Pb/^{206}Pb$ zircon age of 275 to 280 m.y. has been determined for the granite in the Milford-Mason, N.H., area (Aleinikoff, 1978) (Table 1).

FITCHBURG GRANITE

Nomenclature and Historical Background

The Fitchburg Granite of Emerson (1917) is described as a massive, light-colored, medium-grained two-mica granite, with the type locality designated as Rollstone Hill in Fitchburg (Emerson, 1917, p. 232). Dale (1923, p. 354) reported that the Fitchburg Granite on Rollstone Hill has a measurable foliation.

Grew (1970) described the Fitchburg Granite in the Worcester area as a foliated two-mica granite similar to that described by Dale. Peper and Wilson (1978) in the Fitchburg and Ashby quadrangles and Hepburn (unpublished) in the Sterling quadrangle have subdivided the Fitchburg Granite into an eastern band of mildly foliated two-mica granite, a western band of foliated biotite-rich two-mica granite, and subordinate granodiorite bodies.

Numerous granite quarries, most now abandoned, are located in the Fitchburg Pluton area.

Lithologic Description

The Fitchburg Granite in the Nashua River area has been subdivided into two subunits based primarily upon differing modal contents of biotite. Both subdivisions consist of light-colored, indistinctly foliated to foliated granite and are in part hybrid rocks incorporating variable amounts of metasedimentary inclusions in differing degrees of assimilation.

Biotite granite containing less than 6 percent biotite (Dfg)

This subunit of the Fitchburg granite consists of a white to light-gray, indistinctly to well-foliated, fine- to coarse-grained granite composed of oligoclase, quartz, microcline, biotite, and often muscovite. Biotite is present i amounts less than 6 percent. Muscovite is frequently present and occurs in amounts less than 3 percent. Accessory minerals include garnet, magnetite, tourmaline, apatite, and zircon. Microcline and oligoclase feldspar are present in approximately equal proportions, although both may be heterogeneously distributed in the foliated rock types. Locally, especially near contacts with metasedimentary rocks or inclusions, the granite becomes pegmatitic or micropegmatitic and loses foliation.

Biotite granite containing 5 to 15 percent biotite (Dfbg)

This subunit of the Fitchburg granite consists of a light-gray, foliated, medium- to coarse-grained biotite granite and granite gneiss, composed of oligocl quartz, microcline, biotite, and typically muscovite. Biotite is present in amounts ranging between 5 to 15 percent. Muscovite may be present and occurs in amounts less than 3 percent. The foliation is defined by biotite screens and streaks. Locally the rock may be an augen gneiss. The distribution of microcline and oligoclase is variable between gneissic layers.

Radiometric Age

A Rb-Sr whole-rock age of 410 ± 12 m. y. has been determined for Fitchburg Granite located at Malden Hill, near Fitchburg, Mass. (Zartman and Naylor, in press). $^{87}Sr/^{86}Sr$ intercept = 0.7051 ± 0.0014. A Rb-Sr whole-rock age of 380 ± 13 m. y. has been determined for the granite at Millstone Hill, Worcester, Mass., which is a probable member of the Fitchburg Granite (Zartman and Naylor, in press). $^{87}Sr/^{86}Sr$ intercept = 0.7064 ± 0.0169. (Table 1).

CHELMSFORD GRANITE

Nomenclature, Historical Background, and Distribution

Chelmsford Granite was first used as an informal name by Currier and Jahns (1952) to describe a northeast-trending belt of granitoid rocks in the Westford-Chelmsford area. A general description of the Chelmsford and Ayer granite rocks is given by Jahns (1952) and Jahns et al. (1959).

Numerous granite quarries, both inactive and active, are located in the Chelmsford Granite belt. A reference map showing quarry locations and an outline of the historical development of the quarry operations is given by Skehan et al. (1967, pp. 152-153, Fig. 2).

In this report the name "Chelmsford Granite" is restricted in usage to a foliated biotite- and muscovite-bearing granite located in the northeast-trending belt of intrusive rocks situated northwest of the Clinton-Newbury Fault in the Ayer, Pepperell, and Nashua South quadrangles.

Lithologic Description

The Chelmsford Granite (Dcg) consists of a white to light-gray, indistinctly to well-foliated, fine- to coarse-grained granite composed of oligoclase, quartz, microcline, biotite, and muscovite. Mica is generally present in amounts less than 5 percent. Microcline and oligoclase feldspars are present in approximately equal proportions and are distributed homogeneously throughout the rock. Accessory minerals include garnet and magnetite.

Locally, the Chelmsford Granite becomes pegmatitic or micro-pegmatitic and contains no discernible foliation. Bodies of the granite are generally oriented subparallel to the regional foliation; however, contacts on an outcrop scale are distinctly discordant.

Radiometric Age

A $^{207}Pb/^{206}Pb$ zircon age of 383 m. y. has been determined for the Chelmsford Granite at Snake Meadow Hill, Westford, Mass. (Zartman and Naylor, in press). (Table 1).

DIORITE AND MONZONITE

Nomenclature, Historical Background, and Distribution

The Diorite and Monzonite unit forms a large lenticular north-south body and a few minor pods and dikes along the eastern border of the Pepperell quadrangle from Runnell's Bridge, Hollis, N.H., to Dunstable and Groton, Mass., where it merges with rocks associated with the Ayer Granite (Emerson, 1917, p. 222; Gore, 1976a). This unit was mapped and described by Emerson (1917, pp. 221-223) as the Dracut Diorite and associated Gabbro, and the exposures at Lovewell Pond and Hollis Depot (Pepperell northwest 9 th) were described in the text.

The nonspecific terminology of Diorite and Monzonite is used in this report since the diorite is far removed from and is not continuous with the type locality of the Dracut Diorite in Dracut, Mass., although it is presumably related to it.

Lithologic Description

The Diorite and Monzonite unit is an intrusive series. It has been subdivided into subunits which are locally gradational, but also possess crosscutting relationships. The subunits are described in order of increasing age.

Monzonite (DSm)

Consists of a well-foliated, medium- to coarse-grained biotite monzonite composed of oligoclase, microcline, biotite, and quartz. Oligoclase and microcline occur as subhedral augen. Biotite is present in amounts up to 10 percent and defines the foliation. Quartz is present in amounts less than 5 percent.

Quartz monzodiorite and monzodiorite (DSmd)

Consists of a medium- to coarse-grained, foliated to well-foliated, quartz monzodiorite and monzodiorite composed of plagioclase, microcline, biotite, quartz, and generally amphibole. Subhedral plagioclase phenocrysts, 1 to 3 mm in diameter, range in composition from andesine to oligoclase. Subhedral microcline phenocrysts average 3 to 10 mm in diameter. Amphibole is present in amounts less than 5 percent. Biotite makes up approximately 10 percent of the rock, typically occurring as knots or as rims surrounding amphibole. Quartz is present in amounts less than 20 percent. Euhedral sphene, 1 to 2 mm in diameter, is locally abundant as an accessory mineral.

are partially replaced by chlorite. Chlorite contains exsolved rutile needles. Biotite veins cut and separate the amphibolite from the enclosing quartz monzonite. Associated amphibole schists are composed of amphibole, plagioclase, biotite, and chlorite. Minor pelitic schists associated with the amphibolite consist of quartz, plagioclase, biotite, garnet, and sillimanite.

Soapstone (tc)

A small body of soapstone is located along a fault zone. The soapstone consists of carbonate, talc, chlorite, and amphibole. The soapstone was previously quarried at this location and is not presently exposed in place.

RADIOMETRIC AGES

Various igneous rocks in the Nashua River vicinity have been studied radiometrically and are summarized in Table 1. The radiometric ages of the intrusives, excluding K-Ar ages and some zircon ages from the New Hampshire portion of the Fitchburg Pluton, are generally near 400 ± 20 m.y. Field observations indicate that the igneous rocks within this time range consist of an older sequence of gabbro-diorite-granodiorite (420 to 400 m.y.) which is intruded by younger granites (400 to 380 m.y.).

These results imply a Silurian to Early Devonian age for the intrusive rocks (Silurian-Devonian boundary, 410 to 415 m.y.: Bottino and Fullagar, 1966) and an older age for the metasedimentary rocks they intrude. The radiometric ages tightly constrain and locally conflict with the Silurian and Devonian stratigraphic assignment of the metasedimentary rocks in the region. In general, the age relationships are consistent with the conclusion of a number of geochronologists in New England that the Acadian orogeny was a brief intense event occurring approximately 400 m.y. ago (Naylor, 1971; Lyons and Livingston, 1977; Gaudette et al., in press). Granites associated with and continuous with the granite at Malden Hill, Fitchburg, Mass., have a 410 ± 12 m.y. Rb-Sr whole-rock radiometric age (Zartman and Naylor, in press) and cut structural fabrics thought to be associated with Acadian deformation in the Fitchburg area (Peper and Wilson, 1978), which constrains but is consistent with this age determination for the Acadian orogeny.

It is interesting to note that the radiometric ages are only 10 to 20 m.y. younger than the radiometrically determined age of metamorphism and intrusion in the Inner Piedmont province of Virginia and North Carolina. This metamorphic event in the southern Piedmont is believed on the basis of radiometric ages to be Taconic (Rodgers, 1970), with the time of metamorphism at 430 m.y. and age of plutonism around 425 to 435 m.y. (Odom and Fullagar, 1973, p. 144). Acadian deformation and metamorphism in the southern Piedmont is generally believed to have occurred at 355 m.y. (Hatcher, 1978), which is considerably younger than Acadian ages in New England.

The distinct pre-Acadian zircon ages (600 to 475 m.y.) determined by Aleinikoff (1978), Besancon et al. (1977), and Naylor et al. (1969) for some layered gneisses and intrusive granitoid rocks in the New Hampshire portion of

Amphibole diorite and gabbro (DSdg)

Consists of a medium- to coarse-grained, nonfoliated to locally well-foliated amphibole diorite and gabbro composed of plagioclase, amphibole, and biotite with subordinate (less than 5 percent) orthoclase and quartz in interstitial micrographic intergrowths. Plagioclase is andesine-labradorite. Hornblendic amphibole and biotite are locally partially replaced by chlorite. Sphene is a characteristic accessory mineral.

Radiometric Age

A $^{207}Pb/^{206}Pb$ zircon age of 424 ± 6 m.y. has been determined for the Ayer Granite (Zartman and Naylor, in press) located in the Diorite and Monzonite strike belt in the Ayer quadrangle. Diorite from the Exeter Pluton, Exeter, N.H., has a Rb-Sr whole-rock age of 407 m.y. (Gaudette et al., in press).

MAFIC AND ULTRAMAFIC ROCK UNITS

Two small bodies of mafic and ultramafic rock types, closely associated with the belt of Diorite and Monzonite rocks, are located in the Pepperell quadrangle.

Amphibolite (am)

A small body consists of amphibolite and schist surrounded by foliated quartz monzodiorite (DSmd). The amphibolite is composed of amphibole, chlorite, biotite, and olivine. Amphibole and biotite the Fitchburg Pluton (from the Massabasic Gneiss as defined and mapped by Sriramadas (1966)) strongly conflict with the Silurian and Devonian stratigraphic assignment of metasedimentary rocks and the Late Silurian to Early Devonian age of plutonism in the region. The geologic significance of these zircon dates is presently unclear. They may indicate that

1) large inclusions of pre-Silurian rocks are caught up in the Acadian granite suite,
2) the stratigraphy in this area of the Merrimack Synclinorium includes rocks older than Silurian and regional lithotype correlations may need to be revised, or
3) the zircon dates are unreliable and reflect contamination with old detrital zircons.

The K-Ar isotopic ages of micas from intrusive rocks in southeastern New England generally indicate ages younger than Devonian and have been interpreted as Acadian orogeny uplift and erosion cooling ages (Zartman *et al.*, 1970), or reequilibration during Alleghanian metamorphism (Grew, 1970).

Table 1. Radiometric Ages

Rock Name	Location	Radiometric Age (in M.Y.)	Ref.	Notes (Method, etc.)
Ayer Granite	Clinton and Ayer quadrangles. Massachusetts	417 - 428 424 ± 6	5	$^{207}Pb/^{206}Pb$ age on zircon
Ayer Granite	Clinton quadrangle, Massachusetts	420 ± 50 410 ± 50 520 ± 60	6	Pb-Alpha age on zircon
Chelmsford Granite	Westford, Mass. Southeast Snake Meadow Hill	383	5	$^{207}Pb/^{206}Pb$ age on zircon
Chelmsford Granite (Listed as Ayer)	West Chelmsford, Mass. (Fletcher Quarry)	Muscovite 327 ± 17	4	K-Ar age on mineral separate
Fitchburg Granite (also called granite at Millstone Hill)	Worcester, Mass.	380 ± 13 366 ± 15 *1 Muscovite 379 *2	5	Rb-Sr whole rock age. $^{87}Sr/^{86}Sr$ intercept - 0.7064 ± 0.0169 *1 Rb-Sr whole rock age recalculated from data in Ref. 6 *2 Rb-Sr muscovite age recalculated from data in Ref. 6
Fitchburg Granite (also called granite at Malden Hill)	Fitchburg, Mass. Malden Hill	410 ± 12	5	Rb-Sr whole rock age. $^{87}Sr/^{86}Sr$ intercept - 0.705 ± 0.0014
Diorite in Fitchburg pluton	Leominster, Mass. (Leavitt Quarry)	Muscovite 233 ± 8 Biotite 241 ± 13	4	K-Ar age on mineral separate
Binary Granite in Fitchburg pluton	Candia, N.H.	Muscovite 231 ± 10 Biotite 221 ± 6	4	K-Ar age on mineral separate

Table 1. Radiometric Ages (Continued)

Rock Name	Location	Radiometric Age (in M.Y.)	Ref.	Notes (Method, etc.)
275-280 m.y. granite (Milford Granite in Fitchburg pluton of Aleinikoff, 1978)	Milford, N.H.	275 - 280*	1	$^{207}Pb/^{206}Pb$ age on zircon. *One sample shows anomalous 419 m.y. age due to inherited Pb
Intrusive gneiss in Fitchburg pluton	Milford, N.H.	463 - 467	1	$^{207}Pb/^{206}Pb$ age on zircon
Intrusive gneiss in Fitchburg pluton	Manchester, N.H.	600 - 620	7	$^{207}Pb/^{206}Pb$ age on zircon
New Hampshire Plutonic Suite in southeast New Hampshire and southwest Maine				
Diorite in Exeter pluton	Exeter, N.H., Southwest N.H.	400 - 450 (best estimate 407)	2	Rb-Sr whole rock age. $^{87}Sr/^{86}Sr$ intercept - 0.7050. Data discordant
Granodiorite to biotite granite in Webhannet pluton	Southwest Maine	391 ± 42 *1 403 ± 2 *2	2	*1 Rb-Sr whole rock age. $^{87}Sr/^{86}Sr$ intercept - 0.7050 ± 0.0031 *2 Pb-U zircon age
Biotite granite and binary granite in Lyman pluton	Southwest Maine	333 ± 18	2	Rb-Sr whole rock age. $^{87}Sr/^{86}Sr$ intercept - 0.7041 ± 0.0015 Pluton cuts Nonesuch River fault, southwest Maine (Hussey and Newberg, 1978)
Quartz diorite in Newburyport Complex	Northeast Mass. and adjacent N.H.	445 ± 15	5	$^{207}Pb/^{206}Pb$ zircon age, some scatter of data. Pluton intrudes Merrimack Group metasedimentary rocks, but apparently predates biotite grade regional metamorphism.

1. Aleinikoff, 1978
2. Gaudette, Kovach, Fairbairn, and Hussey, in press
3. Lyons and Faul, 1968
4. Zartman, Hurley, Kruger, and Giletti, 1970
5. Zartman and Naylor, in press
6. Zartman et al., 1965
7. Besancon et al., 1977

CHAPTER 3. STRUCTURAL GEOLOGY

REGIONAL SETTING

The Nashua River area is situated structurally on the eastern flank of the Merrimack Synclinorium (Billings, 1956) (Fig. 3). A sequence of Acadian tectonic events has been defined in the central Merrimack Synclinorium of Massachusetts (Quabbin-Ware area) by Peter Robinson and his students (Robinson, 1967, 1976; Field, 1975). Acadian deformation in the central Merrimack Synclinorium included 1) early isoclinal folds of extreme elongation overturned to the west (correlated in time with the nappes of the Bronson Hill Anticlinorium described by Thompson et al., 1968), 2) eastward backfolding of early isoclinal folds, and 3) eastward overthrusting and cataclasis. The early isoclinal folding is defined largely by lithotype correlation of units with the defined Bronson Hill stratigraphy (Field, 1975, pp. 18-19, 117-118) and is contested in part by some geologists working along strike to the south where the cataclasis and overthrusting associated with event 3 form the most conspicuous structural feature (Peper et al., 1976). These geologists assume that a complex stratigraphy is responsible for the lithotype distribution, rather than isoclinal fold repetition.

In eastern Connecticut there is evidence of an eastward-directed imbricate thrust zone (Peper et al., 1976; Peper and Pease, 1976; Wintsch, 1976) associated with isoclinal folding (Dixon and Lundgren, 1968). The basal thrust of this system is the Honey Hill-Lake Char

Fault of Dixon and Lundgren (1968) which strikes northeast into Massachusetts in the vicinity of the Clinton-Newbury and Burlington Fault zones (Skehan, 1968; Dixon and Lundgren, 1968; Castle et al., 1976). This structural development is correlative with tectonic events 2 and 3 of Robinson (1976).

NASHUA RIVER AREA

The stratified rocks in the map area generally have a northeast strike with dips varying from near horizontal to vertical. The simple map pattern masks the fact that the rocks have undergone several periods of deformation.

The rocks have been multiply deformed and display a variety of minor fold and foliation relationships visible on an outcrop scale. The analysis of minor fold and foliation relationships has produced the sequence of structural events summarized in Table 2.

The sequence of structural events is interpreted as follows, listed in order of decreasing age:

- D1 Formation of tight isoclinal folds (F1) concurrent with regional metamorphism (M1) and the development of regional schistosity (S1). (Minor F1 isoclinal folds shown in Plate 2a.)
- D2 Development of subhorizontal chevron folds (F2) and strain-slip cleavage (S2) associated with eastward and northeastward directed thrusts.
- D3 Broad open warping about a north-south axis (F3).
- D4 High-angle faulting along northeast-southwest and northwest-southeast trends. Northeast-southwest fault zones are accompanied by chevron folds with steep axial planes (F4), strain-slip cleavage, and schistosity (S4).

Table 2. Fold and Foliation Relationships

Deformation	Foliation	Folds
D4	S4	F4
High-angle faulting	Schistosity and slip cleavage with a steep dip developed in siltstones and pelitic rocks. Mylonite zones developed in quartzofeldspathic rocks	Tight chevron folds with axial planes parallel to strain-slip schistosity developed in siltstones and pelitic rocks. Chevron folds and kink folds with fractured limbs occasionally developed in quartzofeldspathic granofels
D3	S3	F3
Upright open folding	No associated axial plane foliation	Upright open warps with a general north-south axis
D2	S2	F2
Eastward-directed thrusts and folds	Subhorizontal schistosity and strain-slip cleavage developed in siltstones and pelitic rocks. Subtle foliation and fracture cleavage developed in quartzofeldspathic granofels. Foliation is axial planar to chevron folds and strain-slip folds	Northeast-trending subhorizontal to gently inclined tight chevron folds and strain-slip folds developed in nose and steeply dipping lower limb of larger folds. Fold axes meander in orientation forming a sinusoidal pattern. Several orders of parasitic folds are often developed on fold limbs. Inclined chevron folds with a near vertical upper limb and subhorizontal lower limb (F2 folds) developed in gently inclined upper limb of larger folds
D1	S1	F1
Northeast-trending isoclinal folding associated with regional metamorphism	Development of dominant regional schistosity axial planar to tight isoclinal folds	Development of northeast-trending tight isoclinal folds. Fold noses rarely seen. Parasitic folds on limbs of F1 folds were not observed

Table 2. Fold and Foliation Relationships (Continued)

	Metamorphism	Age Relationships
D4	Chlorite grade retrograde metamorphic zone typically developed adjacent to fault zone in quartzofeldspathic rocks	a) D4 faults cut and deform D2 folds b) D4 faults cut M1 metamorphic isograds and contact metamorphic isograds associated with the Fitchburg Granite c) Northeast-trending faults truncate Pennsylvanian-age granite in the Milford, N.H., area (Aleinikoff, 1978); however, a Pennsylvanian-age granite dike intrudes a minor high-angle fault near Manchester, N.Y. (Plate 3d) d) Northeast-trending faults truncate Pennsylvanian-age sediments in the Worcester, Mass., area (Grew, 1970) e) Jurassic-age lamprophyre dike cuts northeast-trending silicified fault zone in Milford, N.H., area (Aleinikoff, 1978)
D3		a) F3 folds deform S2 schistosity
D2	Partial recrystallization of micas in S2 foliation plane	a) F2 folds deform S1 schistosity and F1 folds (Plate 2b) b) Fitchburg Granite contains inclusions showing F2 folds and S2 schistosity
D1	M1: regional metamorphism development of mineral foliation and amphibole lineation. Helical inclusion trains in unit as garnet and staurolite indicate growth concurrent with deformation	a) Fitchburg Granite, Chelmsford Granite, and the Diorite-Monzonite intrusive suite postdate D1. The intrusives cut S1 foliation, contain metasedimentary inclusions with S1 foliation, and locally overprint M1 regional metamorphism with prograde and retrograde contact metamorphism

Minor Structural Features

Bedding

In outcrop exposures exhibiting bedding or compositional lamination, the dominant schistosity is parallel to the compositional layering. Exceptions occur in the few localities where early generation fold noses can be observed and the schistosity is axial planar to extremely tight isoclinal folds.

In MF-957 (Robinson, 1978), the symbol for bedding is used in the low metamorphic grade pelites and siltstones where it is probable that bedding is represent The symbol for schistosity parallel to compositional layering is used in the higher grade schists and granofels.

Graded and cross-laminated bedding have been observed in a few localities and have given valuable information regarding the stratigraphic section in the area.

Schistosity

In the metasedimentary rocks the major schistosity (S1) is shown primarily by parallel arrangement of muscovite and biotite and is the dominant feature in the medium-grade rocks.

The second schistosity (S2) in the metasedimentary rocks is generally more subtle than schistosity (S1) and is shown by a partial parallel recrystallization of muscovite forming a slip cleavage or fracture cleavage axial planar to crinkle folds or chevron folds. In the low-grade metamorphic rocks schistosity S2 may be more conspicuous than schistosity S1, particularly where chevron folding is intense.

Plate 2. Minor Structural Features

Photo location on following page: a, lower left corner; b, upper left corner; c, lower right corner; d, upper right corner.

a. Isoclinal F1 folds in the Oakdale Formation. Locality 18, Shirley quadrangle.

b. F1 isoclinal fold (axis orientation N45W/10NW) refolded by F2 chevron fold (axis orientation N70E/15NE) in the Worcester Formation. View northeasterly, Locality 8, Shirley quadrangle.

c. F2 chevron folds truncated by S2 strain-slip cleavage in a thrust zone in the Worcester Formation. Locality 14, Shirley quadrangle.

d. Dextral strain-slip cleavage (S4) developed in the Worcester Formation along the Wekepeke Fault zone. View of subhorizontal surface, Locality 8, Shirley quadrangle.

A late, steeply dipping, northeast-trending schistosity is developed adjacent to northeast-trending faults in the low metamorphic grade siltstone and pelites. Equivalent features in the quartzofeldspathic granofels are zones of cataclasis and mylonitization.

Foliation in igneous rocks is shown primarily by parallel orientation of biotite and muscovite plates, biotite schlieren, parallel orientation of elongated inclusions, and to a lesser extent by elongated feldspar and quartz grains.

Minor folds

Minor folds of compositional layering and schistosity are present on an outcrop scale.

Lineations

Lineations shown in the MF-957 (Robinson, 1978) map include mineral lineatio (long axes of amphibole prisms), axes of minor folds, foliation intersections, crinkle lineations, and slickensides. In the Townsend quadrangle, amphibole lineations in the S1 schistosity have the same orientation as F1 fold axes.

Major Folds

Figure 6 shows the location of inferred major folds in the Nashua River area. The folds are defined by stratigraphic correlations and minor structural features, and therefore are based on circumstantial evidence. The folds have been labeled in Figure 6 as F1n and F2n where F1 and F2 denote structural generation and n is an alphabet character specifying a particular fold.

Figure 6. FOLDS

F1a F1 Fold. Alphabet character identifies a specific fold.

F2a F2 Fold. Alphabet character identifies a specific fold.

Anticline.

Syncline.

Overturned Anticline

Overturned Syncline

See Figure 7 for Fault notation.

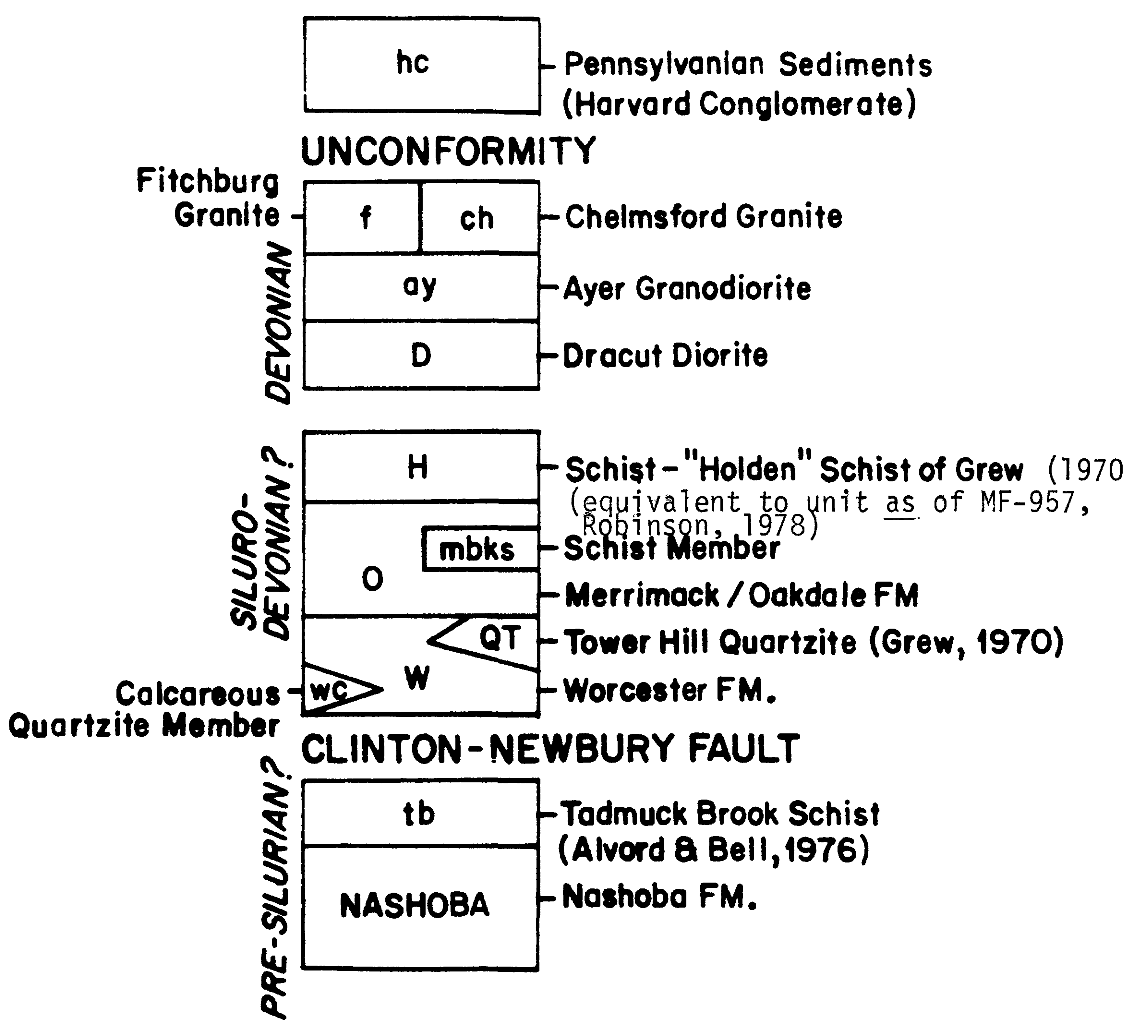
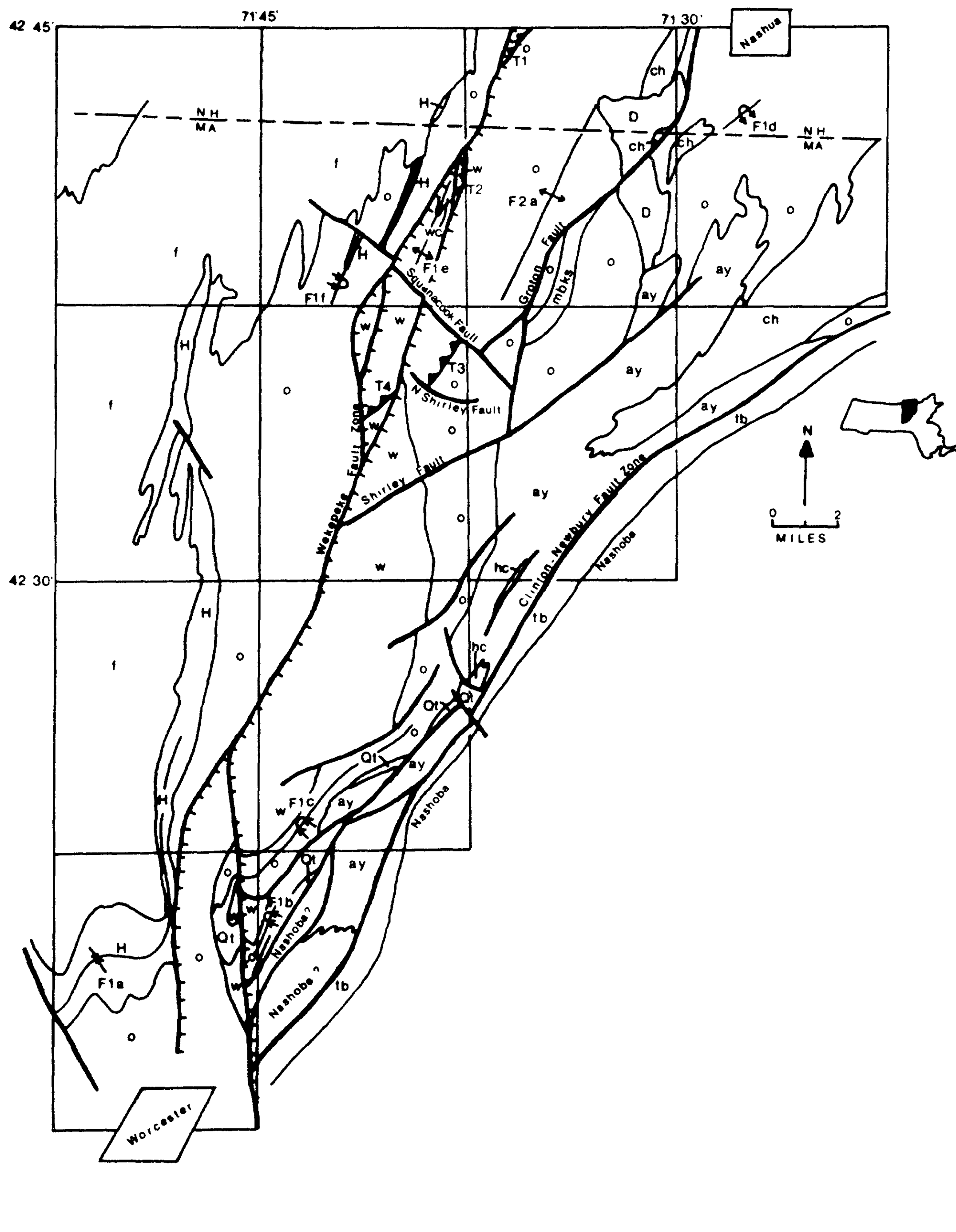


Figure 6. MAJOR FOLDS



Fold F1a in the pelitic schist bordering the Fitchburg Pluton has been extended from the geologic mapping of Tucker in the Wachusett Mountain area, Mass. (Tucker, 1978).

Folds F1b and F1c in the Shrewsbury and Clinton quadrangles are inferred from the lithologic correlation of the pelitic schists of the Worcester Formation (lithotype belt 4, Fig. 4) with the interbedded quartzite and graphite schist of the Tower Hill Quartzite (lithotype belts 2 and 1). An outcrop exposure of a F1 synformal fold in the Worcester North quadrangle (Hepburn, 1976, pp. 374-375, stop 4) apparently lies on the axial trace of fold F1b. The existence of folds F1b and F1c is also supported by the rapidly widening belt of Merrimack Formation northeast of the Clinton quadrangle in the Shirley, Pepperell, Nashua South 7-1/2' quadrangles and the Manchester 15' quadrangle. Fold F1d has been observed in the extensive road-cut exposures in the Merrimack Formation along Rt. 3 in Massachusetts just south of the New Hampshire state line.

Folds F1e and F1f occur in the area that has been mapped in detail. Fold F1e is inferred from the distribution of calcareous quartzite (unit wcs) in a fault-bounded wedge of Worcester Formation. However, sedimentary top structures were not observed in the area and there is a possibility that a change in the sedimentary facies may be the cause of the map pattern. S2 schistosity in this area cuts across the axis of the proposed fold and is not folded into an arch, implying that the proposed fold would be F1, and that little post-D2 rotation along the borders of the D4 faults has occurred outside of the fault zones in this area.

Fold F1f has been defined by lithotype correlation of the garnet-staurolite schist (unit as) and quartzofeldspathic granofels (unit oqfg) in the Townsend quadrangle (as mapped by Robinson, 1978) with units DSgs and DSobg, respectively, of Peper and Wilson (1978) in the Fitchburg quadrangle. The actual fold closure has not been observed; therefore the map pattern could be described as a stratigraphic lens of schist in the quartzofeldspathic granofels. However, the fold interpretation is consistent with extremely tight F1 minor folds that plunge gently northeast in this area. Synformal folds of quartz veins within the schist (locality 23) near the probable closure of fold F1f further supports the fold interpretation.

A broad F2 antiform (fold F2a) occurs along the Nashua River in the Pepperell quadrangle. Deformation associated with D2 appears to become less intense and die out to the northeast.

Faults

Regional faults cause discontinuities in metamorphic grade in the Nashua River area and cause difficulties in assigning regional stratigraphic correlations. Figure 7 shows the location of faults in the Nashua River area and adjacent areas.

Clinton-Newbury Fault

The change from sillimanite zone to biotite zone along the southeast boundary of the Nashua River area coincides generally with the trace of the Clinton-Newbury Fault (Skehan, 1968; Essex Fault of Castle *et al.*, 1976). The Clinton-Newbury Fault is a regionally

Figure 7. FAULTS

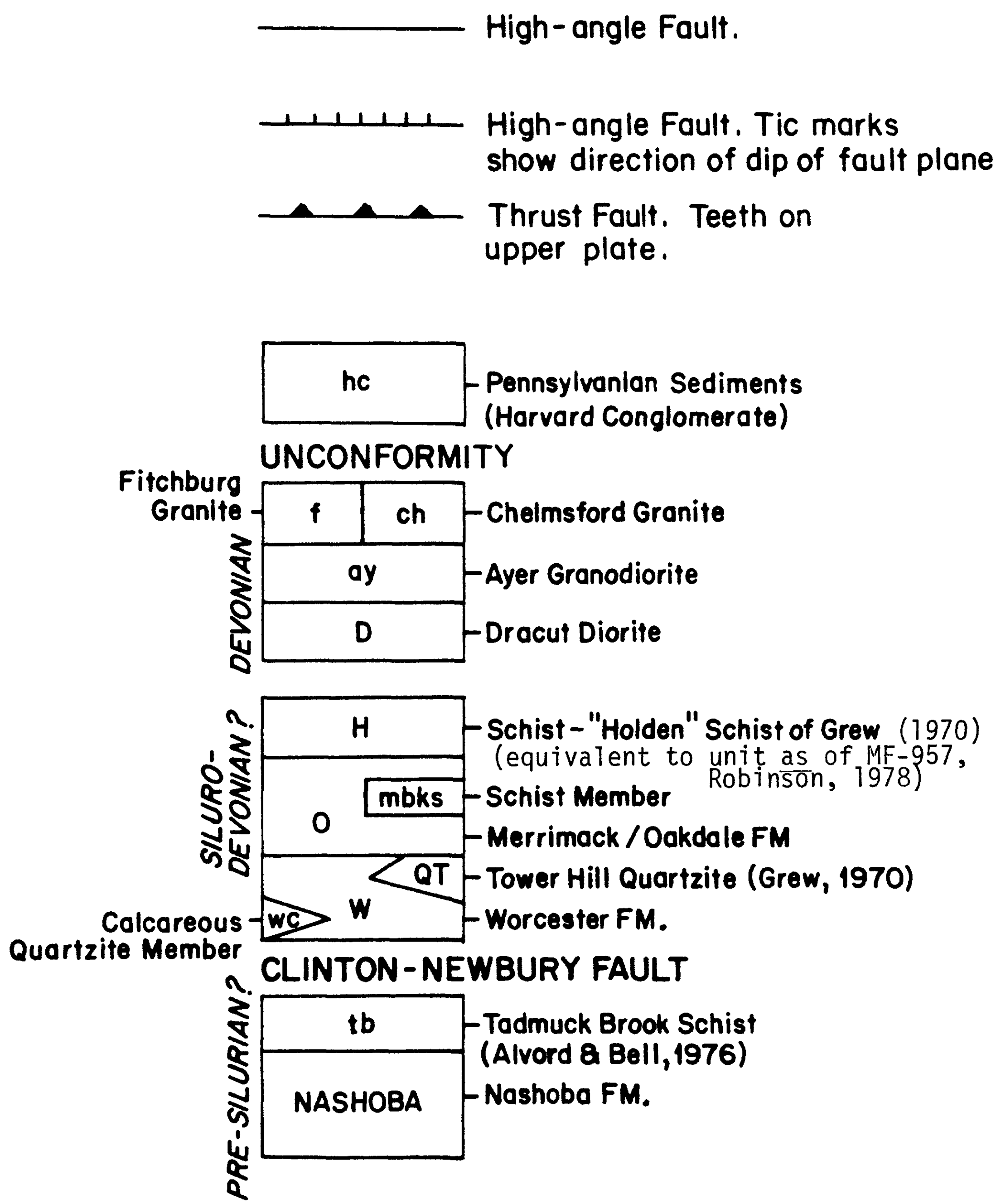
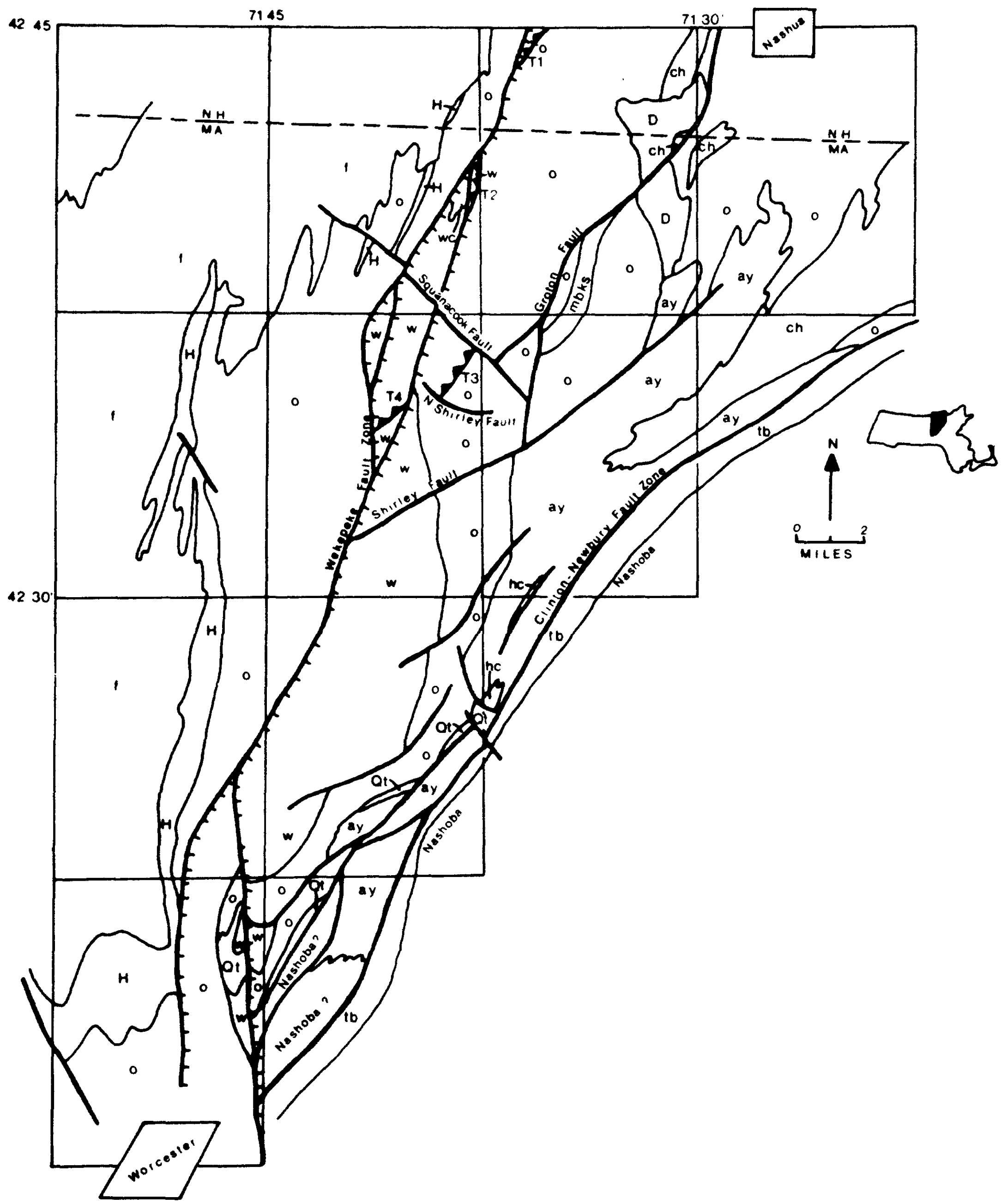


Figure 7. FAULTS



prominent break separating terranes of different metamorphic grade, structural trend, and lithology. In the Worcester-Clinton-Ayer region, the Clinton-Newbury Fault is characterized by a set of broad, poorly defined zones of mylonite and cataclastic rock between the Ayer Granite and Tadmuck Brook Schist (Gore, 1976b; Peck, 1976). Locally a well-developed "button-schist" phyllonite occurs in the Tadmuck Brook Schist along the fault zone. The gneiss at Bare Hill Pond in the Hudson, Mass., quadrangle (Hansen, 1956) lies along the trace of the Clinton-Newbury Fault and is predominantly cataclastic diorite to granodiorite, presumably related to the Ayer Granite. North of Bare Hill Pond a thin deformed band of Harvard Conglomerate is bordered on both sides by the cataclastic gneiss.

It should be noted, however, that not all metamorphic isograds in the vicinity of the fault are related to the metamorphic discontinuity along the Clinton-Newbury Fault. In the Ayer area, the andalusite-sillimanite isograd occurs in the Tadmuck Brook Schist east of the fault zone. The location of this isograd cannot be related to retrograde metamorphism during faulting since the andalusite porphyroblasts are euhedral and extremely coarse grained (2.5 to 10 cm in length). A phyllonite of Tadmuck Brook Schist along the Clinton-Newbury Fault (Rt. 4 interchange on Rt. 3) contains watermelon-seed shaped pods of andalusite partially replaced by sericite in an anastomosing mica foliation, indicating that here mylonitization postdated growth of the andalusite porphyroblasts.

Wekepeke Fault zone

The map area is divided in half by a high-angle fault zone that coincides with the northwestern metamorphic discontinuity juxtaposing actinolite-zone calcareous siltstones of the Oakdale Formation against andalusite- to chlorite-zone pelites of the Worcester Formation. This fault was first recognized by Tilton (1896) in the Nashua River area and was shown by Novotny (1961) to be a fault of regional significance. It was mapped by Peck (1975) in the Clinton, Mass., quadrangle as the Wekepeke Fault. The Pine Hill Fault of Grew (1970) may be the southwestward extension of this fault (Castle et al., 1976). Rodgers (1970) postulated direct or en echelon continuity of this fault with the Flint Hill Fault in the Mt. Pawtuckaway, N.H., quadrangle (Freedman, 1950) and extrapolated the fault into the Casco Bay area of Maine. Recent work by Hussey (1976, personal commun.) in the Berwick, Me., quadrangle appears to corroborate this fault extension into the Nonesuch River Fault and possibly the Norumbega Fault in Maine (Osberg, 1974). The terminology "Wekepeke Fault" is used for this fault in the Nashua River area since the fault has not been traced continuously into the Flint Hill Fault.

The Wekepeke Fault splits into three branches north of Shirley Lake (Shirley quadrangle) which remerge to the northeast near the intersection of Beaver Brook and Gulf Brook (Townsend quadrangle). The intensity of cataclastic deformation is variable along the fault zone, with areas of extensive silicification and retrograde alteration interspersed between areas of intense mylonitization. Mylonite has preferentially developed in the quartzofeldspathic rocks, while the pelites show only the development of slip cleavage and slickenside surfaces.

Exposures of mylonite, silicified mylonite, and quartz veins along the fault trace indicate that the main break of the fault zone dips 60° to 70° southeast. Secondary shear zones and silicified zones west of the dominant break dip southeastward at shallower angles (25° to 30°).

Quarries developed adjacent to the Wekepeke Fault in the Shirley quadrangle provide excellent exposure of the cataclastic rocks associated with the fault zone (localities 7 and 18)(example shown in plate 3a). Early mylonitization, associated with concurrent parallel quartz-vein development, form thin semicontinuous mylonite bands a few millimeters to centimeters in thickness that are periodically spaced through the quartzofeldspathic granofels subparallel to S1 schistosity. Progressive mylonite development associated with minor block rotation during fault movement produced oblique truncation of mylonite and quartz veins (locality 18) (Plate 3b). Mylonite bands display a capacity for flow, filling what appear to be tension fractures oriented perpendicular to the principal shear direction (Plate 3c). Steeply dipping mylonite zones oriented parallel to the main fault zone cut an earlier mylonite with a shallower dip at locality 18.

Fault motion, as indicated by drag folds, is predominantly dip slip, but a component of right-lateral slip is indicated by right-lateral drag along some mylonite surfaces. A pervasive steeply dipping right-lateral slip cleavage has developed in the pelites adjacent to the fault (Plate 2d) and is probably related to this right lateral component of movement. A conjugate set of northeast-trending, steeply-dipping slip planes showing tensional displacement has developed in the pelites adjacent to the fault zone.

Thrust faults

Four thrust faults mapped in the Nashua River area delineate zones of intense slip and strain related to deformation 2 (Fig. 7). The thrusts are not a discrete break but are zones a few meters to tens of meters wide where S2 slip cleavage is locally intense, disrupting and truncating sedimentary layering. The extent of displacement along these zones is not known and may not be extensive.

An excellent exposure along one of these thrust zones occurs at locality 14 (Plate 2c) in the Worcester Formation in the Shirley quadrangle. In this locality the interbedded siltstone and graphitic pelite have developed a strong subhorizontal slip cleavage with layers of intense slip spaced a few inches apart. Between these layers of intense slip, small isolated fold noses of siltstone occur in a homogeneous matrix of graphitic pelite. In this locality the tectonic transport is northeast.

Northeast-trending high-angle faults

Several other northeast-trending high-angle faults occur in the area mapped in detail, but are not as well exposed or as extensive as the Wekepeke Fault. In places their existence may be questioned. These faults truncate metamorphic isograds and D2 structures and therefore are post-D2.

Plate 3. Faults

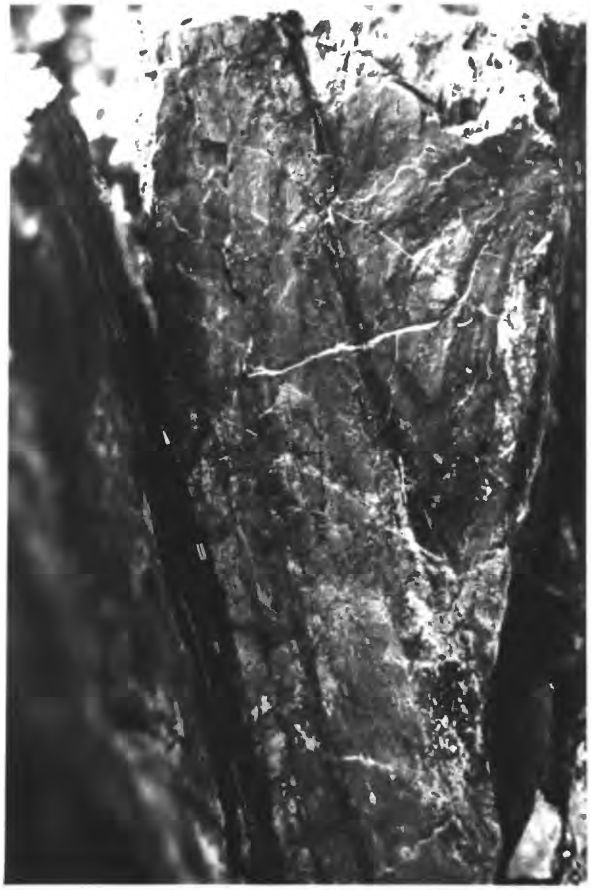
Photo location on following page: a, lower left corner; b, upper left corner; c, lower right corner; d, upper right corner.

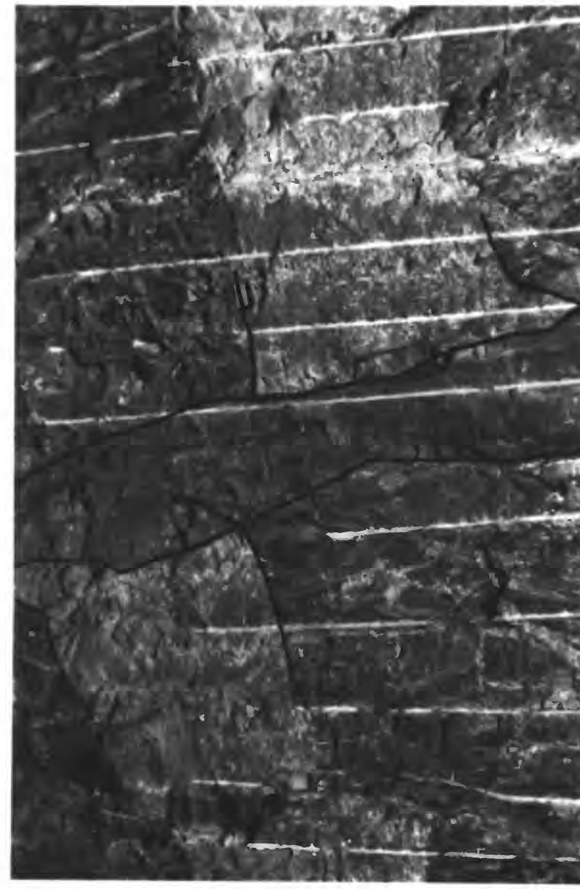
a. Mylonite in the Oakdale Formation in the Wekepeke Fault Zone. Locality 7, Shirley quadrangle.

b. Mylonite zone in the Oakdale Formation showing progressive mylonite development. Early mylonite (gray band) is folded and truncated by shear along a mylonite oriented subparallel to the earlier mylonite. Drag indicates displacement of upper plate to the east. Northerly view of a vertical surface, Locality 18, Shirley quadrangle.

c. Mylonite zone in the Oakdale Formation. Small veins of mylonite (black) have flowed into fractures in the rock oriented at a high angle to the slip direction. Drag indicates displacement of upper plate to southeast. Northerly view of a vertical surface, Locality 18, Shirley quadrangle.

d. Dike of fine-grained biotite granite intruding along a vertical offset in the Massabesic Gneiss Complex near Manchester, New Hampshire. The granite dike has been correlated with the 275 to 280 m.y. granite. The vertical drill holes are approximately five to six feet apart.





The Shirley Fault, named for its occurrence south of the town of Shirley in the Shirley quadrangle, is defined by a zone of sheared phyllite along its length. Displacement of the contact between the Worcester and Merrimack Formations across the fault appears to be minor; however, the fault appears to truncate andalusite and biotite isograds in the Worcester Formation. A few exposures of graphitic phyllite that occur along this fault to the northeast in the Ayer quadrangle (Gore, personal commun.) may be slivers of sheared Worcester Formation caught up in the fault zone.

The Groton Fault strikes northeast from Groton toward Dunstable, Mass., in the Ayer and Pepperell quadrangles. The fault is defined on the basis of sporadic exposures of mylonite and truncations of lithologic units. Unit mbks (Fig. 6) is truncated southeast along strike by the fault in the Ayer quadrangle and a small body of Chelmsford Granite appears to be faulted against mylonitic schists near Dunstable, Mass., in the Pepperell quadrangle. A small body of soapstone in Groton, Mass., is located along a minor branch of this fault.

Unit mbks is truncated by the Groton Fault along its entire extent. The offset of the Diorite and Monzonite (DSmd, DSdg as mapped by Robinson, 1978, in MF-957) pluton in the Pepperell quadrangle, defined by a zone of well-foliated, fine-grained diorite, appears to be slight. The implication is that this fault may have been periodically active, with displacement beginning before intrusion of the Diorite and Monzonite pluton. This circumstantial evidence of Paleozoic fault movements and the apparent lack of any significant Mesozoic displacement appears consistent with the fact that this fault zone lacks the silicification typical of Mesozoic faults elsewhere in New England.

Northwest-trending high-angle faults

Northwest-trending high-angle faults appear to offset and truncate some northeast-trending faults in the Nashua River area; however, the northeast-trending Wekepeke Fault appears to offset the northwest-trending faults in the region.

The Squanacook Fault runs northwest along the path of the Squanacook River from Groton to Townsend. The fault is poorly exposed, and cataclastic or silicified zones related to the fault have not been observed.

The fault has been inferred from

(1) the apparent offset of the aluminous schist unit (unit H, Fig. 7) in the Townsend quadrangle,

(2) the truncation of the Groton Fault and the actinolite zone metasedimentary rocks southeast of the Groton Fault, and

(3) the abrupt change in structural orientation of the Merrimack Formation across the fault in West Groton.

The North Shirley Fault, located south of the town of North Shirley, Mass., in the Shirley quadrangle, is poorly exposed. It is mapped on the basis of the abrupt truncation of sandstone layers in the Merrimack Formation near North Shirley.

CHAPTER 4. METAMORPHISM

INTRODUCTION

Metasedimentary rocks in the Nashua River area are in the chlorite to biotite metamorphic zones east of the Wekepeke Fault and in the actinolite to sillimanite metamorphic zones near the belts of plutonic intrusions to both the east and west of the central metamorphic low. Isograds are generally subparallel to the northeasterly trend of rock units.

Two general rock types, pelite and calcareous siltstone, comprise the metasedimentary section. In the pelitic rocks, various isograds have been mapped based on the first appearance of index minerals biotite, garnet, andalusite, staurolite, and sillimanite. In the calcareous siltstones, isograds have been mapped on the first appearance of biotite and actinolite. Locally the mineral assemblages show retrograde alteration. Table 3 lists simplified mineral formulas used in balancing simple reaction equations. Tables 4 and 5 summarize the observed mineral assemblages in the various metamorphic zones.

Thompson and Norton (1968) introduced the terms "simple" and "complex" to describe types of reactions in model chemical systems, such as the K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (KFMASH) system. Simple reactions are continuous reactions that may be balanced using stoichiometric coefficients appropriate to specified components of the mineral phases. Reactions in the end-member KFASH and KMASH systems are limiting cases to simple reactions in the KFMASH system.

Table 3. Simplified Mineral Formulas Used in Balancing Simple Reaction Equations

Mineral Name	Abbreviations	Simplified Formulas
Kyanite	Kya	Al_2SiO_5
Andalusite	And	Al_2SiO_5
Sillimanite	Sil	Al_2SiO_5
Staurolite	Sta	$(Fe,Mg)_2Al_9Si_4O_{22}(OH)_2$
Almandine	Alm	$(Fe,Mg)_3Al_2Si_3O_{12}$
Grossular	Gr	$Ca_3Al_2Si_3O_{12}$
Chlorite	Chl	$(Fe,Mg)_7Al_4Si_4O_{15}(OH)_{12}{}^*$
Biotite	Bio	$K(Fe,Mg)_3AlSi_3O_{10}(OH)_2{}^*$
Muscovite	Mus	$KAl_3Si_3O_{10}(OH)_2{}^*$
Margarite	Mar	$CaAl_4Si_2O_{10}(OH)_2{}^*$
K-Feldspar	Ksp	$KAlSi_3O_8$
Plagioclase	Pl	$CaAl_2Si_2O_8$ -- $NaAlSi_3O_8$
Diopside	Di	$Ca(Mg,Fe)Si_2O_6$
Amphibole	Am	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2{}^*$
Zoisite	Zo	$Ca_2Al_3Si_3O_{12}(OH)$
Calcite	Cc	$CaCO_3$
Dolomite (Ankerite)	Dol	$Ca(Mg,Fe)(CO_3)_2$
Quartz	Qtz	SiO_2
Magnetite	Mgt	Fe_3O_4
Ilmenite	Ilm	$FeTiO_3$
Sphene	Sp	$CaTiSiO_5$
Graphite	Gra	C

*These compositions may be modified by a Tschermak component $(Fe,Mg)SiAl_{-2}$.

Since Fe and Mg are preferentially partitioned between coexisting phases, simple reactions are the result of two effects, one involving the Fe- or Mg-components and the other involving Fe-Mg exchange. Reactions involving mineral phases that allow substitution of a (Fe,Mg)SiAl$_{-2}$ component (Tschermak substitution), such as chlorite and the micas, have an additional set of independent stoichiometric relations necessary to describe equilibria. In reactions involving two or more phases allowing Tschermak substitution, these additional stoichiometric relations can be written concisely as exchange equilibria between the mineral phases. Simple reactions in general correspond to continuous displacements of three-phase fields on an AFM diagram and would be observed as a change in the relative proportions of phases in the rock with changing metamorphic conditions.

Complex reactions are discontinuous reactions and reflect a distinct change in the topology of coexisting phases. These reactions generally affect a large range of bulk composition and are independent of the proportions of the relevant phases, thus producing easily observed changes that are most suitable as isograds in metamorphic rocks (Thompson, 1957, p. 856). In general, each complex reaction may be regarded as the sum of two or more simple reactions. The right-hand side of each reaction as written is the prograde assemblage.

PELITIC ROCKS

Rocks in the Worcester Formation and unit <u>as</u> comprise the bulk of the noncalcareous pelitic rocks. Rocks in the Worcester Formation are exposed in the chlorite to andalusite zones of metamorphism.

Table 4. Observed Mineral Assemblages in Pelitic Rocks

	Worcester Fm.									Unit as				Worcester Fm. Retrograde Assemblage	
	Chlorite Zone			Biotite Zone			Garnet Zone	Andalusite Zone		Kyanite-Staurolite Zone		Sillimanite Zone			
Quartz	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Muscovite	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Margarite														x*2	x*2
Chlorite	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Biotite					x	x	x	x	x	x	x	x	x		x
Plagioclase		x	x							x	x	x	x		
K-feldspar		x													
Almandine							x		x*1	x	x	x	x		
Staurolite										x	x		x		
Andalusite									x*2						
Kyanite											x				
Sillimanite												x	x		
Carbonaceous material	x	x	x	x	x	x	x	x	x					x	x
Ilmenite	x		x	x		x		>x?	x?	x	x			x*3	x*3
Magnetite				x	x	x	x	x?	x?	x					
Pyrite	x		x												
Tourmaline										x		x	x		
An =		0-2								25	28-30	22 - 25			

*1 – Garnet has been partially to totally replaced by chlorite.

*2 – Andalusite has been partially to totally replaced by an intergrowth of muscovite and margarite micas.

*3 – Ilmenite has been partially replaced by leucoxene.

Unit as is exposed in the kyanite-staurolite zone of regional metamorphism and is in the sillimanite zone near plutonic contacts. Metamorphic reactions in pelitic rocks have been summarized by Thompson and Norton (1968), Albee (1965), and Thompson (1976a). The following descriptions of metamorphic zones are listed in order of increasing metamorphic grade.

Chlorite Zone

Carbonaceous phyllites of the Worcester Formation in the chlorite zone are generally dark gray to green-gray in color. Typical assemblages include

> quartz ± detrital plagioclase (albite) ± detrital potassium feldspar (frequently altered) + muscovite + chlorite + ilmenite + carbonaceous material ± pyrite

Biotite Zone

The biotite zone marks the appearance of biotite in the pelitic rocks. Little change in appearance from the chlorite zone is observed in the graphitic pelites of the Worcester Formation. Typical assemblages include

> quartz ± plagioclase + muscovite + chlorite ± biotite + magnetite + carbonaceous material ± ilmenite

The first appearance of biotite may be caused by a complex reaction of the type

$$\text{Chl} + \text{Ksp} \rightarrow \text{Bio} + \text{Mus} + \text{Qtz} + H_2O$$

which is related to the simple reaction (Thompson and Norton, 1968, p. 327; Thompson, 1979)

$$3\ Mg_7Al_4Si_4O_{15}(OH)_{12}[Chl] + 13\ KAlSi_3O_8[Ksp] \rightarrow$$
$$7\ KMg_3AlSi_3O_{10}(OH)_2[Bio] + 6\ KAl_3Si_3O_{10}(OH)_2[Mus] +$$
$$12\ SiO_2[Qtz] + 5\ H_2O\ ,$$

and also to the exchange reactions

$$MgSiAl_{-2}[Mus] \rightleftharpoons MgSiAl_{-2}[Bio]\ ,$$
$$MgSiAl_{-2}[Chl] \rightleftharpoons MgSiAl_{-2}[Bio]\ ,$$

and the analogous $FeMg_{-1}$ exchange reactions. The importance of Tschermak components in reactions relevant to the biotite isograd has been discussed by Thompson (1979). Detrital potassium feldspar has been observed only in granule conglomerate layers in the Worcester Formation, and many of the granofels layers may not contain potassium feldspar in the chlorite zone. In these rocks, biotite was likely produced by a complex reaction involving some phases with components not represented on the AFM diagram

$$Gra + Mgt + Mus + Qtz + H_2O \rightarrow Bio + Chl + CO_2\ ,$$

which is related to the simple reaction (Thompson, 1972, p. 32)

$$13\ C[Gra] + 26\ Fe_3O_4[Mgt] + 12\ KAl_3Si_3O_{10}(OH)_2[Mus] +$$
$$24\ SiO_2[Qtz] + 36\ H_2O \rightarrow 12\ KFe_3AlSi_3O_{10}(OH)_2[Bio] +$$
$$6\ Fe_7Al_4Si_4O_{15}(OH)_{12}[Chl] + 13\ CO_2\ .$$

Chloritoid is reported from the Worcester Formation in the biotite zone in the Worcester area (Grew, 1970).

Garnet Zone

The garnet isograd marks the first appearance of almandine in the pelitic rocks. Characteristic mineral assemblages in the Worcester Formation include

quartz + muscovite ± plagioclase + chlorite + biotite ± garnet + magnetite + carbonaceous material

In these rocks the typical reaction of the first appearance of almandine garnet is probably reactions of the type (Thompson and Norton, 1968, p. 323; Thompson, 1972)

$$\mathrm{Chl + Mus + Qtz \rightarrow Alm + Bio + H_2O},$$

$$\mathrm{6\ Fe_7Al_4Si_4O_{15}(OH)_{12}[Chl] + KAl_3Si_3O_{10}(OH)_2[Mus] + 15\ SiO_2[Qtz] \rightarrow 13\ Fe_3Al_2Si_3O_{12}[Alm] + KFe_3AlSi_3O_{10}(OH)_2[Bio] + 36\ H_2O},$$

or

$$\mathrm{Gra + Mgt + Mus + Qtz \rightarrow Bio + Alm + CO_2},$$

$$\mathrm{C[Gra] + 2\ Fe_3O_4[Mgt] + KAl_3Si_3O_{10}(OH)_2[Mus] + 3\ SiO_2[Qtz] \rightarrow KFe_3AlSi_3O_{10}(OH)_2[Bio] + Fe_3Al_2Si_3O_{12}[Alm] + CO_2},$$

or a complex reaction of the type

$$\mathrm{Gra + Mgt + Mus + Qtz + Chl \rightarrow Bio + Alm + H_2O + CO_2}.$$

Andalusite Zone

The andalusite isograd marks the first occurrence of the chiastolite variety of andalusite in the carbonaceous pelites of the Worcester

Formation. The andalusite-bearing assemblages show retrograde alteration; however, relict textures indicate the probable prealteration assemblages included

quartz + muscovite + chlorite ± biotite ± garnet ± andalusite + carbonaceous material ,

quartz + muscovite + chlorite ± plagioclase ± biotite + carbonaceous material .

The appearance of andalusite in these rocks is likely related to a complex reaction of the type

$$\text{Chl} + \text{Mus} + \text{Alm} + \text{Qtz} \rightarrow \text{And} + \text{Bio} + H_2O ,$$

which is closely related to the following simple reactions that may be responsible, in rocks of restricted composition, for the first appearance of andalusite:

$$\text{Chl} + \text{Mus} + \text{Qtz} \rightarrow \text{And} + \text{Bio} + H_2O ,$$

$$3\ Fe_7Al_4Si_4O_{15}(OH)_{12}[\text{Chl}] + 7\ KAl_3Si_3O_{10}(OH)_2[\text{Mus}] + SiO_2[\text{Qtz}] \rightarrow 13\ Al_2SiO_5[\text{And}] + 7\ KFe_3AlSi_3O_{10}(OH)_2[\text{Bio}] + 18\ H_2O ,$$

$$\text{Alm} + \text{Mus} \rightarrow \text{And} + \text{Bio} + \text{Qtz} ,$$

$$Fe_3Al_2Si_3O_{12}[\text{Alm}] + KAl_3Si_3O_{10}(OH)_2[\text{Mus}] \rightarrow 2\ Al_2SiO_5[\text{And}] + KFe_3AlSi_3O_{10}(OH)_2[\text{Bio}] + SiO_2[\text{Qtz}] .$$

Retrograde alteration of andalusite schists

The andalusite-bearing carbonaceous pelites of the Worcester Formation have reequilibrated under biotite-zone conditions. Andalusite porphyroblasts are partially or completely replaced by an intergrowth of muscovite and margarite. (Chemical analysis of margarite is given in Appendix II.) Garnet porphyroblasts are partially or completely replaced by a chlorite, quartz, and muscovite intergrowth. Ilmenite laths are partially replaced by leucoxene, and biotite and chlorite prophyroblasts have formed in the recrystallized matrix.

The characteristic mineral assemblages include

quartz + muscovite + margarite + chlorite ± biotite + carbonaceous material.

The retrograde alteration likely involves the retrograde complex reaction

$$\text{Alm} + \text{Chl} + \text{Mus} + \text{Qtz} \leftarrow \text{And} + \text{Bio} + H_2O\,.$$

The garnet replacement textures indicate a continuing retrograde equilibration at lower grades than the above complex reaction by the reaction

$$\text{Chl} + \text{Mus} + \text{Qtz} \leftarrow \text{Alm} + \text{Bio} + H_2O\,,$$

$$6\ Fe_7Al_4Si_4O_{15}(OH)_{12}[\text{Chl}] + KAl_3Si_3O_{10}(OH)_2[\text{Mus}] +$$

$$15\ SiO_2[\text{Qtz}] \leftarrow 13\ Fe_3Al_2Si_3O_{12}[\text{Alm}] +$$

$$KFe_3AlSi_3O_{10}(OH)_2[\text{Bio}] + 36\ H_2O\,.$$

The presence of margarite indicates the following retrograde reaction likely occurred:

Mar + Qtz $\leftarrow$ Pl + And + H_2O,

$CaAl_4Si_2O_{10}(OH)_2$[Mar] + SiO_2[Qtz] $\leftarrow$ $CaAl_2Si_2O_8$[Pl] +

Al_2SiO_5[And] + H_2O.

The albite analog of the above reaction probably accounts for the paragonite content of the margarite micas. The source of plagioclase in the above reaction was likely the granofels layers interbedded with the pelite in this area. The replacement of andalusite by margarite in graphitic chiastolite schists has been observed elsewhere (Guidotti and Cheney, 1976; Velde, 1970).

Staurolite-Kyanite Zone

Pelitic schists in unit <u>as</u> are in the staurolite-kyanite zone west of the Wekepeke Fault. Equivalent schists in the Fitchburg and Sterling quadrangles contain andalusite. The schists are splendent due to the growth of coarse muscovite. Characteristic assemblages include

muscovite + quartz + biotite + garnet + staurolite + plagioclase + ilmenite $\pm$ kyanite.

(Representative chemical analyses of coexisting biotite and garnet in kyanite-bearing rocks are given in Appendix II.) The staurolite porphyroblasts are euhedral and have inclusion-rich cores surrounded by inclusion-free outer rims. Biotite selvages have grown on garnet porphyroblasts. These textures can be explained by a retrograde displacement of the three-phase AFM triangle staurolite-garnet-biotite by the reaction

Sta + Bio + Qtz $\leftarrow$ Alm + Mus + H_2O ,

$$42\ Fe_2Al_9Si_4O_{23}(OH)[Sta] + 33\ KFe_3AlSi_3O_{10}(OH)_2[Bio] +$$
$$213\ SiO_2[Qtz] \leftarrow 166\ Fe_3Al_2Si_3O_{12}[Alm] +$$
$$99\ KAl_3Si_3O_{10}(OH)_2[Mus] + 42\ H_2O\ .$$

Sillimanite Zone

The sillimanite isograd marks the first appearance of sillimanite in the pelitic schists of unit as and member os of the Oakdale Formation. Characteristic assemblages in unit as include

muscovite + quartz + biotite + plagioclase + garnet ±
staurolite + fibrolitic sillimanite .

The characteristic assemblage in member os is

muscovite + quartz + biotite + plagioclase + garnet ±
fibrolitic sillimanite .

In both cases the fibrolitic sillimanite is intergrown with muscovite and biotite. In member os, the first appearance of sillimanite is probably related to a simple reaction of the type (Thompson and Norton, 1968, p. 323)

$$KAl_3Si_3O_{10}(OH)_2[Mus] + Fe_3Al_2Si_3O_{12}[Alm] \rightarrow$$
$$2\ Al_2SiO_5[Sil] + KFe_3AlSi_3O_{10}(OH)_2[Bio] + SiO_2[Qtz]\ .$$

In unit as, the first appearance of sillimanite is probably related to either simple reactions of the type (Thompson and Norton, 1968, p. 323)

$$7\ SiO_2[Qtz] + 4\ KAl_3Si_3O_{10}(OH)_2[Mus] +$$
$$6\ Fe_2Al_9Si_4O_{23}(OH)[Sta] \rightarrow 31\ Al_2SiO_5[Sil] +$$
$$4\ KFe_3AlSi_3O_{10}(OH)_2[Bio] + 3\ H_2O\ ,$$

$$KAl_3Si_3O_{10}(OH)_2[Mus] + Fe_3Al_2Si_3O_{12}[Alm] \rightarrow$$
$$2\ Al_2SiO_5[Sil] + KFe_3AlSi_3O_{10}(OH)_2[Bio] + SiO_2[Qtz]\ ,$$

or to a complex reaction of the type

$$Qtz + Mus + Sta \rightarrow Sil + Bio + Alm + H_2O\ .$$

CALCAREOUS SILTSTONES AND QUARTZOFELDSPATHIC GRANOFELS

The Merrimack and Oakdale Formations contain calcareous siltstones and quartzofeldspathic granofels in the Nashua River area. The Oakdale Formation west of the Wekepeke Fault zone is in the actinolite zone of regional metamorphism, corresponding to the staurolite-kyanite zone in pelitic schists. The Merrimack Formation, located east of the Wekepeke Fault, is in the chlorite and actinolite zones. Metamorphic reactions in calcareous siltstones under similar metamorphic conditions have been studied and described by Ferry (1975). The sequence of metamorphic reactions is shown schematically in Figure 8.

Chlorite Zone

Phyllite and calcareous siltstone in the chlorite zone are generally a light tan to light green-gray color. Mineral assemblages characteristic of the siltstones at chlorite grade include

Table 5. Observed Mineral Assemblages in Calcareous Siltstone and Quartzofeldspathic Granofels

	Chlorite Zone			Biotite Zone					Actinolite Zone											
	Merrimack Formation														Oakdale Formation					
Quartz	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Muscovite	x	x	x	x		x		x					x	x		x	x		x	x	
Biotite				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Chlorite	x	x	x	x	x	x	x	x	x					x							
Calcite			x		x	x	x	x		x											x
Ankerite		x																			
Amphibole									x	x	x							x			x
Almandine																x			x	x	
Diopside																					x
Grossular																					x
Staurolite																			x		
Sillimanite																			x		
Plagioclase	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
K-feldspar	x																				
Epidote							x	x	x	x	x	x	x	x		x		x			x
Ilmenite		x		x	x																
Sphene							x		x	x	x	x			x	x	x	x	x	x	
Anorthite =		0-5		6			≈22-36			32-38			20-38				22-38				42-48

Mineral assemblages include all minerals observed in thin section. If beds or layers of differing mineralogy are present in the thin section, only minerals in a given bed or layer are treated as an assemblage. Each mineral is generally in physical contact with each of the other minerals in the assemblage. Chlorite, clearly replacing biotite and garnet, has been excluded from the tabulated assemblages.

quartz ± detrital plagioclase (albite) + muscovite + chlorite + ankerite + ilmenite ,

quartz + detrital plagioclase (albite) ± detrital K-feldspar (generally altered) + muscovite + chlorite ,

quartz ± detrital plagioclase (albite) + muscovite + chlorite + calcite .

The anorthite content of plagioclase varies from 0 to 5 mole percent.

Biotite Zone

The biotite isograd marks the first appearance of biotite in the calcareous siltstone. The granofels develops a greenish to purple-gray color and begins to lose its fissility. Characteristic mineral assemblages of the biotite zone include

quartz + plagioclase + muscovite + biotite + chlorite + calcite ± zoisite ± sphene ,

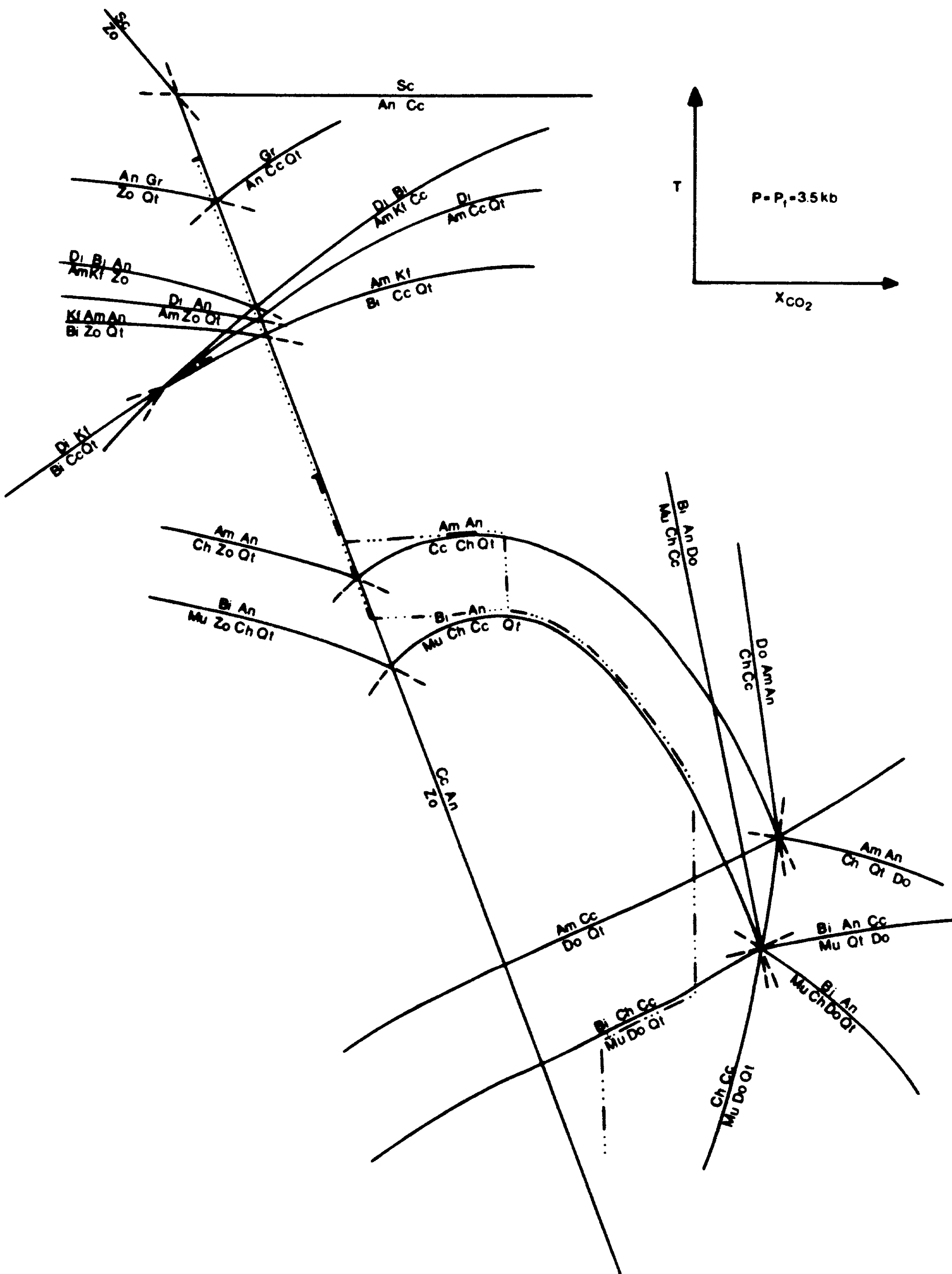
quartz + plagioclase + muscovite + biotite ± chlorite .

The anorthite content of plagioclase generally is between 22 and 38 mole percent. The reaction responsible for the first appearance of biotite is likely

$$\text{Mus} + \text{Qtz} + \text{Dol} + H_2O \rightarrow \text{Cc} + \text{Chl} + \text{Bio} + CO_2 ,$$

$$KAl_3Si_3O_{10}(OH)_2[\text{Mus}] + 3\ SiO_2[\text{Qtz}] + 8\ CaMg(CO_3)_2[\text{Dol}] + 4\ H_2O \rightarrow 8\ CaCO_3[\text{Cc}] + Mg_5Al_2Si_3O_{10}(OH)_8[\text{Chl}] + KMg_3AlSi_3O_{10}(OH)_2[\text{Bio}] + 8\ CO_2 .$$

Figure 8.



T
X_{CO_2}
P = P_f = 3.5 kb
Sc
An Cc
Sc
Zo
Gr
An Cc Qt
An Gr
Zo Qt
Di Bi
Am Kf Cc
Di
Am Cc Qt
Di Bi An
AmKf Zo
Di An
Am Zo Qt
Kf Am An
Bi Zo Qt
Am Kf
Bi Cc Qt
Di Kf
Bi Cc Qt
Am An
Ch Zo Qt
Am An
Cc Ch Qt
Bi An
Mu Zo Ch Qt
Bi An
Mu Ch Cc Qt
Cc An
Zo
Bi An Do
Mu Ch Cc
Do Am An
Ch Cc
Am An
Ch Qt Do
Am Cc
Do Qt
Bi An Cc
Mu Qt Do
Bi An
Mu Ch Do Qt
Bi Ch Cc
Mu Do Qt
Ch Cc
Mu Do Qt

Figure 8

Qualitative T - X_{CO_2} diagram drawn for $P_{total} = P_{fluid} = 3.5$ kilobars involving the mineral phases muscovite (Mu), dolomite (Do), K-feldspar (Kf), quartz (Qt), biotite (Bi), chlorite (Ch), calcite (Cc), calcic plagioclase (An), zoisite (Zo), calcic amphibole (Am), diopside (Di), grossular (Gr), and scapolite (Sc) (diagram modified from Ferry, 1975). Dot-dash curve represents a schematic T - X_{CO_2} reaction path for the calcareous rocks in the Merrimack and Oakdale Formations during regional metamorphism. The dotted curve represents a schematic T - X_{CO_2} reaction path for the Oakdale Formation in the vicinity of the Fitchburg Pluton.

This reaction results in the disappearance of ankerite, the appearance of calcite, and the general modal decrease in muscovite and quartz in the metasiltstones (Appendix I). After ankerite is exhausted in the above reaction, the following biotite-producing reaction occurs at higher temperatures:

Mus + Cc + Qtz + Chl + Albite $\rightarrow$

Bio + Intermediate Plagioclase + H_2O + CO_2 ,

$$5\ KAl_3Si_3O_{10}(OH)_2[Mus] + 8\ CaCO_3[Cc] + 7\ SiO_2[Qtz] + 3\ Mg_5Al_2Si_3O_{10}(OH)_8[Chl] \rightarrow 5\ KMg_3AlSi_3O_{10}(OH)_2[Bio] + 8\ CaAl_2Si_2O_8[Pl] + 12\ H_2O + 8\ CO_2 .$$

This reaction is largely responsible for the modal decrease of muscovite, calcite, and chlorite and the increasing anorthite content of plagioclase in the granofels (Appendix I).

Sphene and zoisite (zoisite-clinozoisite) are first observed in the biotite zone and are probably formed by the following reactions:

Ilm + Mus + Qtz + Cc + H_2O $\rightarrow$ Bio + Chl + Sp + CO_2 ,

$$8\ FeTiO_3[Ilm] + KAl_3Si_3O_{10}(OH)_2[Mus] + 11\ SiO_2[Qtz] + 8\ CaCO_3[Cc] + 4\ H_2O \rightarrow KFe_3AlSi_3O_{10}(OH)_2[Bio] + Mg_5Al_2Si_3O_{10}(OH)_8[Chl] + 8\ CaTiSiO_5[Sp] + 8\ CO_2 ;$$

calcic plagioclase + Cc + H_2O $\rightarrow$ Zo + intermediate plagioclase + CO_2 ,

$$3\ CaAl_2Si_2O_8[Pl] + CaCO_3[Cc] + H_2O \rightarrow 2\ Ca_2Al_3Si_3O_{12}(OH)[Zo] + CO_2 .$$

Actinolite Zone

The actinolite isograd marks the first appearance of a pale green calcic amphibole in the calcareous granofels. The granofels has developed a salt-and-pepper appearance and is typically a purple-brown color. Characteristic mineral assemblages include

quartz + plagioclase + biotite + amphibole ± chlorite + zoisite + sphene,

quartz + plagioclase + biotite + amphibole + calcite + zoisite ± chlorite + sphene,

quartz + plagioclase + biotite + muscovite ± zoisite ± almandine + sphene,

quartz + plagioclase + biotite ± zoisite + sphene,

quartz + plagioclase ± calcite + amphibole ± grossular ± zoisite ± diopside .

The actinolitic hornblende was likely developed by the following reaction:

$$\mathrm{Chl + Cc + Qtz \rightarrow Am + Pl + CO_2 + H_2O},$$

$$\mathrm{Mg_5Al_2Si_3O_{10}(OH)_2[Chl] + 3\ CaCO_3[Cc] + 7\ SiO_2[Qtz] \rightarrow}$$
$$\mathrm{Ca_2Mg_5Si_8O_{22}(OH)_2[Am] + CaAl_2Si_2O_8[Pl] + 3\ CO_2 + 3\ H_2O}.$$

This reaction is responsible for the decrease and disappearance of chlorite and calcite from the modes. The reaction

calcic plagioclase + Cc + H_2O → Zo + intermediate plagioclase + CO_2,

$$3\ CaAl_2Si_2O_8[Pl] + CaCO_3[Cc] + H_2O \rightarrow$$

$$2\ Ca_2Al_3Si_3O_{12}(OH)[Zo] + CO_2,$$

results in the disappearance of calcite and the increase in zoisite in the modes.

Grossular garnet and diopside have been observed in a few calc-silicate layers adjacent to or as inclusions in the granitic rocks of the Fitchburg Pluton. The presence of these minerals indicates metamorphic conditions that are consistent with the sillimanite zone in the pelitic rocks. The calc-silicate layers typically contain a green amphibole, diopside, grossular, plagioclase, quartz, and small residual patches of calcite. The diopside forming reaction was likely

$$Am + Cc + Qtz \rightarrow Di + H_2O + CO_2,$$

$$Ca_2Mg_5Si_8O_{22}(OH)_2[Am] + 3\ CaCO_3[Cc] + 2\ SiO_2[Qtz] \rightarrow$$

$$5\ CaMgSi_2O_6[Di] + H_2O + 3\ CO_2.$$

The grossular forming reaction was likely

calcic plagioclase + Cc + Qtz → Gr + intermediate plagioclase + CO_2,

$$CaAl_2Si_2O_8[Pl] + 2\ CaCO_3[Cc] + SiO_2[Qtz) \rightarrow$$

$$Ca_3Al_2Si_3O_{12}[Gr] + 2\ CO_2.$$

RELATIONSHIP OF METAMORPHISM AND DEFORMATION PHASES

The metamorphic culmination (M1) in the Nashua River area was coincident with the D1 deformation phase. This relationship is indicated by

1) the dominant mineral foliation (muscovite, biotite) that defines the S1 schistosity,

2) the orientation of mineral lineation parallel to F1 minor fold axes, and

3) garnet porphyroblasts and inclusion-rich cores of staurolite that have a helical inclusion pattern showing a small amount of rotation. This foliation defined by the inclusion pattern merges with the S1 mica schistosity at the margins of the porphyroblasts.

M1 apparently outlasted the penetrative deformation associated with D1. This is implied by the inclusion-free rims on staurolite porphyroblasts and biotite selvages on garnet porphyroblasts that indicate a small degree of retrograde equilibration following the culmination of the M1 metamorphism. This retrograde equilibration predates D2, since S2 crenulation cleavage is deflected around the porphyroblasts.

A second metamorphic event appears to be associated with the intrusion of granites in the Fitchburg Pluton area. The sillimanite isograd in the Townsend quadrangle is located in the vicinity of the Fitchburg Pluton. The fibrolitic sillimanite in unit as postdates D2, since the sillimanite sprays are randomly oriented and are not deformed by the S2 crenulation cleavage.

Peck (1976, p. 248), following Emerson (1917), reports that the growth of andalusite in the Worcester Formation appears associated with granite intrusion and correlates the small bodies of granite intruding the Worcester Formation in the Clinton quadrangle with the Fitchburg Granite. Although plutonic intrusions into the Worcester Formation are not exposed in the Shirley quadrangle, the random orientation of the andalusite prisms in the rock (Plate 1d) implies crystallization in a static stress environment, which is consistent with the contact aureole hypothesis. The retrograde alteration of the andalusite schists in the Worcester Formation requires the addition of water to the rocks. The source of this water may have been a hydrothermal aureole surrounding the granite intrusions which caused the andalusite-zone metamorphism, and both the prograde and retrograde metamorphisms may be closely related in time. The retrograde alteration of the andalusite-zone rocks of the Worcester Formation predated at least the latest movement along the Wekepeke Fault, since S4 schistosity has developed in the rock and the zones of retrograde alteration are truncated by minor faults related to the Wekepeke Fault.

ESTIMATES OF PRESSURE AND TEMPERATURE DURING METAMORPHISM

Estimates of Lithostatic Pressure During Metamorphism

The presence of andalusite in the Worcester Formation east of the Wekepeke Fault and in the schists bordering the Fitchburg Pluton in the Fitchburg and Sterling quadrangles west of the Wekepeke Fault indicates a maximum pressure during metamorphism of 3.8 kilobars (Holdaway, 1971). The presence of primary muscovite in the Fitchburg Granite west of the Wekepeke Fault and in the Chelmsford Granite east of the fault suggests a minimum pressure of approximately 3.4 kilobars (intersection of the muscovite + quartz breakdown curve of Chatterjee and Johannes, 1974, with the granite minimum melt curve of Tuttle and Bowen, 1958, under water-saturated conditions). Primary muscovite is present in the nonpegmatitic phases of the granites, and since the activity of water was likely less than one in these melts, the 3.4 kilobar figure is probably too low as a minimum pressure estimate. These pressure estimates strictly refer to only localized areas within the Nashua River area, and large areas lack mineral equilibria sufficient to constrain pressure. However, since 1) pressure is likely to be uniform over an area at a given depth-of-burial, 2) metamorphic quenching commonly occurs relatively late in the deformation history, and 3) the depth of postmetamorphic uplift and erosion is likely to vary only in a slow and regular manner in a region (in the absence of postmetamorphic faults), these pressure estimates are assumed to be valid for the area as a whole. A pressure estimate of 3.5 to 3.8 kilobars is judged as reasonable for areas both east and west of the Wekepeke Fault in the Nashua River area.

Biotite Zone

Ferry (1975, Fig. 22, pp. 116-117) estimates the temperature for first appearance of biotite in calcareous siltstones in the Waterville-Vassalboro area of Maine by the reaction

$$KAl_3Si_3O_{10}(OH)_2[Mus] + 3\ SiO_2[Qtz] + 8\ CaMg(CO_3)_2[Dol] +$$
$$4\ H_2O \rightarrow 8\ CaCO_3[Cc] + Mg_5Al_2Si_3O_{10}(OH)_8[Chl] +$$
$$KMg_3AlSi_3O_{10}(OH)_2[Bio] + 8\ CO_2$$

at 3.5 kilobars to range between 380 and 395°C. Since rocks in the Merrimack Formation are lithologically similar to sedimentary rocks in the Waterville-Vassalboro area of Maine and equilibrated under similar pressure conditions, this temperature estimate appears reasonable for the Nashua River area.

The temperature of first appearance of biotite in the pelitic sedimentary rocks of the Worcester Formation may be estimated using the calculation method of Ferry (1975, pp. 85-89, Appendix IV.A, pp. 173-175) for the following reaction in the KMASH system:

$$3\ Mg_7Al_4Si_4O_{15}(OH)_{12}[Chl] + 13\ KAlSi_3O_8[Ksp] \rightarrow$$
$$7\ KMg_3AlSi_3O_{10}(OH)_2[Bio] + 6\ KAl_3Si_3O_{10}(OH)_2[Mus] +$$
$$12\ SiO_2[Qtz] + 5\ H_2O\ .$$

The presence of graphite in the rocks of the Worcester Formation indicates that the activity of water in the fluid phase (H-O-C system) would be less than 1 (French, 1966; Eugster and Skippen, 1967). Since the quartz-fayalite-magnetite buffer appears to represent adequately f_{O_2} in graphitic schists between 200° and 500°C (Holdaway, 1978, pp. 1412-1413; Hoefs and Frey, 1976), the activity of water in the H-O-C system at $P_{total} = P_{fluid} = 3.5$ to 3.7 kilobars, T = 400°C, can be estimated as 0.7. Under these conditions ($P_{total} = P_{fluid} = 3.7$ kilobars, $a_{H_2O} = 0.7$), the reaction temperature is estimated at 385°C. This temperature estimate is consistent with the temperature range of 300° to 500°C estimated for carbonaceous pelites in the biotite to garnet zones in the Worcester, Mass., area from the crystallinity of graphite (Grew, 1974). It is also consistent with the temperatures of equilibration for biotite-zone pelitic schists determined from oxygen isotope fractionation between quartz and muscovite (Epstein and Taylor, 1967, pp. 56-57).

Retrograde alteration of Worcester Formation andalusite schists

The andalusite-bearing schists in the Worcester Formation have re-equilibrated under biotite-zone conditions. Since both biotite and graphite occur in the retrograde assemblage, a minimum temperature of 385°C appears reasonable. The stability of margarite + quartz in the assemblage can be used to estimate an upper temperature limit. For P = 3.7 kilobars, a_{H_2O} = 0.7, the maximum temperature of the stable assemblage margarite + quartz is approximately 450°C (Chatterjee, 1976, p. 705; Chatterjee, 1974). This is further constrained as the maximum temperature of equilibration since plagioclase feldspar coexisting with margarite is more sodic than the margarite (Ackermand and Morteani, 1973; Frey and Orville, 1974), indicating that the presence of sodium lowers the stability of margarite relative to the calcic end-member.

Staurolite-Kyanite/Andalusite (Actinolite) Zone

Temperatures of the staurolite-kyanite zone pelites in unit as have been estimated using Fe-Mg biotite-garnet geothermometers calibrated by Thompson (1976b), Holdaway and Lee (1977), and Ferry and Spear (1978). The average estimates of temperature range between 470° and 550°C (Table 6) for the staurolite-kyanite schists. The presence of kyanite in these schists and this temperature estimate constrain the

Table 6. Temperature Estimates for Pelitic Rocks in Unit as

Sample[*1]	$\frac{(Fe^{gar})(Mg^{bio})}{(Mg^{gar})(Fe^{bio})}$	Temperature (°C)		
		Thompson, 1976b	Holdaway and Lee, 1977	Ferry and Spear, 1978
T-1002K, spot A	6.0297	442	494	537
T-1002K, spot E	5.594	487	539	561
T-1002K, spot F	5.643	481	533	558
Average		470	522	552
T-1014 gar. core	5.0831	553	605	594
T-1014 gar. core	5.1136	548	601	592
T-1014 gar. rim	5.0395	559	612	598
T-1014 gar. rim	5.0698	555	607	595
Average		554	606	595

*1 T-1002K assemblage contains kyanite.
T-1014 assemblage contains sillimanite.

pressure during metamorphism to be greater than 3.5 kilobars. If a temperature of 500°C is accepted as the temperature of equilibration, then the minimum pressure is estimated as 3.75 kilobars. These metamorphic conditions essentially coincide with the alumino-silicate triple point as determined by Holdaway (1971). The relative proximity of andalusite-bearing schists in the Fitchburg and Sterling quadrangles indicates that the pressure during metamorphism in the Townsend quadrangle likely did not greatly exceed the triple-point pressure. Estimated metamorphic conditions in this area are

$$P = 3.7 \text{ kilobars}, \quad T = 500°C .$$

This temperature is consistent with the 490° to 580°C temperatures of equilibration of staurolite-kyanite zone pelitic schists determined from oxygen isotope fractionation between quartz and muscovite (Epstein and Taylor, 1967, pp. 56-57).

This temperature estimate is also consistent with the temperature estimates of Ferry (1975, Fig. 22, pp. 116-117) for actinolite-zone equilibria in the calcareous metasediments in the Waterville-Vassalboro area of Maine. At a pressure of 3.5 kilobars, Ferry estimates the temperature of formation by actinolite by the reaction

$$Mg_5Al_2Si_3O_{10}(OH)_8[Chl] + 3\ CaCO_3[Cc] + 7\ SiO_2[Qtz] \rightarrow$$
$$Ca_2Mg_5Si_8O_{22}(OH)_2[Am] + CaAl_2Si_2O_8[An] + 3\ CO_2 + 3\ H_2O$$

as ranging between 435° and 500°C, and the formation of diopside by the reaction

$$Ca_2Mg_5Si_8O_{22}(OH)_2[Am] + 3\ CaCO_3[Cc] + 2\ SiO_2[Qtz] \rightarrow$$
$$5\ CaMgSi_2O_6[Di] + H_2O + 3\ CO_2$$

as ranging between 515° and 520°C. The Oakdale Formation in the vicinity of unit as is in the actinolite zone; however, diopside-bearing assemblages were only observed in calc-silicate layers adjacent to or as inclusions in the Fitchburg Granite, or in areas in the sillimanite zone. If the temperature estimates of Ferry (1975) are viewed as appropriate for the Nashua River area, then temperatures in the actinolite zone rocks occur within a 440° to 515°C temperature zone.

Sillimanite Zone

Temperatures determined from Fe-Mg exchange between almandine and biotite in unit as schists in the sillimanite zone range between 550° and 600°C (Table 6). These temperatures are consistent with a pressure range of 3 to 5 kilobars (Holdaway, 1971).

REGIONAL ESTIMATES OF PRESSURE AND TEMPERATURE DURING METAMORPHISM

Metamorphic conditions at the culmination of D1 in the central Merrimack Synclinorium in Massachusetts have been estimated as 650° to 680°C, 6.3 to 6.4 kilobars (Robinson et al., 1977). These metamorphic conditions decrease eastward toward the Nashua River area where conditions have been estimated as 500° to 550°C, 3.5 to 3.8 kilobars west of the Wekepeke Fault. Estimated metamorphic conditions in the chlorite-zone rocks east of the Wekepeke Fault are $T \leqslant 400°C$, $P = 3.5$ to 3.8 kilobars.

Prograde mineralogy in recrystallized mylonites associated with D2 in the central Merrimack Synclinorium of Massachusetts indicates metamorphic conditions of 550°C, 7.2 to 8.0 kilobars (Robinson *et al.*, 1977). S2 schistosity in the Nashua River area is expressed primarily by a partial recrystallization of muscovite mica. Metamorphic conditions during D2 in the Nashua River area were likely in or below the lower greenschist facies.

CHAPTER 5. REGIONAL STRATIGRAPHIC INTERPRETATION

REGIONAL STRATIGRAPHIC SYNTHESIS

Figure 9a shows the distribution of rock types in the Nashua River area. The rocks have been separated into numbered belts identifying distinctive lithotypes that are continuous or nearly continuous along strike. The numbered order of the lithotype belts is not intended to imply stratigraphic order.

Several geologists who have worked in various portions of the Nashua River area have proposed different stratigraphic sections, based both on sedimentary topping evidence at formation boundaries and regional correlation. A summary of the various proposed stratigraphic sections is shown in Figure 9b.

The proposed regional stratigraphic section (Fig. 10) is a synthesis based on sedimentary topping evidence at formation boundaries within the Nashua River area, and is dependent upon two lithologic correlations.

The correlation of calcareous siltstones and quartzofeldspathic granofels of belts 3 and 5 (Fig. 9a) across the Wekepeke Fault zone is based entirely upon lithotype similarity. The bulk chemistry and sedimentary characteristics of these two belts are nearly identical. The correlation of graphitic pelites and graywackes of belt 4 with the graphitic pelites, quartzites, and conglomerates of belts 1 and 2 is based on sedimentary topping evidence, general lithologic similarity, and structural evidence. Crossbeds and graded belts in belt 4 along

Figure 9.

SUMMARY OF PROPOSED STRATIGRAPHIC SECTIONS

A. LITHOTYPE BELTS

IG	Intrusive Plutonic Rock.

LITHOLOGY EAST OF CLINTON-NEWBURY FAULT ZONE

tb	Rusty and Grey Weathering Pelitic Schist.
Nashoba	Quartzofeldspathic Gneiss. Minor Amphibolite and Marble.

LITHOLOGY WEST OF CLINTON-NEWBURY FAULT ZONE
(No Stratigraphic Significance Implied by Order)

7	Terrestrial Conglomerate and Pelitic Sedimentary rocks.

6	Graded Bedded Pelite, Pelite, and Lustrous Mica Schist.
5	Quartzofeldspathic Granofels.
4	Cyclically Bedded Graphitic Pelite and Graywacke. Minor Calcareous Lenses.
3	Calcareous Siltstone and Quartzofeldspathic Granofels.
2	Quartzite and Conglomerate Interbedded with Minor Pelite.
1	Graphitic Pelite, and Graphitic Pelite Interbedded with Minor Clean Quartzite.
1a	Massive Bedded, Slightly Sulfidic Pelite.

Figure 9a.
LITHOTYPE BELTS IN THE NASHUA RIVER AREA

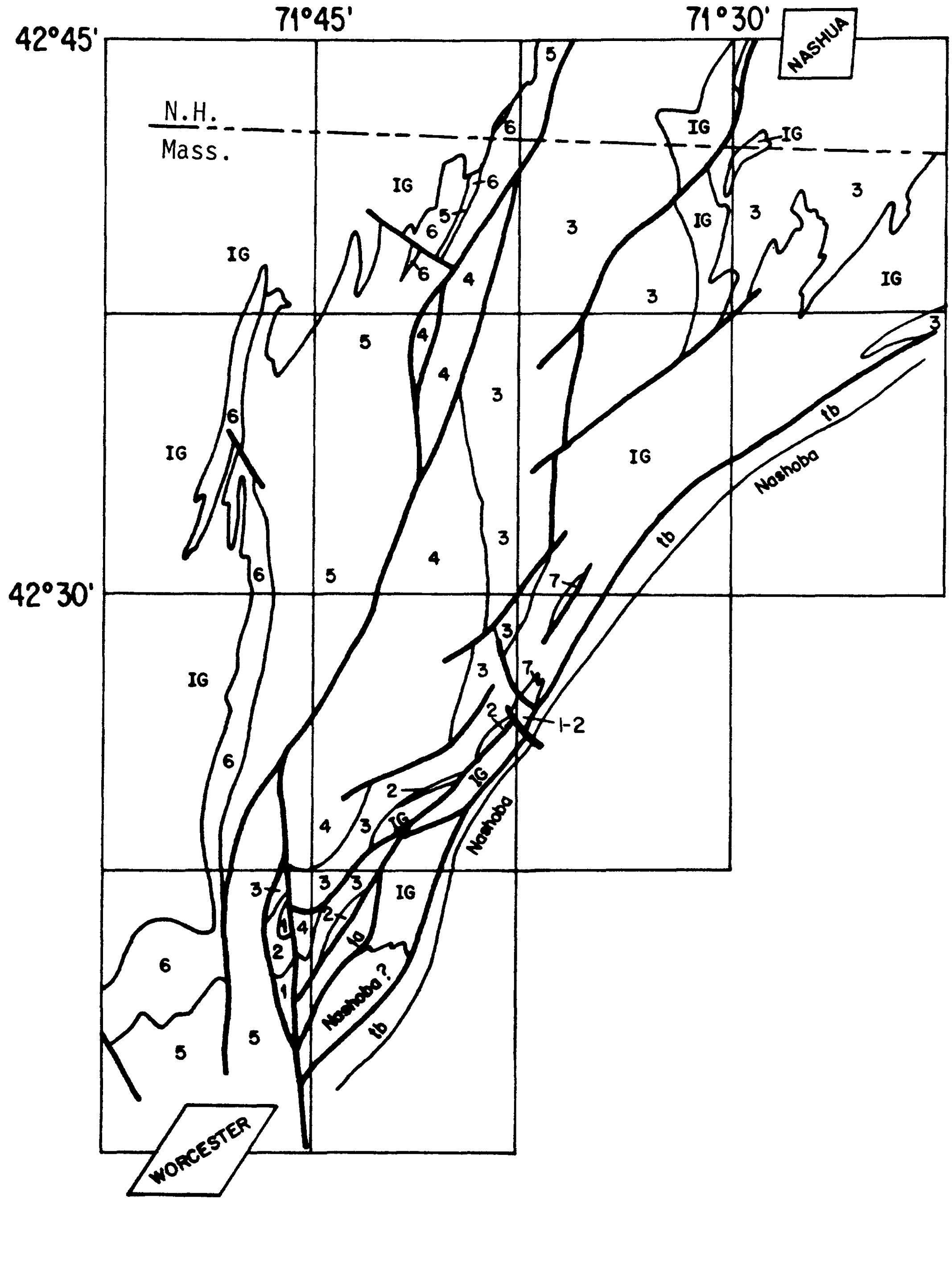


Figure 9b.
COMPARISON OF PROPOSED STRATIGRAPHIC SECTIONS

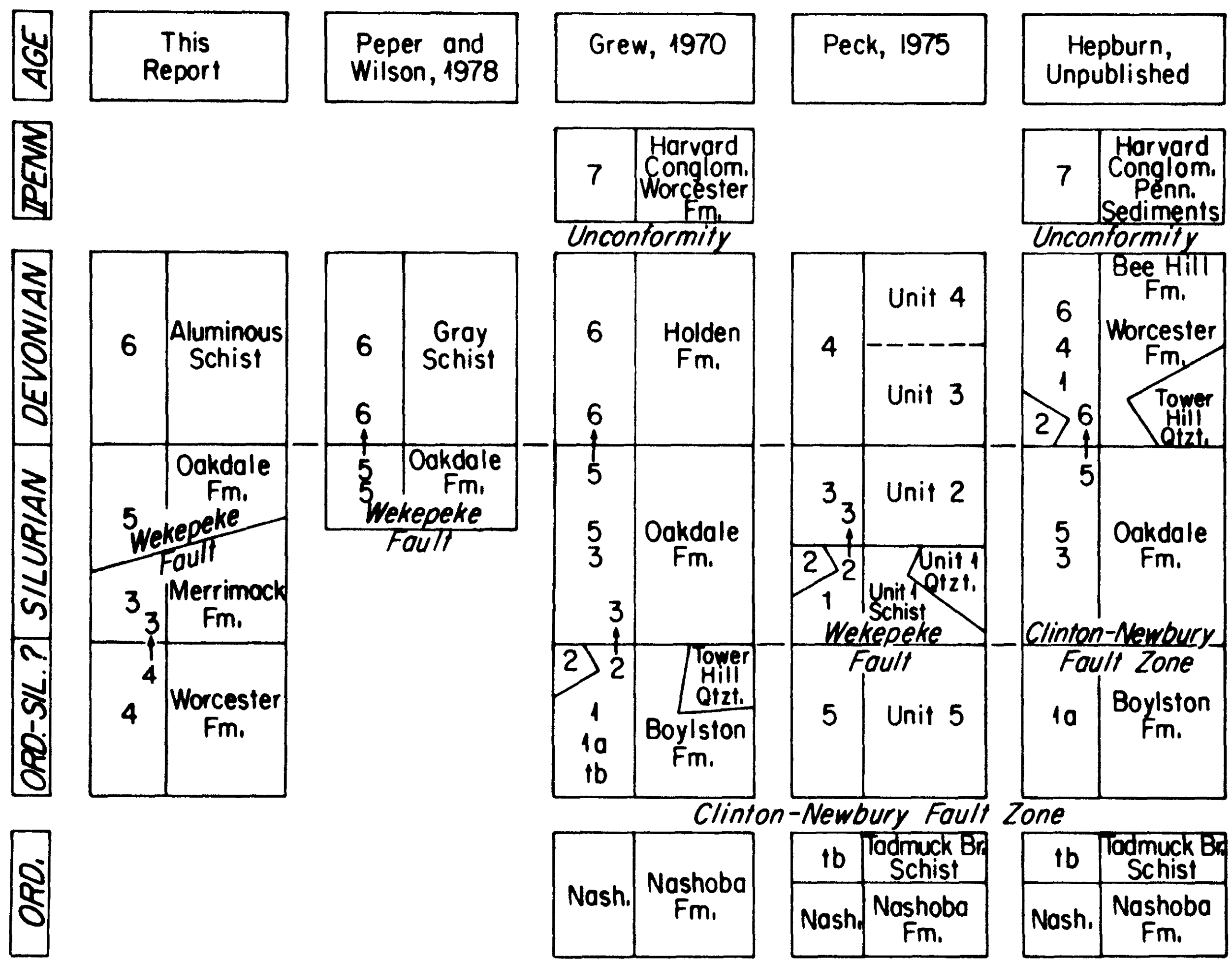
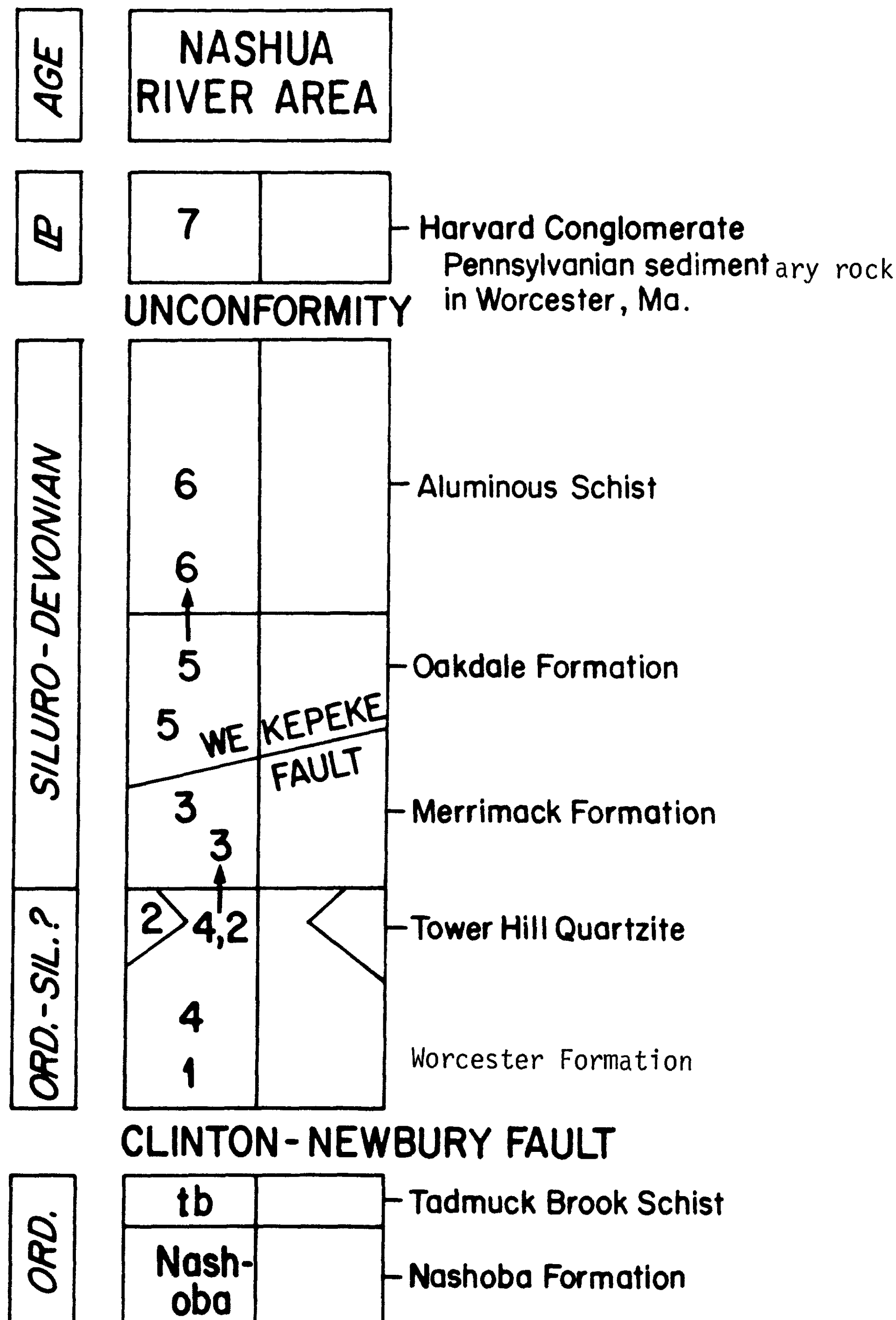


Figure 10.
REGIONAL STRATIGRAPHIC SYNTHESIS



the contact between belts 3 and 4 in the Shirley quadrangle (locality 6) indicate that belt 3 overlies belt 4. Grew (1970) and Peck (1976, p. 245) report that belt 1 and 2 rocks stratigraphically underlie belt 3 in the Clinton and Worcester North quadrangles.

Belts 1, 2, and 4 contain thinly laminated graphitic pelite. Belts 1 and 2 contain thin to massive lenticular beds of clean quartzose conglomerate and quartzite interbedded with the graphitic pelite. The quartzites appear to occur preferentially near the top of the section, near the contact with belt 3, but little of belts 1 and 2 is preserved due to truncation by the Clinton-Newbury Fault zone. The lenticular distribution and sedimentary characteristics of the quartzites are consistent with sediments which have been reworked and winnowed by currents. They may represent shoal areas as thought by Peck (1976, p. 245), or perhaps more likely turbidite channels within the marine basin. Belt 4 does not contain any significant amount of clean quartzite; however, two small quartzite exposures in the Shirley quadrangle are important in establishing that clean quartzite does exist in or near the stratigraphic top of belt 4. In the Shirley quadrangle (east of Shaker Rd., 0.3 mile north of Rt. 2) a 60 m lens of quartzite occurs in belt 3 near the contact with belt 4. At locality 14 (Shirley quadrangle) the graphitic pelites of belt 4 contain a 10 meter slump block of nongraphitic quartzo-feldspathic sandstone, indicating that areas of clean quartz and quartz-feldspar sand existed within the basin during deposition. These sand areas may be the quartzites in belts 1 and 2.

The correlation of belts 4 with 1 and 2 is strengthened by the observation of a synformal F1 minor fold located in the narrow band of belt 3 which separates belt 4 from 1 and 2 in the Worcester North and Clinton quadrangles (Hepburn, 1976, Stop 4) (fold F1b, Fig. 6). This minor fold appears to be in the nose of a larger F1 synformal fold, which may explain the increase in the width of lithotype belt 3 along strike to the northeast in the Shirley and Pepperell quadrangles and the repetition of lithotype belts 1, 2, and 4 on both sides of belt 3.

ENVIRONMENT OF DEPOSITION

Worcester Formation

A thinly laminated, cyclically bedded sequence of interbedded sandstone, siltstone, and shale is characteristic of the Worcester Formation. The sandstones and siltstones typically contain appreciable amounts of matrix and can be described as graywackes. Sequences of graded and cross-laminated beds alternate with cyclically bedded homogeneous shale and graywacke throughout the unit. Rare granule conglomerate layers with intraformational slate fragments occur. Slump folds (Plate 1b) and slump blocks occur in some coarse-grained layers. Tongue-shaped slump masses of siltstone (1 to 7.7 m thick), which wedge out rapidly in the updip direction, are reported in the Worcester Formation in the Clinton quadrangle (Peck, 1976, p. 247, units 3 and 4).

The sedimentary characteristics of the Worcester Formation indicate deposition as part of a turbidite facies. This term is used as a general classification covering all gravity-driven mass flows which transfer previously deposited material from marginal point sources into a deep basin. These resedimented deposits may have accumulated from a variety of mechanisms other than true turbidity currents, such as debris flows, grain flows and fluidized flows of both high and low density (Ricci Lucchi, 1975, p. 137). Characteristics of the Worcester Formation which indicate turbidite facies deposition are as follows:

1) cyclically bedded couplets of thinly layered, fine-grained sandstone, siltstone, and pelite with extensive lateral persistence of both bed thickness and lamination

2) graded and cross-laminated beds within the cyclically bedded units. Turbidite layers C, D, and E of the Bouma (1962) sequence have been observed

3) penecontemporaneous slumps and slump-folds

4) rip-up fragments of siltstone and shale in the coarser grained layers

5) lenticular beds of boulder conglomerate, granule conglomerate, and sandstone that exhibit graded bedding in some localities.

The slump blocks and slump folds in the Worcester Formation indicate that the turbidites were deposited in the slope-basin association of Ricci Lucchi (1975). The slope facies does not necessarily imply a "continental slope" *per se*, but merely an inclined area transitional between a shelf or basin margin and basin floor. Slope deposits are typically fine grained since they represent fallout from dilute suspension.

The persistence of thin lamination indicates that the sedimentation rate was rapid enough or environmental conditions were sufficiently restrictive to eliminate an extensive bottom fauna of burrowing organisms. The presence of carbonaceous dust and graphite-rich layers indicates that during deposition of the Worcester Formation the basin received a substantial amount of organic matter that was not oxidized before burial. A discussion of the distribution, age relationships, and environment of deposition of carbonaceous marine pelites is given by Berry and Wilde (1978).

The characteristics of the quartzites in the Worcester Formation (lithotype belts 1 and 2, Fig. 9) require special comment. The quartzites are variable in their characteristics and contain

1) cobble conglomerates with well-rounded, generally monomict fragments of clean quartzite in a quartz sand matrix. The layers contain no carbonaceous material and little mica. Grading is generally absent. Beds are typically tens of cm thick and are interbedded with a few pelite layers.

2) granule conglomerates containing quartz and feldspar fragments and rare slate fragments. Some layers show graded bedding. Beds are typically a few cm to 10 cm thick and are interbedded with pelite layers.

3) quartzose sandstones showing lenticular bedding. The sand lenses are a few cm long and thick and are defined by thin layers of graphitic pelite. These bedding characteristics indicate the development of small-scale ripple marks on the bedding surface. Beds are typically a few cm to tens of cm thick and are interbedded with thin pelite layers.

4) thinly laminated quartzose to quartzofeldspathic sandstone. The layers contain little carbonaceous material or mica.

5) a cyclically bedded sequence of thinly bedded (0.5 cm) parallel-laminated sand and carbonaceous pelite. Proportions vary, but pelite generally is dominant.

The change from 1 to 5 in general represents a south to north traverse along the strike of lithotype belts 1 and 2. The conglomeratic layers may represent localized debris flows, possibly within channels. The sandstones showing lenticular bedding and the rocks showing thin parallel lamination of sand and pelite were probably sediments that have been winnowed and reworked by bottom currents.

Merrimack and Oakdale Formations

Rocks in the Merrimack and Oakdale Formations display persistent layering, uniform thin lamination, and cyclical bedding of siltstone and phyllite. Rare sandstone layers show graded bedding. The sediments originally consisted of thinly layered silt, clay, and calcareous mud and sand. Sedimentation was rapid enough or environmental conditions were sufficiently restrictive to eliminate burrowing organisms that would otherwise have destroyed the persistent thin lamination.

Granule conglomerates, lenses containing intraformational siltstone fragments, and lenses of graded sandstone indicate that the sedimentary basin received sporadic inputs of coarse-grained detritus. Deposition probably occurred in the basin-plain association of Ricci Lucchi (1975). The basin-plain is an essentially flat, subhorizontal, depositional area where turbidity currents exhaust their energy space. Generalized current directions need to be determined from a statistical analysis of many data points in a region.

3) The deformational history of the rock, including both strain and rotational translation, needs to be evaluated to correct distortion to the primary sedimentary features.

The lack of many localities displaying well-exposed sedimentary features indicating current direction and the difficulty of accurately evaluating the details of deformation at these localities prevent a rigorous determination of current directions in the Nashua River area. Only two localities (localities 5 and 19) in the map area contain enough information to estimate current directions. Both localities occur in the Worcester Formation, so the information is restricted to one unit in the stratigraphic section. Furthermore, two data points are a small sample from which to draw conclusions. It is assumed that restoration of the beds to horizontality by unfolding the strata using flexure folds with axes oriented parallel to the F2 minor fold axes in the area introduces only minor distortion of paleocurrent vectors.

Current directions at locality 5, Shirley quadrangle, are to the northwest, as indicated by truncated crossbeds and scour and fill. Current directions at locality 19, Shirley quadrangle, are to the southeast, as indicated by slump folds. The current directions indicated by these slump folds are, in general, consistent with the easterly current directions indicated by similar slump folds in the Worcester Formation reported by Peck (1976, pp. 247-248) from the Clinton quadrangle. The current directions indicated by cross-stratification at locality 5 may be and gradually abandon their suspended load. Turbidity flows reaching the basin plain may represent either tails of currents that have left most of their load in a turbidite fan system or large, fast-moving flows that bypass the fan and deposit material directly on the basin plain.

Unit as

The aluminous schist unit (as) in the Townsend quadrangle displays few sedimentary features and is poorly bedded due to metamorphic recrystallization. A portion of the aluminous schist unit that has been hornfelsed adjacent to the Fitchburg Pluton in the Fitchburg (Peper and Wilson, 1978) and Sterling (Hepburn, unpublished) quadrangles displays graded cyclical couplets of pelite and micaceous granofels. Beds are a few centimeters to 8 cm thick. Where sedimentary features are preserved, the unit has the character of a turbidite sequence, probably in the basin-plain association of Ricci Lucchi (1975). Portions of the unit are slightly graphitic.

PALEOCURRENT DIRECTIONS

The quantitative determination of paleocurrent directions from primary sedimentary features in deformed rocks is hampered by a number of difficulties:

1) Sedimentary features need to be well-developed and exposed in an area that offers a three-dimensional view of the features.
2) Current directions in both fluvial and marine deposition systems are typically not unidirectional in either time or

related to bottom currents flowing subparallel to the slope bathymetry. If these results may be extrapolated to the depositional basin as a whole, it appears that the source of detritus lies west of the Nashua River area.

PROVENANCE

Some characteristics of provenance may be inferred from detrital material found in the sedimentary basin. Folk (1965, pp. 65-99) summarizes some of the previous work and describes the techniques used to infer provenance from detrital material. Detrital fragments in the coarser grained beds in the low-grade metamorphic zones give the best evidence regarding provenance. Rounded multigranular fragments of quartz and feldspar with straight grain boundaries, found in granule conglomerate beds in the Worcester and Merrimack Formations, are indicative of igneous-metamorphic provenance. Grew (1970, p. 127) also reports multigranular detrital grains of quartz and feldspar from granofels beds in the Worcester Formation in the Worcester area. Rounded grains of detrital myrmekite in the Merrimack Formation are indicative of a plutonic provenance. Characteristics of detrital quartz grains in the Worcester and Merrimack Formations are consistent with a plutonic-metamorphic provenance.

Detrital zircons from the Oakdale Formation have Pb/U and Pb/Th ages of approximately 1200 m. y. (Aleinikoff, 1978), which represent the crystallization age of the zircons from the source area. These ages are consistent with a Grenville province source from areas west of the Merrimack Synclinorium.

United States Department of the Interior

Geological Survey

Bedrock Geology of the Nashua River Area, Massachusetts - New Hampshire

By Gilpin Rile Robinson, Jr.

Open-File Report
81-593

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. This report was originally submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in geology at Harvard University, Cambridge Mass., March 1979.

1981

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CORRELATION AND AGE OF STRATIGRAPHIC SECTION

The Worcester coal mine, located southwest of the Nashua River, near Worcester, Mass., has received considerable geological study (summarized by Grew et al., 1970). Fossils collected from the coal mine by White (1912), the correlation of phyllites at the coal mine with nearby phyllites, and the observation of conformable contacts between stratigraphic units (Perry and Emerson, 1903) prompted Emerson (1917) to call all metasedimentary rocks in the Worcester-Nashua area Carboniferous in age. Subsequent work by Grew (1970, 1973) has shown that Carboniferous rocks, of limited extent, do exist in the Worcester area, and that all rocks of a demonstrable Carboniferous age have unconformable or fault contacts with adjacent pre-Carboniferous rocks.

Fossils have not been discovered in the Merrimack, Oakdale, and Worcester Formations or unit as in the Nashua River area; therefore an age assignment to these units must be based upon field relationships and regional correlations. Attempts to recover microfossils from the Worcester Formation by Andrew Knoll and the Merrimack Formation by John Repetski proved unsuccessful. Any age assignment to these formations, therefore, is somewhat speculative.

Radiometric dates on intrusive plutonic rocks provide minimum stratigraphic ages, dependent upon the reliability of the radiometric age determination. The Ayer Granite has a 424 ± 6 m.y. age (Pb/Pb zircon age: Zartman and Naylor, in press) and is intrusive into the Merrimack Formation in the Clinton and Ayer quadrangles. This implies a Silurian or older age for the Merrimack Formation. An Ordovician or older age for the Merrimack Formation is indicated by the 445 ± 15 m.y. radiometric age of the Newburyport Complex (Zartman and Naylor, in press) which intrudes the Merrimack Formation near Newbury, Mass. However, this isochron shows considerable scatter and is best regarded as tentative.

The granite at Malden Hill, Fitchburg, Mass., has a 410 ± 12 m.y. age (Rb-Sr whole-rock age: Zartman and Naylor, in press) and is intrusive into the Oakdale Formation and unit as. The Exeter Pluton near Exeter, N.H., is intrusive into the Merrimack Group (Billings, 1956) of southeastern New Hampshire and southern Maine and has a 407-m.y. age (Rb-Sr whole-rock: Gaudette, Kovach, Fairbairn, and Hussey, in press). These rocks are generally the oldest of a series of Acadian syntectonic to posttectonic plutonic rocks with ages averaging 400 ± 20 m.y. that intrude the pre-Pennsylvanian rocks of the Nashua River area.

Zircons from granofels layers in the Oakdale Formation have Pb/U and Pb/Th ages of approximately 1200 m.y. (Aleinikoff, 1978). Zircon morphology suggests they are detrital and therefore represent the crystallization age of the provenance. The zircon ages do not reflect an Ordovician age of the source area, which may be significant since Ordovician-age sedimentary and volcanic rocks, and gneisses were probably exposed in the Bronson Hill Anticlinorium during the Early Silurian and were likely the provenance for at least part of the Merrimack Synclinorium sedimentary basin during the Silurian (Boucot, 1968). The implication is that

1) the Merrimack Synclinorium sedimentary rocks in the Nashua River area are older than Silurian,

2) the Merrimack Synclinorium basin in the Nashua River area did not receive Ordovician detritus, and its deposits are solely derived from Grenville detritus, or

3) the input of Ordovician detritus was insignificant in comparison to the amount of older detritus.

The Oakdale and Merrimack Formations can be correlated with the Merrimack Group (Billings, 1956, p. 43) of southeastern New Hampshire and southern Maine. This correlation was first proposed by Emerson (1917, p. 59) and has been accepted by later workers (Grew, 1970; Peck, 1976). The Merrimack Formation in the Nashua River area has been mapped along strike into southern Maine. The Merrimack Group has been tentatively correlated by lithotype similarity with a sequence of fossiliferous Silurian and Devonian formations exposed near Waterville, Maine (Billings, 1956; Hussey, 1968; Osberg, 1968; Pankiwskyj et al., 1976) and is the basis for the proposed Silurian and Devonian age of the Oakdale Formation, Merrimack Formation, and unit as. The Worcester Formation, which underlies the Merrimack Formation, may be older than Silurian and has been tentatively assigned an Ordovician to Devonian age.

However, this correlation is not consistent with the 445 ± 15 m.y. radiometric age of the Newburyport Complex, which is intrusive into the Merrimack Formation (Zartman and Naylor, in press) or with some of the zircon dates from intrusive rocks in the New Hampshire portion of the Fitchburg Pluton (Aleinikoff, 1978). At present, the writer prefers the lithotype correlation with fossiliferous sedimentary rocks in the Waterville, Me., area over the age constraints determined by radiometric dates on intrusive plutons. This preference is based, in part, upon the uncertainties involved in zircon radiometric analysis (Higgins et al., 1977).

RELATIONSHIP OF THE OAKDALE FORMATION TO THE MASSABESIC GNEISS COMPLEX IN NEW HAMPSHIRE

The Oakdale Formation in the Townsend quadrangle strikes northeast into the Fitchburg Pluton, where granitic intrusive rocks form a migmatite zone containing numerous lenticular inclusions and inclusion swarms of Oakdale Formation. The granites have intruded the meta-sedimentary rocks along foliation planes, and inclusion trains of distinctive rocks, such as unit as, may be followed for some distance. Locally as much as 20 percent of a migmatite zone may be Oakdale Formation, and many inclusions are nearly completely assimilated in the granites. Biotite schlieren and lenticular plagioclase-rich segregations within the granite bodies are interpreted as assimilated Oakdale inclusions. Occasional calc-silicate layers composed of plagioclase, amphibole, diopside, and/or grossular occur.

This zone has been mapped to the northeast along strike in the Milford, N.H., 15' quadrangle as Massabesic Gneiss Complex (Aleinikoff, 1978) (Fig. 11). A U-Pb-Th radiometric study of zircons from the Massabesic terrane indicates that (1) granitic gneisses that intrude layered gneisses in the belt of Massabesic Gneiss Complex as mapped by Aleinikoff give primary U-Pb-Th zircon ages of 650 and 475 m.y.; (2) layered gneiss with a proposed metavolcanic protolith near Milford, N.H., gives primary zircon ages of 650 m.y.; (3) detrital zircons in layered Massabesic Gneiss Complex have a 1200-m.y. primary U-Pb-Th age;

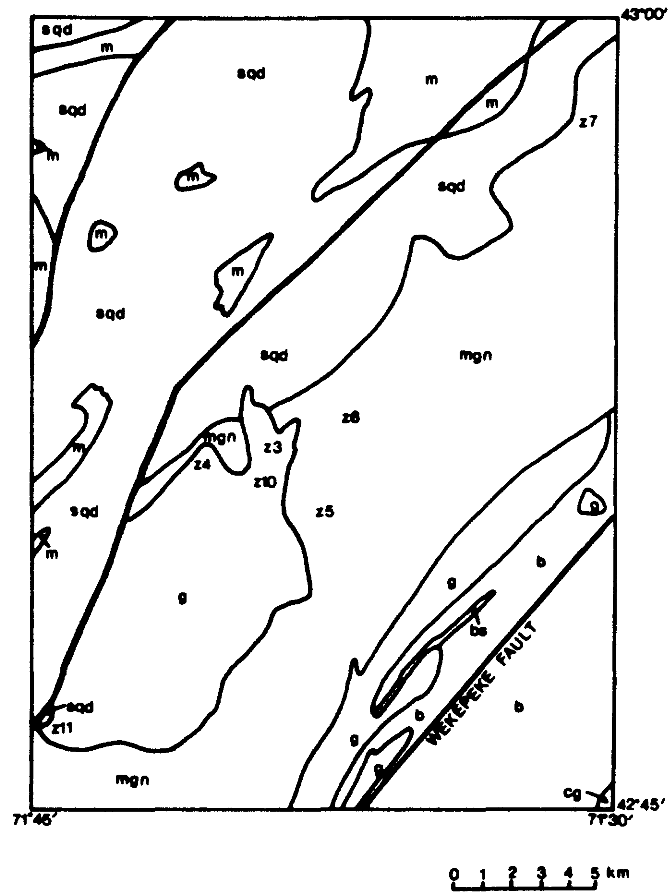


Figure 11. Generalized geologic map of the Milford, N.H. quadrangle. Modified from Aleinikoff (1978).

g	275-280 m.y. granite
sqd	Spaulding Quartz Diorite and local Kinsman Quartz Monzonite bodies
cg	Chelmsford Granite
m	Paleozoic metasediments (undivided)
bs	Berwick Formation schist (unit as)
b	Berwick Formation (Merrimack and Oakdale Formations)
mgn	Massabesic Gneiss (of Ordovician age, Aleinikoff, 1978)
z5	Location of zircon samples

and (4) crosscutting biotite granite gives primary zircon ages of 280 to 275 m.y. Aleinikoff has described the Massabesic Gneiss Complex stratigraphy as a metavolcanic belt with concurrent granitic intrusions developed at 650 m.y. ago between Milford and Manchester, N.H. His metavolcanic belt passes laterally into the Oakdale Formation (Berwick Formation of Aleinikoff) sedimentary basin (detrital zircons: 1188 m.y.). Granite with a 475 m.y. age intrudes the "metavolcanic"-Oakdale belt, forming an extensive migmatite zone. Biotite granite with a 275 m.y. age also intrudes this belt.

An apparent conflict between the proposed Silurian and Devonian age of the Oakdale Formation and the proposed Proterozoic Z to Ordovician age of the Massabesic Gneiss Complex occurs in this area. The conflict may be resolved by one of the following three explanations:

(1) The Oakdale Formation and its equivalents contain rocks older than Silurian, and regional lithotype correlations need to be revised;

(2) Large inclusions of pre-Silurian rocks occur in the Devonian granite suite of the Fitchburg Pluton; or

(3) The zircon dates are unreliable and reflect contamination with the 1200 m.y. detrital zircons in the Oakdale Formation. However, a study of the zircons from the 475 m.y. intrusive gneiss gives no evidence to substantiate detrital cores within the zircons (Aleinikoff, 1978, pp. 179-181).

At present, I favor explanations 2 and 3. The two localities for the 475 m.y. intrusive gneiss occur in the central portion of the

Milford, N.H., 15' quadrangle and intrude poorly bedded quartzofeldspathic gneiss that does not resemble the well-bedded gneiss of the Oakdale Formation (Fig. 11). Aleinikoff has described these poorly bedded quartzofeldspathic gneisses as felsic metavolcanics (excellent exposure for example at locality Z5). It is not clear whether the metavolcanic gneiss can be traced into the Oakdale Formation migmatite, and it is questionable that the "Ordovician migmatite" is as extensive as shown by Aleinikoff. Furthermore, intrusives along the strike belt of Aleinikoff's "Ordovician migmatite" in the Townsend and southern Milford quadrangles contain inclusions of Oakdale Formation and unit as that exhibit D1 schistosity and folds and D2 schistosity and crinkle folds. If these deformation events are indeed Acadian, then the intrusive rocks cannot be Ordovician. In addition, the biotite granodiorite mapped by Aleinikoff in the southwest portion of the Milford quadrangle as Spaulding(?) Quartz Diorite was mapped by Peper and Wilson (1978) in the Ashby quadrangle as Dfbg. The Spaulding Quartz Diorite has been dated as Devonian by Lyons and Livingston (1977) and thus should intrude the "Ordovician migmatite" of Aleinikoff's Massabesic. However, Peper (personal communication) reports that Dfbg is cut by intrusive rocks (Dfbqm of Peper and Wilson, 1978) in the strike belt of the Massabesic Gneiss Complex.

Furthermore, geochronologists recognize the problems associated with inherited zircons in U-Pb-Th analysis and a number of cases of zircon contamination have been documented (summarized by Higgins *et al.*, 1977). Inherited zircons may not always be discernable by color, morphology, or the presence or absence of metamict zircons in plutonic suites, and relatively low temperatures (350° to 400°C) are sufficient to cause recrystallization of radiation-damaged zircon lattices and open the U-Pb-Th systematics of domains in zircons (Gebauer and Grunenfelder, 1976; Gastil *et al.*, 1967; Naeser, 1976).

CHAPTER 6. GEOLOGIC HISTORY

Table 7 summarizes the geologic history of the Nashua River area. The Paleozoic stratigraphic section has been deformed by two Acadian events that preceded the latest Devonian granites in the Fitchburg Pluton (380 m.y.). The oldest deformation phase (D1) produced northeast-trending tight isoclinal folds (F1) coincident with regional metamorphism and the development of regional schistosity parallel to F1 axial planes. Event D1 is likely correlative with the recognized deformation that produced the westward-directed isoclinal folds of extreme elongation in the western Merrimack Synclinorium and Bronson Hill Anticlinorium of Vermont and Massachusetts.

Deformation D2 produced subhorizontal northeast-trending eastward-directed chevron folds (F2) and thrusts coincident with the development of a secondary fracture cleavage and foliation (S2). Event D2 is likely correlative with the thrusting and deformation associated with the Honey Hill-Lake Char thrust system in the Merrimack Synclinorium of Connecticut, although the intensity of deformation appears to have diminished to the northeast.

Gentle upright open folds (F3) deform S2 schistosity and postdate D2. Northeast-trending high-angle faults and subordinate northwest-trending faults (D4) truncate the previous structural fabrics, metamorphic isograds, and lithologic units. Adjacent to the faults are zones of intense chevron folding (F4), schistosity development (S4), and hydrothermal alteration and retrograde metamorphism.

Table 7. Geologic History

Age	Tectonics	Minor Structures	Metamorphism	Intrusions
Triassic	High-angle tensional faulting (reactivated?) along northeast-southwest trend. (Northwest-southeast high-angle faults – age uncertain)	Mylonitization and silicification along Wekepeke Fault system and other northeast-trending faults. S4, F4 minor structures developed		Basalt dike in Townsend quad. (age uncertain)
Permian(?)		(Open warping with no associated axial plane foliation – F3 minor folds. Age uncertain)	(Pennsylvanian and Permian metamorphism) Contact metamorphism	275-280 m.y. granite
Pennsylvanian	Deposition of Pennsylvanian terrestrial sedimentary rocks in Worcester, Mass., area			
Pennsylvanian to Devonian	(Initiation of high-angle faulting localizing the deposition of Pennsylvanian strata)	(Mylonitization along Clinton-Newbury Fault system and other northeast-trending faults)		
Devonian	(Intrusion may be syntectonic with fold-thrust tectonics described below; more likely posttectonic)	Flow foliation in plutonic rocks	Contact metamorphism	Intrusion of Chelmsford and Fitchburg Granites

Table 7. Geologic History (Continued)

Age	Tectonics	Minor Structures	Metamorphism	Intrusions
Devonian to Silurian		Foliation	Contact metamorphism (regional metamorphism	Diorite and Monzonite intrusion
Devonian	Fold-thrust tectonics. General west-over-east transport. (Possible initiation of high-angle faulting)	Development of thrusts and chevron folds. Chevron folds with gently inclined axial planes (F2) and strain-slip cleavage (S2) developed in nose and lower limb of larger folds. Inclined chevron folds (F2b) developed on upper limb of larger folds. Fold axes trend northeast	Waning regional metamorphism	
Devonian	Isoclinal folding. Scale of folding unknown	Development of tight isoclinal folds with strong axial plane foliation (F1). When visible, folds present on a scale from 10's of cm to 10's of meters. (Quartz-carbonate veining – involved in subsequent metamorphism)	Regional metamorphism	
Devonian through Ordovician	Deposition of strata in a deep marine eugeosynclinal basin			

ACADIAN METAMORPHISM

POSSIBILITY OF ALLEGHANIAN METAMORPHISM

Many K-Ar isotopic ages of micas from intrusives in southeastern New England are Permian and may represent either Acadian orogeny uplift cooling ages (Zartman et al., 1970) or an Alleghanian re-equilibration of isotopic ages (Grew, 1970, p. 128). Carboniferous rocks in the Worcester area and the presumed Pennsylvanian Harvard Conglomerate at Pin Hill, Harvard, Mass. (which, as shown by Thompson and Robinson, 1976, unconformably overlies the Ayer Granite), are regionally metamorphosed and deformed, and associated phyllites contain biotite-garnet or chloritoid. Therefore, a Carboniferous or younger metamorphism of at least biotite grade has affected portions of Massachusetts as far west as Worcester and possibly as far north as Harvard.

This metamorphism, however, appears largely constrained to the Pennsylvanian basin and adjacent areas, and may have been of short duration, since Paleozoic sedimentary rocks nearby are in the chlorite zone and some mica ages from Devonian intrusive rocks in the area apparently are unaffected by the Permian metamorphism. For example, the Rb-Sr muscovite age of the granite at Millstone Hill, Worcester, Mass., is 379 m.y. (Zartman and Naylor, in press) and the K-Ar muscovite age of the Chelmsford Granite, West Chelmsford, Mass., is 327 ± 17 m.y. (Zartman et al., 1970). K-Ar mica dates from rocks in the Fitchburg Pluton area, however, show Permian ages of 230 to 240 m.y.

The Alleghanian metamorphism may in part be related to, or the cause of, the emplacement of granite plutons with a 275 to 280 m.y.

radiometric age within the Fitchburg Pluton in New Hampshire. Thermal re-equilibration in response to this intrusive event may explain the 100 m.y. difference in K-Ar mica ages from granites in the Fitchburg Pluton (230 to 240 m.y.) versus the Chelmsford Granite (330 m.y.).

AGE OF FAULTING

Thrust faults associated with deformation phase D2 are Acadian in age and precede the intrusion of at least the youngest Devonian granites in the Fitchburg Pluton (380 m.y.).

Deformation phase D2 in the Nashua River area is presumably contemporaneous with the development of imbricate thrusts in the Brimfield area of Massachusetts and Connecticut (Peper _et al._, 1975) and the Honey Hill-Lake Char thrust in Connecticut (Dixon and Lundgren, 1968). Dixon and Lundgren (1968, p. 228) state: "Large-scale folding, metamorphism, and the inception of faulting were most likely overlapping aspects of one major tectonic event." Mylonitization associated with these thrusts postdated only slightly the Acadian thermal peak as indicated by

(1) recrystallization of the Honey Hill-Lake Char mylonites to sillimanite-zone assemblages (Dixon and Lundgren, 1968, p. 226)

(2) recrystallization of mylonite in the Warren, Mass., area to an assemblage indicating metamorphic equilibration at 7 to 8 kilobars and 550°C (Robinson _et al._, 1977), and

(3) the occurrence of pegmatitic segregations in tension gashes and shear zones associated with mylonite zones in the Brimfield area (Peper, personal communication).

However, Dixon and Lundgren (1968, p. 229) state:

> "Folding of the early cataclastic rocks, truncation of metamorphic isograds, . . . ultramylonite dikes and breccias, and slickensided foliation surfaces all indicate that significant displacements continued in the fault zone after metamorphic conditions ceased. . . . We believe that fault activity probably continued through the Pennsylvanian and possibly into Permian time."

Block *et al.* (1979) present evidence that the Honey Hill Fault zone may still be active in the Moodus area of Connecticut.

Clinton-Newbury Fault

The Clinton-Newbury Fault has traditionally been thought of as a high-angle eastward-directed thrust similar in age and nature to the Honey Hill-Lake Char Fault in Connecticut (Skehan, 1968; Alvord *et al.*, 1976; Bell and Alvord, 1968). Pre-Pennsylvanian mylonitization along the Clinton-Newbury Fault trend is indicated by the deposition of the Pennsylvanian Harvard Conglomerate (Thompson and Robinson, 1976) unconformably upon cataclastic Ayer Granite on North Vaughn Hill near Hudson, Mass. Post-Pennsylvanian movement along the fault zone is indicated by

(1) the truncation of Harvard Conglomerate along the east side of Pin Hill, Harvard, Mass., by a branch of the Clinton-Newbury Fault;

(2) incorporation of a thin band of Harvard Conglomerate within the cataclastic Ayer Granite north of Bare Hill Pond, Hudson, Mass.;

(3) faults, apparently related to the Clinton-Newbury Fault, that bound the sedimentary block containing the Pennsylvanian fossil locality at the Worcester coal mine. A shallow, northwest-dipping thrust bordering the fossil locality (Clinton Fault of Castle et al., 1976) juxtaposes Paleozoic rocks structurally above the Pennsylvanian sedimentary rocks (Castle et al., 1976, p. 14; Grew, 1970, p. 221; Skehan, 1968, pp. 284, 287); and

(4) graphitic coaly material in fault gouge found in borings made at Memorial Hospital in Worcester, Mass., approximately 2740 m southwest of the Worcester coal mine (Peck, 1976, p. 249).

K-Ar ages of mylonites from the Clinton-Newbury Fault in the vicinity of Newbury, Mass., give Early Permian ages of 248 to 272 m.y. These ages may reflect either uplift and erosion cooling ages (Zartman et al., 1970) or the age of mylonitization and recrystallization; both alternatives indicate that cataclasis associated with the Clinton-Newbury Fault is pre-Triassic in age (Rand, 1974, p. 15). This is supported by the observation of an undeformed (based on petrography) diabase dike with a K-Ar whole-rock age of 199 ± 9 m.y. intruding the Clinton-Newbury mylonite in the Newbury, Mass., area (Rand, 1974, p. 15).

Evidence for Pennsylvanian or younger thrusting exists elsewhere in New England not far from the Nashua River area. The North Border Fault of the Boston Basin and the Ponkapoag Fault, both part of a swarm of faults that apparently merge with the Lake Char Fault, thrust Paleozoic rocks over Pennsylvanian or older sedimentary rocks (Billings, 1976; Cuppels, 1961). The Ponkapoag Fault thrusts basement rocks over fossiliferous Pennsylvanian sedimentary rocks in the Norfolk Basin (Billings, 1976). The thrust nature of the North Border Fault is spectacularly demonstrated in the Malden Tunnel where Paleozoic volcanic rocks are thrust over the Cambridge Argillite of probable Pennsylvanian age (Billings and Rahm, 1966).[*1]

Recently, thrust faults have been identified that cut Pennsylvanian sedimentary rocks in the Narragansett Basin of Rhode Island (Skehan et al., 1977). It is interesting to speculate that the Pennsylvanian thrusts are reactivated along the late Acadian thrust trends.

High-Angle Faults

Northwest-trending high-angle faults have been thought to be the youngest faults in the region since they appear to offset northeast-

[*1]The hypothesized Pennsylvanian age of the Cambridge Argillite rests mainly on lithotype correlation of rocks in the Boston Basin with rocks in the nearby Norfolk and Narragansett Basins and the discovery of what appear to be two poorly preserved fossil logs in the Roxbury Conglomerate (Burr and Burke, 1900; Billings, 1976) which stratigraphically underlies and interfingers with the Cambridge Argillite (Billings, 1976). Recent radiometric age determinations on felsic volcanic rocks that intrude the Roxbury Conglomerate indicate a pre-Carboniferous age for the basin (Hepburn, personal communication). The Roxbury Conglomerate must be younger than the Dedham Granite (580 to 600 m.y.) since it contains Dedham cobbles and unconformably overlies the Dedham.

trending faults in the Worcester area (Grew, 1970, p. 226). This appears to hold in some cases; the Squanacook Fault, for example, truncates the northeast-trending Groton Fault in the northwest corner of the Ayer quadrangle. However, the position of the Wekepeke Fault is fairly tightly constrained and does not appear to be offset by the Squanacook Fault. In addition, the Wekepeke Fault zone may offset the Squanacook Fault, although this is not well constrained.

The implication is that the northeast-trending high-angle faults represent different periods of final movement. The northeast-trending faults associated with mylonitization and cataclasis, but no silicification, appear to predate the northwest-trending faults. A dike of the 275 to 280 m.y. granite has intruded along a small vertical offset in the Massabesic Gneiss Complex near Manchester, N.H. (Plate 3d), and the Nonesuch River Fault, an extension of the Wekepeke Fault, is intruded by the Lyman Pluton (333 m.y. Rb-Sr whole-rock age) in southeastern Maine (Hussey and Newburg, 1978; Gaudette et al., in press). These cross-cutting relationships indicate that the northeast-trending high-angle faults initiated movement by Late Devonian to Pennsylvanian time. The deposition of Pennsylvanian conglomeratic sedimentary rocks in the Worcester area was likely determined and localized by earlier faulting (Grew, 1976, pp. 388-389). The unsilicified northeast-trending faults appear to have had some post-Pennsylvanian movement, since Pennsylvanian sedimentary rocks are truncated by the Clinton-Newbury Fault.

Northeast-trending faults associated with silicification appear to postdate the northwest-trending faults. These northeast-trending faults appear to have had pre-Jurassic movement, since a Jurassic lamprophyre dike cuts a northeast-trending silicified zone in the Milford quadrangle (Aleinikoff, 1978, pp. 66-69). The northwest-trending faults, therefore, are probably Permian to Jurassic in age and are possibly related to faulting along the Monteregian Hills-White Mountain-New England Seamount trend. A transform fault along the New England Seamounts offsets magnetic lineations of presumed Mesozoic age in the western Atlantic (Fletcher et al., 1978).

Relationship of High-Angle Faults to Carboniferous Rift Systems in Canada

Wilson (1962), Webb (1967), and Grew (1976) propose that some of the high-angle faults in the Nashua River area, such as the Clinton-Newbury and Wekepeke Faults, connect across Maine and the Gulf of Maine with the fault systems associated with the Fundy basin rift (Belt, 1968). Ballard and Uchupi (1975) present evidence for a fault-bounded Carboniferous basin in the Gulf of Maine that merges with the Fundy Fault system, although relations are complex in this area due to Triassic and Jurassic faulting along similar trends. The Pennsylvanian sedimentary rocks and associated faults in east-central Massachusetts may represent a continuation of the Carboniferous rift system in eastern Canada. Deposition of Pennsylvanian sedimentary rocks in the Nashua River area may have been localized along the fault zones (Clinton-Newbury Fault), and at present only a few outliers of the sedimentary rocks remain.

The Clinton-Newbury Fault may define a zone of substantial displacement, since rock types on both sides of the fault zone are lithologically dissimilar, and no correlation of rock types has yet been made across the fault in this area. However, basement rocks with Avalonian ages (580 to 600 m.y.) occur on both sides of the Clinton-Newbury Fault (Naylor, 1975; Besancon et al., 1977). If these basement rock types with 580 to 600 m.y. ages are believed to represent similar crustal blocks, then the discontinuity separating the Avalon and Grenville provinces does not coincide with the Clinton-Newbury Fault. Webb (1967) estimates 60 to 125 miles of dextral strike-slip motion along Carboniferous faults associated with the Fundy basin rift in New Brunswick and Newfoundland.

Substantial displacement along the Wekepeke Fault is probable since metamorphic isograds and lithologic contacts are truncated, but the fault does not appear to define a discontinuity between different crustal blocks. Structural, metamorphic, and lithologic correlations can be made across the fault zone.

UPLIFT AND EROSION RATES IN THE NASHUA RIVER AREA

Post-Acadian uplift and erosion rates can be estimated in a few areas in New England in or adjacent to the Nashua River area. Post-Acadian regional uplift and erosion are not homogeneous, as indicated by the trace of the aluminosilicate triple-point isobar in New England (Thompson and Norton, 1968, Fig. 24-1, p. 320). This line is the approximate trace, on the present erosion surface, of a fossil isobaric surface corresponding to the pressure of the kyanite-andalusite-sillimanite triple point. Since significant overpressures in excess of lithostatic pressure are not likely to be developed or maintained in rocks under metamorphic conditions, this isobaric surface closely approximates a surface of equal crustal depth. Areas on the kyanite side of the triple-point isobar, such as Connecticut, the Western Merrimack Synclinorium in Massachusetts, and the Bronson Hill Anticlinorium, are exposed at greater depths of erosion than areas on the andalusite side of the isobar, such as eastern New Hampshire, eastern Massachusetts, and Maine.

Carmichael (1978) has expanded this concept of Thompson and Norton (1968) and has mapped a series of bathograds (a metamorphic isograd that delineates a higher-pressure-phase assemblage from a lower-pressure-phase assemblage) and bathozones in New England. The Nashua River area and adjacent areas in New Hampshire along strike to the northeast lie in bathozone 3 of Carmichael which corresponds to an estimated pressure range of 3.3 to 3.8 kilobars. This is consistent with the estimates of pressure during Acadian metamorphism in the Nashua River area presented here.

The bathograds and bathozones reflect a frozen equilibrium established during the Acadian metamorphism that is now exposed at the earth's surface. From this information alone only very generalized erosion rates, which ignore oscillatory uplift and downwarping and which are averaged over a 400 m.y. span, may be estimated. For the bathozone 3 areas, erosion rates estimated in this manner are 0.031 to 0.035 mm/yr.

A more detailed estimate of erosion rates requires depth estimates of the rocks presently exposed at the earth's surface at a number of different times in the past. Three types of evidence have been used to further constrain the erosion rate estimates:

1) the presence of erosional unconformities constrained in time,
2) estimates of the depth of emplacement of post-Acadian plutons that have measured radiometric ages, and
3) estimates of depth of fission-track and mica K-Ar "cooling ages" using assumed geothermal gradients.

The depth-time estimates utilizing fission-track and K-Ar mica ages involve the greatest uncertainty, since the ages reflect a kinetic (diffusion) process that is both temperature- and time-dependent and the depth is dependent upon estimates of paleogeothermal gradients. Laboratory diffusion and annealing studies have been undertaken, and the results extrapolated to geologic conditions of temperature and time (10 to 100 m.y.) to estimate the effective diffusion or annealing closing temperatures of various minerals. The argon diffusion closing temperature for muscovite and biotite micas is estimated to be below 300°C, based on the argon diffusion in phlogopite experiments of Giletti (1974). A temperature range of 260° to 300°C is used here as an estimate. Fission-track annealing temperatures are estimated at 200°C for zircon and 100°C for apatite (Naeser, 1976).

The present-day geothermal gradient in New England is approximately 20°C/kilometer, determined from the heat flow studies of Birch et al. (1968, p. 445). They estimate that corrections to the geothermal gradient over the past 200 million years would be less than a 2°C/kilometer increase. However, the estimates of pressure and temperature during Acadian metamorphism (T = 500° to 550°C, P = 3.5 to 3.8 kilobars) in this area indicate a temperature distribution hotter than could be achieved solely by a geothermal gradient of 20°C/kilometer. After this period of metamorphism, the temperature distribution gradually readjusts toward the "typical" geothermal gradient. A time span greater than 30 m.y. appears necessary for this thermal readjustment, as indicated by Frey (1978, p. 132) who cites present-day measurements of 20° to 50°C/kilometer gradients in the Alps which reflect a 20 to 38 m.y. metamorphic event and rapid erosion rates. A geothermal gradient of 25°C/kilometer for the periods between tectonic episodes is assumed in the following erosion rate calculations and appears to give reasonable results.

Wilson (1965) and Creasy (1974) have estimated the depth of crystallization of the White Mountain Magma Series (now renamed White Mountain Plutonic-Volcanic Suite) in the Ossipee Lake area of New Hampshire as 6 to 6.5 kilometers (1.6 to 1.75 kilobars). Radiometric dates on rocks of the White Mountain Plutonic-Volcanic Suite from this area generally range between 170 and 190 m.y. (summarized by Creasy, 1974, Table 2-1, pp. 23-24; Table 2-2, p. 26).

The age of the unconformity beneath the Pennsylvanian sedimentary rocks at Worcester, Mass., is ambiguous, but was likely established before 280 to 290 m.y. ago. The Pennsylvanian sedimentary rocks in this locality contain fragments of the nearby granite on Millstone Hill (Grew, 1970). The radiometric age of the granite on Millstone Hill has been determined as 380 m.y. (Zartman and Naylor, in press). The granite contains primary muscovite (Grew, 1970), which constrains the pressure during crystallization of the granite to be greater than the pressure at the intersection of the muscovite + quartz breakdown curve with the granite minimum liquidus under water-saturated conditions.

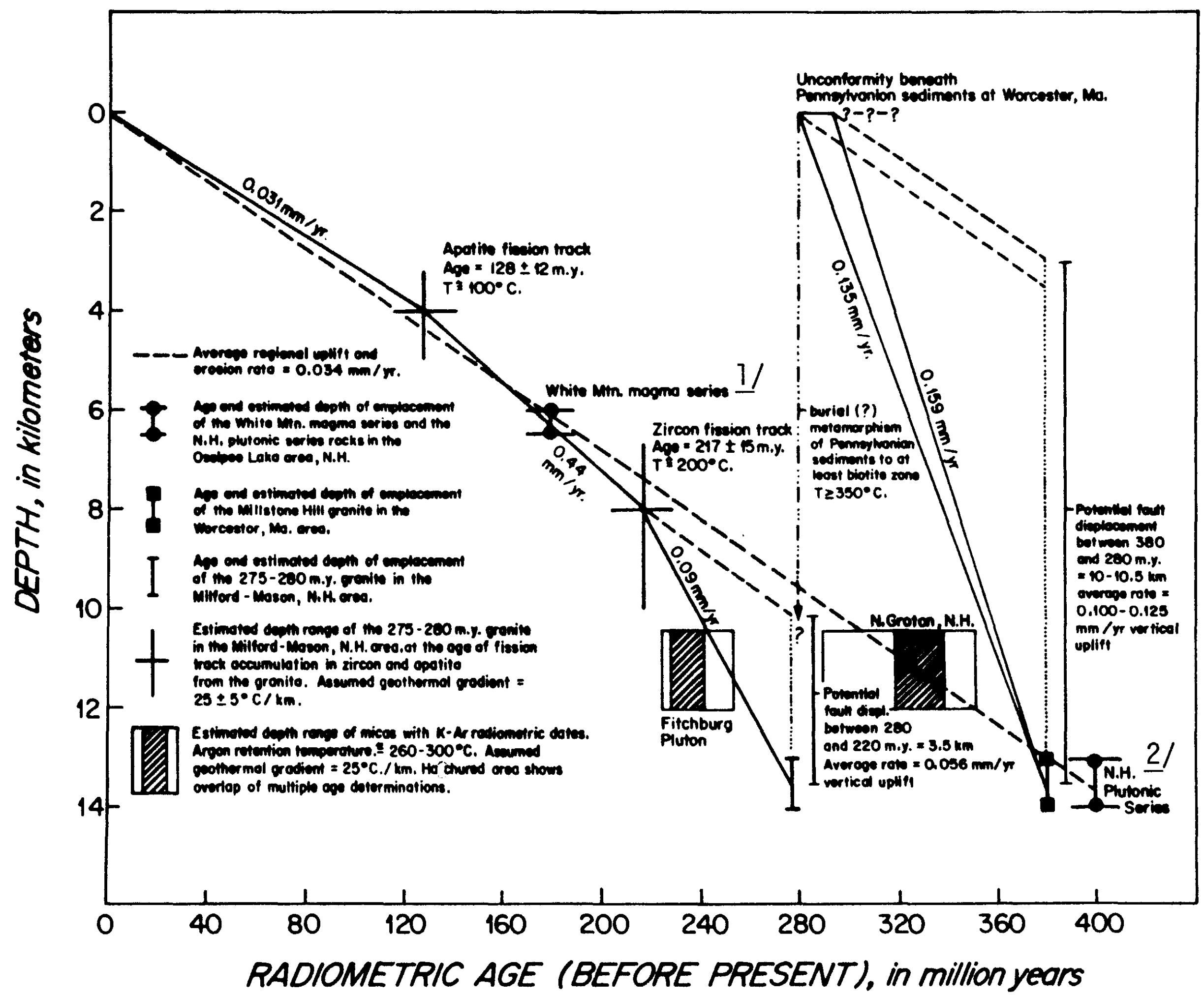
Experimental determinations place the pressure of intersection at about 3.4 kilobars (Chatterjee and Johannes, 1974; Tuttle and Bowen, 1958). Andalusite occurs in the pelitic schists adjacent to the Fitchburg Pluton in this area, which constrains the pressure to be below 3.8 kilobars. Depth estimates for the emplacement of the granite at Millstone Hill range between 13 and 14 kilometers.

Similarly, Aleinikoff (1978) reports primary muscovite from the 275 to 280 m.y. granite in the Milford-Mason, N.H., area. Estimates of depth of crystallization here are also 13 to 14 kilometers.

The above information has been compiled in Figure 12. Interestingly, the depth-time relationships in the Ossipee Lake area constrained by the age and pressure estimates of Acadian metamorphism, K-Ar mica ages from pegmatites, the age and depth of emplacement of the White Mountain Plutonic-Volcanic Suite, and the present-day erosion surface can be adequately fit using a uniform erosion rate of 0.034 mm/yr. This rate is accepted here as an estimate of the background regional uplift and erosion rate for the Nashua River area that is independent of faulting. Furthermore, this model fits the estimated depth of fission-track ages of zircon and apatite from granite near Milford, N.H., indicating that from 220 m.y. ago to the present this area essentially conformed to the regional erosion rate.

However, periods of rapid uplift and erosion 400 to 220 m.y. ago are indicated for at least local areas in the region. In the Worcester area, the unconformity beneath the Pennsylvanian sedimentary rocks indicates that erosion rates are greater than 0.135 to 0.159 mm/yr. during the 80 to 100 m.y. postdating the Acadian orogeny. A similar situation

Figure 12.
ESTIMATED EROSION RATES



1/ Now renamed White Mountain Plutonic-Volcanic Suite
2/ Now renamed New Hampshire Plutonic Suite

exists for the Harvard Conglomerate, which is unconformably deposited upon the muscovite-bearing Ayer Granite in the Harvard, Mass., area. An unknown thickness of Pennsylvanian sedimentary rocks was deposited, and metamorphic conditions in the Pennsylvanian basin reached at least biotite zone ($T \geqslant 350°C$). This metamorphic event appears localized, though, since nearby areas of Paleozoic sedimentary rocks are in the chlorite zone and the Rb-Sr mica age (muscovite: 379 m.y.) of the granite at Millstone Hill, Worcester, Mass., has not been reset.

Rapid uplift and erosion postdating the emplacement of the 275 to 280 m.y. granite in the Milford-Mason, N.H., area are also indicated. An erosion rate of 0.09 mm/yr is estimated for the 60 m.y. period postdating the emplacement of the granite. K-Ar mica ages (230 to 240 m.y.) from nearby portions of the Fitchburg Pluton are consistent with a resetting of isotopic ages in response to the thermal effects of the granite intrusion. This may explain the approximately 100 m.y. difference in K-Ar mica ages between the Chelmsford Granite, Chelmsford, Mass., (327 ± 17 m.y.) and the Fitchburg Granite (230 to 240 m.y.).

Both areas of rapid erosion occur adjacent to zones of high-angle faults, in particular the Wekepeke Fault and the Clinton-Newbury Fault. Using the regional average erosion rate of 0.034 mm/yr as a background value allows vertical throw on the high-angle faults to be estimated. Possible vertical throw on the Clinton-Newbury Fault in the Worcester area is estimated at 10 to 10.5 kilometers, or a rate of 0.100 to 0.125 mm/yr fault-related vertical uplift between 380 to 280 m.y. ago. Possible vertical throw on the faults bounding the block containing the 275 to 280 m.y. granite at Milford, N.H., is estimated at 3.5 kilometers or a rate of 0.056 mm/yr between 280 and 220 m.y. ago. It is probable that the Pennsylvanian sedimentary rocks in the Worcester area were deposited as alluvial fans off the fault scarps, and several thousand kilometers of sediment were possibly deposited along the Clinton-Newbury Fault scarp. Periodic reactivation of the fault zones and the intrusion of the 275 to 280 m.y. granite may account for both the deformation and metamorphism evident in the localized areas of Pennsylvanian rock.

SUMMARY OF GEOLOGIC HISTORY

Osberg (1978) presents a regional geologic synthesis for the Appalachians in New England in terms of a complex plate-tectonic model. His synthesis is generally consistent with the summary presented here; however, some reinterpretation is required to be consistent with some radiometric age information.

Much of New England is underlain by deformed, metamorphosed, and intruded sedimentary rocks of Cambrian to Devonian age unconformably overlying Precambrian basement of two distinct ages (Fig. 3). Basement rocks with a 900 to 1100 m.y. radiometric age (Grenville) are confined west of the Connecticut Valley and are exposed in the Berkshire Hills, Green Mountains, and the Adirondack Mountains as well as Canada. Basement rocks with a 550 to 650 m.y. radiometric age (Avalonian) are exposed in southeastern Newfoundland, coastal New Brunswick, and southeastern Massachusetts, although an exposure of Avalonian-age gneiss occurs farther west in the core of the Pelham

Dome in Massachusetts (Naylor, 1975). The extent of Avalon basement presented here differs from the interpretation of Osberg (1978), who considers all gneisses in the domes of the Bronson Hill Anticlinorium to be eroded remnants of a 450 to 550 m.y. "island arc." However, a few exposures of plutonic rocks with Avalonian ages occur within this area (Naylor, 1975). The Dry Hill Gneiss in the core of the Pelham Dome in the Bronson Hill Anticlinorium has a Pb^{207}/Pb^{206} age of 575 m.y. and is unconformably overlain by the Ammonoosuc Volcanics of Middle Ordovician age. Peter Robinson (1976) has recognized a sillimanite-orthoclase grade metamorphism in this gneiss which predates deposition of the Ammonoosuc Volcanics. This indicates that at least local areas of granitoid basement rocks with an Avalonian age occur as far west as the Bronson Hill Anticlinorium. Furthermore, local areas of granitoid gneiss in the Fitchburg Pluton near Manchester, N.H., have a Pb^{207}/Pb^{206} age of 600 to 620 m.y. (Besancon et al., 1977).

The Taconic orogeny may mark the time of juxtaposition of the Grenville and Avalonian basement types in New England, since Ordovician (Graptolite zone 12-13) volcanic rocks and schists are the oldest units that can be correlated across the zone of basement convergence located between the Berkshire Hills-Green Mountains and the Bronson Hill Anticlinorium. The Taconic orogeny resulted in the development of the Taconic allochthon, other thrusts with a westward tectonic transport involving basement and cover rocks, and volcanism and plutonism (Highlandcroft Plutonic Series of Billings, 1956) along the Bronson Hill Anticlinorium. Volcanic and plutonic rocks of similar age may exist in localized areas in the Fitchburg Pluton (Aleinikoff, 1978).

The Bronson Hill "geanticline," Somerset "geanticline," and Merrimack "geosyncline" were structural features by at least the Late Ordovician. Shelf and beach-type deposits were developed along the flanks of the geanticlines during the Early Silurian, while deeper water sediments were deposited in the Merrimack geosyncline. Lithofacies relationships indicate filling of the Merrimack basin from both western (metamorphic, plutonic, and volcanic) and eastern (dominantly volcanic) sources from at least late Llandoverian through early Ludlovian time (Pankiwskyj et al., 1976). The Silurian sedimentary rocks the central and western Merrimack Synclinorium in Maine are interpreted as proximal, intermediate, and distal turbidite deposits (Rangeley and Perry Mounta Formations, Sangerville Formation, and Waterville Formation, respectively) derived from the geanticlinal terranes to the west and transported downslope to the east. This is consistent with the depositional model developed for the Nashua River area.

From early Ludlovian through Early Devonian time, thick turbidite sequences of sandstone, siltstone, and shale were deposited in the basin and overlapped the geanticlinal areas. The source of at least some of these turbidite sequences appears to be from the east (Osberg, 1978), p. 140) and may reflect a source from the emergent landmass to the east just prior to the Acadian orogeny. The Silurian and Devonian section in the Merrimack basin is greater than 6000 meters thick (Pankiwskyj et al., 1976).

The Early Devonian Acadian orogeny may mark the juxtaposition of the relatively undeformed Avalonian basement block (Boston-Nova

Scotia-Avalon Peninsula area) with the Merrimack geosyncline "island arc-turbidite basin" belt. The Honey Hill, Lake Char, and Burlington Fault zones presently define this junction in Massachusetts and Connecticut.

The direction of tectonic transport in the early phases of the Acadian orogeny was towards the west. Early major recumbent folds face west and associated thrust plates moved toward the west. Major anticlinoria and synclinoria generally developed along earlier trends. In the Bronson Hill Anticlinorium, original west-facing recumbent folds have been refolded to produce a second generation of recumbent folds that face east. Imbricate thrusts with eastward tectonic transport accompanied this deformation and are the dominant structural feature in parts of the Merrimack Synclinorium in Connecticut.

High-angle faulting was initiated after the Acadian orogeny and is probably responsible for the localized basins containing terrestrial sedimentary rocks of Pennsylvanian age in the Worcester, Norfolk, and Narragansett areas (Lyons, 1971). Faults bordering these basins may be related to the Fundy Fault system in Canada, and perhaps involve significant right-lateral slip (Webb, 1967). The development of coarse conglomeratic sedimentary rocks in these basins indicates a rugged topography was present at least locally.

In the Milford, N.H., and Narragansett, R.I., areas, granites with a 275 to 280 m.y. age have intruded Paleozoic metamorphic rocks. In at least the Narragansett area, deformation accompanied the intrusion of the "Alleghanian" granite. In the Worcester, Mass., area, the outliers of Pennsylvanian sedimentary rocks are deformed and are in the biotite zone of metamorphism. This deformation is possibly related to Carboniferous or younger movement along the bordering fault zones.

The Triassic and Jurassic basin in Connecticut and Massachusetts, northeast-trending silicified fault zones, and northeast-trending basalt dikes are related to a period of Mesozoic high-angle faulting and basalt intrusion. These Mesozoic faults locally coincide with the location of earlier faults. The rifting during the Carboniferous to Jurassic was likely related to the opening of the Atlantic Ocean. Veins containing zeolite assemblages in both Paleozoic and Mesozoic rocks are widespread in New England and suggest the possibility of a pervasive zeolite metamorphism of Triassic and Jurassic age (Osberg, 1978).

APPENDIX I. ESTIMATED MODES AND SAMPLE LOCATIONS OF METASEDIMENTARY ROCKS. MODE NUMBERS IN VOLUME PERCENT.

I.A. Estimated Modes of the Merrimack Formation Chlorite Zone

Rock	P-009	P-007 b	P-007	SR-329
Quartz	39 *2	51 *2	63	63
Plagioclase	tr	2	5	tr
Biotite				
Muscovite	30	10	15	16
Chlorite	20	32	2	7
Calcite		5 *3		
Ankerite	11		15	14
Epidote *1			tr	
Rutile			tr?	
Ilmenite	tr			tr
Sphene				
An =	0-4		0-5	

*1 Zoisite and clinozoisite are included with epidote.

*2 Quartz occurs preferentially in thin laminae defining compositional layering.

*3 Calcite occurs preferentially in quartz-rich laminae.

I.A (continued). Description and Location of Specimens

P-009. Siltstone. Outcrop on Rt. 119, 900 feet west of crossing over Bancroft Brook, Pepperell, Mass. (Pep. S. W. 1/9).

P-007b. Chlorite phyllite. Outcrop on Mt. Lebanon St., 800 feet southwest of intersection with Shirley St., Pepperell, Mass. (Pep. S. W. 1/9).

P-007. Siltstone. Outcrop on Mt. Lebanon St., 800 feet southeast of intersection with Shirley St., Pepperell, Mass. (Pep. S. W. 1/9).

SR-329. Siltstone. Outcrop on north side of Rt. 2, 250 feet east of Jackson Rd. exit ramp from westbound lane of Rt. 2, Harvard, Mass. (Shir. S. E. 1/9).

I.B. Estimated Modes of the Merrimack Formation. Biotite Zone.

Rock	P-020a	P-020b	P-520	P-021	P-2006	P-2004
Quartz	46	10	17	33 *3	59	75
Plagioclase	3			tr	6	tr
Biotite	18	40 *2	35 *2	3	25	19
Muscovite		30	30	30		1
Chlorite	8	20	17	30	tr	1
Calcite	25				10	3
Ankerite				4 *4		
Epidote *1					tr	1
Ilmenite	<1		1 *5			
Sphene					tr	
An =	22-34				33-36	

*1 Zoisite and clinozoisite are included with epidote.

*2 1 to 2 mm biotite porphyroblasts.

*3 Quartz occurs preferentially in quartz-rich laminae.

*4 Carbonate mineral unidentified.

*5 Ilmenite intergrown with magnetite.

I.B (continued). Description and Location of Specimens.

P-020a. Granofels. Outcrop in river bank beneath the Hollis St. bridge over the Nissitissit River, Pepperell, Mass. (Pep. C. C. 1/9).

P-020b. Biotite-rich schist. Outcrop in river bank beneath the Hollis St. bridge over the Nissitissit River, Pepperell, Mass. (Pep. C. C. 1/9).

P-520. Biotite-rich schist. Outcrop on Rt. 111, 3800 feet south of intersection of Dow St. with Rt. 111, Pepperell, Mass. (Pep. C. C. 1/9).

P-021. Siltstone. Outcrop on Hollis St., 1000 feet northeast of the intersection of Hollis St. with Elliott St., Pepperell, Mass. (Pep. C. W. 1/9).

P-2006. Granofels. Outcrop in abandoned quarry located 700 feet southeast of the intersection of the Groton-Pepperell town line and the Boston and Maine Railroad line east of the Nashua River, Groton, Mass. (Pep. S. C. 1/9).

P-2004. Granofels. Outcrop on east side of Boston and Maine Railroad line east of the Nashua River, 4100 feet south of the intersection of the rail line with Groton St. and 500 ft. north of the intersection of the rail line with the Groton-Pepperell town line, Pepperell, Mass. (Pep. S. C. 1/9).

I.C. Estimated Modes of the Merrimack Formation. Actinolite Zone.

Rocks	P-106	P-184a	P-184b	P-185	P-139
Quartz	49	48	38	35	59
Plagioclase	17	27	30	10	14
Biotite	14	8	10	40	15
Muscovite				14	
Chlorite		2			
Calcite	2 *2				2
Amphibole	16	12	15		6 *3
Epidote *1	2	3	7	1	4
Sphene	tr				tr
An =	32-38	32-36	32-36	20-38	35

*1 Zoisite and clinozoisite are included with epidote.

*2 Calcite preferentially located around biotite grains.

*3 Amphibole typically in clusters, often associated with zones higher in zoisite content.

I.C. (continued). Description and Location of Specimens

P-106.	Granofels. Outcrop on Knoll, 1000 feet west of Rt. 111-A and 1600 feet south of the intersection of Rt. 111-A and Conant Rd., Nashua, N.H. (Pep. N. E. 1/9).
P-184a and P-184b.	Granofels. Outcrop is 170 feet southwest of Fletcher St. and 700 feet southeast of the intersection of Fletcher St. with River St., Dunstable, Mass. (Pep. C. E. 1/9).
P-185.	Granofels. Outcrop on southwest side of Drake Hill, 170 feet east of Fletcher St., 600 feet south of intersection of Fletcher St. with River St., Dunstable, Mass. (Pep. C. E. 1/9).
P-139.	Granofels. Outcrop in woods, 400 feet north of Parker Rd., 2700 feet southeast of the intersection of Kemp St., Paddin Rd., and Parker Rd., Groton, Mass. (Pep. S. E. 1/9).

I.C. (continued). Estimated Modes of the Merrimack Formation. Actinolite Zone.

Rocks	P-590a	P-590b	P-130	P-1527	A-615
Quartz	58	56	47	47	48
Plagioclase	20*2	6	16	32	tr
Biotite	20	11	12	20	26*3
Muscovite					21
Chlorite					5
Calcite		tr			
Amphibole	tr	18	16		
Epidote*1	2	9	9	1	
Sphene	tr	tr	tr	tr	
Magnetite					1
An =	33-39				

*1 Zoisite and clinozoisite are included with epidote.

*2 Plagioclase occurs in coarse granular clusters.

*3 1 to 2 mm biotite porphyroblasts oriented across foliation.

I.C. (continued). Description and Location of Specimens

P-590a & P-590b.	Granofels. Outcrop on Rock Mill Rd., 400 feet west of intersection of Rock Mill Rd. with Parker Rd., Groton, Mass. (Pep. S. E. 1/9).
P-130.	Granofels. Outcrop on Knoll in woods, 1800 feet northwest of the intersection of Depot St. and Brook St., Dunstable, Mass. (Pep. C. E. 1/9).
P-1527.	Granofels. Outcrop on west side of railroad tracks, 1600 feet south of the intersection of the railroad tracks with River St., 1000 feet north of the Dunstable township boundary, Dunstable, Mass. (Pep. C. C. 1/9).
A-615.	Mica schist. Outcrop on northeast side of railroad tracks, 300 feet northeast of the Rt. 111 overpass over the railroad tracks, Groton, Mass. (Ayer, N. C. 1/9).

I.D. Estimated Modes of the Oakdale Formation. Actinolite Zone.

Rocks	P-521a	P-521b	SR-331	SL-1500	S-5-E	T-1176	T-1010	T-1021
Quartz	36	50	50	38	43	56	54	60
Plagioclase	31	10	25*2	17	24	15	16	15*3
Biotite	2	20	18	27	18	15	17	6
Muscovite			5-6	18	12			
Chlorite	10							
Almandine			1-2*4		1			
Calcite		tr						
Amphibole	13	15				10	7	17
Epidote*1	8	5	tr		2	4	5	2
Sphene	tr		tr		tr	tr	1	
An =	33-48	32-38			36		35	36-39

*1 Zoisite and clinozoisite are included with epidote.

*2 Plagioclase is partly sericitized.

*3 Plagioclase partly replaced by zoisite.

*4 Almandine occurs as elongated patches parallel to compositional lamination that show slight helitic rotation of inclusions.

I.D. (continued). Description and Location of Specimens

P-521a & P-521b. Granofels. Outcrop south of Worcester Rd., 800 feet west of the intersection of Worcester Rd. with Beaver Brook, Hollis, N.H. (Pep. N. E. 1/9).

SR-331. Granofels. Outcrop on unnamed road, 2400 feet southeast of its crossing over Rt. 2. Outcrop is north of Mechanic St., south of Rt. 2 and east of the North Nashua River, Leominster, Mass. (Shir. S. W. 1/9).

SL-1500. Granofels. Outcrop is on east side of Holman Rd., 500 feet north of intersection of Holman Rd. with Northfield Rd., Lunenburg, Mass. (Shir. N. W. 1/9).

S-5-E. Granofels. Outcrop is on trail, 1000 feet north-northeast of the intersection of Fall Brook with the North Nashua River. Outcrop is 500 feet south of the intersection of unnamed road, powerline, and trail, Lancaster, Mass. (Shir. S. W. 1/9).

T-1176. Granofels. Outcrop is on south side of Highland Rd., 1000 feet east of the intersection of Adams Rd. with Highland Rd., Townsend, Mass. (Town. C. C. 1/9).

T-1010. Granofels. Outcrop is on Knoll, 400 feet south of Warner Rd. and 800 feet east of the intersection of Ball Rd. with Warner Rd., Townsend, Mass. (Town. C. E. 1/9).

T-1021. Granofels. Outcrop in woods, 1200 feet south of Pepperell Rd., 1600 feet southeast of the intersection of Pepperell Rd. with Proctor Hill Rd., Brookline, N.H. (Town. N. E. 1/9).

I.D. (continued). Estimated Modes of the Oakdale Formation. Actinolite Zone.

Rocks	T-1001	T-1083	T-1081	T-1082	T-1033ba	T-1033bb	T-1033a
Quartz	50	50	49	40	50	48	33
Plagioclase	25	34	29	35	35	33	42
Biotite	19	16	14	10	13	4	
Muscovite	tr						
Chlorite	2						
Almandine	4						
Grossular							7*3
Diopside							1
Calcite							tr
Amphibole			8*2	15	tr	13	15
Epidote*1	tr		tr	tr	2	2	2-3
Sphene		tr	<1	tr	tr	tr	
An =	22-34		30		36	39	42-48

*1 Zoisite and clinozoisite are included with epidote.

*2 Amphibole forms poikiolitic grain clusters.

*3 Grossular forms poikiolitic balls 2 to 4 mm in diameter.

I. D. (continued). Description and Location of Specimens

T-1001. Granofels. Outcrop on north side of Proctor Rd., 1700 feet northwest of intersection of Proctor Rd. with Spaulding St., Townsend, Mass. (Town. S. C. 1/9).

T-1083. Granofels. Outcrop on ridge south of Rt. 119 and north of railroad tracks, 2550 feet northeast of intersection of Rt. 119 and the southern extension of Meetinghouse Hill Rd., Townsend, Mass. (Town. C. S. 1/9).

T-1081. Granofels. Outcrop on north side of railroad tracks, 850 feet east of the intersection of the railroad tracks with Meetinghouse Hill Rd., Townsend, Mass. (Town. S. C. 1/9).

T-1082. Granofels. Outcrop in railroad cut, 1800 feet west of the intersection of the railroad tracks with Meetinghouse Hill Rd., Townsend, Mass. (Town. S. C. 1/9).

T-1033ba & T-1033bb. Granofels. Outcrop on south side of Rt. 130, 200 feet west of the Pepperell-Townsend quadrangles border, Brookline, N.H. (Town. N. E. 1/9).

T-1033a. Calc-silicate granofels. Outcrop on south side of Rt. 130, 200 feet west of the Pepperell-Townsend quadrangles border, Brookline, N.H. (Town. N. E. 1/9).

I.E. Estimated Modes of Unit <u>as</u>

	Staurolite-Kyanite Zone				Sillimanite Zone	
	T-1002	T-1002K	T-1006	T-1144	T-1012	T-1014
Biotite	15	30 *6	13	12	9	13 *6
Muscovite	25	30	30	33	29	21
Quartz	35	21	41	44	37	49
Plagioclase	15	14	10	2-3	22	11
Garnet	3 *1	3 *7	3 *1	5 *3	2	4 *7
Staurolite	7 *2	1 *4	3 *2	3-4 *2	--	--
Kyanite	--	2	--	--	--	--
Sillimanite	--	--	--	--	1 *5	2 *5
Magnetite			tr			
Ilmenite	tr		tr			
Tourmaline	tr	tr	tr	tr	--	tr
An =	25	28-30	26	25	22-23	22-23

*1 Inclusions of quartz and sometimes staurolite, ilmenite, or biotite form mildly rotated helical bands in the garnet porphyroblasts. Biotite selvages rim garnet.

*2 Staurolite porphyroblasts have an inclusion-rich core showing mild helical rotation and an inclusion-free outer rim.

*3 Inclusion bands in garnet porphyroblasts are at an angle to the planar fabric in the rock. Biotite selvages rim garnet porphyroblasts.

*4 Staurolite is present as relict anhedral grains.

*5 Fibrolitic sillimanite occurs, is intergrown with muscovite, biotite, and quartz.

*6 Composition of biotite, determined by microprobe analysis, listed in table below.

*7 Composition of garnet, determined by microprobe analysis, listed in table below.

I.E. (continued). Description and Location of Specimens

T-1002 and T-1002K.	Mica schist. Outcrop on Knoll, 300 feet northeast of Proctor Rd., 1700 feet northwest of intersection of Proctor Rd. with Spaulding Rd., Townsend, Mass. (Town. S. C. 1/9).
T-1006.	Mica schist. Outcrop located in woods, 2300 feet west of intersection of Chestnut St. with Locke Rd., Townsend, Mass. (Town. C. E. 1/9).
T-1144.	Mica schist. Outcrop located in woods, 1800 feet north and 500 feet west of the intersection of South Row Rd. and Emery Rd., Townsend, Mass. (Town. S. C. 1/9).
T-1012.	Mica schist. Outcrop 180 feet east of Oak Hill Rd., 1000 feet north of intersection of Oak Hill Rd. with Massachusetts State Line, Brookline, N.H. (Town. C.E. 1/9).
T-1014.	Mica schist. Outcrop west of Oak Hill Rd., 2600 feet southwest of intersection of Oak Hill Rd. with Bohannon Bridge Rd., Brookline, N.H. (Town. N. E. 1/9).

APPENDIX II. Chemical Analysis of Minerals Determined by Electron Microprobe Analysis.

Chemical analyses are in mole percent. Appropriate amounts of H_2O have been added to the analysis of silicate minerals.

	W[1]			Y[3]						Z[4]					
Biotite Analysis	K	Na	Tot	Fe	Mg	Ti	Fe + Mg + 2 Ti	Al	Fe+Mg+2Ti+Al Total	Al	Si	Tot	Total Al	Wt%	Total Wt% (+4.3% H_2O)
T-1002K spot A	.900	.032	.932	1.309	1.071	.125	2.630	.313	2.943	1.378	2.622	4.000	1.754	94.95	99.25
T-1002K spot E	.852	.028	.880	1.196	.999	.140	2.475	.4825	2.958	1.2025	2.764	3.9665	1.685	97.53	101.83
T-1002K spot F	.867	.036	.903	1.242	1.046	.143	2.574	.4260	3.000	1.3510	2.638	3.989	1.777	94.88	99.18
T-1014	.795	.027	.822	1.372	.874	.157	2.560	.428	2.998	1.330	2.670	4.0	1.768	95.08	99.38
T-1014	.840	.024	.864	1.356	.869	.158	2.541	.440	2.981	1.340	2.660	4.0	1.780	96.01	100.31

Garnet Analysis	Mg	Mn	Ca	Fe	Total [3]	Al[2]	Si[3]	Wt%
T-1002K spot A	.303	.430	.139	2.233	3.105	2.022	2.917	101.23
T-1002K spot E	.330	.354	.195	2.211	3.090	2.004	2.941	100.21
T-1002K spot F	.330	.356	.189	2.211	3.086	2.002	2.964	100.63
T-1014 rim	.281	.383	.114	2.323	3.101	1.987	2.955	100.65
T-1014 core	.291	.338	.111	2.322	3.062	1.937	3.006	100.98

Composition of Margarite replacing Andalusite Porphroblast.
Locality 4, Shirley quadrangle.

Na	K	Ca	Si	Al	tot. wt. %
0.277	0.021	0.668	2.140	3.897	100.46
0.302	0.011	0.704	2.083	3.940	100.22
0.305	0.011	0.694	2.094	3.928	999.66
0.294	0.013	0.689	2.106	3.922	100.08 (average)

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