Robinson, P., 2003, Tectonic-stratigraphic-metamorphic perspective of the New England Caledonides, west-central Massachusetts (Trips A1, C1), in, Brady, J.B., and Cheney, J.T., eds, Guidebook for Field Trips in the Five Colleges Region, New England Intercollegiate Geological Conference, 95th annual meeting, Amherst and Northampton, MA, p. A1-1 to A1-54.

TECTONIC-STRATIGRAPHIC-METAMORPHIC PERSPECTIVE OF THE NEW ENGLAND CALEDONIDES, WEST-CENTRAL MASSACHUSETTS

by
Peter Robinson, Professor Emeritus, Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003 and Consultant, Geological Survey of Norway, N-7491 Trondheim, Norway
peter.robinson@ngu.no

with the following contributors (There were many contributions to my understanding of central New England geology by former students and colleagues at the University of Massachusetts and elsewhere as noted. Some contributions are included directly in this guidebook article or are related directly to included material; other contributions were outside the direct coverage of the field trip, but important in overall understanding. Contributions made by participants in the Advanced Mapping Class are too extensive to include. I apologize in advance for significant omissions from these lists.):

Direct: David D. Ashenden, Henry N. Berry IV, Jon Bull, Vincent Dellorusso, David C. Elbert, L. Peter Gromet (Brown University), Michael T. Field, Catherine Hodgkins, Kurt Hollocher, Scott Laird, Suzanne A. McEnroe, Stuart Michener, Charles Onasch, Lisa Oxboel, Virginia L. Peterson, Robert Reed, Margaret Roll, John C. Schumacher, Charles Shearer, Michael L. Williams, Peter J. Thompson, Jennifer A. Thomson, Robert J. Tracy, and Robert D. Tucker

Indirect: Farrukh Ahmad, Lewis D. Ashwal, Eileen Belvin, the late Marland P. Billings (Harvard), Jon Boothroyd, Dwight Bradley (U.S.G.S.), Laurie L. Brown, Page Chamberlain (Dartmouth), Kurt Denkler (U.S.G.S), D. B. Finkelstein, the late Richard N. Goldsmith (U.S.G.S.), James O. Guthrie, David J. Hall, the late Leo M. Hall, David Halpin, Anita Harris (U.S.G.S.), the late Norman L. Hatch (U.S.G.S.), Chris Hepburn (Boston College), Albert Hine, J. Craig Huntington, the late Howard W. Jaffe, Jack Kick, David Klepacki, the late G. W. Leo (U.S.G.S.), the late John B. Lyons (Dartmouth), R. S. Naylor (Northeastern), Jordan Makower, David Maczuga, Bob Moench (U.S.G.S.), Peter Morton, Philip Osberg (Maine), M. H. Pease (U.S.G.S.), John D. Peper (U.S.G.S.), Paul Pinet, J. S. Pomeroy (U.S.G.S.),Thomas Pyke, Nicholas M. Ratcliffe (U. S. G. S.), Doug Rankin (U.S.G.S.), J. M. Rhodes, John Rodgers (Yale), John Rosenfeld (U.C.L.A.), Kathleen Sioui, Frank Spear (R.P.I.), George Springston, the late Rolfe S. Stanley (Univ. of Vermont), Heather Stoddart, Lynne Stophen, James B. Thompson, Jr. (Harvard), Newell J. Trask (Harvard), Walt Trzcienski, the late D.R. Wones (V.P.I) and E-an Zen (U.S.G.S.)

BACKGROUND AND PURPOSE OF TRIP

In fall 1993, in connection with the GSA Meeting in Boston, a three-day transect field trip across Massachusetts was conducted by Nick Ratcliffe, Chris Hepburn and myself, and the Guidebook was published as part of the NEIGC series. The middle day of that trip concerned the geology of west-central Massachusetts. In March 2002 I conducted a similar one-day trip, piecing together previous material and notes with an itinerary adjusted to temporary conditions, but the Guidebook was reproduced in a very limited edition. For the 2003 NEIGC I have chosen to consolidate old 1993 material and new material and references as comprehensively as possible, including some material from a 1992 NEIGC Guidebook and a 1986 IMA Guidebook, to give an up-to-date view of present progress and the many future challenges in the region. Both the 1993 and 1992 Guidebooks are available at low cost from University of Massachusetts, whereas the 1986 Guidebook is out of print. I hope this revised version will make the point that without an ongoing program of field research in the region, no amount of technologically advanced analytical and theoretical studies can be brought to their full potential, and lead to a clearer understanding of all of the many complex processes that took place in this heart of the Appalachian Mountain Belt. Due to difficult access from Norway and uncertainties concerning outcrop access, the mileage log of the 1993 trip is retained throughout, but with supplemental directions to other outcrops.

The State of Massachusetts and adjacent New York contain a nearly complete section across the northern Appalachians (Figure 1). From the Prudential Center in Boston to Mount Greylock (3491') in the northwestern part of the State is a distance of 178 km. On a clear day both of these points can be seen from the summit of Mount

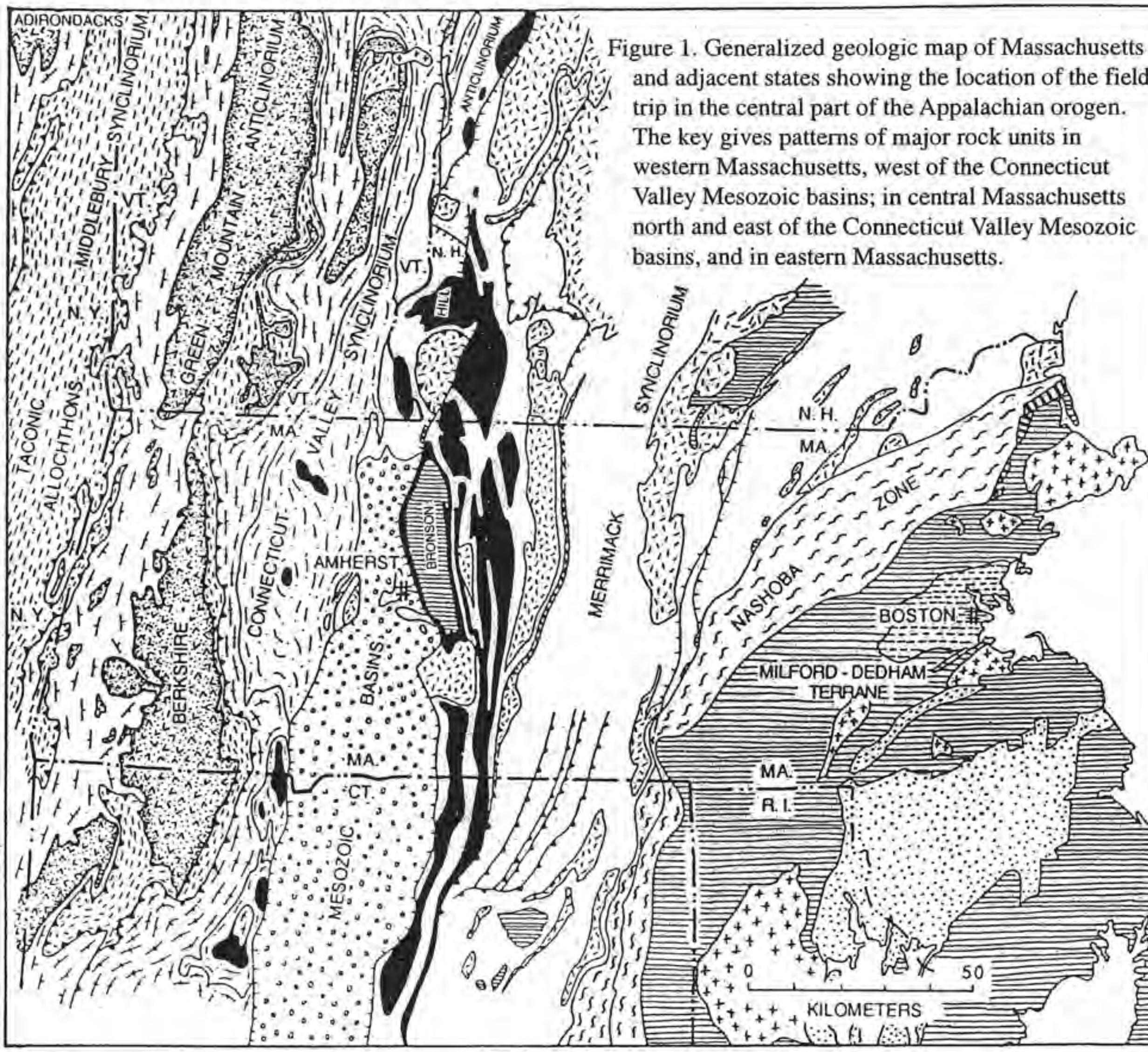


Figure 1. Generalized geologic map of Massachusetts and adjacent states showing the location of the field trip in the central part of the Appalachian orogen. The key gives patterns of major rock units in western Massachusetts, west of the Connecticut Valley Mesozoic basins; in central Massachusetts north and east of the Connecticut Valley Mesozoic basins, and in eastern Massachusetts.

Key to patterns -- Western Massachusetts: Laurentian Middle Proterozoic basement - dots and v's; Cambrian-Ordovician carbonate bank and shelf - dip symbols; Cambrian-Ordovician Taconic facies, Hoosac Formation and lateral equivalents - fine dashes; Cambrian-Ordovician accretionary prism - crossed dashes; Gneisses of magmatic arc in cores of domes - black; Silurian-Devonian Vermont sequence - dash-dot. **Central Massachusetts:** Late Proterozoic in Pelham dome, Massabesic Gneiss in N. H., and Willimantic dome in Ct. - horizontal ruling; Ordovician plagioclase gneisses in cores of domes - black; Ordovician, Silurian and Lower Devonian of Bronson Hill anticlinorium and Merrimack synclinorium - not patterned; Late Ordovician to Pennsylvanian intrusives - random dashes; Triassic-Jurassic sedimentary rocks and basalts - pattern of large open dots. **Eastern Massachusetts:** Late Proterozoic of eastern New England - horizontal ruling; Late Proterozoic of Boston basin - dashed horizontal ruling; Ordovician to Devonian alkalic plutons - crosses; Nashoba zone - curvy lines; Late Silurian to Early Devonian Newbury Volcanics - dark cross stripes; Pennsylvanian Narragansett, Norfolk, and Worcester basins - dots; Triassic of Essex County basin - circle.

Wachusett (2006') in the middle part of the State. This is a distance equivalent to that from Como south of the Alpine suture to Zurich in the Swiss Plain. As compared to northern New England, where the distance across the orogen is more than 450 km, in southern New England the belt narrows to barely 200 km. As might be expected with such a drastic narrowing, this is accompanied by a great increase in the intensity of tectonism, plutonism and metamorphism. This narrowing also makes it possible to examine a representative selection of highly varied rock types and tectono-stratigraphic terranes, within the scope of a single three-day field trip and small geographic range. Such a trip would take advantage of the 1983 Bedrock Geologic Map of Massachusetts (Zen et al., 1983). The map compilation team organized by E-an Zen contained a group of geologists with various interests and very different geographic backgrounds in the State, who shared their expertise and worked hard on the various compromises needed to portray such diverse geology on a single map sheet. The exercise helped to place the State's geology within a broader tectonic framework as outlined by Hatch et al. (1984), and set the stage for additional work that has been in progress for two decades, producing several significant revisions based on stratigraphic relations, on new radiometric ages, and on quantitative petrology.

In its broadest outlines Massachusetts appears to be composed from rocks related to four tectonic plates active in the Paleozoic, and its structural and metamorphic features are mainly the product of five orogenic events, the Late Ordovician Taconian (455-440 Ma), the Late Silurian to Early Devonian Acadian (420- 385 Ma), the Late Devonian to Early Mississippian Quaboagian (370-350) , the Late Pennsylvanian Northfieldian (305-285 Ma) and the Permian Alleghanian (270-260 Ma) (Robinson et al., 1998). The separation of the Late Devonian to Early Mississippian tectono-thermal events, now named Quaboagian, from the Acadian is a significant change since 1993. The Late Pennsylvanian tectono-thermal events that were recognized then, are here named Northfieldian (see discussion, end of STOP 2). The broader tectonic implications of these episodes have yet to be assessed. The above features were then modified during Mesozoic extension associated with the opening of the modern Atlantic, involving faulting with vertical displacements as great as 8 km.

The western part of the Massachusetts consists of rocks formed on or near the margins of Laurentia in Proterozoic through Late Ordovician time. Ample evidence indicates that Laurentia occupied an equatorial position in the early Paleozoic. The transect trip began there, although this choice was more the result of logistical convenience than scientific choice. Some of us would rather have begun at the east end and worked toward the North American craton to avoid the impression of North American chauvinism that is induced conceptually by the particular location of the Atlantic as a result of Mesozoic continental rifting.

The eastern part of the State consists of rocks formed on or near the Avalon plate. In earlier work it was supposed that this mass collided with Laurentia during the Ordovician Taconian orogeny. However, more recent paleomagnetic work as well as lithostratigraphic work suggests it was part of Gondwana which separated from that plate in the Cambrian but remained in high southern latitudes through the Ordovician and only arrived at the latitude of Laurentia in the Devonian. The main mass of Gondwana seems not to have arrived in vicinity of New England until the late Paleozoic, and cannot be recognized in any on-land exposures, although the late Paleozoic geology of Rhode Island strongly suggests its influence.

The central part of the State contains rocks formed on or near "craton X" as described by Zen (1983) or "medial New England" of Osberg (Robinson et al., 1998). This contains the Ordovician volcanic and intrusive rocks of the Bronson Hill magmatic arc as well as late Proterozoic rocks of general Avalon affinity, but uncertain structural position. The closing of an ocean between Medial New England and Laurentia and its collision with Laurentia are generally associated with the Late Ordovician Taconian orogeny. The closing of a second sedimentary and oceanic belt between the amalgamated Laurentia - medial New England and the Avalon plate is generally associated with the Devonian Acadian orogeny. A number of structural and metamorphic events in the late Paleozoic are thought to be related to the collision of Gondwana with the amalgamated Laurentia-Medial New England- Avalon. Most, but not all, Appalachian geologists believe this last collision zone lay outside the New England area, though its effects were strongly felt in local areas.

Our first day in the field in 1993 was mainly concerned with features formed on the Laurentian margin. The principal structural effects are those of the Taconian orogeny, though as we worked eastward there was a progressive increase in Acadian tectonic and metamorphic effects. The principal tectono-stratigraphic units, described in a more or less tectonically upward progression include the following:

1) North American Grenvillian and post-Grenvillian basement, seen only in its highly deformed state in the Berkshire thrust sheets and not in its pristine state as in the nearby Adirondacks;
2) The Laurentian eo-Cambrian, Cambrian, Lower Ordovician passive margin sequence consisting of early rift clastics, earliest Cambrian littoral sands, and the Cambrian-Ordovician carbonate bank and back-reef facies;
3) Unconformably overlying Late Ordovician graywacke-shale sequence of the Taconian foreland basin;
4) Eo-Cambrian, Cambrian, Lower Ordovician continental slope-rise clastics contemporaneously deposited oceanward of 2) but now largely preserved in the Taconian allochthons thrust over previous units;

5) Metamorphosed clastic rocks similar in part to 4) but characterized by abundant rift related volcanics and considered to have been deposited on thinned Laurentian continental crust or oceanic crust. Based on analogies with adjacent Quebec, young oceanic crust and mantle were obducted onto this sequence in the Late Cambrian to Earliest Ordovician, and are now preserved in Massachusetts as deformed lenses of mafic and ultramafic rocks;
6) Vestiges of fore-arc basin deposits and volcanics formed in front of the overriding Bronson Hill magmatic arc and now constituting the uppermost part of the Taconian accretionary prism;
7) Gneisses constituting the leading edge of the Bronson Hill arc exposed within Devonian or younger gneiss domes;
8) The Silurian-Lower Devonian sequence of the Connecticut Valley belt that overlaps the Taconian suture.

The second day in the 1993 transect was and the day of this 2003 trip is concerned with features formed on medial New England and its Ordovician and Silurian-Devonian cover. Because this region was on the upper plate of the Taconian collision, Taconian effects aside from magmatism and volcanism appear to be restricted to modest unconformities. The dominant effects took place in the Acadian and in the newly recognized Quaboagian episodes, ranging from fold and thrust nappes to granulite facies metamorphism and gneiss domes. We will also examine the results of newly discovered Late Pennsylvanian ductile deformation and metamorphism, here named Northfieldian, which is distinct from the end Paleozoic Alleghanian orogeny that deforms late Pennsylvanian fossiliferous sedimentary strata in Rhode Island and southeastern Massachusetts.. The major tectono-stratigraphic units from deepest to shallowest include the following:

A) Late Proterozoic (613 Ma) alkalic igneous rocks and quartzites of Avalon affinities with controversial contact relations with overlying rocks;
B) A Late Ordovician (455-443 Ma) intrusive complex of felsic to mafic calc-alkaline rocks that may be the roots of a magmatic arc,
C) A Late Ordovician cover sequence of tholeiitic arc volcanics ranging from basalts through andesites to rhyolites and overlying black shales;
D) A Silurian-Devonian cover in which the Silurian is in two facies, a thin western conglomerate and calcareous facies overlying the ruins of the Taconian orogen, and a thicker eastern shale-graywacke facies forming continental slope-rise deposits on the post-Taconian North American margin.

The third day of the transect in 1993 was devoted to fault systems and strata at the junction between medial New England and Avalon, and to the characteristics of the Boston Avalon zone. Critical to Acadian plate interpretations is the contrast between the Silurian continental slope-rise clastics of paleo-North America and the poorly exposed fossiliferous Late Silurian - Early Devonian coastal volcanics of arc affinities attached to Avalon. The fault-bounded Nashoba terrane of Ordovician or older rocks has been variously assigned to medial New England or Avalon. Once on Avalon proper, the sequence includes:

I) Late Proterozoic stratified rocks and volcanics,
II) Cross-cutting Late Proterozoic granites,
III) Vendian spore-bearing strata of the Boston basin,
IV) Early and Middle Cambrian shelf strata with Baltic faunal affinities,
V) Late Ordovician through Devonian alkalic plutons,
VI) Pennsylvanian continental clastic basins.

BRONSON HILL ANTICLINORIUM AND WESTERN PART OF THE MERRIMACK SYNCLINORIUM, CENTRAL MASSACHUSETTS

INTRODUCTION

Before 1965, and the application of plate tectonics, the Bronson Hill anticlinorium was known for fossil-based stratigraphy of medium- to high-grade metamorphic rocks and for gneiss domes. As early as 1890 B. K. Emerson (1898) carried out mapping with a keen sense of stratigraphy, but it was Marland P. Billings (1937), beginning in the Littleton-Moosilauke area in New Hampshire in 1933, that began the modern wave of detailed stratigraphic mapping. Billings and co-workers also developed the concept of gneiss domes. In 1966 Billings took the author to the location near Haverhill, N. H., where an eastward view toward Sugarloaf Mountain and Oliverian Notch, brought Billings the sudden realization of dome structures. Initially the domes were considered to be Devonian laccolithic intrusions, but Jarvis Hadley (1942) showed that they contain a tectonic fabric post-dating their igneous history. In 1969 Naylor proved that the granitoid rocks in the domes are Ordovician, but the exact nature of the contact between the granitoid rocks and their stratified Ordovician cover still remains controversial. An intrusive contact (Leo, 1991), an unconformity (Robinson, 1981), a detachment fault (Tucker and Robinson, 1990) and a thrust fault (M. J. Kohn and F. S. Spear, Personal Communication, 1991) have all been proposed. Important discoveries since the time of Billings and Hadley include the recognition of major west-directed Acadian fold nappes by J. B. Thompson, Jr. (Thompson et al., 1968); the discovery of new fossil localities, some in high-grade metamorphic rocks (Boucot et al., 1958; Boucot and Thompson, 1963; Elbert et al., 1988); the recognition of metamorphic overhangs in the Connecticut Valley region (Thompson at al., 1968; Spear and Chamberlain, 1986) and of mid-Paleozoic metamorphism as high as the pyroxene-granulite facies (Hess, 1969, 1971; Tracy et al., 1976; Hollocher, 1985; Robinson et al., 1989); the demonstration that the early fold nappes are followed by major synmetamorphic thrust nappes (P. J. Thompson, 1985; Robinson et al., 1991; Berry, 1989); and the discovery that the last ductile deformation and metamorphism in part of the anticlinorium was Late Pennsylvanian (Tucker et al., 1988; Gromet and Robinson, 1990; Robinson et al., 1992) rather than Devonian. In addition, fairly recent geochronology (Robinson et al., 1998) indicates that the strong tectonics, plutonism and metamorphism of central Massachusetts occurred in three separate episodes, the Acadian from Late Silurian to Lower Devonian, the Quaboagian from Upper Devonian to Lower Mississippian and the Northfieldian in Upper Pennsylvanian, whereas adjacent New Hampshire appears to be dominated by the earliest.

Within the context of this field trip, emphasizing plate-tectonics, and within the imposed space and time restrictions, a complete summary and field examination of regional stratigraphy and tectonics is impossible. I can only provide a broad outline, within which the significance of individual stops can be evaluated, and in which the conditions of field, petrologic, and geochronologic studies can be appreciated. Because of the constraints of geography, the types of rocks and problems covered will shift radically from stop to stop. The importance of individual observations and detailed studies is highly varied, and is commonly not realized until decades after the original work. The larger the problem that is to be resolved, the smaller the data base available to resolve it. Thus, when it comes to plate tectonics, the available data base is minimal.

STRATIGRAPHY AND INTRUSIVE ROCKS

For this trip the rock layers and igneous intrusions have been subdivided into seven units, each with its own problems of protoliths, plate-tectonic setting, and tectonic and metamorphic history, that will be included here although outside the narrow realm of stratigraphy. Next to each heading the stops are listed where the unit will be seen. Naturally the deepest and oldest rocks have the most complex history and the most difficult to put in context.

Late Proterozoic Basement (STOPS 2, 2A, 2B, 7)

The Dry Hill microcline Gneiss, with its Pelham Quartzite Member, and the Poplar Mountain quartz-biotite Gneiss, with its basal Poplar Mountain Quartzite Member in the core of the Pelham gneiss dome (Ashenden, 1973; Robinson et al., 1992) are the deepest and oldest rocks exposed in the Bronson Hill anticlinorium. The stratigraphic relations suggest that the Dry Hill Gneiss forms the core of an early, probably Quaboagian, east-directed recumbent fold nappe, that is both overlain and underlain successively by Poplar Mountain Quartzite and Poplar Mountain Gneiss. A suspected late Proterozoic igneous age for the Dry Hill was demonstrated by Naylor et al. (1973) and confirmed by Tucker and Robinson (1990) based on euhedral zircons with a U-Pb age of 613±3 Ma.. The Dry Hill Gneiss is considered to be a series of alkali rhyolite lavas or pyroclastics (Hodgkins, 1985) with minor interbedded quartzites and the major Pelham Quartzite Member. The Poplar Mountain Gneiss is a geochemically related sequence of quartz-mica gneisses of sedimentary derivation with the Poplar Mountain Quartzite Member and with local felsic interbeds identical to the Dry Hill Gneiss. Rare mafic rocks in the Poplar Mountain Gneiss and Quartzite, and Dry Hill Gneiss appear to be transitional or alkali basalt compositions (Englander et al., 2002). An intrusive origin for the Dry Hill cannot be ruled out because the associated quartzites yield detrital zircons only in the age range 2800-930 Ma, and none of Dry Hill age. The late Proterozoic of the Pelham dome most closely compares in the region with Potter Hill Gneiss and associated quartzites from the Hope Valley terrane of southeastern Connecticut, considered by most to be part of Avalon. Furthermore, Robert Ayuso (personal communication, 1993) believes that the radiogenic Pb isotopic signature of the Dry Hill overlaps the Pb isotopic range in Proterozoic rocks in Avalon. Detrital single zircons from the Pelham Quartzite Member are in three age groups that correspond to inheritance ages in one sample of Dry Hill Gneiss. These age groups are consistent with either South American or Laurentian sources.

The Dry Hill Gneiss has yielded U-Pb ages on sphene (Tucker et al., 1988) and Sm-Nd and Rb-Sr mineral isochrons (Gromet and Robinson, 1990) showing that the last significant ductile deformation and metamorphism was Late Pennsylvanian (305-285 Ma) in an episode here called "Northfieldian". One of the minerals involved is garnet that shows prograde growth zoning. In his isotopic studies Gromet has found no convincing evidence that the Dry Hill Gneiss was ever subjected to Acadian or Quaboagian metamorphism, and he has postulated that the Dry Hill Gneiss was a part of Avalon that was underthrust into its present position during the Late Pennsylvanian. In a single-zircon study of the Poplar Mountain Gneiss Tucker (Robinson et al., 1992, p. 160) has found a variety of Proterozoic discordant grains and three concordant grains at 585, 370, and 302 Ma. These might be interpreted, respectively, as Late Proterozoic igneous zircon from the Dry Hill Gneiss or a related rock, Quaboagian zircon from a dismembered pegmatite, and Northfieldian metamorphic zircon. These results are consistent with structural arguments that the Dry Hill Gneiss and related rocks were in roughly their present position in time to be involved in Quaboagian east-directed recumbent folding.

If the Dry Hill Gneiss and related rocks do represent the basement of the Ordovician Bronson Hill magmatic arc, then their provenance is crucial to plate-tectonic interpretations. The proposal of Dalla Salda et al. (1992) that the Taconian orogeny was a continental collision between Laurentia and western South America could be consistent with the detrital zircons from the Pelham Quartzite as well as paleomagnetic reconstructions (Trond Torsvik, personal communication, 1993) showing western South America at roughly equatorial latitudes in the Ordovician when the Avalon part of Gondwana was still at high southern latitudes. The Pb isotopic data of Ayuso would then have to be explained in terms of some broader effect within Gondwana. If the Gromet interpretation of Pennsylvanian underthrusting of Avalon crust is correct, then the basement of the Bronson Hill magmatic arc will have to be sought elsewhere. See Robinson et al. (1998) for additional discussion of this problem.

Paleozoic Undercover (STOP 6)

In the southern part of the Pelham dome, near the upper contact of the Late Proterozoic rocks described above, there is a sequence of sillimanite- and kyanite-bearing mica schists, amphibolites, quartzites, and gneisses. These were mapped together as the Mount Mineral Formation and were interpreted as a more aluminous facies of the upper layer of Poplar Mountain Gneiss in the northern part of the dome. These proved to have relics of a near granulite-facies metamorphism overprinted with kyanite-staurolite-muscovite grade assemblages. These were interpreted (Roll, 1987) as relics of a Proterozoic metamorphism overprinted by the "ambient" Acadian facies. The U-Pb isotopic research of Tucker (Robinson et al., 1992) has caused a drastic reinterpretation. Monazite U-Pb ages in the rocks with granulite-facies relics are 367±2 (Quaboagian), whereas monazites in schists and quartzites with kyanite-muscovite overprints are 298±2 Ma (Northfieldian). Thus, within a hundred meters of the Dry Hill and related rocks we have evidence of Late Devonian to Early Mississippian (Quaboagian) metamorphism of the same age and temperature, and of slightly higher pressure than the Quaboagian central Massachusetts granulite-facies high! Studies of detrital zircon grains within the upper muscovite-bearing quartzite of the Mount Mineral Formation have yielded three grains with concordant ages of 459, 441 and 439, proving that the quartzite can be no older than the early Silurian and is probably the Lower Silurian Clough Quartzite (see below). Correlation of other parts of the thin Mount Mineral Formation with various Ordovician, Silurian and Lower Devonian units is probable. A plagioclase gneiss in the lower part of the Mount Mineral Formation has yielded a U-Pb zircon age of 456 Ma (Robinson et al., 1992, p. 164)), slightly older than the oldest gneisses dated at 455 Ma. among the standard dome gneisses. The outcrop of the Mount Mineral Formation must now be considered as part of a tectonic window beneath Ordovician intrusive basement, bounded upward either by a Quaboagian east-directed thrust or, less probably, by a Quaboagian east-directed fold nappe containing the Ordovician intrusive rocks.

Late Ordovician Intrusive Basement (STOPS 3, 5, 8, 8B, 8C, 13)

The predominant rocks exposed in the cores of the domes are quartz-feldspar gneisses and amphibolites, interpreted to be a highly deformed and metamorphosed intrusive igneous complex. The petrology, geochemistry, and setting of these rocks is discussed in detail by Hollocher et al., 2002, and their setting is also discussed by Robinson et al. (1998). In some parts the complex is homogeneous, representing large intrusive masses of calc-alkaline granite or tonalite. Elsewhere it is strongly layered with alternating tonalite and monotonous hornblende-biotite amphibolite (see STOP 8), but lacking amphibolites with Fe-Mg amphiboles and felsic rocks with garnet, muscovite and sillimanite characteristic of the overlying Ammonoosuc Volcanics. The complex resembles rocks in other orogens inferred to have come from the roots of an island arc. Extensive U-Pb zircon dating based on large well studied exposures (Tucker and Robinson, 1990) has yielded a total age range of 455-443 Ma. The upper age limit corresponds almost exactly to the recognized time of emplacement of the Giddings Brook slice of the Taconic allochthons (Hollocher et al., 2002). Thus, the magmatic rocks exposed here cannot represent the magmatic arc as it existed prior to the Taconian collision, as in the case of the gneisses exposed in the Shelburne Falls dome (Karabinos et al., 1998), but only rocks produced during the collision and subsequent metamorphism of the suture zone, for which Hames (Hames et al., 1991) has determined a hornblende Ar-Ar cooling age of about 440 Ma. The fact that the older of these intrusive ages and the age of the Upper Ammonoosuc rhyolite (see below) correspond very closely to the age of emplacement of the Giddings Brook slice, suggested to Hollocher et al. that this magmatism was tied to a continuation of southeast-directed subduction of Laurentia under the Bronson Hill arc (see also Robinson et al., 1998 and Ratcliffe et al., 1999) and not related to a Late Ordovician flip to northwest-directed subduction beneath Laurentia as proposed by Karabinos et al. (1998, 1999) and more recently by Moench and Aleinikoff (2003).

Late Ordovician Stratified Cover (STOPS 4, 5, 8A, 8C)

The Ordovician intrusive complex is separated from the Ordovician stratified cover by a sharp planar contact. The overlying strata consist of the Ammonoosuc Volcanics and the Partridge Formation. The belt can be traced discontinuously into Maine where equivalents of the Partridge contain Caradocian graptolites (Harwood and Berry, 1967).

The Ammonoosuc Volcanics consists of three mappable members (Robinson, 1963; Schumacher, 1988), and ranges in present mappable thickness from 30 to 1300 meters. The Mafic Lower Member consists predominantly of metamorphosed basaltic and andesitic lavas and tuffs of tholeiitic arc affinities or their hydrothermally altered equivalents, with relatively minor felsic interbeds. Locally pillows, graded tuffs, agglomerates, and other features are preserved even in sillimanite-grade rocks. Although hornblende is typical of many of these rocks, great chemical variety leads to metamorphic assemblages with garnet, epidote, diopside, and particularly anthophyllite, gedrite and cummingtonite. The hydrothermally altered basalts are metamorphosed to cordierite-gedrite gneisses, locally with garnet, kyanite, sillimanite, staurolite, spinel, corundum and sapphirine. Locally the top of the Member is marked by marble, marble-matrix volcanic conglomerate, or diopside-rich amphibolite. The Middle Garnet-Amphibole Quartzite Member (STOP 4), commonly with cummingtonite and/or gedrite, hornblende, and magnetite is a widespread very thin unit considered to be a deposit from volcanic exhalations and marking an abrupt change in character of volcanism, from predominantly mafic to predominantly felsic. The Felsic Upper Member consists of metamorphosed rhyolites and dacites or their hydrothermally altered equivalents. These are characteristically peraluminous rocks, as indicated by the abundance of metamorphic garnet and muscovite, believed on the basis of major and trace-elements to have melted from a basaltic source. The hydrothermally altered equivalents are now various muscovite, kyanite, and sillimanite-rich rocks, including the sillimanite nodular gneiss to be seen at STOP 4. A metamorphosed quartz-phyric rhyolite from the Felsic Upper Member, about 30 m below the base of the Partridge Formation (see road log after STOP 1), has yielded a U-Pb zircon age of 453±2 Ma. The lower part of the Ammonoosuc Volcanics in the type area in New Hampshire is known to be much older in that it is intruded by the 469 Ma. Joslin Turn Pluton (Moench and Aleinikoff, 2003). Possibly the lower member in Massachusetts is also this old. A graded rhyolite overlying Partridge schist at Lisbon, New Hampshire has yielded a U-Pb zircon age of 443 Ma, similar to some of the gneisses of the intrusive basement discussed above. Moench and Aleinikoff assign this rhyolite to the Quimby Volcanics, suggesting a different tectonic setting for the Quimby as compared to the true Ammonoosuc. They favor correlation of the Upper Ammonoosuc of central Massachusetts with the Quimby, and the Middle Member with the type Partridge, but the older ages of the Massachusetts rhyolite (453 Ma) and overlying Partridge rhyolite (449 Ma, see below) do not require such a correlation.

The overlying Partridge Formation is dominated by metamorphosed sulfidic black shales, now garnet-mica-kyanite or sillimanite-ilmenite-graphite-pyrrhotite schists. The lower part contains abundant volcanic interbeds (Hollocher, 1985) like those of Lower and Upper Members of the Ammonoosuc. That mafic volcanism characteristic of the Lower Ammonoosuc continues into the Partridge, suggests that the Felsic Upper Ammonoosuc may not represent a termination of mafic magmatism so much as a prodigious and possibly very brief explosive punctuation by felsic magmatism. A 1 m-thick pyroclastic rhyolite bed about 10 m above the base of the Partridge has yielded a U-Pb zircon age of 449+3-2 Ma.

The basal contact of the Ammonoosuc is a major regional problem. It has been described as an intrusive contact (Billings, 1937; Leo 1991), but none of the well mapped contacts within the Ammonoosuc or between the

Ammonoosuc and Partridge are ever seen truncated by the contact, nor do any of the mafic xenoliths in the gneisses correspond to any of the distinctive and unusual amphibolites of the Ammonoosuc. It has also been described as an unconformity (Robinson, 1981) on the basis of three occurrences of quartzite and quartz-pebble conglomerate at the base of the Ammonoosuc, and the petrographic and geochemical dissimilarity of the two sequences (Robinson et al., 1989). Present geochronology indicating the two sequences overlap in age, seems to preclude both these possibilities, and to suggest instead a fault, possibly a detachment fault in an arc setting, that juxtaposed a tholeiitic back-arc cover sequence on top of the roots of an adjacent calc-alkaline arc. Further work will aim to resolve the question, including detrital zircon work on the basal conglomerate from its one excellent exposure.

Silurian-Devonian Stratified Cover (STOPS 1, 3, 5, 10, 11, 12, 14, 15)

The Silurian-Devonian cover rests unconformably on the older rocks, locally in contact with the Partridge Formation, the Ammonoosuc Volcanics, or the tonalitic gneisses and amphibolites of the Ordovician intrusive basement. The Silurian and earliest Devonian section is divided into two facies, originally separated by a tectonic hinge situated close to the present eastern edge of the Bronson Hill anticlinorium (Fig. 2). A western sediment source is inferred from studies of less metamorphosed strata in Maine. The western sequence or Connecticut Valley belt is a relatively thin and discontinuous section deposited across the ruins of the Taconian orogeny near the Connecticut Valley and to the west. The eastern sequence or Merrimack belt is a much thicker, continuous sequence of coarse and more impure clastic sedimentary rocks deposited east of the tectonic hinge, either in an extensional trough or as part of the continental slope-rise deposits of post-Taconian North America. This latter interpretation could be consistent with the separation of South America following the Taconian collision according to the interpretation of Dalla Salda et al. (1992), although this has found few adherents in the last decade, and the paleogeography of the Taconian collision remains uncertain.

The thin western Silurian consists of two units, the Late Llandovery Clough Quartzite, and the Pridoli to Lochkovian Fitch Formation. The basal Clough is typically conglomerate with over 95% vein quartz pebbles with garnet and muscovite ± sillimanite in the matrix. The conglomerate is succeeded upward or in facies relation with finer-grained well bedded quartzite. The uppermost part of the Clough, where exposed, is a metamorphosed calcareous sandstone, commonly diopside-grossular calc-silicate, with rare fossil fragments including crinoid columnals and brachiopods preserved in coarsely crystalline calcite (Boucot et al., 1958). The Fitch Formation is predominantly metamorphosed calcareous shale, now commonly zoisite-diopside-biotite calc-silicate, with interbeds of sulfidic shale, now mica schist, and rare interbeds of marble. At Littleton, New Hampshire, where corals and

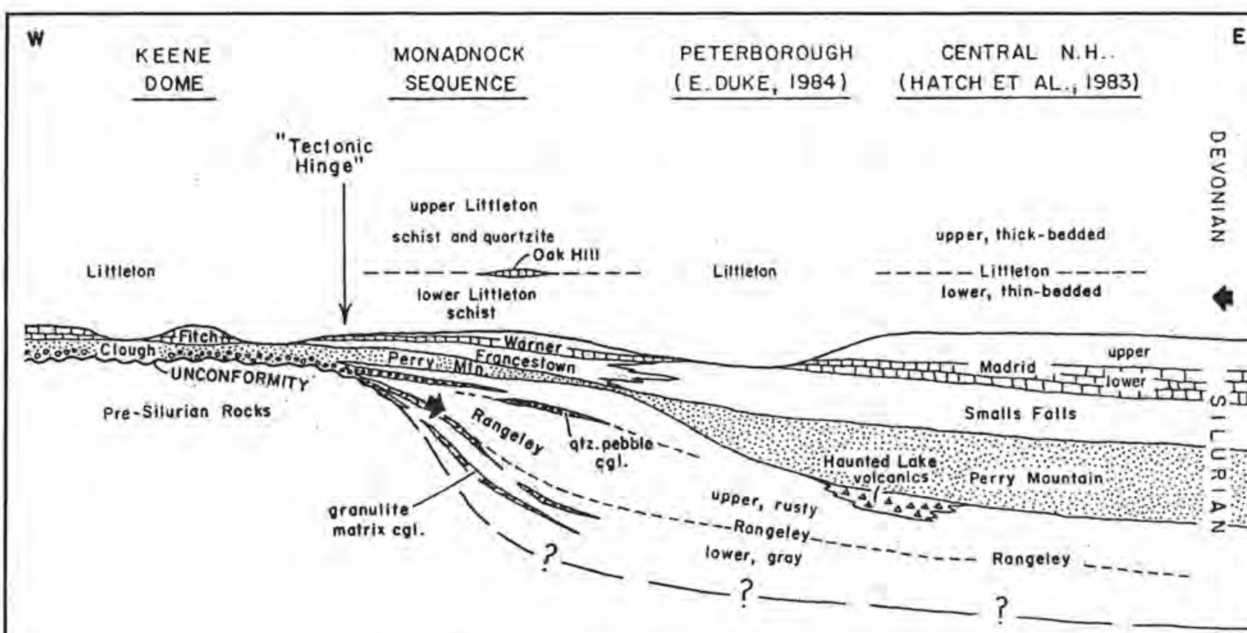


Figure 2. Reconstructed stratigraphic profile across the "tectonic hinge" between the Keene dome of the Bronson Hill anticlinorium and areas in the Merrimack trough to the east. Heavy black arrows show a change in sediment source direction from Silurian to Devonian. From P. J. Thompson, 1985, Figure 2, also 1986 IMA Guidebook, Figure H-22.

brachiopods had long been known (Hitchcock, 1871; Billings and Cleaves, 1934), a study of conodonts (Harris et al., 1983) indicates a Pridoli (uppermost Silurian) age. At Bernardston, Massachusetts, a crinoid-bearing marble (STOP 1) has yielded Lochkovian (lowermost Devonian) conodonts (Elbert et al., 1988). The conodont used to make the Lochkovian assignment at Bernardston has since been found to be more abundant in the Pridoli of the Silurian-Devonian type section in Bohemia (Leonart Jepsen, personal communication, Lund, Sweden, 1993), but no formal resolution of this matter has yet been reached.

The thick eastern Silurian is dated by lithic correlation with fossiliferous strata in central and eastern Maine (Robinson et al., 1991). It begins with the thick Lower Silurian Rangeley Formation (STOPS 5, 11, 12) of mixed graphitic and sulfidic feldspathic turbidites with small lenses of calc-silicate rock and rare lenses of polymict conglomerate. This grades upward into the relatively thin Perry Mountain Formation, a more quartzose, better bedded, thinner bedded turbidite, locally characterized at its top by apatite-bearing garnet quartzite or garnet-magnetite iron formation (Robinson and Elbert, 1992). The Rangeley-Perry Mountain is overlain by a distinctive sulfidic zone, possibly related to a widespread anoxic event originally assigned to Wenlock. In the west this is a calcareous, now calc-silicate section, the Francestown Formation. In the east this is interbedded sulfidic pelite and quartzite, the Smalls Falls Formation (STOP 10), in which the action of primary sulfur-reducing bacteria led to extremely light sulfur isotopes (Tracy and Rye, 1981) and assemblages of pyrite-pyrrhotite-graphite-pure Mg cordierite-pure Mg biotite-sillimanite-orthoclase-rutile under granulite-facies conditions (Tracy and Robinson, 1988). However, these particular sulfidic rocks should probably be reassigned to Ludlow on the basis that the graptolites of the correlative Parkman Hill Formation in central Maine are now assigned to the early Ludlow (Tucker, Osberg and Berry, 2001). Detailed work by Berry (1989, 1992) in central Massachusetts suggests that some of the extreme sulfide-rich rocks occur within the Rangeley section, well below the Smalls Falls level. Above the sulfidic zone are thick calcareous feldspathic turbidites and interbedded shales, now interbedded biotite granulites, calc-silicates, and schists, of Ludlow to Lowest Devonian age, named Warner Formation in New Hampshire or Madrid Formation in Maine. Within this upper package in Maine evidence has been found for the earliest reversal of source direction from North America in the west to tectonic lands to the east, presumably the approaching margin of Avalon preceding the Acadian orogeny. In Maine, and presumably also in Massachusetts, the better-defined Merrimack-belt sequence appears to grade eastward into a section from lowest to highest Silurian dominated by calcareous turbidites like the Warner-Madrid. Such rocks, of uncertain Silurian age, have been assigned to the Paxton Formation (STOPS 14, 15) in east-central Massachusetts. The pattern of Late Silurian - Earliest Devonian sediment sources is discussed in more detail in Robinson et al. (1998).

The major Lower Devonian stratigraphic unit is the Littleton Formation (STOPS 1, 3) of metamorphosed carbonaceous non-sulfidic shale and quartzose sandstone, dated by brachiopods as Emsian (Boucot and Arndt, 1960) in western New Hampshire. It is interpreted as a westward spreading deltaic complex or Acadian flysch with a source in early Acadian tectonic lands to the east (Hall et al., 1976; Robinson et al., 1998)). In the western part of the Bronson Hill anticlinorium Littleton is overlain with apparent unconformity by Erving Formation, a controversial unit consisting of alternating metamorphosed basaltic tuff and calcareous siltstone and shale (Robinson et al., 1988). Robinson et al. (1988) have correlated Erving with a section in the Connecticut Valley synclinorium consisting of Goshen Formation, Waits River Formation, Standing Pond Volcanics, and Gile Mountain Formation, thus implying that these units are also Devonian. These correlations are strengthened by the major and trace element similarities (J. C. Hepburn, personal communication, 1990) of Erving and Standing Pond Volcanics, and Emsian plant fossils have recently been described from correlatives of the Gile Mountain in southern Quebec (Hueber et al., 1990). Trzcienski et al. (1992), on the basis of interpretations in Vermont, suggested that the Erving is Ordovician. They no longer adhere to this Ordovician age assignment, but they can demonstrate that the Whately thrust, a key element in stratigraphic interpretations, is not present at its type locality in Whately, though not ruled out elsewhere (Trzcienski et al., 1993).

Acadian to Quaboagian and Northfieldian Intrusions (STOP 9)

Devonian and Mississippian intrusions are abundant and beyond detailed coverage in this guidebook. They range from early tectonic to post-tectonic and gabbro to granite. Several have been studied in detail. Geochronologic work mainly by R. D. Tucker, cited by Robinson et al. (1998), but not yet published in detail, now allow many intrusions to be placed in three major groups, an early group of Acadian intrusions, a middle Belchertown group, and a late Neo-Acadian or Quaboagian group, which is the largest. Late Pennsylvanian intrusions, here called Northfieldian, consist entirely of granitic pegmatites confined to the vicinity of the Pelham dome including the

Warwick dome and the Kempfield anticline. The igneous ages provide strong constraints on ages of regional metamorphism.

The Acadian intrusions include the Prescott Complex gabbro (Makower, 1964) at 412 Ma., the Spaulding Tonalite (Shearer, 1983; Thompson, 1985) in southern New Hampshire at 408±2 Ma., the Ashuelot intrusion of Kinsman Granite in southern New Hampshire (Clark and Lyons, 1986) at 403±3Ma, and the chemically similar Coys Hill Granite (Thompson, 1985) in southern New Hampshire and Massachusetts at 396±2 Ma. The Kinsman and Coys Hill Granites appear to be partial melts from highly aluminous crust, though not from the surrounding Silurian-Devonian pelites (Clark and Lyons, 1986).

The Belchertown Quartz Monzodiorite (Ashwal et al., 1979), dated at 380 ±5 Ma, has many of the peculiarities of sanukitoids, granitoid melts derived from small fraction high temperature melts from mantle (G. N. Hansen, personal communication, 1992) and in addition has somehow acquired an extremely high oxidation state with co-existing end-member magnetite and a 50/50 ilmenite-hematite solid solution.. It shows locally preserved contact effects overprinted by later strong regional metamorphism, including large sillimanite pseudomorphs after contact-metamorphic andalusite. The primary two-pyroxene Quartz Monzodiorite is converted along hydrated shear zones to Hornblende Monzodiorite Gneiss. It is not yet known if the overprinting metamorphism and ductile deformation is Late Devonian - Early Mississippian (i.e. Quaboagian) or Late Pennsylvanian Northfieldian like the rocks of the nearby Pelham dome. The intrusion also contains abundant xenoliths of strongly foliated amphibolite, probably from the Fourmile Gneiss, that probably were treated to an earlier Acadian (or Taconian?) regional metamorphism.

The largest intrusions in central Massachusetts, include the Hardwick Tonalite (Shearer, 1983; Shearer and Robinson, 1988), Nichewaug sill of augite diorite (Shearer, 1983), and the Fitchburg Plutonic Complex (Maczuga, 1981). The Hardwick Tonalite, although geochemically similar to the Spaulding Tonalite of New Hampshire (Shearer, 1983) and directly along strike from it, has yielded much younger ages of 360±1 Ma. in the Hornblende tonalite member, and 361±2 Ma. in the microcline porphyry member (Robinson and Tucker, 1992). The Wachusett Hornblende Tonalite member of the Fitchburg Complex has yielded an age of 359±1 Ma. consistent with an earlier age on the Rollstone Hill Granite member of 360 Ma (Zartman et al., 1991). The Hardwick Tonalite, Nichewaug sill, and Fitchburg Complex show locally preserved contact-metamorphic effects strongly overprinted by regional metamorphism and deformation that must have ended after 359 Ma and which I have named Quaboagian. There is also the pegmatite cutting folded rock in Monson Gneiss at Quabbin Reservoir, which itself is cut by mylonites which are folded. It gives a U-Pb zircon age of 366±1 Ma. Although small in area and not yet dated, the tonalite intrusions mapped by Berry (1989) in the Brimfield-Sturbridge area are important because they cut across nappe-stage folds and thrusts, but are overprinted by the peak regional granulite-facies metamorphism and cut by backfold-stage mylonites (Finkelstein, 1987; Berry, 1989). The undeformed Fitzwilliam and related granites in southernmost New Hampshire (Shearer 1983; Thompson 1985) give ages of 354±1 Ma and may provide a maximum age for the end of Quaboagian regional metamorphism and deformation at that tectonic level.

With the exception of the Kinsman and Coys Hill Granites, the tonalites and granites fall near or on the boundary between I- and S-type granitoids, and have many of the characters of subduction-type magmatism. However, high K, P and Mn, suggest a connection to basaltic magmas in an extensional setting should also be considered (Shearer and Robinson, 1988).

Triassic-Jurassic Continental Sedimentary Rocks, Jurassic Basalts, and Jurassic and Cretaceous Diabase Dikes

The Connecticut Valley of Massachusetts and Connecticut is extensively underlain by Late Triassic and Early Jurassic continental sedimentary rocks and Jurassic basaltic lavas in the Northfield, Deerfield, and Hartford basins, best dated by fossil pollen (Cornet, 1977). These strata lie in a complex half graben structure with the major fault along the east side, having a vertical displacement of about 5 km in northern Massachusetts, increasing to about 8 km at the Connecticut line. They serve to conceal important information for Appalachian geology, but the displacements on the faults give us information in the third dimension not otherwise available. The crystalline highlands to the east and west are cut by four sets of Jurassic tholeiite dikes, two correlative with the first and third lava extrusions in the valley (McEnroe and Brown, 1992, 2000), two younger Jurassic sets not related to any lavas, and two sets of Cretaceous tholeiite dikes, unlike the alkali diabases and lamprophyres typical of the Cretaceous intrusions elsewhere in New England (McEnroe et al., 1987; McEnroe, 1989).

STRUCTURAL DEVELOPMENT

Introduction

Before the advent of multiple results of precise geochronology on igneous and metamorphic minerals around 1991, the structural and metamorphic development of west-central Massachusetts was considered to have been mainly the product of the Devonian Acadian orogeny lasting roughly from 410 Ma. to 360 Ma. The developmental history was commonly grouped into an early nappe stage, an intermediate and poorly understood backfold stage, and a late gneiss dome stage. This simple view was utterly demolished by new geochronology, production of a more precise Devonian time scale (Tucker et al., 1998) indicating a Devonian period beginning at 418 Ma and ending at 362 Ma, and new stratigraphy and geochronology in Maine (Robinson et al., 1998; Tucker et al., 2001). Present evidence suggests that what was previously considered "Acadian" ductile deformation and regional metamorphism, should be divided into three distinct episodes spread over more than 100 m.y.: 1) Acadian 410-385 Ma; Quaboagian ("Neo-Acadian") 370-350 Ma, and Northfieldian 305-285 Ma. The last is not to be confused with true Alleghanian at 270-260 Ma. The process of sorting out which structural and metamorphic features belong with each of these episodes has begun, as indicated below, but is far from finished.

Taconian Deformation

Notable in the Bronson Hill anticlinorium and the eastern flank of the Berkshire anticlinorium, is the lack of evidence for major pre-Silurian deformation just beneath the Silurian-Devonian rocks. The base of the Clough Quartzite does cut down from the Partridge through the Ammonoosuc and locally into the underlying Ordovician intrusives, but the author has found only one place where there is evidence for a pre-Silurian fold, and all evidence for pre-Silurian faults (detachments, etc.) is circumstantial. This is surprising in view of the closeness of known major Taconian folds and thrusts. The best explanation is that Silurian-Devonian strata were deposited mainly on rocks of the Bronson Hill arc above the Taconian subduction and deformation zone.

Acadian Nappe Stage

Most of the structural features previously described as belonging to the nappe stage were probably produced during the Acadian period. This is partly argued on the basis of structural continuity with central and northern New Hampshire and Vermont where currently available geochronology does not indicate importance of the two later episodes, although that could change.

The early nappe stage produced west-directed fold nappes with tens of kilometers of transport (Thompson, 1954; Thompson et al., 1968; Robinson et al., 1991) during regional metamorphism, soon after the end of Early Devonian sedimentation, and very soon after the intrusion of the Kinsman Granite. This granite was dated in Cardigan pluton by Sm-Nd and U-Pb garnet at 413±5 Ma (Barreiro and Aleinikoff, 1985), in the Ashuelot pluton at 403±3 Ma. (Robinson et al., 1998) and in the Coys Hill pluton in Massachusetts at 396±2 Ma (Robinson et al., 1998). The best characterized of these fold nappes are the Bernardston nappe (STOP 1) and the overlying Skitchewaug nappe near Springfield, Vermont, first described by J. B. Thompson. Curiously, many of the important fossil localities are localized close to the anticlinal hinges of these two nappes.

More subtle and more difficult to characterize are the later thrust nappes (P. J. Thompson, 1985; Robinson et al., 1991), also formed fairly early in the regional metamorphism, which cut through the pile of earlier fold nappes, leading to very confusing contact relations. Most important of these is the Brennan Hill thrust, which brings previously folded strata of the western part of the Merrimack belt westward over folded strata of the Connecticut Valley belt. A second and higher major thrust, the Chesham Pond thrust, just beneath the Cardigan pluton of Kinsman Granite and inferred to run along the west margin of the Coys Hill Granite in Massachusetts (STOP 9), brings a more eastward facies of the Merrimack belt, including the Smalls Falls Formation, over a more westward facies including the Francestown Formation. Farther east Berry (1989, 1992) has recognized that early west-directed folds are truncated by a series of west-directed thrust slices, each involving pre-Silurian granitoid and stratified basement (STOP 13) and Silurian strata of the Merrimack belt, all formed before peak Quaboagian granulite-facies metamorphism at 370-350 Ma (Thomson et al., 1992). Field trip STOPS 1, 2, 3, 4, 6, 7, and 8 are below the Brennan Hill thrust, STOP 5 may be on it, Amherst and STOP 11 are above it, and STOPS 9, 10, 12, 13, 14, and 15 are above the Chesham Pond thrust. In west-central Massachusetts east of the Connecticut Valley only the rocks in the Amherst block, down-dropped 5-8 km on the Mesozoic fault, preserve isotopic evidence of Acadian metamorphism in the form of 399-400 Ma ages of zircon in pegmatites and monazite in mica schists (Robinson et al., 1998).

Quaboagian Backfold Stage

Very few if any minor structural features relate to the Acadian nappe stage, in central Massachusetts. In the backfold stage, well preserved fabrics formed that overprint the peak-metamorphic fabric in the granulite-facies region. This was when the east side of the Bronson Hill anticlinorium, with its west-directed fold and thrust nappes was overturned to the east, and also when the main and Tully bodies of Monson Gneiss were transported northward and overturned, so they now lie above surrounding younger strata. It was also probably the time of east-directed recumbent folding and thrusting of Proterozoic to Lower Devonian strata near the Pelham dome. The most important early Quaboagian fabric is an E-W trending lineation, rarely accompanied by parallel folds and commonly by a consistent west-over-east shear sense along the lineation. This fabric is observed in both stratified and intrusive rocks east of the Bronson Hill anticlinorium (Peterson and Robinson, 1993), including the 359 Ma Fitchburg Complex and the Late Proterozoic Massabesic Gneiss, and is progressively overprinted by a late Quaboagian N-S to NE-trending "dome-stage" fabric and folds as the Bronson Hill anticlinorium is approached (Figure 3). U-Pb dating of monazite in the granulite-facies region suggests setting at about 369-362 Ma, probably close to the onset of post-peak shearing. STOP 11 will show this early Quaboagian E-W fabric in the Conant Brook shear zone, where it is progressively overprinted by late Quaboagian dome-stage shearing.

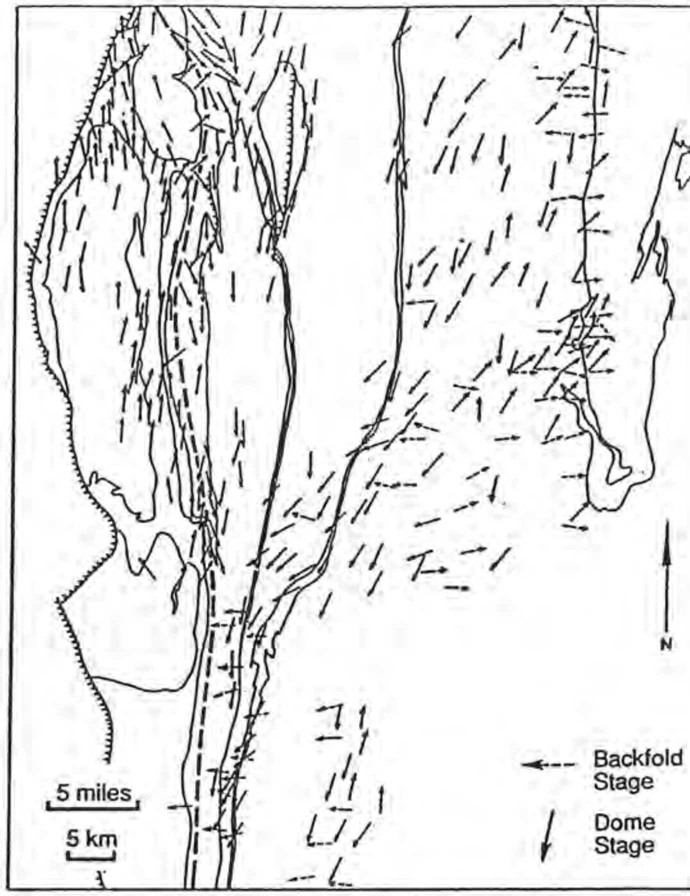


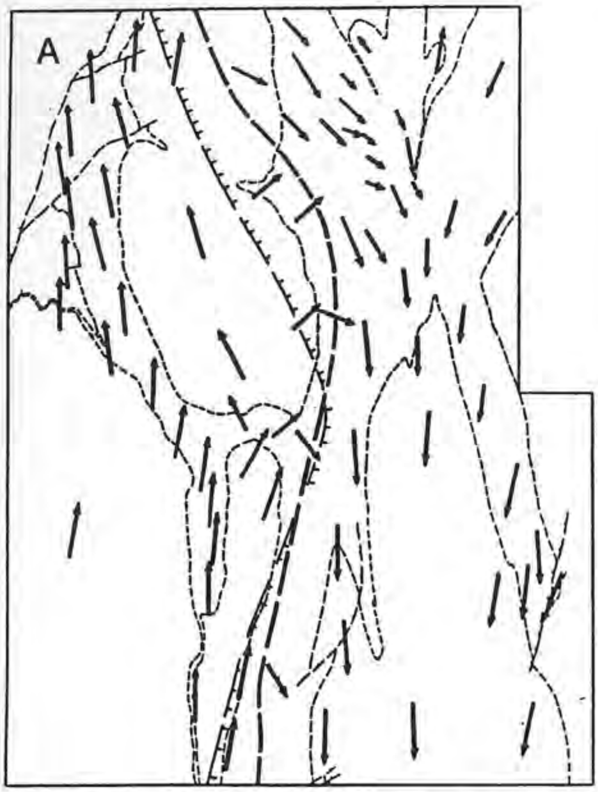
Figure 3. Regional map showing distribution and representative orientations of Quaboagian backfold- and Quaboagian and Northfieldian dome-stage lineations across central Massachusetts (from Peterson, 1992). Heavy dashed line shows the eastern limit of strong late Pennsylvanian Northfieldian ductile deformation and recrystallization.

Quaboagian Dome Stage

The Quaboagian dome stage is characterized by N-S to NE-trending, mostly south-plunging folds, and parallel lineations. The folds outline the major domes in the eastern part of the Bronson Hill anticlinorium. Mineral grain shapes and elongate conglomerate pebbles indicate this is a stretching lineation quasi-parallel to fold axes. This was poorly understood, until Peterson (1992a, b, Peterson and Robinson, 1993) discovered a right-lateral shear fabric in sillimanite-orthoclase grade rocks parallel to this lineation near the east margin of the Monson Gneiss (Stop 11) and inferred its origin by orogen-parallel elongation. A wider study awaited in 1993 for shear fabrics parallel to lineation, using Peterson's techniques, and still awaits (Robinson and Peterson, 2002).

Northfieldian Dome Stage

Elongation lineations quasi-parallel to fold axes occupy an enormous region in central Massachusetts, as described above. In the northern part of the Pelham dome, where lineation plunges gently north, a series of late asymmetric folds including sheath and tubular folds formed during lineation-parallel shear, indicate north-over south shear parallel to the axis of the dome (Ashenden, 1973; Onasch, 1973). This sense was confirmed in fabric analyses



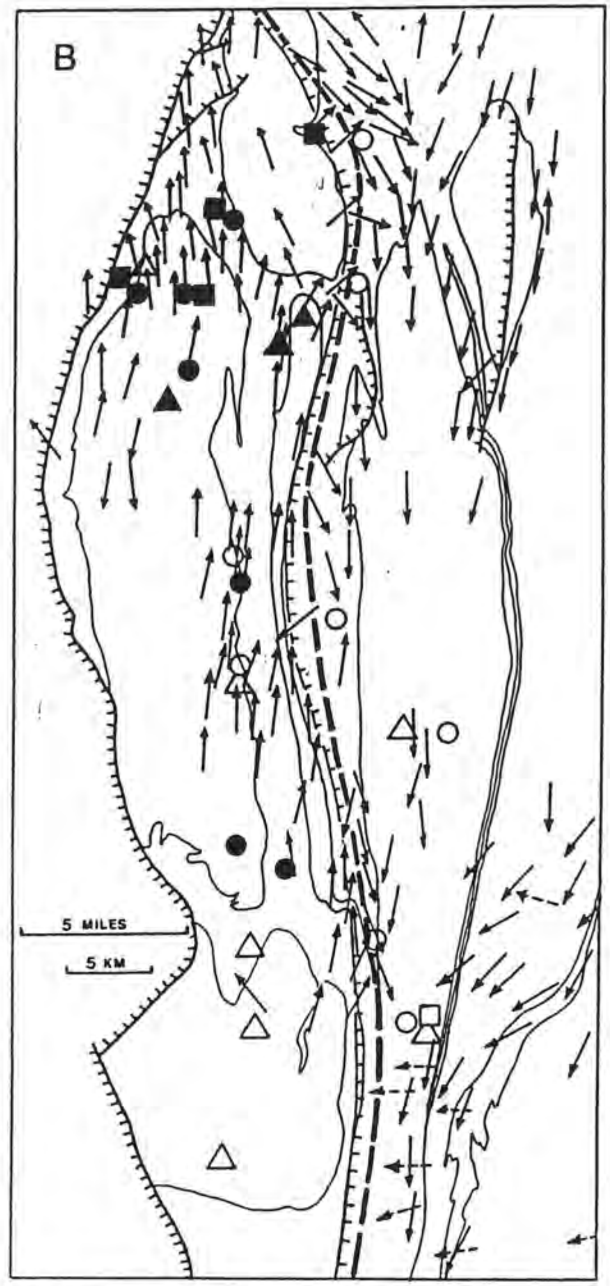


Figure 4. The "great swirl" of mineral lineations in north-central Massachusetts.

A) Distribution of mineral lineations in the Orange area (Robinson, 1963). Each arrow represents the mean of a subarea containing from tens to hundreds of lineation measurements. Length of arrows is inversely proportional to plunge as follows: long arrow - 0-30°; intermediate arrow - 30-60°; short arrow 60-85°. Heavy dashed line is the trace of the "great swirl" defined as the locus of points where lineation plunges due east. Adjacent hachured line is best estimated position of the fibrolitic sillimanite isograd.

B) Compilation of lineation data over a broader region combined with information on distribution of Belchertown-Quaboagian and Northfieldian metamorphic and igneous ages. Heavy dashed line is the trace of the "great swirl" defined as the locus of points where lineation plunges due east. Adjacent hachured line is the Quaboagian fibrolitic sillimanite isograd. Closed symbols indicate Northfieldian ages, open symbols Quaboagian and Belchertown ages. Circles - U-Pb ages on metamorphic minerals by Tucker; triangles - U-Pb ages on igneous minerals by Tucker; squares - Rb-Sr or Sm-Nd isochrons on metamorphic minerals by Gromet. Of the two Quaboagian metamorphic ages west of the swirl, both are in relict Mount Mineral schist. Of the five Quaboagian- Belchertown igneous U-Pb zircon ages west of the swirl, one is 350±2 Ma in relict sillimanite pegmatite in the Mount Mineral Formation and the other four are from Belchertown Quartz Monzodiorite. Since drafting of this map, several new ages have been added, including a 359 Ma monazite age from the West Leverett area in the western cover of the Pelham dome.

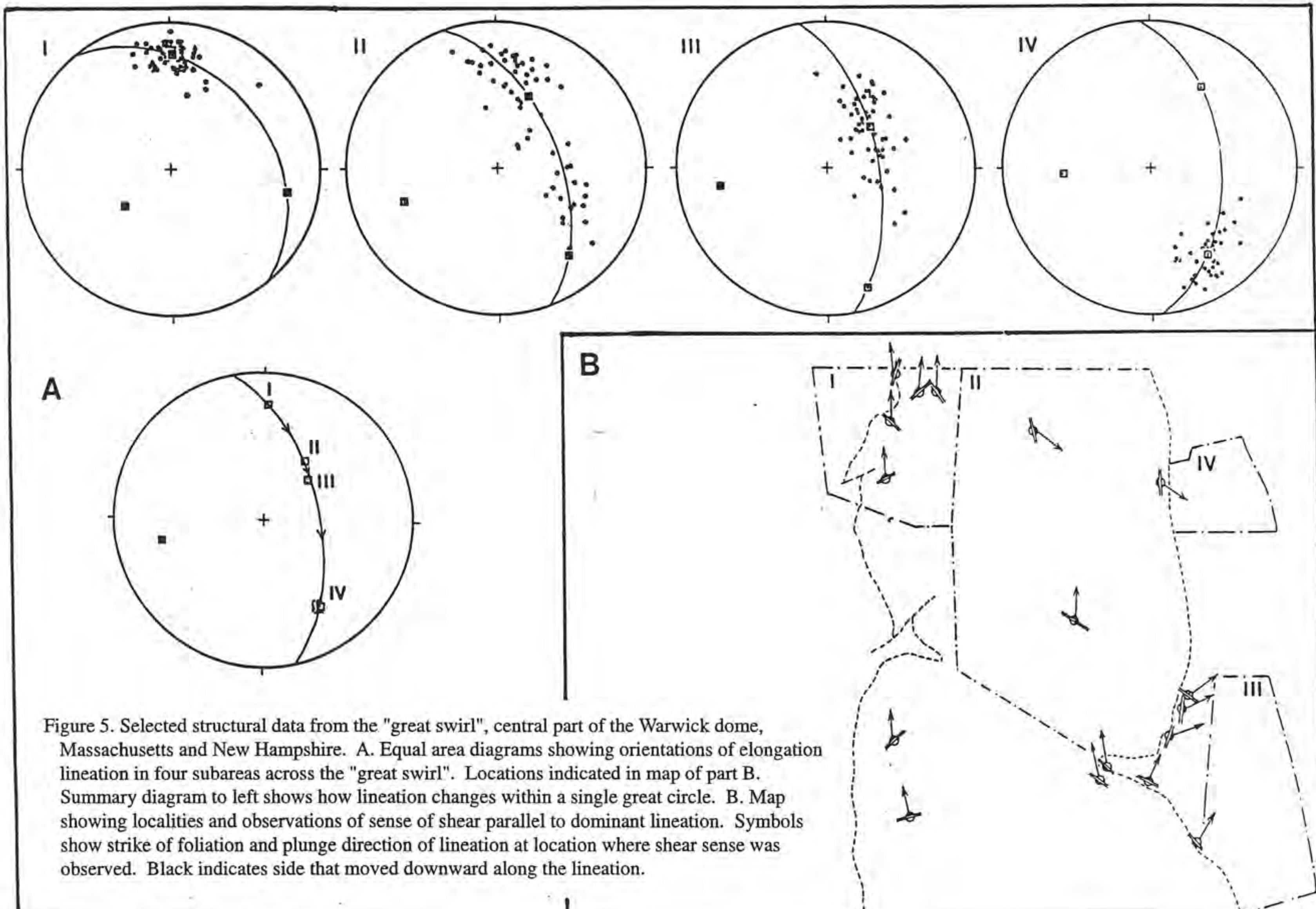


Figure 5. Selected structural data from the "great swirl", central part of the Warwick dome, Massachusetts and New Hampshire. A. Equal area diagrams showing orientations of elongation lineation in four subareas across the "great swirl". Locations indicated in map of part B. Summary diagram to left shows how lineation changes within a single great circle. B. Map showing localities and observations of sense of shear parallel to dominant lineation. Symbols show strike of foliation and plunge direction of lineation at location where shear sense was observed. Black indicates side that moved downward along the lineation.

by

Reed (1993; Reed and Williams, 1989) and it can be shown that upper levels were sliding south relative to deeper levels throughout the length of the Pelham dome. In going from the region of north-plunging lineations in the northern part of the Pelham dome eastward to the region of south-plunging lineations in the southern part of the Keene dome (Figure 3), one might expect the lineations to pass through the horizontal. In fact they are connected by a swirl within which lineations plunge due east down the dip of the foliation. This "great swirl" (Robinson, 1963), has long been a puzzle, and was thought to be a product of strain reorientation during the Acadian (Dellorusso and Robinson, 1989). A solution appeared from the U-Pb dating of metamorphic titanite and monazite by Tucker (Robinson et al., 1992) showing that the axis of the swirl is essentially the locus along which Quaboagian metamorphic minerals were recrystallized in the Late Pennsylvanian Northfieldian (Figures 4, 5). A new model for the swirl (Peterson et al., 1993) is that it is the pattern of Quaboagian lineation as it passes progressively westward into a Northfieldian strain field.

METAMORPHISM

At face value, the pattern of metamorphic zones in west-central Massachusetts is a classic Barrovian one, from the chlorite zone of the Connecticut Valley metamorphic low and to the granulite facies in the central-Massachusetts high (Tracy et al., 1976; Robinson et al., 1989). The abundance of normal shale compositions as contrasted to the Moine-Dalradian of Scotland makes the characterization of metamorphic facies relatively easy. The abundance of mafic rocks, especially Fe-Mg amphibole rocks of the Ammonoosuc and Partridge, has allowed successful parallel studies (Robinson and Jaffe, 1969a,b; J. C. Schumacher and Robinson, 1987; J. C. Schumacher, 1988; Robinson et al., 1982b; Hollocher, 1985, 1991; Schumacher et al., 1989, 1990; Renate Schumacher, 1986). Closer scrutiny, however, leads to many unsolved problems.

West of the Mesozoic Connecticut Valley fault near the north border of Massachusetts, metamorphism is progressive and apparently (?) Acadian from chlorite zone through biotite, garnet (STOP 1), and staurolite zones until sillimanite-muscovite assemblages are attained just beneath the Ashuelot Pluton of Kinsman Granite. The Ashuelot Pluton gives a U-Pb age of 403 Ma, but monazite in a sillimanite schist west of its contact gives a Quaboagian age of 358 Ma (Robinson et al., 1998). This is a region of inverted metamorphism in which structurally higher rocks in fold and thrust nappes are at higher metamorphic grade, and has been studied in greater detail in western New Hampshire (Spear and Chamberlain, 1986; Elbert, 1988; Spear et al., 1990). This metamorphism reaches sillimanite-muscovite-orthoclase grade in the Amherst block of Rangeley Formation exposed between the Deerfield and Hartford Mesozoic basins, where early Acadian U-Pb monazite ages are obtained at around 400 Ma (R. D. Tucker, personal communication, 1992, Robinson et al., 1998), similar to monazite ages in the sillimanite-orthoclase Acadian high in central New Hampshire (Eusden and Barreiro, 1988).

In an extensive region east of the Mesozoic fault, pelites are much coarser grained and contain the assemblage muscovite-biotite-garnet-staurolite with or without kyanite. Garnets (STOP 3, STOP 6)) show prograde growth zoning (Tracy et al., 1976) and the rocks yield estimated temperatures of about 580° and estimated minimum pressures of 6 kbar. Based on new geochronology (Robinson et al., 1992, 1998) we know this metamorphism was Late Pennsylvanian or Northfieldian and overprints largely unknown patterns of Acadian and Quaboagian metamorphism. However a Quaboagian monazite age of 359±1 Ma. has been obtained in a quartzite with a relict sillimanite-muscovite assemblage in West Leverett just east of the Connecticut Valley fault (not shown in Figure 4 but see Robinson et al., 1998). This is involved in another swirl of lineation described by Oxboel et al. (1997). We also know that part of the Mount Mineral Formation (see Paleozoic Undercover) was subjected to near granulite-facies Quaboagian metamorphism with assemblages of sillimanite, orthoclase, garnet (Pyrope 35), biotite, and rutile indicating 700°C and 6.8 kbar (STOP 6), similar to but at higher pressure than the Quaboagian central Massachusetts granulite-facies metamorphic high (STOPS 8A, 8B, 10-15).

Beyond the eastern limit of the Northfieldian overprinting, a rational pattern of zones appears in pelites containing monazites of predominantly Quaboagian age (Robinson et al., 1998), beginning with sillimanite-muscovite-staurolite (II) (STOP 4), then sillimanite-muscovite (III) (STOP 5), sillimanite-muscovite-orthoclase (IV) (Tracy, 1978), sillimanite-orthoclase (V) (STOP 8 A), and finally sillimanite-orthoclase-garnet-cordierite (VI) (STOPS 10-15). However, the pattern bears no rational relation to obvious structural features or distributions of intrusive rocks, although it does seem to follow the shape of a positive gravity anomaly (Kick, 1975; Fitzpatrick, 1978). Nearly everywhere east of the Bronson Hill anticlinorium, locally close to Quaboagian or probable Quaboagian intrusions, pelites can be found containing sillimanite pseudomorphs after andalusite, indicative of early high-temperature low-pressure Quaboagian metamorphism before the onset of granulite-facies conditions. Pelites imply peak metamorphic conditions at 700-800°C and 6-6.5 kbar (Thomson, 1992, Thomson et al., 1992), and very dry as shown by the rarity of retrograde reactions on mineral rims except simple local ion exchange, even within such post-peak features as the Conant Brook shear zone (Peterson, 1992a; Thomson et al., 1992). There is evidence of cooling at the same or slightly increasing pressure in garnet-sillimanite-quartz symplectites inside cordierites (Thomson, 1992; Thomson et al., 1992).

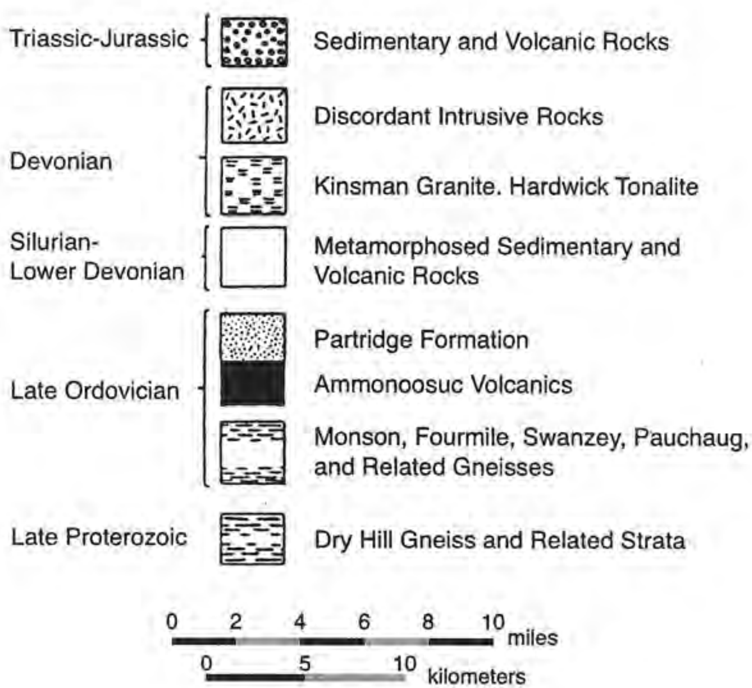
In the Quaboagian sillimanite-muscovite zone, cordierite-gedrite gneisses show the development of aluminous enclaves indicative of pressure release during uplift of the Keene gneiss dome (Robinson and Jaffe, 1969a; Schumacher and Robinson, 1987). In higher grade mafic rocks Hollocher (1985, 1991) has charted the progressive breakdown of Fe-Mg amphiboles and then of hornblende to produce augite-orthopyroxene-plagioclase assemblages (STOPS 8A, 8B, 13), and then the beginnings of the breakdown of biotite to produce orthopyroxene + orthoclase (STOP 13). New evaluations of conditions in these pyroxene granulites suggest peak conditions as high as 850°C [Schumacher, Hollocher and Frost, in preparation). Berry has described several occurrences of marble containing wollastonite in quartz-calcite-anorthite rocks and has shown that grossular-rich garnet only grows at calcite-anorthite or wollastonite-anorthite contacts when supplied with requisite FeO and MgO from adjacent diopside (Berry, 1989; Robinson, 1991). He has also described a gneiss (Thomson et al., 1992) with the assemblage biotite-plagioclase-orthoclase-garnet-corundum-sillimanite-spinel close to experimental calibrations and indicating a temperature of 800-825°C at 6-6.5 kbar.

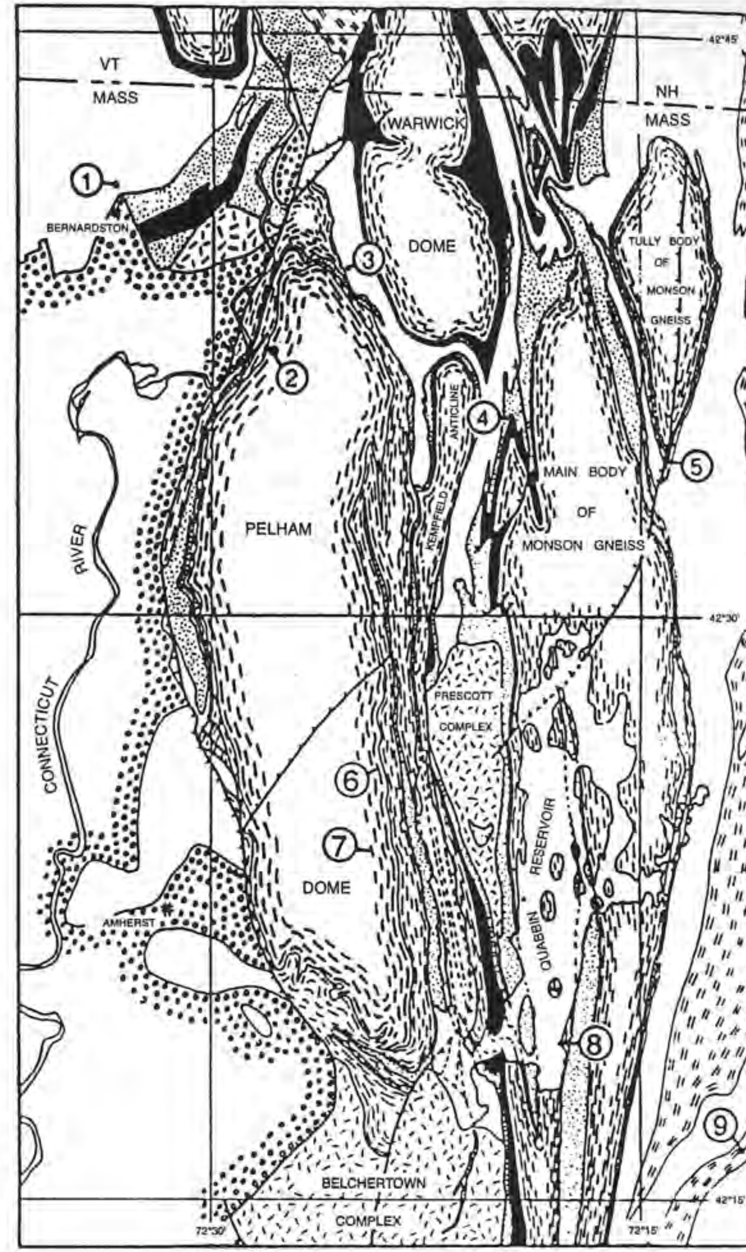
It is speculated that the early low-pressure Quaboagian heating, indicated by the widespread occurrence of andalusite pseudomorphs, may have accomplished much of the necessary dehydration required to produce the later granulites. This could have occurred under extensional conditions that thinned the crust and brought mantle close to the surface (Berry and Robinson, 1989), or by delamination of continental lithosphere in front of a subduction zone, allowing asthenosphere to come close to the base of the crust and provide both heat and mafic magmas that gave the impetus for most of the Quaboagian magmatism. This vision is in stark contrast to the model of Chamberlain and Sonder (1990) for the Acadian of nearby central New Hampshire, who propose that an abundance of heat-producing elements in the Silurian-Devonian section under deep burial could have provided all of the thermal energy for Acadian metamorphism and magmatism. The very importance of mafic and intermediate Acadian and Quaboagian magmas in the region, for example the Acadian Spaulding Tonalites, and the Quaboagian Hardwick and Wachusett tonalites belies this interpretation. At present, by contrast with the Acadian, the evidence indicating the importance of Quaboagian magmatism, tectonics, and metamorphism far outweighs the broader stratigraphic evidence upon which to build a tectonic model. The same may be said for the Northfieldian Late Pennsylvanian deformation and metamorphism. Altogether, then, there is very much yet to be done in field-based studies relating stratigraphy, igneous activity, structure, metamorphism and tectonics, and the surprises of the future are likely to be fully as exciting as those of the past.

ACKNOWLEDGEMENTS

The research results covered in this guidebook article involved a large number of persons over a period of 45 years. I have tried to acknowledge them at the front as either direct or indirect contributors. Several of the stop descriptions have been adapted from guidebook material published previously and this is cited for each stop. The research covered in this article was supported by the U. S. Geological Survey during preparation of the Massachusetts Bedrock Map and by National Science Foundation Grants to Robinson both before and after. The original manuscript was prepared while the author was a guest researcher at the Department of Mineralogy and Petrology at Lund University, Sweden, 1993, with modifications in March 2002 and July-August 2003. The author thanks his wife, Suzanne A. McEnroe, his daughter Alexandra R. McEnroe, and the Editors John Brady and Jack Cheney for their support in the concluding stages.

Figure 6. Generalized geologic map of north-central Massachusetts and adjacent states, showing gneiss domes of the Bronson Hill anticlinorium and the locations of Stops 1-9.





ROAD LOG

From the University of Massachusetts proceed via Route 116 and Interstate 91 to junction of Interstate Route 91 and Massachusetts Route 2, west of Greenfield, where the mileage log begins. The road log includes all of the main stops in detail, but for supplemental STOPS 2A, 2B, a supplemental log is given. Most stops are on private property. Please respect outcrops and the rights of landowners.

Mileage

0.0 Proceed north on Interstate Route 91.
2.5 Route 2 bears right. Stay on I 91 North. Cuts in Late Triassic Sugarloaf Arkose.
7.6 Take Exit 28B for Route 10 South.
7.8 Bear right (west) on Route 10 South. Cross over I-91, enter village of Bernardston.
8.5 T junction with U. S. Route 5. Turn right (north).
9.1 Outcrop left, Sugarloaf Arkose, north end of Deerfield basin.
9.2 Pull onto grassy shoulder on right (east) side and park. Cross road. Route 5 is heavily traveled at times. Walk up short dirt track, through gate into pasture. CLOSE GATE BEHIND YOU!!

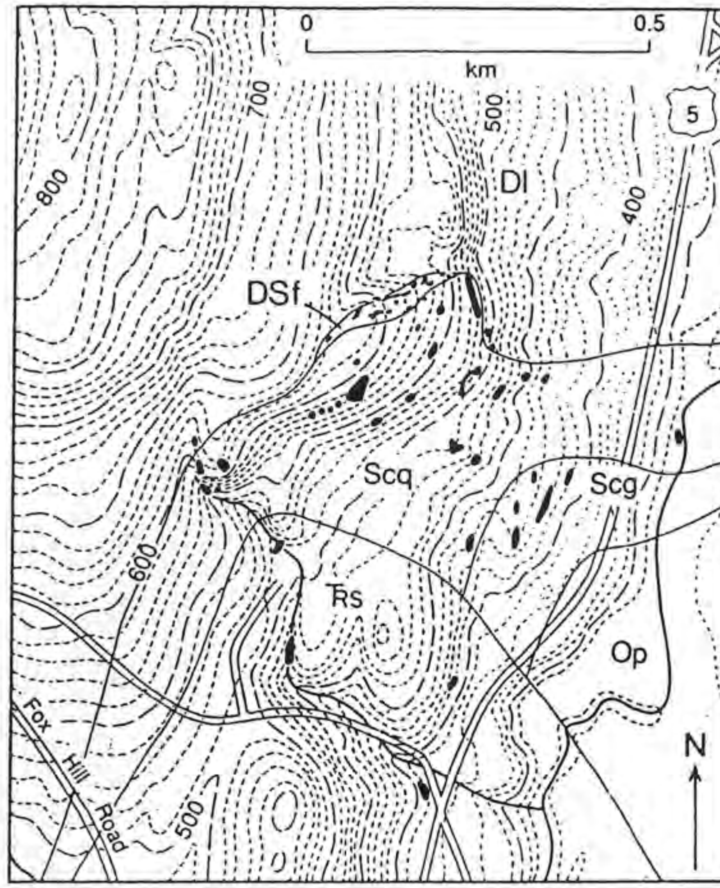
STOP 1. BERNARDSTON FOSSIL LOCALITY (55 minutes) See Figures 6, 7, 8, 9. for complete stop description see Robinson and Elbert (1992); Elbert (1988). Outcrops in lowest part of pasture are in the lower member of the Clough Quartzite, gray-weathering phyllite containing quartz-muscovite-chlorite-biotite-garnet-graphite-leucoxene typical of the lower- to middle-garnet zone. Outcrops approximately halfway up the pasture are metamorphosed conglomerates of the middle member of the Clough, with a few schistose clasts as well as an impure schistose matrix. Cross barbed-wire fence at edge of woods at northwest corner of pasture and continue north on logging road. Outcrops on west side of road, are clean, quartz-pebble conglomerates with quartzite matrix, typical of Clough as mapped by most workers. Pebbles are uniformly vein quartz. Proceed to point where road takes nearly right-angle bend to the west, the location of the no-longer-exposed stratigraphically highest part of the Clough with its fossiliferous section interpreted to be a metamorphosed marine deposit with stenohaline, marine invertebrates (Boucot et al., 1958) of Llandoverian to Wenlockian age.

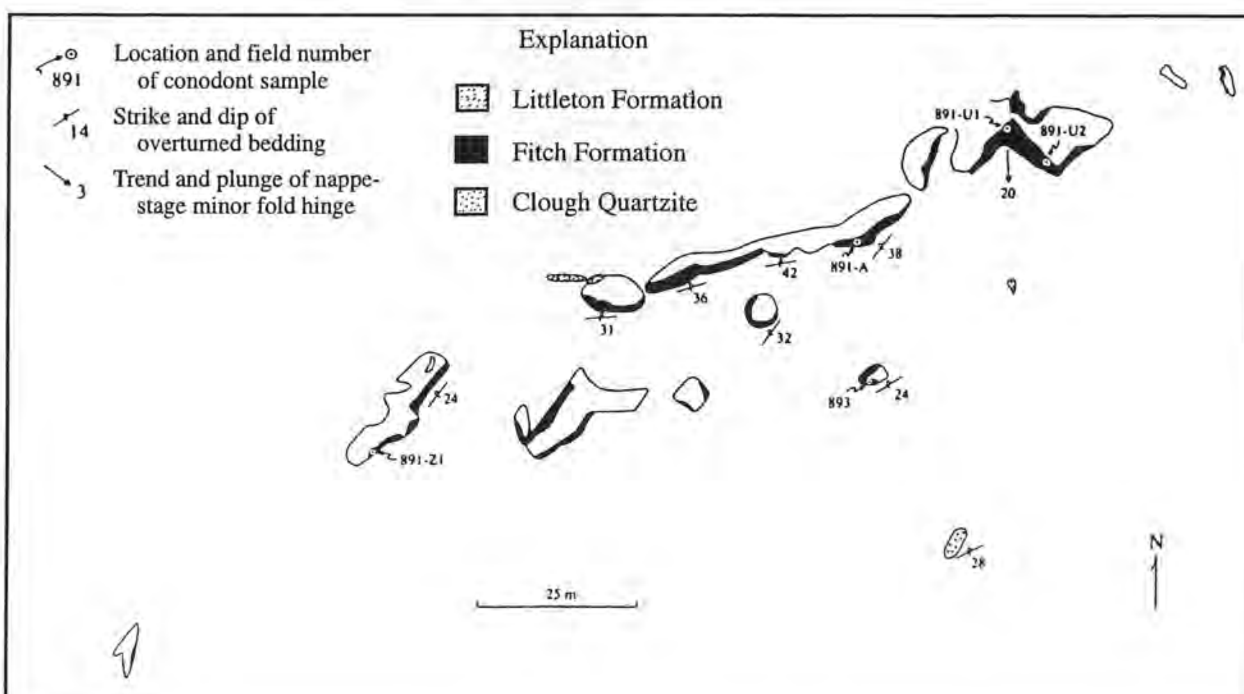
Marbles of the Fitch Formation are exposed in pits dug during mining of a magnetite bed in the 18th and 19th centuries mostly north of the road. Here it is chiefly white to light-gray calcite marble containing scattered crinoid ossicles up to 3 cm diameter, columnals to 5 cm long, recrystallized coral fragments, and 1-3 percent quartz, epidote, and pyrite. Over 1000 recognizable conodonts were recovered from 129 kg of the marble, the world's largest and highest grade (CI=8) collection of regionally metamorphosed conodonts (Elbert et al., 1988), indicative of the Lochkovian (earliest Devonian) *woschmidti* to *eurekaensis* Zones. Lensoid bedforms, relict crossbedding(?), abrupt grain size variations, wide size range of bioclasts, and the fossils indicate deposition in a near-shore, shallow-water, variable, but generally high-energy, marine environment, and suggest that the Fitch near Bernardston was a carbonate shoestring sand formed as a channel filling, bar, or beach. A bed of magnetite-chlorite-quartz-garnet granulite, as much as 0.8 m thick, is present in several pits . One small outcrop of gray schist and quartzite of the Littleton Formation is at the north edge of the pits. The map pattern of the Fitch, suggests that it unconformably overlies the Clough, and the Fitch is unconformably(?) overlain by Littleton . The southerly dip of units, clear-cut stratigraphic distinctions and paleontological ages, show the rocks are inverted. This inverted belt continues tens of kilometers north along strike as the inverted limb of the Bernardston nappe, lowest of the Acadian fold nappes at this latitude.

Retrace route to vehicles. Leave fences, gates as found. Continue north on Route 5.
9.7 Right onto Burke Flat Road.
9.9 Bridge over Interstate 91.
10.0 Junction, Bald Mountain Road, bear right.
11.3 Junction Route 10, turn left (Route 10 north).
12.4 Concrete house in trees on left. Excavation yielded quartz phyric rhyolite from Upper Member of Ammonoosuc Volcanics, with zircons giving concordant age of 453±2 Ma (Tucker and Robinson, 1990). Thin rhyolite tuff bed in inverted lower Partridge Formation a few hundred yards north gave discordant zircon fractions on chord pointing to age of 449+3-2Ma.
14.3 Outcrops both sides, sulfidic schists and amphibolites, Partridge Formation.
15.0 Bennett Meadow Bridge, Connecticut River.
15.6 Cross railroad bridge. Lower Jurassic conglomerate of Turners Falls Sandstone, Northfield Mesozoic basin is exposed at base of fill to left.

Figure 7. Detailed contact and outcrop map in the vicinity of the Bernardston fossil locality, Stop 1, from Elbert et al., 1988. Unit symbols: Op - Ordovician Partridge Formation; Scg - gray garnet-mica phyllite member of Lower Silurian Clough Quartzite; Scq - Silurian Clough Quartzite including pebble conglomerate; DSf - Lower Devonian - Silurian Fitch Formation marble; Dl - Lower Devonian Littleton Formation gray garnet-mica phyllite; Trs - Upper Triassic Sugarloaf Arkose.

Figure 8. Tape and compass map from Elbert et al. (1988) showing conodont sample localities and stratigraphic units exposed (outcrops patterned in pits (outlined) in the Fitch Formation marble at Bernardston (see Figure 7). Sample location 893 lies in the pit a few meters southwest of a right angle bend in a logging road. Other marble-bearing pits are north of the road, mostly under large hemlocks. Structure symbols apply to the closest outcrops.





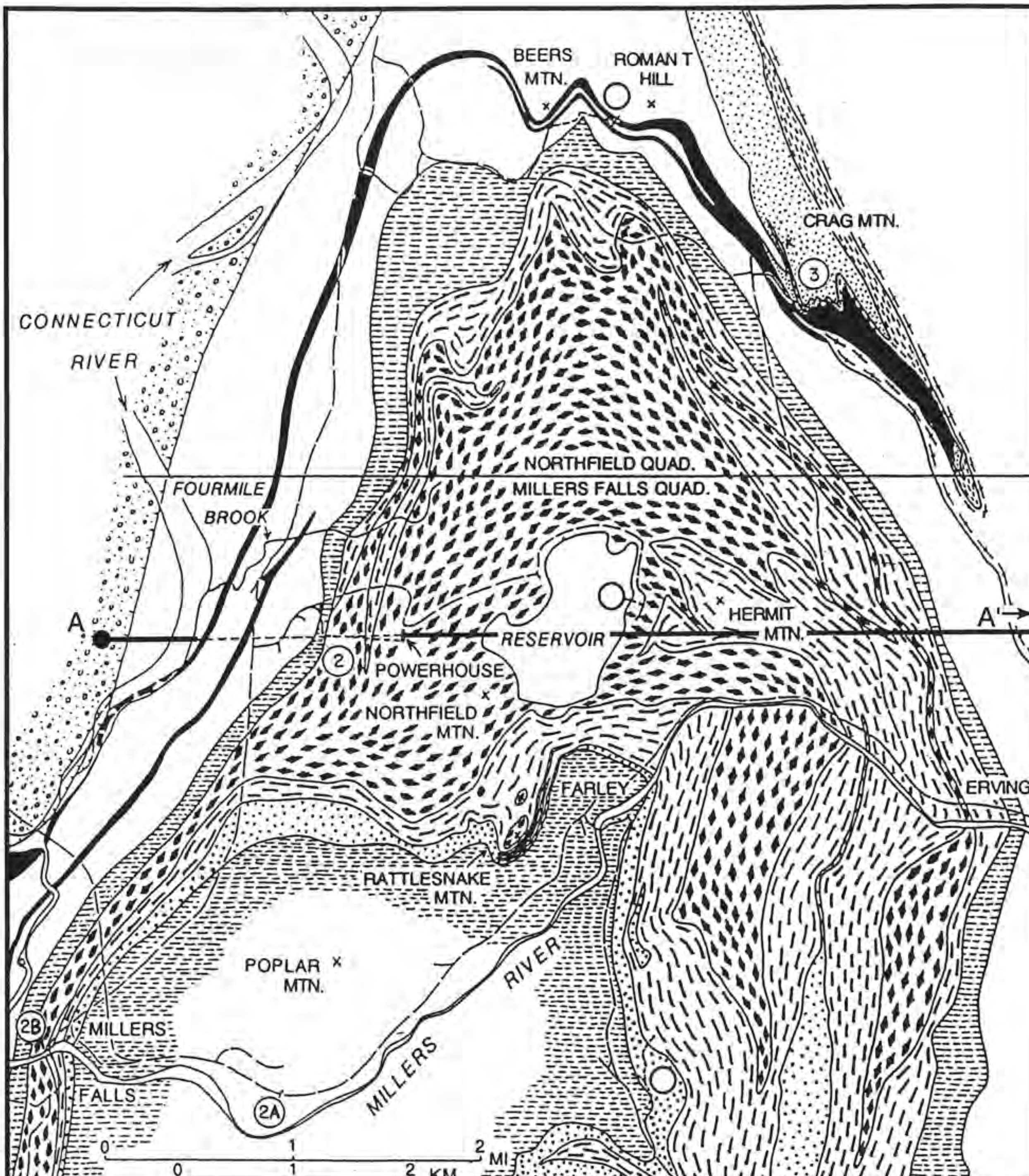


Figure 10. Detailed map of the north-central part of the Pelham dome showing the locations of Stops 2, 2A, 2B and 3. For key to patterns see Figure 11.

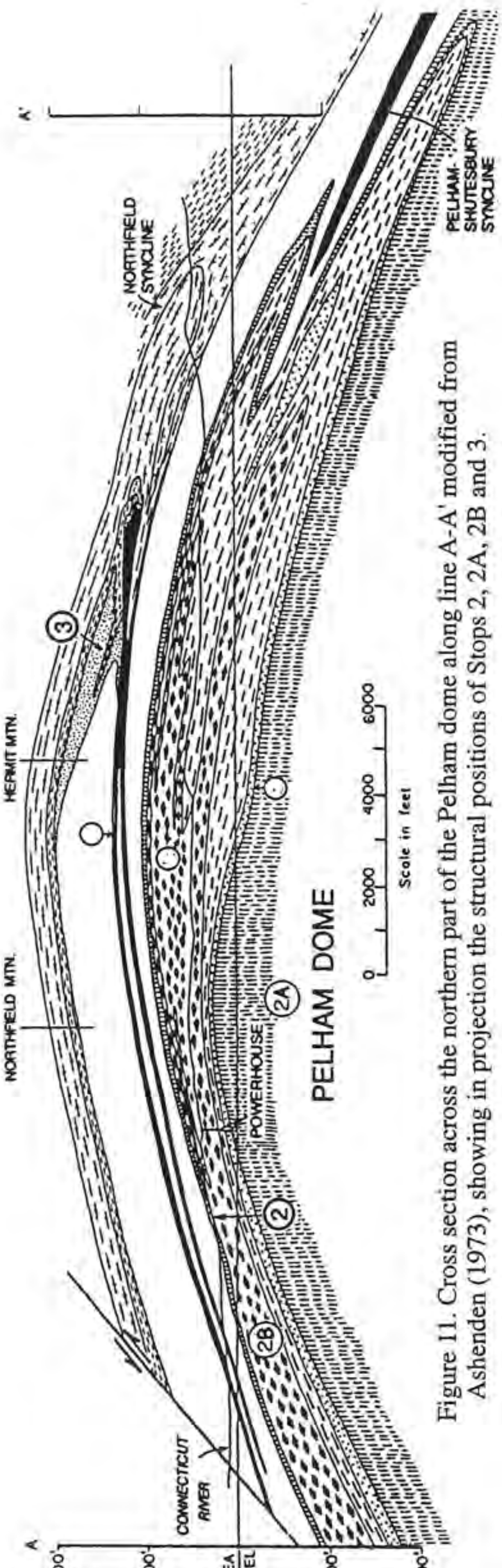
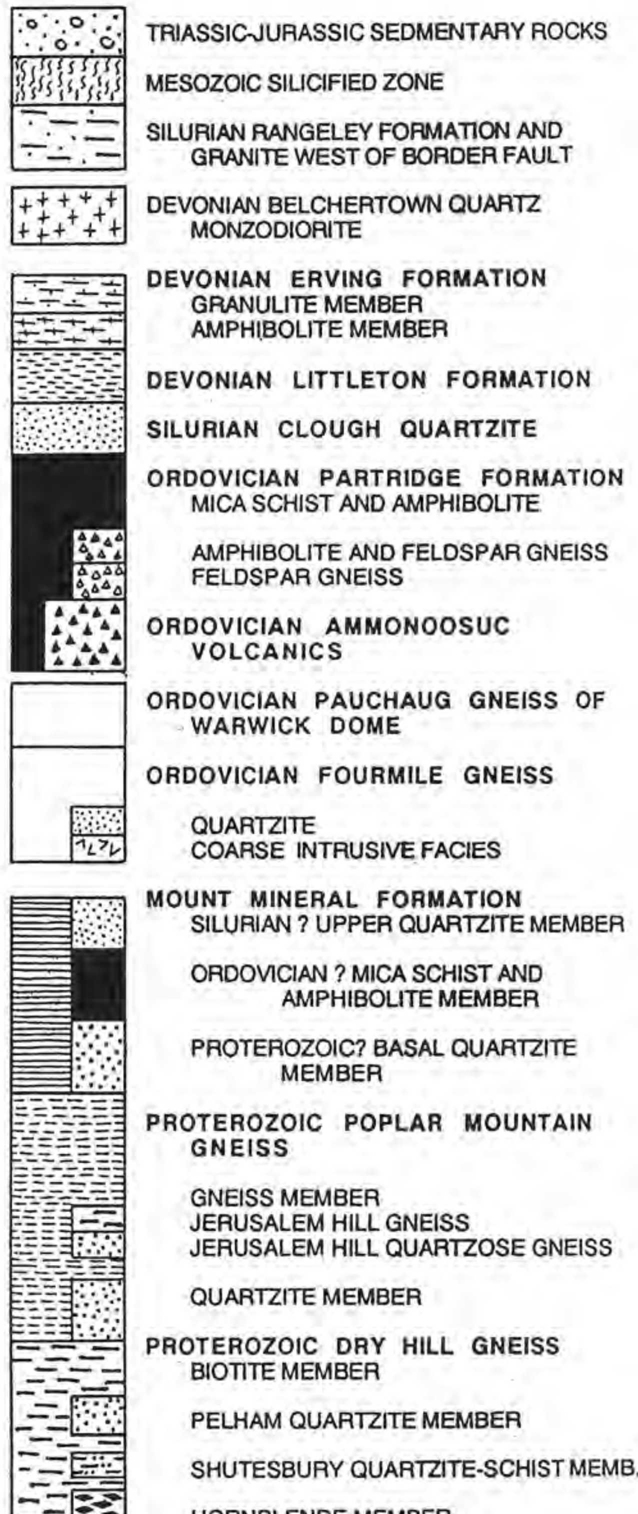


Figure 11. Cross section across the northern part of the Pelham dome along line A-A' modified from Ashenden (1973), showing in projection the structural positions of Stops 2, 2A, 2B and 3.

Key to patterns for units in Figures 10, 11, 19, and 20.



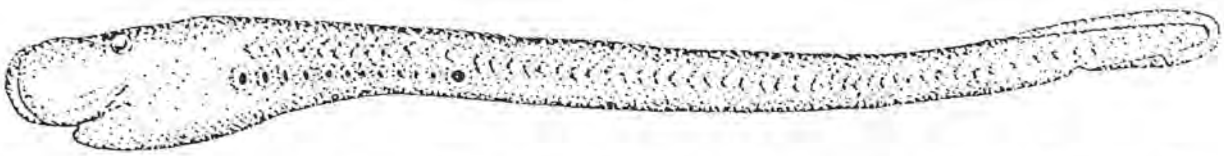
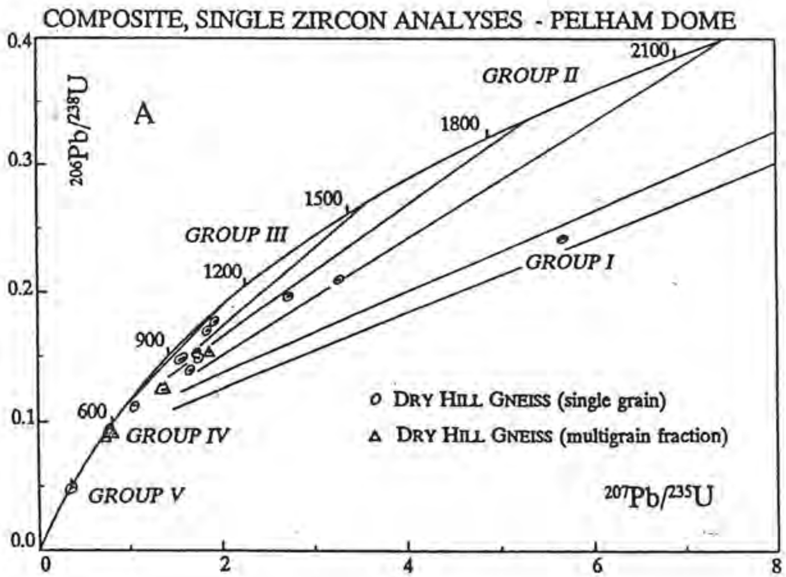


Figure 9. Reconstruction of the worm-like conodont identified as the first vertebrate. About 4.5 times actual size. From a drawing by Richard J. Aldridge in Natural History as reproduced by Browne (1992).

15.7 Flashing light, stop sign, turn right (south) on Route 63.
20.4 Bridge, Fourmile Brook. Type locality of Fourmile Gneiss (Ashenden, 1973).
21.0 Turn left (east) into entrance to Northfield Mountain Pumped Storage Hydroelectric Project.
21.2 Junction for Visitor Center on right. **Access to STOP 2 is now highly restricted** and it is surrounded by new fences. Access for the field trip in Fall 2003 has been formally denied, but a record of the geology is retained here. For this reason supplemental STOPS 2A and 2B have been inserted and should be taken after STOP 3. At junction stay straight.
21.4 Fork. Bear left toward warehouse.
21.5 Fork. Bear right (south) to warehouse.
21.7 Turn around in warehouse lot and park .

STOP 2. DRY HILL GNEISS HORNBLENDE MEMBER OVERLAIN BY POPLAR MOUNTAIN QUARTZITE AND GNEISS (25 minutes) See Figures 10, 11, 12, 13, 14; for more complete description see Robinson et al. (1992) STOPS 1 and 2. The man-made outcrops extend from the parking lot east and then south around the warehouse toward the mouth of the Access Tunnel to the underground powerhouse. Here we are at the top of a west-dipping layer of Dry Hill Gneiss 750 feet thick (Figure 11) that is interpreted as the core of an east-directed recumbent anticline, probably Quaboagian. At STOP 2 the Hornblende Member of the Dry Hill is in direct contact with the overlying Poplar Mountain Quartzite, exposed in the drainage area at the bend in the fence. The contact between the Quartzite and the overlying Gneiss is near the Warehouse Parking lot, and the sequence is locally repeated by a northwest-plunging late asymmetric fold. The Dry Hill Gneiss here is typical of the Hornblende Member (Ashenden, 1973; Hodgkins, 1985), with interlayered gray-pink biotite-feldspar gneiss and pink hastingsite leucogneiss, containing quartz, microcline, oligoclase, green biotite, hastingsite, and accessory allanite, sphene, epidote, calcite, garnet, apatite, zircon, and pyrite. Widely spaced megacrysts of pink maximum microcline (Laird, 1974) as large as 15 cm across with local graphic quartz intergrowths may be fragments from tectonically dismembered pegmatites. The tiny garnets appear to show metamorphic growth zoning. The bulk composition is typical of an A-type alkalic granite, including an extremely high FeO/MgO ratio, such as the Pikes Peak or Cape Ann, or an equivalent rhyolite, and is very close to the Potter Hill Gneiss in the Hope Valley terrane in southeastern Connecticut (Hodgkins, 1985). The Dry Hill is considered to be a volcanic sequence produced in an extensional environment.

The Dry Hill was first sampled for isotopic studies near the pumped storage reservoir at the top of Northfield Mountain (Naylor et al., 1973; Gromet and Robinson, 1990; Harrison et al.,1989; Tucker and Robinson, 1990). Multigrain zircon analyses from there form a well defined discordia. All analyses are discordant over a moderate range (15-31%) and two analyses of clear faceted sphene are concordant at 292 ±5 Ma. Regressed with the sphene, the data define intercept ages of 613 ±3 Ma and 289 ±4 Ma, interpreted by Tucker and Robinson (1990) as the time of igneous crystallization and metamorphic recrystallization, respectively. Samples from that location also give evidence of Pennsylvanian isotopic resetting as a result of recrystallization accompanying strong ductile deformation according to the Rb-Sr, Nd-Sm and U-Pb studies of Gromet. A Rb-Sr mineral and whole-rock isochron suggests recrystallization at 292±5 Ma, in good agreement with the U-Pb sphene ages reported above. The Sm-Nd data indicates near complete homogenization of the rare earth isotopes and growth of new minerals, such as garnet at this time. A hornblende ^{40}Ar-^{39}Ar plateau age of 287 ±1 Ma (Harrison et al., 1989) is also consistent with Late Pennsylvanian metamorphic recrystallization. Multi- and single-grain zircon and sphene analyses from Dry Hill Gneiss collected behind the Warehouse suggest a complex history. A U-Pb analysis of faceted sphene from this sample produced a concordant age of 293 ±5 Ma (Tucker and Robinson, 1990). Two zircon grains yielded near concordant (<2% discordant) analyses at the presumed eruption age of the protolith (ca. 600 Ma,); another two yielded near concordant analyses at the known time of sphene growth. Detailed study of other grains suggests igneous growth at about 613 Ma around grains with inherited ages in three groups, 2850-2550 Ma; 2150-1850 Ma; and 1350-1220 Ma (Tucker and Robinson, 1991).



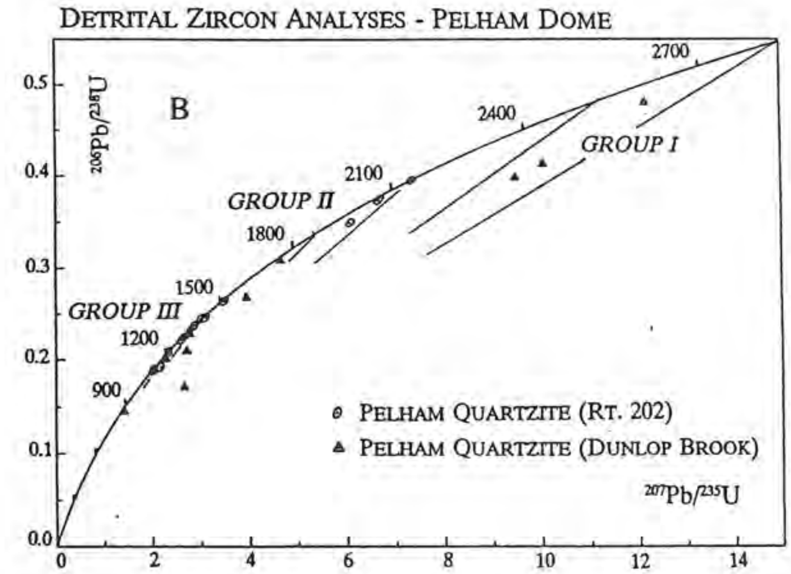
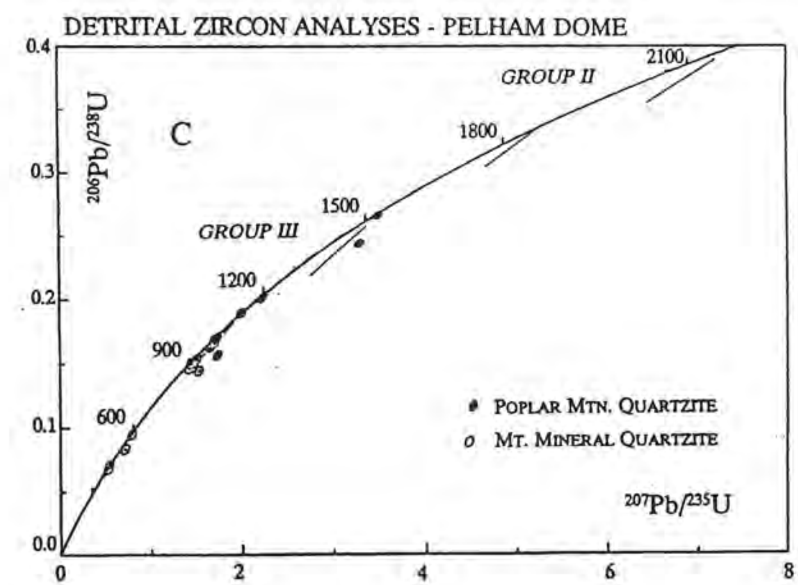


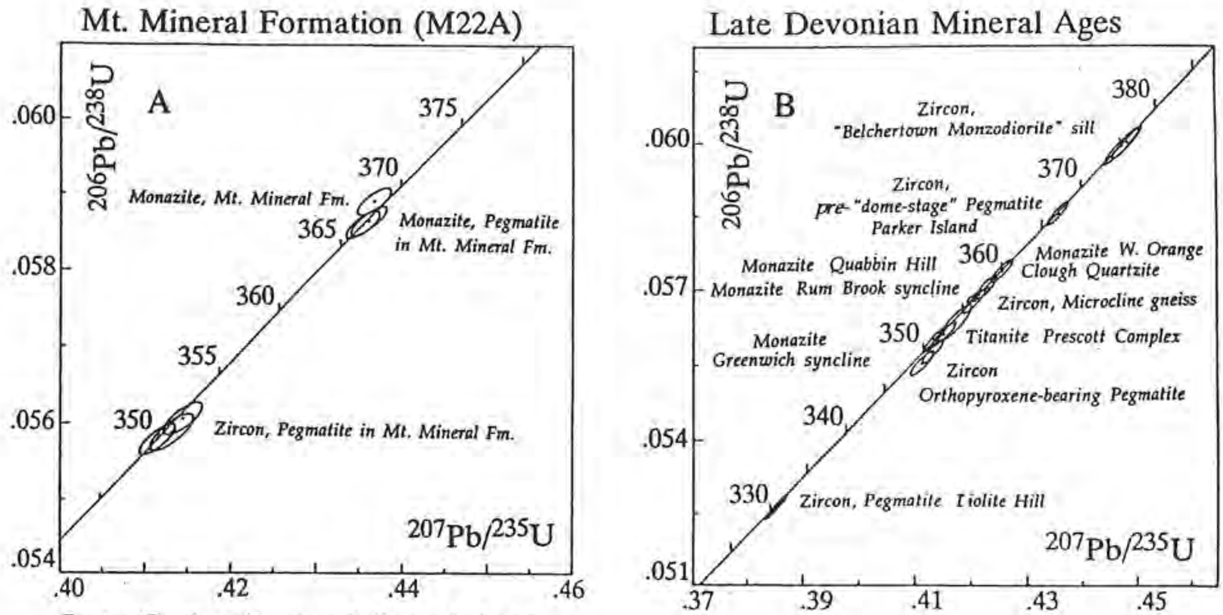
Figure 12. Concordia diagrams of U-Pb zircon analyses from the Pelham dome done by Bob Tucker.

A) Multi- and single-grain zircon analyses from the Late Proterozoic (613 Ma) Dry Hill Gneiss at Northfield Mountain (see text).

B) Thirty analyses of detrital single zircons from the Pelham Quartzite Member of the Dry Hill Gneiss and the quartzite inlier on Dunlop Brook (see Fig. 19).

C) Single detrital zircon analyses from the inverted Poplar Mountain Quartzite at Stop 6 of Robinson et al., 1992 and from the upper quartzite member of the Mount Mineral Formation at Stop 8 of Robinson et al., 1992 (see Fig. 21). Greater than 85% of the analyses are concordant despite up to sillimanite-orthoclase-grade metamorphism, at least in the Mount Mineral sample.





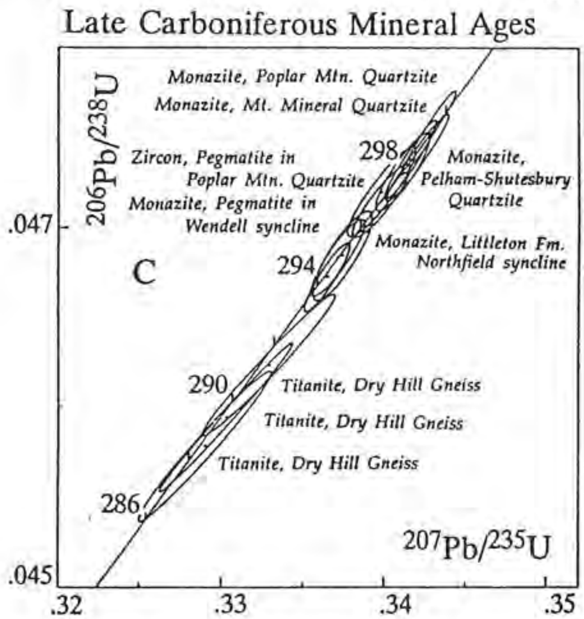


Figure 13. Concordia diagrams of monazite, zircon, and titanite (sphene) from north-central Massachusetts done by Bob Tucker.

A) Monazite and zircon from sillimanite-orthoclase pegmatite M22A at Stop 9 of Robinson et al., 1992, and monazite from adjacent mylonitic Mount Mineral schist and from a mylonitic Mount Mineral schist at Stop 6 of this field trip..

B) Quaboagian zircon, monazite and titanite (sphene) ages from a variety of rocks in a broad region east of the Warwick dome and Kempfield anticline.

C) Late Pennsylvanian Northfieldian zircon, monazite, and titanite (sphene) ages from a variety of rocks within the Pelham dome, the Northfield and Wendell synclines, and the Kempfield anticline.

The prominent mineral lineation trends north-south parallel to the dome axis and to the mineral lineation in mantling strata of the dome. In many outcrops mineral lineation has suffered great circle rotation by variably oriented late asymmetric folds (Ashenden,1973; Onasch, 1973). Lineation development preceded some asymmetric folds and followed others, and was part of the same process. The asymmetric folds, variably overturned to southeast, south, or southwest, show a "separation angle" of 20° that is bisected by the mineral lineation, indicating that the lineation is parallel to their transport direction. The folds were in process of rotation into parallelism with the lineation, but did not achieve it so completely here in the dome as they apparently did in the mantling strata. The consistent asymmetry of these folds throughout the dome, regardless of structural or stratigraphic position, implies relative southward sliding of the cover relative to the core. Such a sense is consistently demonstrated by microfabrics described in detail by Reed and Williams (1989) and Reed (1993), including asymmetric tails on microcline megacrysts in dome gneisses, and asymmetric growth fabrics in garnet, staurolite, and kyanite in pelites of the cover. These studies and the isotopic dating imply that this major strain field is Late Pennsylvanian. Here I use the name Northfieldian for this well defined pre-Alleghanian episode, based on the names of the Mountain and the early colonial Town. An alternative name might be "Sebagoan" based on a major intrusive episode and surrounding metamorphism in western Maine (Robinson et al., 1998).

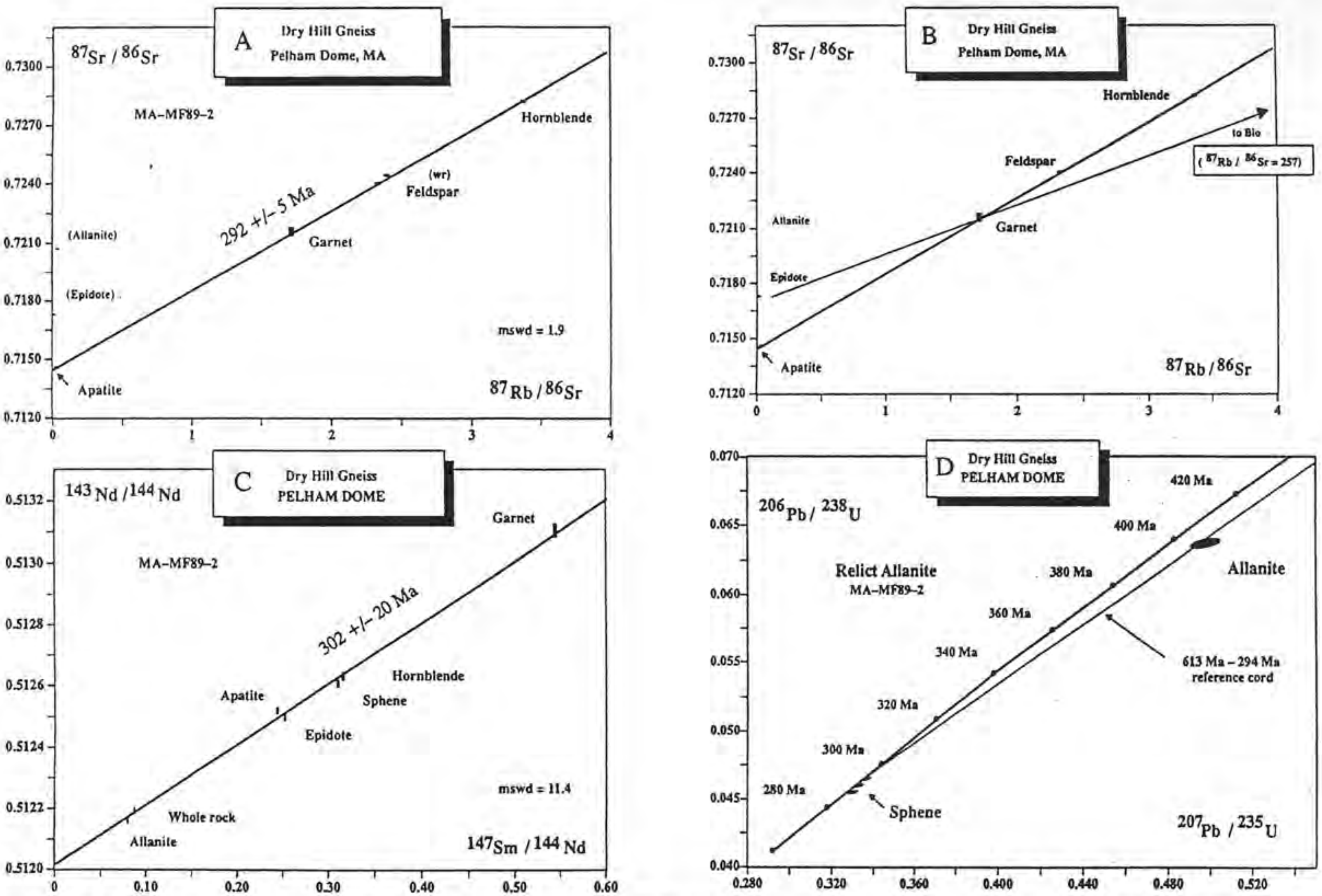


Figure 14. Isotopic results from the Pelham dome by Peter Gromet. (A) Rb/Sr isochron diagram for minerals and whole-rock from the Hornblende Member of the Dry Hill Gneiss at Northfield Mountain at Stop 1 of Robinson et al., 1992. Analyses represented by error boxes corresponding to the external 2-sigma-mean errors. (B) Rb/Sr isochron diagram with allanite, epidote, and biotite from the same rock. (C) Sm/Nd isochron diagram of minerals and whole-rock from the same rock. Reference chord of 302 ± 20 Ma is defined by most minerals and whole-rock except apatite. Sphene and allanite are solution aliquots of minerals in D. (D) U-Pb concordia diagram showing allanite and three concordant analyses of clear faceted sphene from the same rock. Also shown is the reference chord defined by Tucker and Robinson (1990).

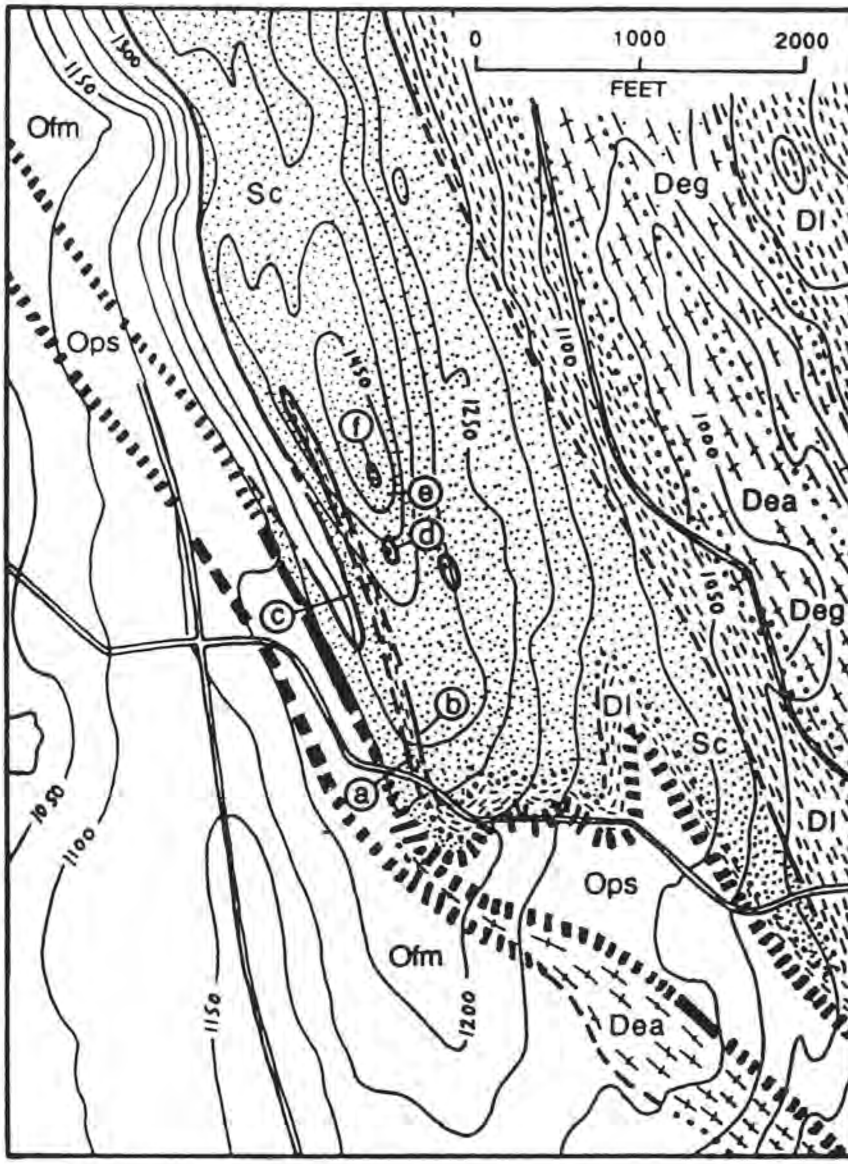


Figure 15. Detailed map of the Crag Mountain area showing stops on the walking log.

Ofm - Fourmile Gneiss
Ops - Partridge Formation
Sc - Clough Quartzite
Dl - Littleton Formation
Deg - Erving Formation Granulite member
Dea - Erving Formation Amphibolite Member

After stop return north.

21.8 Bear left at three-way junction. Return to Route 63.
22.3 Junction with Route 63. Turn right (north).
23.0 Cross north over Fourmile Brook.
25.7 Sharp right turn, South Mountain Road. Sign for Linden Hill School.
26.9 Road ascends dip slope, west limb of Pelham dome.
28.5 Four-way junction. Straight up hill on Sky Farm Road.
28.9 Crest of hill. Park to right and walk up driveway on left (north) side for outcrops of STOP 3.

STOP 3. CLOUGH QUARTZITE AND DEFORMED CONGLOMERATE, LITTLETON SCHIST AND FOURMILE GNEISS IN RECUMBENT FOLDS AT CRAG MOUNTAIN (55 minutes) See Figures 10, 11, and 15; for more complete description see Robinson et al. (1992) STOP 4. Crag Mountain and Brush Mountain are held up by massive Clough Quartzite and conglomerate involved in a series of east-directed recumbent folds, probably of the Quaboagian back-fold stage, that involve all stratigraphic units from the Fourmile Gneiss to the Lower Devonian Erving Formation. On the basis of widely spaced hinge locations, the folds appear to trend north-northeast at an angle to the dome axis (see Laird, 1974, Fig. 20).

Follow driveway, which is also the Metacomet Trail (white blazes) northward to first outcrop on left.

a. Coarse gray muscovite-biotite-garnet-staurolite-graphite-ilmenite schist of Littleton Formation in Crag Mountain syncline. North-plunging crenulation and mica lineation. This unit contains typical growth-zoned garnets (Tracy, et al., 1976; Robinson, 1991, Figure 6). Reed and Williams (1989) have shown that garnets, and staurolites were growing in these rocks during north-over-south shearing. Tucker has obtained a concordant monazite age from the same rock of 295±3 Ma, indicating the metamorphism and deformation are Northfieldian.

b. First outcrop on right. Foliated and lineated pegmatite with broken feldspars in Clough on east limb of Crag Mountain syncline. Slightly to north and east is deformed fine conglomerate with sword-like stretched pebbles parallel to fold axes.

c. Proceed north on driveway. Where it turns left and Metacomet Trail turns right, go straight on older trail. Where older trail turns right (east) up steeper slope, turn sharply west off trail to outcrops on brink of hill 75 feet away. Clough Quartzite containing a foliated pegmatite sill is here in direct contact with Fourmile Gneiss of the Pelham dome, in the core of the Jacks Brook recumbent anticline . The contact, well exposed for three miles north of here, is interpreted as an unconformity (Emerson, 1898; Balk, 1956; Robinson, 1963). The Fourmile is a dark type, with strong north-south lineation consisting of quartz, andesine, microcline, biotite, and hornblende with accessory epidote, garnet and apatite. The petrology and geochemistry of the Fourmile Gneiss, including this outcrop of "Northern Gneiss" is described by Hollocher et al, 2002.

d. Return to trail and proceed up hill to schist in trail, a tectonic inclusion of Littleton in Clough.

e. Continue up steep trail to "The Crag" of Clough conglomerate. View to east, southeast, and south, including Mount Grace (1617'), formed of Ammonoosuc Volcanics up to 4000' thick in a cross fold on the east flank of the Warwick dome. Mt. Monadnock (3165') with its satellites Little Monadnock (1883') and Gap Mountain (1862') lie to the right of Mt. Grace. Farther on the eastern horizon are the Pack Monadnock Group, Watatic (1832') and Wachusett (2006') on the west contact of the Fitchburg plutons.

f. Summit of Crag Mountain (1503'). Best stretched pebbles and cobbles, oriented as a result of Pennsylvanian Northfieldian shearing. Type area for "northfieldite" a siliceous border of the "Pelham granite" (Emerson, 1915. 1917) here in "pseudoconglomeratic" facies. Pebbles are more than 90% vein quartz with minor quartzite and black quartz-tourmaline vein material suggesting deep chemical weathering of the nearby Ordovician source. Pebbles and cobbles are sword-blade-like ellipsoids or cigars with extreme elongation parallel to fold axes. On one outcrop, five miles north, average axial ratios of 1 : 5 : 27.5 were measured, giving axial ratios of 0.19 : 1.01 : 5.24 to a unit sphere of equal volume, and an elongation of five parallel to fold axes. This lineation is the transport direction of a group of asymmetric folds inside the Pelham dome that are rotated toward the lineation. At Crag Mountain all folds seem to be coaxial, suggesting nearly total rotation into the transport direction. All these features indicate Northfieldian shearing and elongation parallel to the axis of the orogen. Extensive view west and southwest. To southwest north-plunging foliation arch of Pelham dome is expressed in topography around Northfield Mountain Reservoir. Beyond the Connecticut Valley rise the Berkshire Hills and the Green Mountains including Haystack and Stratton. On the far horizon is Mt. Greylock (3,491'), the highest point in Massachusetts, and an eastern Taconic slice.

After STOP 3, if following main road log, drive east down steep slope. If including STOPS 2A and 2B as a substitute for STOP 2 turn vehicles around after STOP 3 and follow supplemental road log beginning at the same point. Supplemental road log for STOPS 2A and 2B is listed just below after mileage 32.3 and brings participants back to mileage 33.4 of the main log after these stops. .

29.5 Sharp right (south) on Gulf Road.

32.1 Fork. Bear left.

32.3 Turn left (east) onto Route 2, center of Erving.

33.4 Paper mill at Stoneville, narrow Wendell syncline. Type area of the Erving Hornblende Schist (Emerson, 1898).

SUPPLEMENTAL ROAD LOG - STOPS 2A AND 2B

0.0 Following STOP 3 do U-turn at driveway and return to four-way junction.

0.4 Four-way junction. Turn sharp left (south). Pavement ends.

0.9 Erving Town Line (sign gone). Pavement begins. Descend Mountain Road to valley of Millers River.

3.3 Junction with Route 2. Turn right (west).

5.2 Village of Farley, Town of Erving. Cliffs of Rattlesnake Mountain to right expose base of Dry Hill Gneiss with structurally underlying Poplar Mountain Quartzite and Gneiss; a classic but strenuous traverse.

5.8 Junction with Old State Road. Stay left on Route 2.

7.2 Begin passing lane.

7.4 Large road cut on both sides. Pull off to right as far as possible on soft shoulder near beginning of exposure. LEAVE FLASHERS ON. STAY COMPLETELY OFF PAVEMENT Best access to top of exposure is short trail at east end

STOP 2A. POPLAR MOUNTAIN GNEISS AT DEEPEST EXPOSED LEVEL IN THE PELHAM DOME (20 MINUTES) This major road cut lies almost exactly on the axis of the Pelham dome and at the lowest structural level easily accessible to a field trip (Figure 10, 11, 16). It lies below the steep slopes of Poplar Mountain and contains rocks utterly typical of the Poplar Mountain Gneiss, particularly of the thick zone exposed in the Millers River window beneath the Dry Hill Gneiss.

The dominant rock type is a dark gray biotite-quartz-plagioclase-microcline gneiss, commonly with minor muscovite and garnet. Typical of the unit are large and very large irregular megacrysts of white maximum microcline (Laird, 1974), as contrasted with pink maximum microcline megacrysts in the Dry Hill Gneiss. The association of coarse quartz-microcline intergrowths suggests the feldspars may be sheared relics of pegmatites. In addition, the biotites are red-brown as contrasted to green biotites in the Dry Hill Gneiss. The bulk composition is more variable than in the Dry Hill Gneiss (Hodgkins, 1985), and Ashenden (1973) speculated that the unit is mainly of sedimentary derivation, possibly arkoses derived by weathering of the protolith of the Dry Hill Gneiss, and deposited in a more reducing environment. Locally there are thin layers of quartzite and calc-silicate rock that support this sedimentary model. There is also a variety of blocks and boudins of unusual rocks including amphibolite, hornblendite, and calc-silicate rock in various locations at this outcrop.

The structure is dominated by subhorizontal foliation and a strong mineral lineation plunging gently north. On vertical surfaces parallel to the lineation there are superb examples of the types of asymmetric shear fabrics described in detail by Reed (1992), showing a north-over-south shear that is consistent with the abundant late asymmetric folds elsewhere in the dome (STOPS 1A, 2, 3, 6, 7, 8). Typically there is an asymmetric pattern of foliation and strain shadows around the microcline megacrysts, but there is little evidence of ductile deformation of the microcline itself. This is consistent with petrologic evidence that the Northfieldian (Pennsylvanian) deformation and recrystallization took place at 550-600°C.

Most detrital zircons extracted from the Poplar Mountain Gneiss at this outcrop (Figure 16) have yielded very discordant analyses (11-53%), thus minimizing their usefulness for establishing the sedimentary provenance. However, two analyses of single, clear, faceted zircon are concordant within uncertainty (±1% of the $^{207}Pb/^{206}Pb$ age), indicating crystallization ages of ca. 585 and 370 Ma. Another analysis is ca. 12% discordant with a

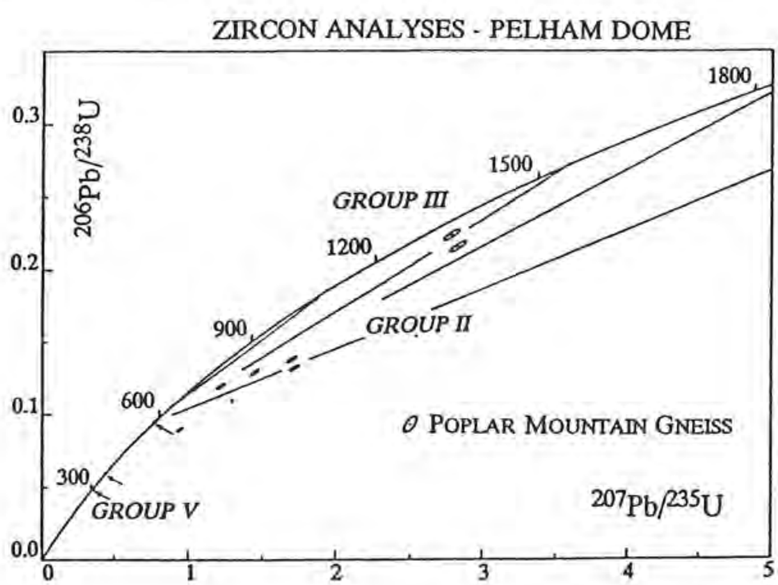


Figure 16. Concordia diagram of ten single-grain zircon analyses from the Poplar Mountain Gneiss at Stop 2A by Bob Tucker. Most grains are very discordant, plotting generally within age groups II and III. Two other analyses (see arrows) are concordant at 585 Ma and 370 Ma, and a third (arrow, Group V) has a $^{206}Pb/^{238}Pb$ age of 302 Ma (Th/U = 0.032) suggesting that it is of metamorphic origin.

$^{206}Pb/^{238}U$ age of 302 Ma. The youngest grain clearly grew in a Th-depleted metamorphic environment (Th/U = 0.032, U = 80 ppm), thereby suggesting that Northfieldian metamorphic zircon growth may have produced the strong discordance observed for these detrital grains. Particularly interesting, however, are the two concordant zircon analyses at 585 Ma and 370 Ma. If interpreted as detrital zircon, the younger of these analyses defines the *maximum sedimentation age* of the protolith, and hence a Late Devonian or younger age for the Poplar Mountain Gneiss. Equally possible, however, is that a sheared Quaboagian pegmatite, possibly represented in outcrop by the large microcline megacrysts, was the source of the younger concordant zircon, in which case a Quaboagian metamorphic history for the gneiss is implied. This scenario is compatible with isotopic evidence gathered elsewhere (including STOP 6 and Robinson et al, 1992, STOPS 8 and 9), where a Quaboagian (367-350) sillimanite-orthoclase grade metamorphism is clearly demonstrated in the Mount Mineral Formation.

Continue west past outcrop. Note that foliation dip changes from northeast to north to northwest.
7.6 Outcrop ends.
8.0 Old State Road. Continue west on Route 2. **At this point mileage record stops.**
Bear left across traffic at awkward exit for Route 63 and village of Millers Falls. Follow this about 1/2 mile to junction with Route 63.
Turn left (south) on Route 63 in Village of Millers Falls and cross grade crossing of Central Vermont Railroad.
Proceed south down hill toward north end of bridge across Millers River. Do not cross bridge but turn right into parking lot and park close to west side of bridge abutment. Walk east on narrow trail a few meters to small outcrop amid concrete on west side of bridge abutment.

STOP 2B. DRY HILL GNEISS, HORNBLENDE MEMBER, INTRUDED BY JURASSIC SILL OF THE PELHAM-LOUDVILLE SYSTEM (10 MINUTES) This is a convenient opportunity to observe the typical Hornblende Member outside the Northfield Mountain Project, dated there at 613 Ma. Here the layer dips gently west and lies in the core of the giant east-directed recumbent anticline, structurally above, but probably stratigraphically below the Poplar Mountain Gneiss seen at STOP 2A (Fig. 11) The base of the exposure shows the top chilled margin of a Jurassic Millers Falls sill of the Pelham-Loudville system. That system of intrusions is the most abundant in west-central Massachusetts, exposed both east and west of the Connecticut Valley Mesozoic basins. In major- and trace-element chemistry it corresponds exactly with the Hampden Basalt and Granby Tuff, the third extrusive episode in the Hartford Basin (McEnroe, 1989; McEnroe and Brown, 1992, 2000).

Following STOP 2B retrace route back to Route 2 and proceed east past STOP 2A, noting the crest of the dome exposed in better perspective. Continue east through the Village of Erving and resume formal road log at 33.4 in Stoneville.

END SUPPLEMENTAL LOG

33.4 Paper mill at Stoneville, narrow Wendell syncline. Type area of the Erving Hornblende Schist (Emerson, 1898).
33.9 Cut on left at junction with Route 2A, Ammonoosuc Volcanics and Northfieldian pegmatite on west limb of Kempfield anticline. Bear left on Route 2.
34.2 Tree-covered cuts Monson Gneiss and pink Northfieldian pegmatites of the Kempfield anticline.
34.4 Big bridge over Millers River.
34.8 Orange Town Line.
35.1 Vegetated outcrops, east limb of Kempfield anticline.
35.3 Exit 14; stay on Route 2. Outcrops in ramp on right, Littleton Formation with fine Quaboagian fibrolite just east of Northfieldian overprint.
36.6 Pull off on right on grass beyond road cut and just beyond passing lane. Cross carefully to east side of highway at first opportunity.

STOP 4. PARTRIDGE FORMATION AND AMMONOOSUC VOLCANICS IN THE LAKE MATTAWA SYNCLINE (30 minutes) See Figure 17. This stop is to examine typical exposures of these formations at a logistically favorable location. They are in the lower sillimanite zone, on the western limb and along the axis of the Lake Mattawa syncline, a south-plunging Quaboagian dome-stage syncline in structurally inverted rocks on the overturned northwest flank of the main body of Monson Gneiss. The road cut is in sulfidic schist of the Partridge with the assemblage quartz-muscovite-biotite-garnet-sillimanite-plagioclase-graphite-ilmenite-

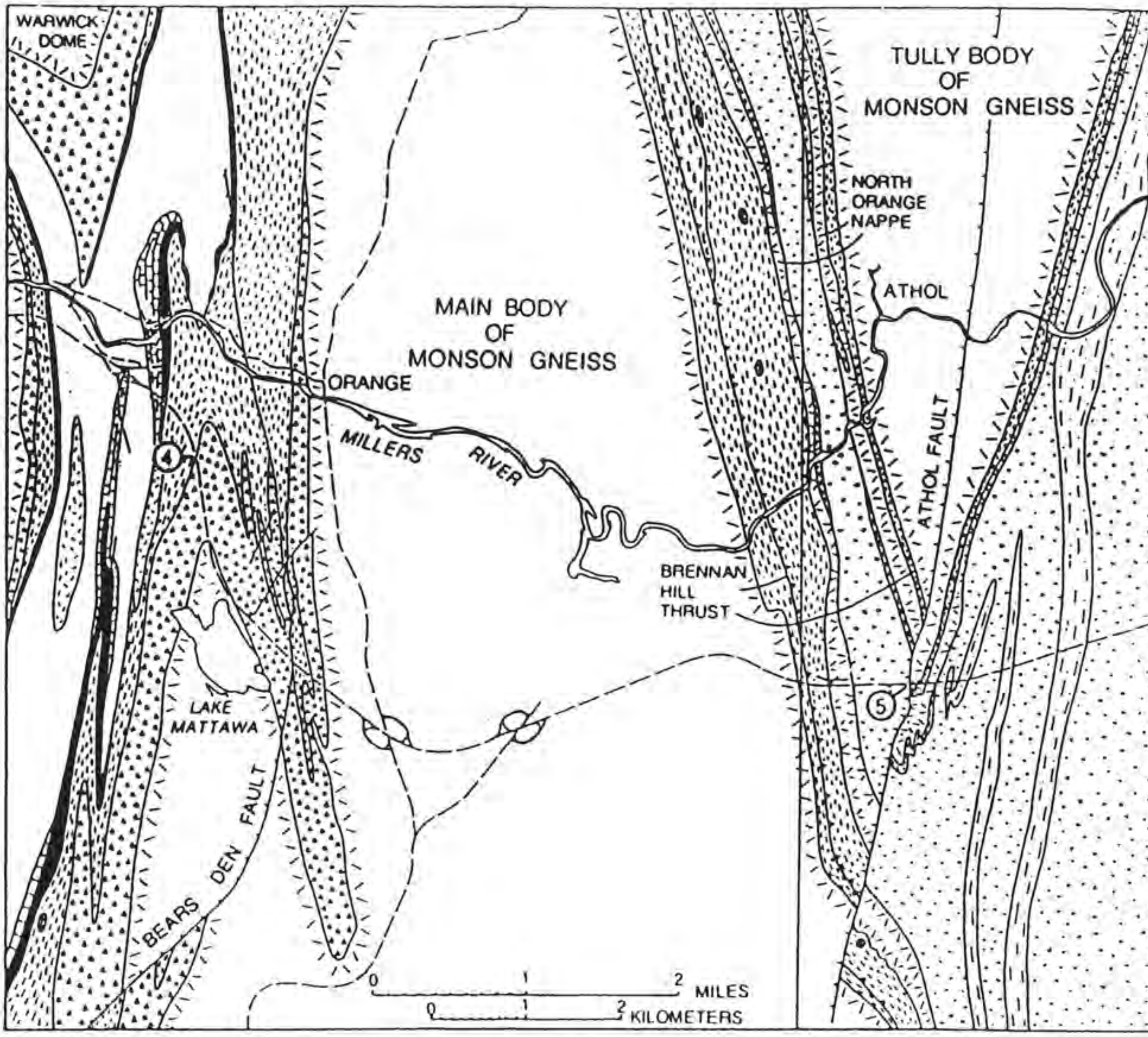


Figure 17. Generalized geologic map of the central part of the Orange quadrangle and the west edge of the Athol quadrangle showing locations of Stops 4 and 5. All obvious fold hinges plunge 10-30° south and formed during the Quaboagian dome stage. In western part of map these folds are in previously inverted strata, so younger rocks appear in anticlines, older rocks in synclines. The main body of Monson Gneiss itself lies along the Williams Pond syncline. In the eastern part of the map, the North Orange nappe and the Brennan Hill thrust are repeated across the Temple Hill fold, believed to have formed during the Quaboagian backfold stage. The south end of the Tully body is a south-plunging anticline.

Key to patterns: Monson Gneiss - tick-marked border; Ammonoosuc Volcanics - triangles; Partridge Formation - fine dashes; Partridge Formation, ultramafic pods - cross pattern; Clough Quartzite - black; Fitch Formation - brick pattern; Rangeley Formation, gray schists - heavy dots; Rangeley Formation, sulfidic schists - dash-dot; Littleton Formation - not patterned; Devonian granite - uniform ticks.

pyrrhotite. Staurolite is present in nearby exposures. Also not represented are layers of amphibolite and felsic gneiss, the typical volcanic interbeds that make up substantial parts of the Formation. A mica and sillimanite lineation plunges 10-30° south parallel to minor and major folds of the Acadian dome stage. Monazite in sillimanite-staurolite Clough Quartzite 1 mile to the north has given a Quaboagian U-Pb age of 360 Ma.

The rest of the stop is a traverse up a gentle hillside, stratigraphically downward in the Ammonoosuc but structurally upward to the axis of the Lake Mattawa syncline, and then to exposures on the east limb. Four rocks on this traverse were part of Schumacher's (1988) study of the geochemistry of the Ammonoosuc. None were studied in detail mineralogically. First there are exposures of quartz-feldspar gneiss of the Felsic Upper Member including one with protruding quartz-sillimanite nodules believed to be a hydrothermally altered felsic volcanic. After a narrow covered interval, where the Middle Member should be exposed, bear slightly to the southeast to exposures of typical hornblende and hornblende-anthophyllite amphibolites of the Mafic Lower Member, inferred to be metamorphosed low/K tholeiites. These include one large exposure of a south-plunging fold hinge with south-plunging hornblende lineation, probably the Lake Mattawa syncline itself. Then move northeast to an exposure on the east limb, of the Middle Garnet-Amphibole Quartzite Member, that is probably of volcanic exhalative origin, and forms a key marker horizon between older predominantly mafic and younger predominantly felsic volcanism. Then move northwest to course gedrite-garnet gneisses typical of parts of the Lower Mafic Member, close to the synclinal axial plane. Some gedrite-garnet and gedrite-cordierite gneisses of the Lower Ammonoosuc are basaltic rocks that underwent extensive hyrothermal sea water alteration before regional metamorphism (Schumacher, 1988). Descend to bus.

Continue east on Route 2.

37.4 Lake Mattawa on right. Depression in Monson Gneiss in inverted position, core of Lake Mattawa syncline. Hill north of lake is Monson Gneiss in nose of syncline.

38.2 Road cuts, both sides. Partridge schist and amphibolite in inverted position in core of Walnut Hill anticline.

38.4 Vegetated cut on right, contact between Ammonoosuc and stratigraphically lower, structurally higher Monson, east limb of Walnut Hill anticline.

38.7 Exit 15 for Route 122. Stay on Route 2.

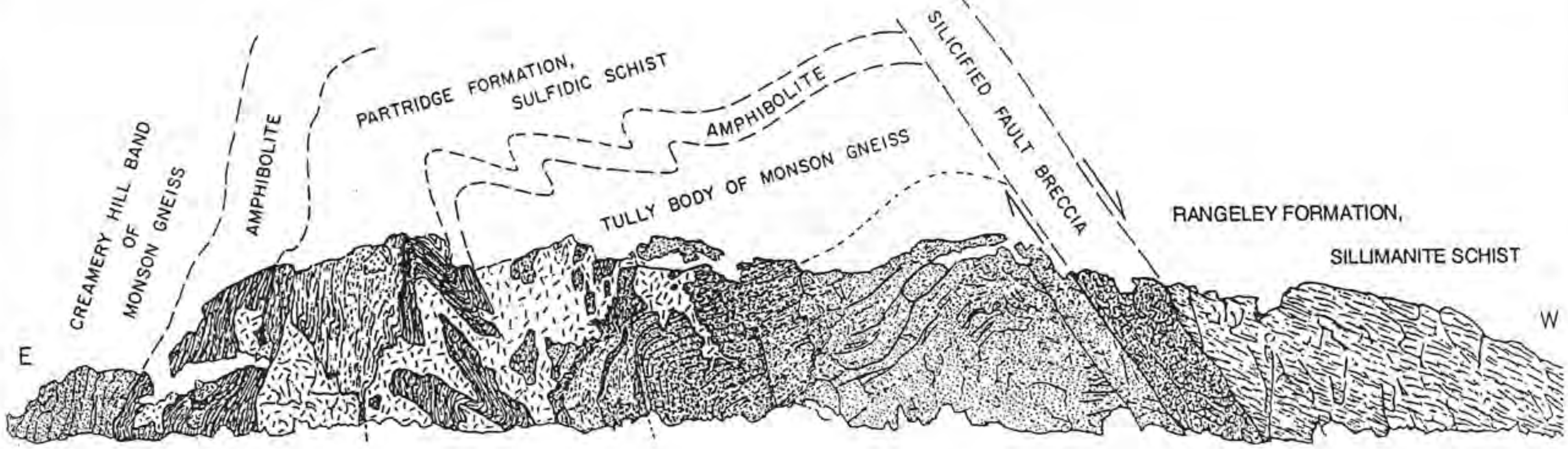
40.1 Interchange; Route 202 enters from south. Continue on Route 2.

41.7 Bushy cut on right, east part of main body Monson Gneiss.

42.5 Large, long trench cut, both sides. If traffic permits, and you intend to proceed west after this stop, **bear left across highway to broad and firm grass strip, north side.** Much safer and better for viewing than the narrow area on south side. Since Figure 18 was drafted (Robinson, 1979) south side of Athol cut has been blasted back about ten feet which has changed some details, but not altered essential features.

STOP 5. SOUTH END OF TULLY BODY OF MONSON GNEISS, BRENNAN HILL THRUST, AND NORTH ORANGE FOLD NAPPE, CUT BY MESOZOIC NORMAL FAULT (30 minutes) See Figures 17 and 18; for detailed description see Robinson and Elbert (1992) STOP 7. The south end of the Tully body exposed here is a simple anticline, probably of Quabogian age, overturned to the east and plunging gently south-southwest. Dome-stage asymmetric folds occur on both limbs. It is cut just west of its crest by the west-dipping Athol normal fault, bringing gray schists of the Rangeley Formation on the west limb down about 1300 feet into contact with Monson Gneiss of the core. The fault zone is about ten feet wide and contains gouge zones, hematite-stained and cemented breccia, intense silicification, and vuggy quartz veins, all features characteristic of known Mesozoic faults. Here the fault strikes N4W, but regionally it strikes N15E.

A thin layer of rusty Partridge schist on the east limb of the anticline, has been traced for many miles. Bedded amphibolites at both contacts probably belong to the Partridge, although it is tempting to consider that they might represent the Ammonoosuc Volcanics. Next east of the schist and amphibolite is a layer of Monson Gneiss (Creamery Hill band) that has been traced entirely around the southern part of the Tully body (see Figure 18 inset) and is interpreted as an Acadian anticlinal fold nappe of gneiss that formed contemporaneously with the Bernardston nappe. A similar band of Monson Gneiss (North Orange band) east of the main body of Monson Gneiss is interpreted as the same recumbent anticline repeated by folding about the same syncline that separates the two bodies. The North Orange band has been traced from North Orange to the northern edge of the Palmer quadrangle in southern Massachusetts (see STOP 8C, this field trip). Three anticlinal hinges for this early fold, now named the North Orange nappe, can be seen in Figure 18 inset. It has been severely involuted, both by Quaboagian dome-stage folding and by the complex probably Quagoagian backfolding that included northward transport of the main and Tully bodies (see Robinson et al., 1991, Figure 9). By unwinding these deformations one can conclude that the original transport direction for this nappe was east to west. Elsewhere it can be shown that the North Orange nappe lies above the Brennan Hill thrust, hence the thrust must also lie in this outcrop, probably close to the contact between the Partridge and the gneiss in the core of the Tully body.



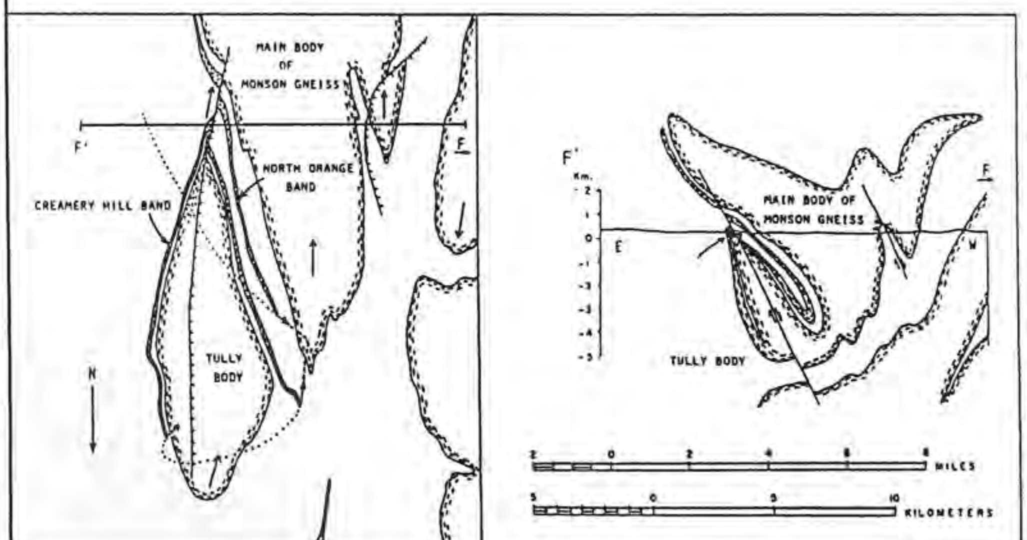


Figure 18. Sketch of south wall of rock cut at Stop 5. Mesozoic Athol fault cutting the Quaboagian anticlinal crest of Tully body of Monson Gneiss. Approximate location of the cut is shown by nearly invisible stippled rectangle indicated by arrow in inset cross section. The major anticlinal or dome axis and satellitic folds of probable Quaboagian age are parallel to a strong Beta maximum (10% per 1% area) with trend N22E and plunge 18°SW (Robinson, 1963). The Creamery Hill band of Monson Gneiss is interpreted (see insets) as an extremely attenuated Acadian basement nappe, the North Orange nappe, separated from the main and Tully bodies by an extremely attenuated isoclinal Acadian syncline and by the Acadian Brennan Hill thrust. The North Orange nappe is interpreted as a fold of the same generation as the Bernardston Nappe but lying tectonically higher and more easterly (Robinson et al., 1991, Fig. 30). Drawing does not have constant scale. Outcrop is approximately 50 feet (15 meters) at highest point.

Outcrops of Rangeley schist east and west of the dome consist of quartz, biotite, muscovite, garnet, and minor sillimanite and graphite, an assemblage characteristic of the zone above the breakdown of staurolite, but below the first occurrence of sillimanite+orthoclase. Abundant pegmatite segregations that may be a product of partial melting, consist of about equal proportions of quartz and sodic oligoclase with minor muscovite, biotite, and garnet. A pegmatite dike occurs on the eastern contact of the gneiss of the Tully body. It appears to have been generated by partial melting in gneiss of the Tully body, injected through the contact amphibolite (note discordant contacts) into the overlying Partridge, and folded in a series of large normal asymmetric folds.

Return west on Route 2.
45.3 Take Exit 16 for U. S Route 202 South and stay on it to STOP 6.
49.5 Small cut, Monson Gneiss, right.
49.8 Moosehorn Road, right. Stay on 202. Half mile up road on Fisk Hill is belt of calcareous quartzite and quartz-pebble conglomerate on Monson - Ammonoosuc contact. Before recent U-Pb ages, this locality and two others were taken as evidence of an unconformity between Monson and Ammonoosuc.
50.7 Pavement outcrops, both sides. Gedrite-plagioclase gneiss of Mafic Lower Member of Ammonoosuc.
53.4 Low cut on right at pass. Cooleyville Granitic Gneiss of the Prescott Complex with small gabbro xenoliths (Makower, 1964).
55.4 West Branch, Swift River. Valley of west arm of Quabbin Reservoir eroded in gneiss of Kempfield anticline and Fourmile Gneiss, east limb of Pelham dome, separated by the thin southern part of the Wendell syncline.
56.8 Low outcrops, left, Partridge in extremely thin Pelham-Shutesbury syncline.
57.2 Cuts, Fourmile Gneiss between Pelham-Shutesbury syncline and Mount Mineral Formation.
57.7 Descend long straight incline and pull off into paved ditch on right just before steep gravel driveway. LEAVE FLASHERS ON. Walk up driveway about 30 feet, turn sharp left (west) on old road and descend to Atherton Brook. Cross brook on stepping stones and walk about 200 yards northwest to small outcrops about 100 feet southwest of stream bank (Ashwal Loc. 160).

STOP 6. SCHIST OF MOUNT MINERAL FORMATION WITH RELICT QUABOAGIAN GRANULITE FACIES MINERALS OVERPRINTED BY NORTHFIELDIAN KYANITE-MUSCOVITE ASSEMBLAGE (30 minutes) See Figures 19 and 20. Detailed description of these outcrops is given in Robinson et al. (1992). They were first discovered by Lew Ashwal during Advanced Mapping Class in fall 1972. The western outcrop consists of coarse mylonitic sillimanite-orthoclase-garnet-biotite schist with a north-plunging Northfieldian dome-stage anticlinal fold superimposed on an older west-over-east shear fabric. Locally there are sillimanite lineations parallel to the fold and to the earlier fabric. The garnet with extreme resorption zoning described by Roll (1987; Robinson, 1991) and orthoclase of high structure state came from this outcrop. The relict Quaboagian assemblage includes sillimanite, orthoclase, biotite, garnet (pyrope 35, spessartine 1.1) and rutile, indicative of about 700°C and 6.8 kbar. Garnet rims fall off to pyrope 10-11. They are commonly in a matrix of muscovite, biotite, and kyanite indicative of more hydrous Northfieldian re-equilibration conditions at about 580°C and 6 kbar. Orthoclase is commonly rimmed by a fine-grained of muscovite and sodic plagioclase against the aluminous matrix. The schists at this outcrop successfully resisted Northfieldian recrystallization due to scarcity of water, and they contain an older, probably Quaboagian E-W linear fabric involving oriented sillimanite, highly elongate quartz ribbons, and tails around orthoclase and garnet, and evidence that orthoclase was undergoing strong grain-size reduction with limited recrystallization. The granular top surface of the outcrop is sillmanite-orthoclase-garnet-rutile mylonite with subordinate biotite, in which quartz, plagioclase and orthoclase all underwent severe grain-size reduction with minimal recovery. These features are evidence of an earlier higher temperature phase of shearing with top-side-east, probably soon after the peak of Quaboagian granulite-facies metamorphism. A U-Pb age of 367 ±2 Ma was obtained from metamorphic monazite in this rock. The eastern outcrop consists of mica schist containing kyanite, staurolite, muscovite, biotite, and euhedral garnets, that is believed to be chemically equivalent to the western outcrop but has undergone hydration and complete chemical reconstitution during Northfieldian metamorphism and deformation. The garnets have the characteristics of ones that have undergone prograde growth zoning. In this outcrop there is strong evidence of north-over-south shearing parallel to a subhorizontal Northfieldian mineral lineation.

Continue south, Route 202.
58.1 Cut on right. Early Jurassic Pelham Fe-rich tholeiite dike 15 m thick in schist, Mount Mineral Formation.
58.3 Cuts on right. Amphibolites, Mount Mineral Formation. (Robinson et al., 1992).
59.8 Cut on right, turn out, left. View of Quabbin Reservoir and Mt. Wachusett (2006').

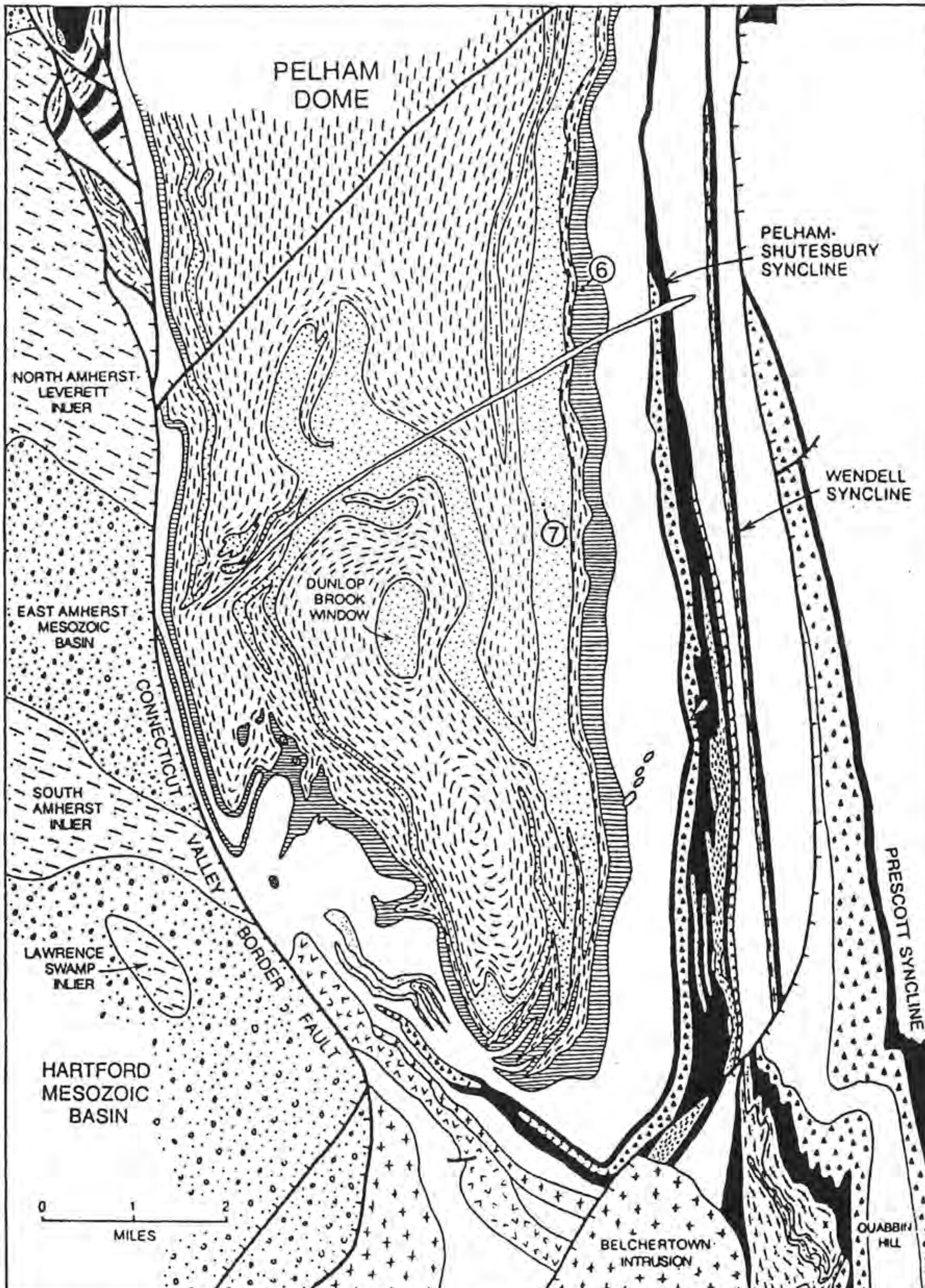


Figure 19. Generalized geologic map of the southern part of the Pelham dome from Robinson et al. (1992) showing locations of Stops 6 and 7. For key to patterns see Figure 11.

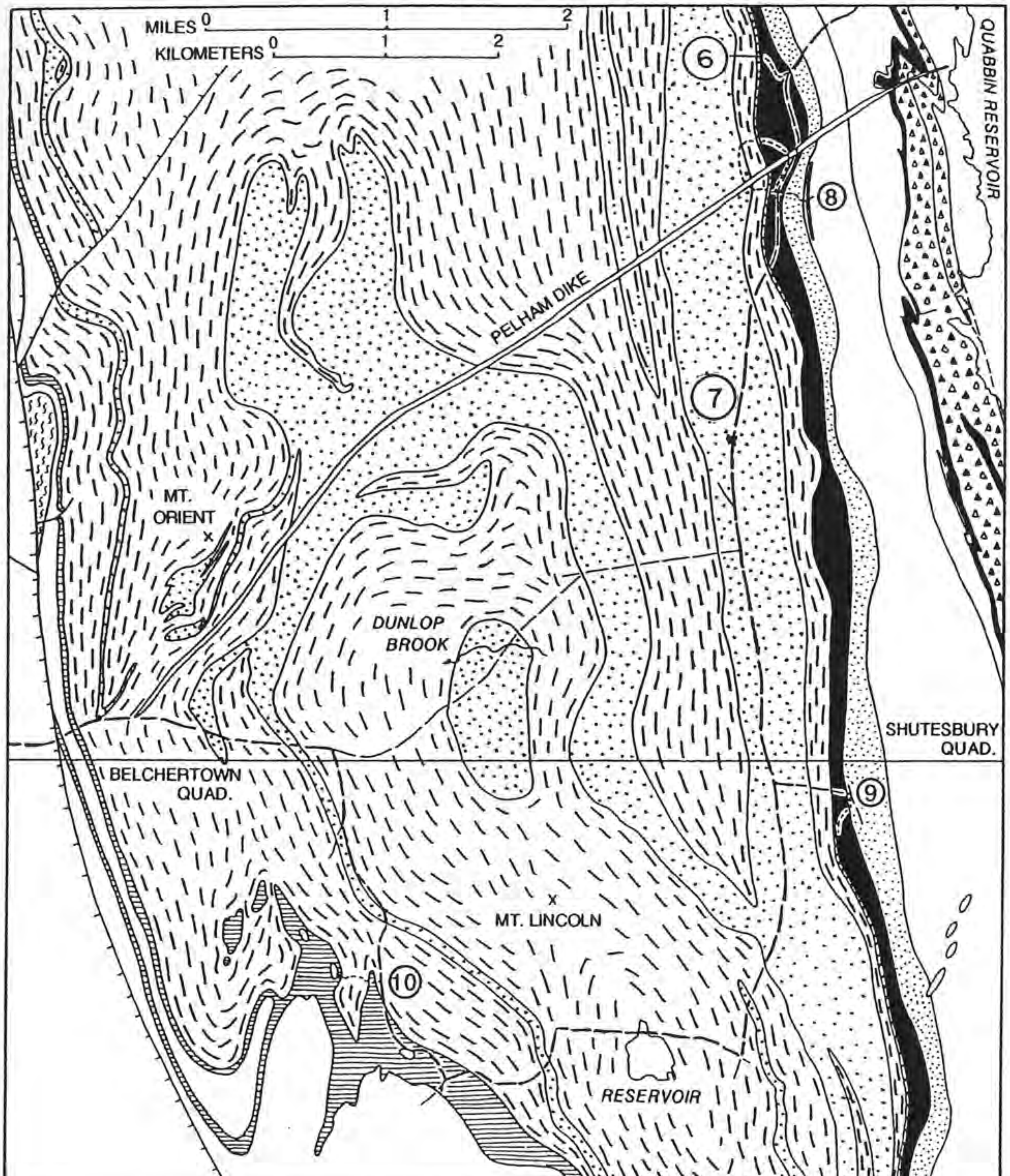


Figure 20. Detailed map of the south-central part of the Pelham dome showing locations of Stops 6 and 7. Also shows details of internal stratigraphy of Mount Mineral Formations and locations of Stops 8, 9, and 10 of Robinson et al., 1992. For key to patterns see Figure 11.

STOP 7. PELHAM QUARTZITE ON EAST LIMB OF PELHAM DOME (10 minutes) See Figures 19 and 20. This rock and enclosed zircons obtained are discussed in detail in Robinson et al. (1992). The Pelham Quartzite commonly contains actinolite indicative of a former dolomite cement. Eighteen detrital zircons from this outcrop, and another twelve detrital zircons from a quartzite at Dunlop Brook, were analyzed as individual crystals. In brief, those from this outcrop are less than 6% discordant, hence indicate reliable source ages. Combined with somewhat more discordant results from Dunlop Brook, the detrital grains fall into the same age groups found in the Dry Hill Gneiss at STOP 2, the oldest between 2616 and 2679 Ma.. The youngest detrital grain has a $^{207}Pb/^{206}Pb$ age of 933 Ma, establishing a *maximum* depositional age of the quartzite. Late Proterozoic, ca. 700-600 Ma, detritus is apparently lacking in the Pelham, Dunlop Brook, and Poplar Mountain Quartzites, implying the Dry Hill Gneiss was not a major source of detritus nor were any other rocks of Late Proterozoic (Avalonian) affinity. Good agreement between age groups defined by the detrital-grain and composite-grain studies suggests that the source of inheritance in the Dry Hill (See Figure 12) was detritus at the site of eruption, with sources in Early and Middle Proterozoic rocks. Commonly actinolite and quartz show a N-S trending Northfieldian lineation.

60.5 Continue Route 202 past yellow light at Amherst Road.
60.8 Cut, right, Pelham Quartzite.
63.0 Cut, left, Dry Hill Gneiss beneath Pelham Quartzite.
64.9 Small cut, right, beginning descent to Belchertown, Dry Hill Gneiss dip slope, south end of dome, Pennsylvanian sphene age.
67.9 Lights, Junction U. S. Route 202 and Mass. Route 9. Turn left (east) on Route 9.
71.0 Turn left (northeast) and enter Quabbin Reservation.
71.6 Headquarters and Visitor Center, Quabbin Reservoir with view of west arm. Toilet facilities are available here. **NOTE:** Since the road log was prepared in 1993 all vehicular traffic has been stopped on Winsor Dam. To continue the road log return to Route 9, cross the Swift River below the dam, turn left at next entrance to Quabbin Reservation, and proceed west to road junction at east end of spillway where road log is resumed at 72.1.
72.1 Junction at east end of spillway bridge. Turn right (north) toward Quabbin Hill. Spillway is underlain by deformed Spillway stock of Belchertown Complex intruding Lower Devonian Erving Formation (Guthrie, 1972). Based on regional considerations, the folds and lineation are probably Northfieldian.
72.7 Cuts, right, folded refolded felsic apophyses of Belchertown intrusion in Erving Granulite (Halpin, 1965).
73.5 Direct through rotary.
73.9 Enfield Overlook, left. View over Prescott Peninsula to Mount Monadnock, New Hampshire.
75.1 Outcrop near gate, left, Partridge Formation sillimanite-muscovite schist containing metamorphic monazite yielding a Quaboagian U-Pb age of 359 Ma. (Robinson et al., 1992). This lies east of the Kempfield anticline and the "great swirl" of lineation.
76.0 Turn left (east) toward Goodnough Dike.
76.2 Bear left at fork.
76.5 Turn around at rotary and park, at west end of Goodnough Dike. Here there is a view of the east arm of Quabbin Reservoir, underlain by the main body of Monson Gneiss. There is a small exposure here in lieu of STOP 8 if high water.
77.0 Turn left (south) on Reservation Road toward Ware.
78.0 Reservation Road and Route 9. Turn left (east) on Route 9.
79.6 Large cut on left, Brimstone Hill. Cross carefully to outcrop and stay in paved drain away from dangerous traffic. STOPS 8A, 8B and 8C are provided for general information and for the common possibility that permission cannot be obtained to enter through locked gates into a restricted part of Quabbin Reservation.

STOP 8A: PARTRIDGE FORMATION SCHIST AND AMPHIBOLITE AT BRIMSTONE HILL (20 minutes) (Robinson et al., 1982c). See Figures 21, 22, 23. Partridge sulfidic sillimanite-orthoclase schist, amphibolite, and felsic gneiss, Greenwich stratigraphic syncline. The syncline is probably a late Quaboagian anticline bringing younger cover from beneath the structurally higher Monson Gneiss. Monazite from the felsic gneiss has yielded a Quaboagian 350±3 Ma. U-Pb zircon age. The following information is from the 1986 IMA Guidebook based on research results of R. J. Tracy (1975, 1978, and Tracy et al., 1976) and Kurt Hollocher (1985, 1991).

This outcrop lies in the Greenwich syncline, an infold of Ordovician cover rocks that is surrounded by the main body of Monson Gneiss. The northern part of the syncline has a less than 20m-thick section of Ammonoosuc Volcanics with three mappable members resting directly on the Monson Gneiss, and the rest of the Greenwich

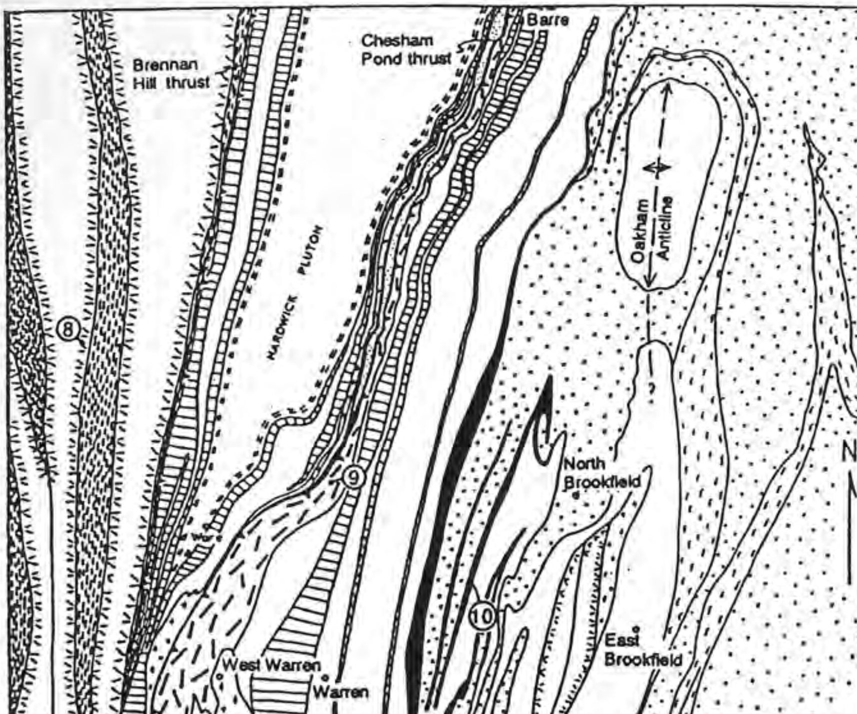


Figure 21. Generalized geologic map of part of south-central Massachusetts showing the locations of Stops 8-15 (modified from Robinson et al., 1989). This shows the proposed southward extensions of the Brennan Hill and Chesham Pond thrusts, reinterpretations of the Brimfield-Sturbridge area (Berry, 1989), and the Conant Brook shear zone (Peterson and Robinson, 1993). Dashed line south of Monson and Sturbridge is the gas pipeline trench (see Stop 12). Key to patterns: Pre-Silurian Monson Gneiss and Leadmine Pond Gneiss (southeast) - bordered by ticks; Ordovician Ammonoosuc Volcanics and Partridge Formation - fine heavy dashes; Lower Silurian Rangeley Formation sulfidic schist - unpatterned; Rangeley gray schist - horizontal ruling; Middle Silurian sulfidic calc-silicate of Francestown Formation (west of Coys Hill), Middle Silurian extremely sulfidic schist of Smalls Falls Formation, Lower Silurian extremely sulfidic schist of Rangeley Formation - black; Upper Silurian Madrid Formation - fine dots; eastern facies Silurian Paxton Formation - coarse dots; eastern facies gray schist - curvy dashes; eastern facies sulfidic schist - fine light dashes; Coys Hill Granite pluton - large dashes; Hardwick Tonalite - double dash border; tonalites, diorites and gabbros - crosses.

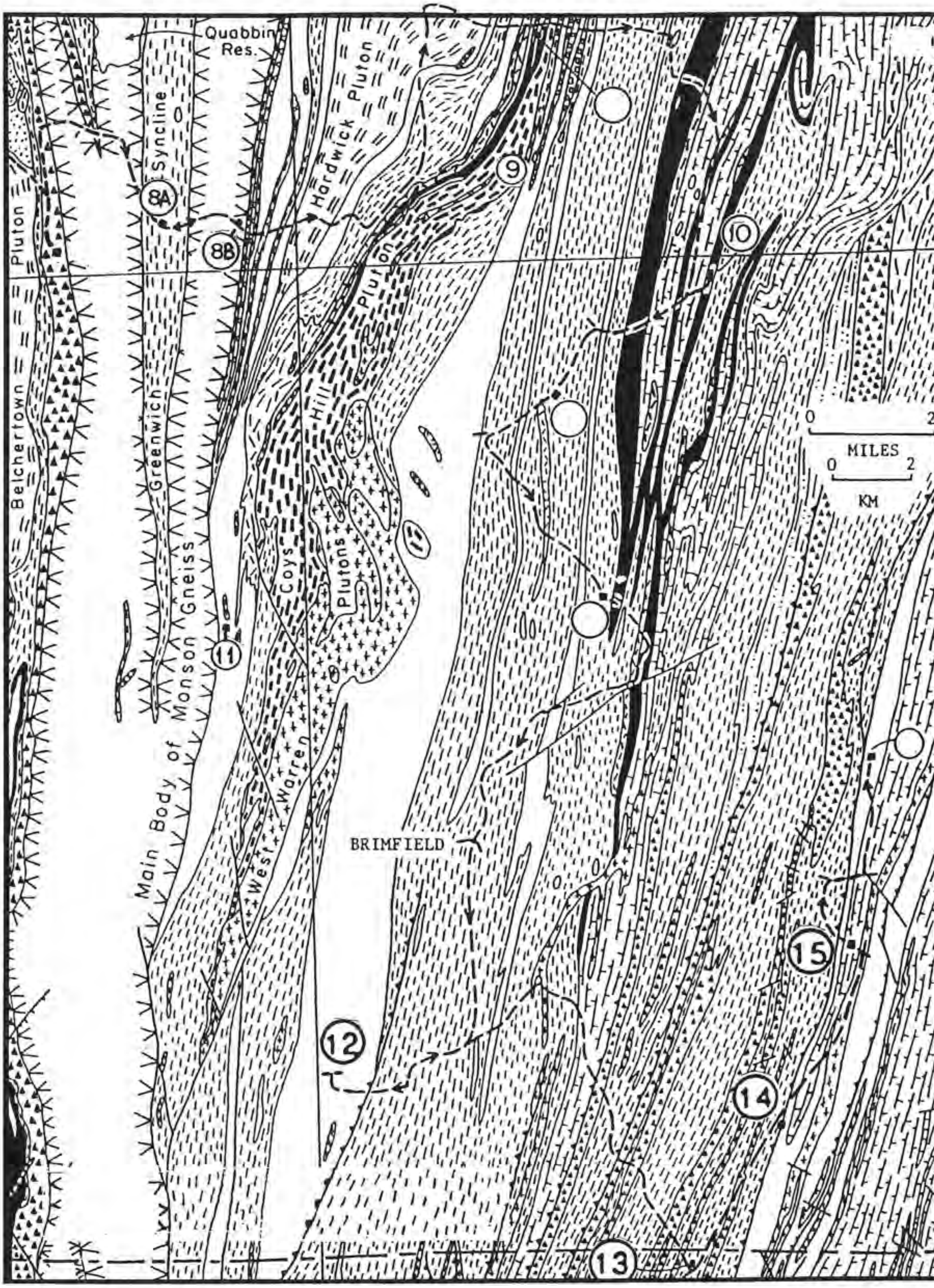


Figure 22. Bedrock geologic map of south-central Massachusetts showing locations of Stops 8A, 8B, 9, to 15. Map patterns are based on Zen et al. 1983 and do not reflect map revisions made by Berry 1989 for which see Figure 21.

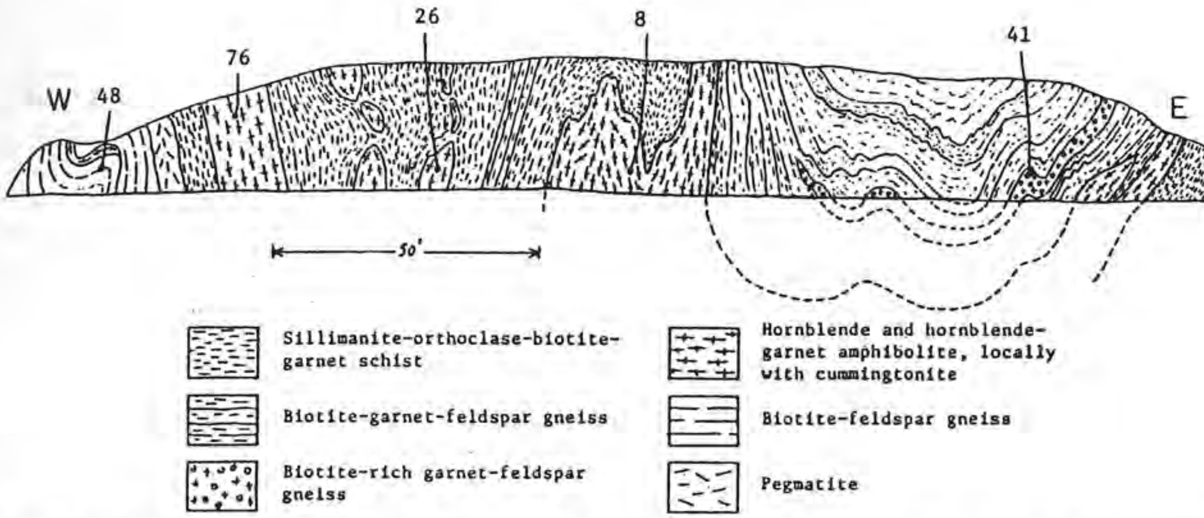


Figure 23. Schematic sketch of the outcrop at Stop 8A, Brimstone Hill. Lithologic units and sample locations are shown (after Robinson et al. 1982c). Modes and bulk chemical analyses of samples 8, 26, 41, and 48. a mode of sample 76, and electron probe analyses of minerals in sample 76 are given in Hollocher 1985 (from 1986 IMA Guidebook).

syncline is occupied by the Partridge Formation. In the Greenwich syncline it is largely composed of rusty-weathering schists and amphibolite, with lesser quantities of felsic and intermediate volcanics, calc-silicate rocks, and fine-grained garnet quartzite (coticule). Most of these rock types are exposed at STOP 8A as well as several types of pegmatites.

Proceed to east end of road cut beyond the edge of Figure 23 where the best mica schist is exposed. The assemblage here, typical of Zone V, is quartz-orthoclase-garnet-biotite-sillimanite-graphite-ilmenite- pyrrhotite (sample 507B, Tracy et al., 1976; Tracy 1978). The rock has a mylonitic aspect and most of the orthoclase is concentrated in water-clear megacrysts with crushed borders set in a fine-grained matrix crammed with fine-grained prismatic sillimanite. The garnet has only a modest amount of retrograde zoning with compositions of core and rim ( ) as follows: Almandine 76.5 (78.1), Pyrope 16.2 (14.5), Spessartine 3.7 (3.8), Grossular 3.6 (3.7). Biotite has Xmg of o.460 and 0.211 Ti per 11 oxygens. The orthoclase has the composition: Or 85.7, Ab 13.5, An 0, Cn 0.8, whereas the plagioclase is An 27.9, Ab 70.5, Or 1.6. The orthoclase lattice parameters indicate an intermediate orthoclase structural state. The ilmenite is about 96% $FeTiO3$, 3% $Fe2O3$, and 1% $MnTiO3$. The rock is extremely rich in biotite and poor in garnet, and yields an estimated prograde garnet-biotite temperature of 660°C and a retrograde temperature of 620°C. (For details see Robinson et al., 1982c).

Several of the amphibolite bodies at STOP 8A are associated with coarse-grained tonalitic veins and pods, bearing the commonly coarse mafic minerals cummingtonite, biotite, hornblende ± garnet. These segregations are considered to be crystallized partial melts derived from the amphibolite. Samples 8 and 26 are both cummingtonite and quartz-bearing hornblende amphibolites (modes and analyses in Hollocher, 1985). Sample 8 has no leucocratic veins or pods, and has apparently not undergone partial melting. Sample 26 has an assemblage similar to sample 8, but is more Si-rich, has a lower ratio $Mg/(Mg+Fe^{2+})$ and more sodic plagioclase and contains cummingtonite and garnet-bearing melt veins. Sample 76, from a rock almost identical to sample 26, includes part of a melt segregation. Electron probe analyses of this sample are given by Hollocher (1985, 1991). Melting probably took place because of H_2O provided by the dehydration reaction:

$$35 \text{ Cum} + 5 \text{ Bio} + 67 \text{ Plag (An83)} + 2 \text{ Ilm} = 31 \text{ Hbl} + 42 \text{ Gar} + 99 \text{ Qz} + 10 \text{ H}_2\text{O}$$

which reduces to the melting reaction:

$$\text{Cum} + \text{Bio} + \text{Plag} + \text{Ilm} = \text{Hbl} + \text{Gar} + \text{Liquid}$$

The melt zones in the mafic rocks at this outcrop are very inhomogeneous, making it difficult to determine their mode or chemical composition. It is unclear what quantity of the mafic minerals were actually dissolved in the liquid, and what quantity grew to large size because the liquid inhibited nucleation and enhanced diffusion.

Sample 41 is from an unusual garnet- and orthoclase-bearing biotite gneiss of intermediate composition that contains monazite as its principal radioactive mineral. Monazite was not found elsewhere in the Partridge Volcanics. Sample 48 is a garnet-bearing felsic gneiss, probably metamorphosed dacite from the extreme west end of the outcrop. This gneiss is associated with abundant garnet-bearing pegmatite (See Hollocher, 1985, for modes and bulk chemical analyses.

Cross carefully back across Route 9 to vehicles and continue east on Route 9.
80.3 Sharp left (north) on Fisherdick Road.
82.9 Junction, Greenwich Plain Road. Move near gate and transfer to vans for one-mile drive to stopping point for Richards Ledges. Vans will be taken through locked Gate 49 by special arrangement with Quabbin Reservoir Management. Ledges can be reached on foot in 30 minutes of walking in area of public access. Follow main gravel road straight until shore of Reservoir can be seen. Ledges are reached by walking south about 5 minutes.

STOP 8: MONSON GNEISS AT RICHARDS LEDGES (40 minutes) See Figure 21. Characteristics of Monson Gneiss near Quabbin Reservoir are discussed in greater detail by Robinson et al. (1989), STOP 1, and a detailed discussion of petrology and geochemistry of the Monson Gneiss is given by Hollocher et al., 2002. The outcrops in this area are from Quaboagian metamorphic Zone V, within the main body of Monson Gneiss on the west limb of the Quaboagian Greenwich syncline, the center of which was shown at STOP 8A. They are composed of gray tonalitic gneisses, amphibolite, hornblendite, and gabbroic anorthosite. Recent precise radiometric dating of a variety of these rocks by R.D. Tucker has shown an age range from 454 to 443 m.y. (+3/-2 on six best samples, +9/-3 and +11/-8 on two others). First impressions at these outcrops can lead observers to wildly divergent opinions about the origin of the rocks. At one extreme the well layered character of some outcrops suggests the Monson might be predominantly a layered volcanic sequence, possibly even conformable with the overlying Ammonoosuc Volcanics (Naylor, "stratified core gneiss", 1969). At the extreme, many of the rocks are coarse-grained, massive, and contain abundant and varied inclusions suggesting an intrusive igneous origin. Except for rare diopside calc-silicate and quartzite layers, the Monson consists of rocks of broadly igneous composition (Robinson, 1963, 1967; Hollocher, 1987, 1988) as follows:

A) Coarse to fine felsic gneisses, generally massive and intrusive-looking, including dark-gray biotite-hornblende-andesine tonalite, medium-gray biotite-oligoclase tonalite, light-gray biotite-garnet-oligoclase tonalite, light-gray to pink microcline-hornblende augen gneiss, and rare white microcline-albite-quartz-biotite-garnet alaskite.

B) Mafic and ultramafic rocks as large and small blocks, commonly included in or interlayered with the more felsic types. Ultramafic rocks include serpentine and talc-bearing lenses, olivine hornblendite, augite hornblendite, and hornblendite (Tracy et al., 1984). Small patches of hornblendite may be residues of partial melting. Mafic rocks include coarse amphibolites that look like massive gabbros, some with relict ophitic texture; fine amphibolites commonly containing patches that are probably recrystallized plagioclase or mafic phenocrysts and commonly cutting metamorphic foliation and layering indicating they are dikes (one such dike in the Keene Gneiss dome is dated at 381+3/-2 by Tucker and Robinson, 1990; both date and rock resemble the Belchertown intrusion); anorthosite and gabbroic anorthosite gneiss (best examples are bluish-gray glacial boulders with attached Monson Gneiss); composite mafic and intermediate blocks with gabbro, amphibolite, hornblendite, and biotite gneiss; rare hornblende-gedrite-garnet-plagioclase-biotite rock; and stratified amphibolite that looks most like metamorphosed layered mafic tuffs.

C) Felsic rocks in small intrusions probably or possibly synchronous with Acadian or Quaboagian metamorphism such as coarse white biotite-tonalite pegmatite; medium-grained white to pink biotite-garnet tonalite gneiss ("spaghetti rock") similar to migmatitic layers in adjacent cover rocks; medium-grained, white to pink biotite-hornblende tonalite gneiss ("hornblende spaghetti rock"); and fine medium-gray biotite-epidote tonalite. The ultimate source of these melts is the Monson Gneiss itself (Hollocher, 1988). A coarse pegmatite cutting folded rock in Monson Gneiss at Parker Island, Quabbin Reservoir, which itself is cut by mylonites which are folded, gives an early Quaboagian U-Pb age zircon age of 366±1 Ma. This implies that the mylonites and the later folds are later Quaboagian. The earlier fold set that this pegmatite cuts may thus be Acadian. By structural analogy with a nearby Partridge Formation outcrop, this earlier fold set also deforms partial melt segregations (Tracy, 1975, 1978) that may thus also be Acadian.

Field, petrologic, and geochemical studies by Hollocher show the Monson to be a complex of metamorphosed intrusive rock types with only a minuscule supracrustal component. If it is part of a plutonic complex, then the well layered character of many outcrops must be attributed to deformation, either in the Quaboagian or Acadian or earlier. The rocks are petrologically and geochemically distinct from metamorphosed volcanics in the physically overlying Ammonoosuc Volcanics and Partridge Formation, but they closely resemble rocks in other orogens described as in the roots of a calc-alkaline island arc (Barker and Arth, 1984; Hamilton 1988).

Road log resumes at junction outside the gate..

83.7 Bear right, Poor Farm Road.

85.1 Junction, Mass. Route 9, Ware Center. Turn left (east) on Route 9.

85.5 Cut on left. Turn sharp right onto small section of old Route 9 that lies south of the present road. Walk carefully across to outcrop and stay within paved drainage ditch away from traffic.

STOP 8B. Amphibolite in Monson Gneiss (10 minutes) See Figures 22, 24, and detailed description and tables by Hollocher in the IMA Guidebook (Robinson et al., 1986); Acadian Sm-Nd mineral age (Gromet and Robinson, 1990); quartz-plagioclase--orthopyroxene pegmatite with Quaboagian U-Pb age igneous zircon.

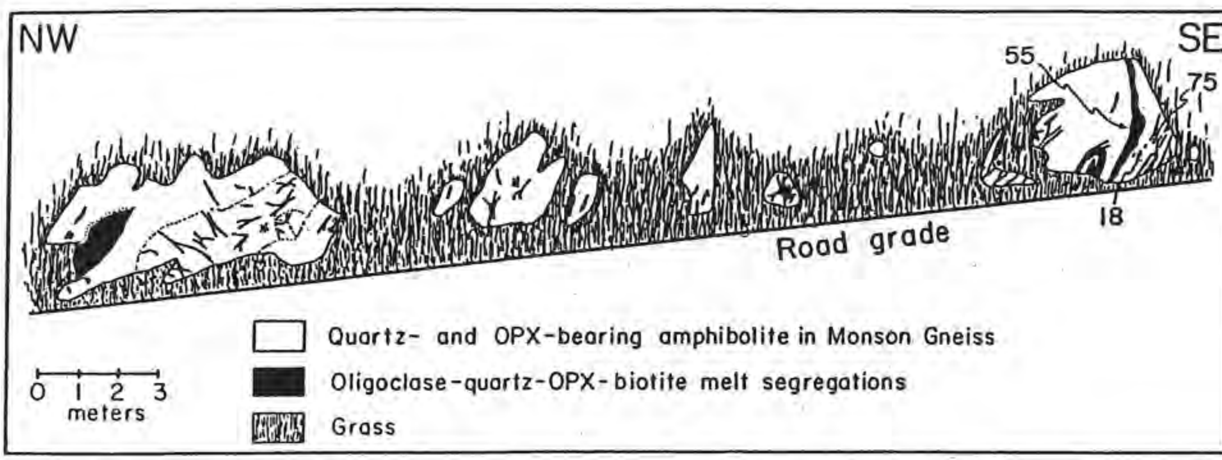


Figure 24. Amphibolite outcrops at Stop 8B in Monson Gneiss. This quartz-bearing amphibolite has orthopyroxene, which was formed by completion of the prograde reaction:

Cum + An = Opx + Hbl + Ab Qz + H_2O

The H_2O released initiated small degrees of partial melting. The partial melts are tonalitic and occur as small dikes and anastomosing veins. Plagioclase crystals up to 4 cm across and orthopyroxene crystals up to 2.5 cm across rimmed by retrograde cummingtonite, can be found. Modes for samples 18, 55 and 75, bulk chemical analyses of samples 55 and 75, and electron-probe analyses of minerals in sample 75 are in tables in Hollocher 1985 (from 1986 IMA Guidebook).

This outcrop occurs entirely within a large elongate amphibolite body that extends for several kilometers along the east side of the main body of Monson Gneiss. The amphibolite lies entirely within Monson Gneiss, and probably represents metamorphosed shallow intrusive gabbro. The principal rock type is a dark gray amphibolite composed largely of hornblende and plagioclase with minor quantities of quartz and orthopyroxene. The orthopyroxene is partly retrograded to polysynthetically twinned cummingtonite. The orthopyroxene was produced by the completion of the cummingtonite dehydration reaction:

12 Cum + 1 Anorthite = 2 Hbl + 36 Opx + 11 Qz + 10 H_2O.

This amphibolite has undergone small degrees of partial melting to produce anastomosing veins and small dikes of orthopyroxene- and biotite-bearing tonalitic rock (sample locations in Figure 24). Modes and bulk analyses of 55 and host amphibolite 18 are given by Hollocher (1985). The H_2O necessary to initiate melting was probably produced during cummingtonite breakdown, so the dehydration reaction given above reduces to the melting reaction:

$$Cum + Plag = Hbl + Opx + Liquid$$

The veins and dikes have coarse plagioclase crystals that are gray because of ilmenite exsolution rods. The plagioclase crystals are white in places where they have been recrystallized. All orthopyroxene crystals in the tonalite veins and dikes in this outcrop have thick cummingtonite rims that are the result of the retrograde hydration reaction:

$$Opx + Qz + H_2O = Cum$$

Continue east on Route 9.

85.6 Cut on left (north), easternmost outcrops of Monson Gneiss in contact with Partridge Formation. East end of this series of outcrops is mylonitized gray Rangeley pelite in Conant Brook shear zone (Peterson, 1992a, b; Peterson and Robinson, 1993). Park across road on south side and cross carefully to north.

STOP 8C. Typical tonalitic gneiss of Monson with rare amphibolite layers (10 minutes). Foliation dips steeply west as is typical all along the east edge of the main body of Monson Gneiss. Eastward from this outcrop there are exposures of Partridge schist and amphibolite, then an excellent but very narrow exposure of very strongly layered Monson Gneiss that constitutes the North Orange Nappe as already described at STOP 5, then more rusty schist, then gray Rangeley schist, which would be both east of and above the Acadian Brennan Hill thrust and also inside the Quabogian Conant Brook shear zone. (Details in Robinson et al., 1982a).

Continue east on Route 9.

86.9 Junction with Route 32, center of Ware. Stay east on Route 9.

While passing through Ware, once anointed by Saturday Evening Post as "The town that can't be licked", it is worthwhile to go back about 170 years to the time when the adjacent town was Quabbin or Enfield, later flooded by the Reservoir. In those days (as described in an early Town History of Quabbin) all citizens were expected to put in so many days per year working on the public roads, or hire someone else to fill in. Thus, every summer there were groups of citizens, hired or otherwise, working the roads for many days. It once happened that the road crew from Quabbin and the crew from Ware met at the mutual town line about lunch time on a hot day and passed a sultry and possibly extended lunch hour telling stories and reciting poems. During this, a gifted Quabbin citizen came forth with the following poem to put the Ware citizens in their proper place:

Dame Nature once in makin' land,
Had left over stones and sand,

She picked it up and laid it down,
Between Coys Hill and Belchertown,

She said "Yeow paltry stuff lie there!"
And made a town and called it Ware.

In reprisal, the Ware group alleged that "Quabbin was so poor a rabbit c'n't make a livin' off a half an acre of it." and " 'T'wa'n't good for nuthin' 'cept growin' skunk cabbidges". Thus the groups parted company and went about their business on the roads. One can speculate if these last remarks were repeated in the Massachusetts Legislature in the 1920's when it was voted to abolish the Town of Enfield in favor of the Quabbin Reservoir.

87.3 Bridge, Ware River.

88.5 Junction, Route 32 turns left. Stay right on 9.

89.4 Low outcrops on left, sulfidic calc-silicate, Francestown Formation, Monadnock sequence, N. H.

89.6 Turn across traffic to dirt pull out on left. Exit on traffic side and walk west on old route 9 past large exposures of Coys Hill granite, both sides. Right (north) on trail to picnic site and eastward overhanging outcrops of Coys Hill Granite.

STOP 9. COYS HILL PORPHYRITIC GRANITE (20 minutes) See Figures 21, 22. This stop is to examine briefly the Coys Hill Granite, a major lithic unit in the Merrimack synclinorium of Massachusetts, equivalent to the Kinsman Granite of New Hampshire. The Coys Hill forms a key marker across central Massachusetts (see blue unit on State Map). Immediately west of it is exposed a sequence of strata that correlates partially to the Monadnock sequence in southwestern New Hampshire (Thompson, 1985). The latter includes Lower Silurian Rangeley, Lower Silurian Perry Mountain, Middle Silurian Francestown , Upper Silurian Warner, and Lower Devonian Littleton Formations, of which the Rangeley, Francestown, and upper Warner are recognized in this part of Massachusetts. Based on contact relations in the Monadnock area, Peter J. Thompson (1985) has postulated a major Acadian thrust, the Chesham Pond thrust, carrying the Kinsman Granite westward over the already folded Monadnock sequence. By analogy, it is suggested that the west margin of the Coys Hill Granite is also an early west-directed thrust. Due to time constraints, only the Coys Hill will be examined. At this locality and in most of Massachusetts the Coys Hill is a coarse gneiss in which K-feldspar phenocrysts have tectonically rounded ends. Abundant garnets are probably Quaboagian metamorphic porphyroblasts, rather than the igneous garnet phenocrysts as in the center of the Cardigan pluton in New Hampshire. One might mistake the granite as a pegmatite formed during metamorphism, however, here and elsewhere, it is cut by later fine-grained tonalite dikes, and both granite and tonalite were deformed and metamorphosed together. A Sm-Nd garnet phenocryst age of 413 Ma in New Hampshire (Barreiro and Aleinikoff, 1985), a U-Pb zircon age of 403 Ma by R. D. Tucker on the Ashuelot pluton of the Kinsman Granite (Robinson et al., 1998), a U-Pb monazite age of 396 Ma by R. D. Tucker on the Coys Hill Granite in northern Massachusetts, the geochemistry (Clark and Lyons, 1986), the occurrence of gabbro xenoliths, and the consistent textural features regardless of metamorphic grade, show that the Coys Hill and Kinsman were major peraluminous intrusions produced by crustal melting induced by mantle-derived melts in the Acadian orogeny.

Continue east on Route 9.
92.7 Route 67 enters from right. Stay on Route 9.
93.7 Stoplight in center of West Brookfield.
93.8 Bear left on Route 67 at West Brookfield common .
94.6 White farm house (registered Holsteins, Talvy Farm) left. Turn into barnyard for disembarkation. Vans reverse direction to go west after stop. Walk north on farm road along southeast side of long outcrop.

STOP 10: SMALLS FALLS FORMATION, SULFIDE-RICH SCHIST (30 minutes) See Figure 21, 22; for more detailed description see Robinson et al. (1989). The outcrop has an irregular smoothed surface covered by a thick crust of iron oxides and sulfates. The surface contains many 3-5 cm pits inside which fresh-looking pyrite is typically visible. We have found only traces of megascopic pyrrhotite in the outcrop but still believe much of the outcrop's character is due to its weathering. Partly weathered rock just beneath the crust looks white because of the abundance of colorless silicates. Much fresher rock has a bluish look. The outcrop consists of two main rock types, sillimanite and biotite-bearing quartzites, and aluminous schists with variable proportions of sillimanite, biotite and cordierite. The biotites vary from very pale reddish-brown Fe-bearing ones to colorless Mg end-members. We first thought these were muscovites in a retrograded fault zone, but optics and probe analyses, show they are biotites. The assemblage in two analyzed samples from this outcrop (FW-882E and FW-882Y of Tracy and Robinson, 1988, originally collected by Mike Field) is quartz-orthoclase-plagioclase-biotite-cordierite-sillimanite-rutile-pyrite-pyrrhotite-graphite. The XMg of biotite in these samples is 0.995 and 0.999 (less than 0.05 weight % FeO) and they contain 0.065 and 0.074 Ti per 11 oxygens. The K-feldspar has a composition Or 91.5, Ab 8.4, An 0.1 and plagioclase is An 32.7, Ab 57.6, Or 0.8.

The cordierites, which are full of quartz, sulfide and graphite inclusions, appear as black to bluish lumps. They are essentially pure Mg end-members (very low to undetectable FeO and MnO) and lack pleochroic haloes around monazite inclusions, presumably due to lack of iron to be oxidized by alpha bombardment. These two cordierites contain between 1.0 and 1.5 weight percent H_2S (sulfur analyzed by probe and reported as H_2S) as also does one other cordierite from another locality reported by Tracy and Robinson (1988). These sulfur-bearing cordierites only occur with pyrrhotite + pyrite assemblages which buffer very high sulfur activities that in turn produce significant molar proportions of H_2S in ambient high-temperature fluids (up to 50 mol. percent or higher). Because of the extreme narrowness (to put it mildly) of the sillimanite-biotite-cordierite three-phase "field" on the AFM (Ksp) diagram, this rock essentially lies on the univariant reaction Mg-biotite + sillimanite + quartz = Mg-cordierite + K-feldspar + V and can be considered divariant only because of the Na content of the K-feldspar. Preservation of the evidence of highly unusual localized fluid compositions in unusual rock types, for example the H_2S-rich fluids characteristic of parts of this outcrop, can be taken as a persuasive argument that there was a very limited volume of metamorphic fluid at peak conditions and that its chemistry was locally, rather than externally, controlled. Unusually light sulfur isotopes in the sulfides from these rocks (Tracy and Rye, 1981) indicate high activity of sulfur-reducing bacteria during early Late Silurian sedimentation. These isotope ratios survived metamorphic temperatures in excess of 700°C.

From barnyard go west (right) on Route 67.
95.5 Rejoin Route 9, at West Brookfield common.
95.6 Stoplights, continue west, Routes 9 and 67.
96.6 Left (southwest) on Route 67.
98.0 Rusty cut on left (Robinson et al., 1989, STOP 6), biotite-garnet-cordierite-sillimanite-orthoclase-pyrrhotite schist. Zoned Type C garnet (Tracy et al., 1976) collected here. Estimated peak conditions 680-725°C and 6.1 kbar
98.3 General Henry Knox Monument, left. In winter 1775-1776 a group from the Continental Army passed this way dragging cannon captured by Ethan Allen and his "Green Mountain Boys" from the British at Fort Ticonderoga on Lake Champlain. The cannon were used by General George Washington during the siege of the British in Boston until they evacuated the city on March 17, 1776. The cannon were then hauled back to Fort Ticonderoga in time to be recaptured by the British in spring 1777, during the early stages of "Bœuf" Burgoyne's ultimately fatal southward drive from Canada, ending at the Battle of Saratoga. General Knox later became the first U.S. Secretary of War under President Washington.
99.1 Center of Warren.
101.4 Stoplight, West Warren.
101.8 Junction with Ware Road. Stay on 67.
103.0 Low crops, right, Coys Hill Granite.
103.2 Right on Old Warren Rd.
103.8 Large cut on right is southernmost exposure of Gneiss of Ragged Hill and east edge of Conant Brook shear zone (Peterson, 1992b, STOP 2).
104.4 Large outcrop, both sides. Park on right (north), beyond first large outcrop to disembark. Vans proceed about 0.2 miles to turnaround point, return on eastbound side for participant pick up after stop.

STOP 11: QUABOAGIAN BACK-FOLD AND DOME-STAGE SHEAR FABRICS, RANGELEY FORMATION, CONANT BROOK SHEAR ZONE (20 minutes) See Figures 21, 22 and 25. This outcrop (P100 of Peterson and Robinson, 1993) is described in detail in Peterson (1992a, b). It offers a 3-dimensional cross-strike exposure of graphitic and sulfidic schists within the Conant Brook shear zone. It preserves domains in which each of two Quaboagian lineations and related fabrics are dominant, an E-W trending, steep, backfold-stage lineation, and a later shallow N-S trending dome-stage lineation. Schist about 8-10 meters from the west end of the outcrop is dominated by the steep lineation and there is little or no evidence of the shallow lineation. Steep lineation is evident on foliation surfaces in the field and in thin section, defined by abundant coarse sillimanite, elongate quartz grains and the stretching direction of porphyroclast tails. On the front of the outcrop, parallel to this lineation, numerous kinematic indicators suggest a consistent west-side-up sense. Farther west foliation surfaces commonly show both lineations. At the west end of the outcrop, a strong shallow south-plunging mullion-like lineation is evident on the foliation surface, also defined by aligned sillimanite and stretched quartz. Sections cut perpendicular to each finite strain axis here show no evidence for the steep lineation. On top of the outcrop at the west end, numerous kinematic indicators show a dextral or west-side-north sense of shear. Observations in outcrop and thin section across the transition from steep to shallow lineations suggest the following : 1) Both share essentially the same anastomosing mylonitic foliation, but in detail, it is a composite foliation consisting of two sets of anastomosing folia each related to one lineation. 2) The style of shear deformation associated with each is indistinguishable, and there was no apparent difference in metamorphic conditions. 3) It is hard to determine relative age of the two fabrics, however the steep one generally appears older. The principal assemblage in the shear zone is quartz-sillimanite-orthoclase-plagioclase-biotite-garnet, and garnet-biotite thermometry suggests temperatures were as high as 750°C. Garnets are chemically homogeneous, except where retrograde ion exchange has occurred near adjacent biotites, suggesting the absence of late metamorphic fluid. A few less-deformed (younger?) pegmatites contain coarse muscovite, otherwise unstable in these schists, and around these the schists are heavily sericitized.

104.8 Go to vans facing east on south side of road.
106.1 Rejoin Route 67. Turn right (south).
108.4 Pass beneath Mass. Turnpike.
110.8 Junction with U. S. Route 20 East. Turn left.
111.3 Brimfield Town Line.
114.7 Right turn (southeast) on Hollow Road.

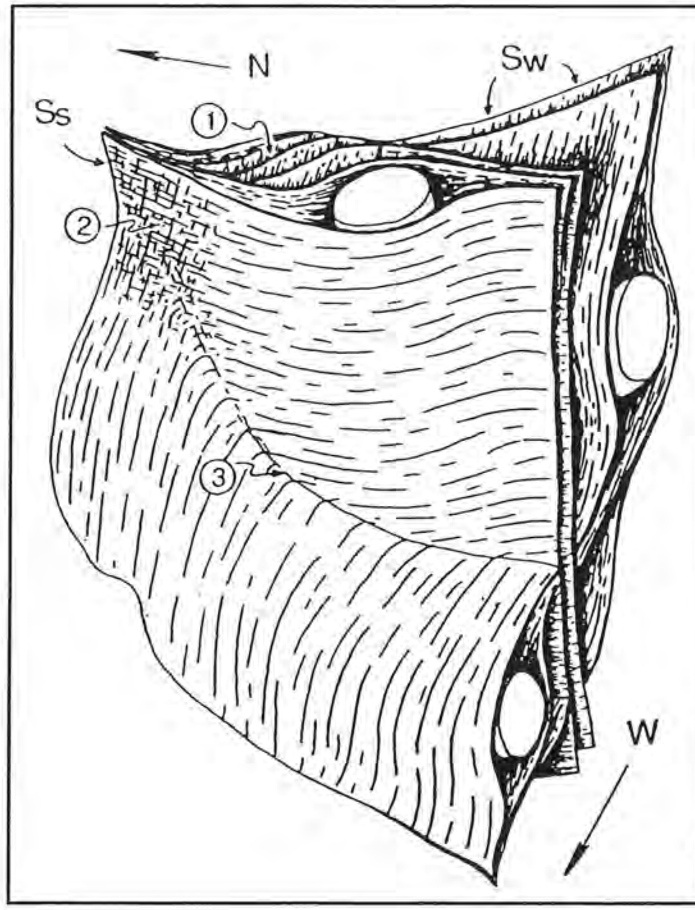


Figure 25. Composite sketch based on field and thin-section observations showing relationship between Quaboagian backfold stage Sw and Quaboagian dome-stage Ss foliation and related lineation at Stop 11. The lines on foliation surfaces represent the lineations on that surface. Angle between the two sets of folia is exaggerated. From Peterson 1992 and Peterson and Robinson, 1993.

118.1 Stop sign, turn right (south).
118.2 Stop sign. Bear right (south) onto Route 19 in Wales, MA.
118.4 Sharp right (west) off Route 19 onto Monson Road.
119.2 Bear right (west) onto McBride Road as Monson Road swings left.
119.6 Three way junction. Bear right (north) onto Mt. Hitchcock Road.
119.7 Tennesee Gas Pipeline. Site of trench in fall 1985.

STOP 12. WELL BEDDED COARSE GRAY PELITIC GNEISS OF THE RANGELEY (?) FORMATION, MT. PISGAH (20 minutes) See Figure 21, 22; for more complete description see Thomson et al. (1992, STOP 4). The attraction here is very fresh highly deformed granulite-facies pelitic gneiss rich in sillimanite and cordierite with coarse garnets that appear to have formed within felsic melt segregations. A sample of this is now displayed in the Smithsonian Museum Hall of Rocks. Originally, best outcrops and samples occurred east along the pipeline over the brow of the hill to the steepest east-facing slope. There have been changes in recent years and many loose blocks have been broken up or lost in the grass. The best outcrop is now a small but spectacular one at the top of the hill. Gneiss samples from the lower slope vicinity typically have garnet Alm 67, Pyr 29, Spes 1, Gro 3, biotite $X_{Mg} = 0.56\text{-}0.63$ and Ti/11 oxygens = 0.252-0.300, cordierite $X_{Mg} = 0.76$, plagioclase An34, estimated temperatures of 710-785°C, and estimated pressures of 5.6-6.9 kbar. A tiny, since obliterated, road-bed outcrop nearby contained sillimanite pseudomorphs after andalusite up to 3 cm in diameter and 9 cm long in veins of K-feldspar, quartz, and biotite with euhedral garnets up to 2 cm across.

Pegmatites consisting of K-feldspar, quartz, plagioclase, cordierite (0.5mm to 10 cm), sillimanite, garnet, and biotite appear to be the product of in situ partial melting. Pegmatite cordierite typically has XMg = 0.65-0.70, except adjacent to garnet where it is 0.80-0.84; in contrast to cordierite within gneisses where XMg = 0.76-0.78, except up to 0.82 adjacent to garnet. The unusually Fe-rich cordierites suggest pegmatite melting took place at lower pressure than peak granulite-facies conditions recorded in the gneisses. Estimated conditions of pegmatite genesis are: gar/crd = 714°C; gar/bio = 700°C; qz-sill-gar-crd = 5.5-6.1 kbar (Tracy et al., 1976) or 4.8-5.2 kbar (Bhattacharya, 1986); GAsP = 5.3 kbar. The pegmatite cordierites show internal symplectic intergrowths of garnet (0.25-3 mm)+sillimanite+quartz, skeletal sillimanite+quartz intergrowths against garnet, and symplectites of pale-green low-Ti biotite (Ti/11oxygens < 0.02)+sillimanite+quartz against large K-feldspar grains. Symplectite garnets in contact with cordierite X_{Mg} .79-.84 are Alm 62.6-68.2, Pyr 26.7-33.2, Spe 1.8-2.2, Gro 2.4-3.1 suggesting gar/crd =.562-601°C, qz-sill-gar-crd = 7-7.5 kbar. Apparently large Fe-rich pegmatite cordierites did not re-equilibrate during peak granulite facies conditions recorded in the gneisses, but did respond by symplectite formation during cooling. Together these rocks record part of a P-T path in which compression with heating appears to have been followed by further compression with cooling, or at least isobaric cooling if newer pressure calibrations are employed.

Turn around and return south on Mt. Hitchcock Road. Return to Route 19 via McBride and Monson Roads.
121.1 Turn left (north) on Route 19.
122.3 Bear right (east) on Holland Road at blind intersection.
123.2 Wales/Holland Town Line.
124.1 T junction. Turn right (south) on Brimfield Road, Holland.
124.5 Cut on right (see Robinson et al., 1989)coarse grained orthoclase-biotite-garnet-cordierite-sillimanite-pyrrhotite gneiss, T =790°C, P = 6.3 kbar.
126.2 Crossroads and stoplight, Holland with windmill! Go straight.
126.3 First view of Hamilton Reservoir on left.
127.6 Causeway, Hamilton Reservoir. Cordierite pegmatite (Tracy and Dietsch, 1982) collected from rubble.
129.3 Cut on left, Connecticut State Line Monument, calc-silicate gneiss.
129.5 Beginning of interchange at Mashapaug Road beyond truck depot. Park on grass strip to right and cross north to south end of large outcrop.

STOP 13. LEADMINE POND GNEISS AT MASHAPAUG ROAD, PYROXENE GRANULITE OF TONALITE COMPOSITION (20 minutes) See Figure 21, 22, 26; for detailed description see Robinson et al. (1989) The dominant rock is a dark-gray two-pyroxene granulite in the central part of the outcrop. On the northwestern end are felsic garnet-biotite tonalitic gneiss and intermediate garnet-orthopyroxene-biotite gneiss. On the southeast end are calc-silicate granulites and calcite-diopside-quartz-sphene-scapolite-apatite-biotite pegmatite. Berry (1989) has assigned these rocks to the pre-Silurian basement within an early Acadian thrust slice. The granulite-facies metamorphism is probably Quaboagian.

The granulite in the central part has the composition to have been a quartz amphibolite at lower grade, but all amphibole has broken down leaving an orthopyroxene-clinopyroxene-plagioclase-quartz-biotite assemblage. The plagioclase is An 43.7, Ab 55.5, Or 0.9, Cn 0, and contains exsolution lamellae of orthoclase An 0.4, Ab 10.7, Or 85, Cn 3.9. Augite has an Mg ratio of 0.67 and Wo content of 0.44; orthopyroxene 0.52 and 0.014 respectively. Biotite is red-brown, typical for high-Ti biotite at this grade, with Mg ratio of 0.536 and 0.273 Ti/11 oxygens. The original hornblende may have broken down by the continuous Fe-Mg and Ca-Na reaction: Hornblende + quartz = orthopyroxene + augite + plagioclase + H_2O. Similar quartz-bearing but more magnesian assemblages still contain hornblende together with its breakdown products, and quartz-free assemblages contain hornblende even at this grade. The granulite has undergone partial melting, with crystallized melts forming a 3-dimensional network of tonalitic veins containing pyroxenes, quartz, and plagioclase. The fluid-absent melting reaction: Hornblende + quartz = orthopyroxene + augite + plagioclase + hydrous melt, is proposed. The two-pyroxene granulite does not contain K-feldspar, but the garnet gneiss to the northwest does contain orthopyroxene-biotite-K-feldspar-quartz formed by the reaction: Biotite + plagioclase + quartz = K-feldspar + orthopyroxene + garnet + H_2O.

Bear right (south) from parking place.
129.6 Stop sign. Turn left (east) on bridge across Interstate 84.
129.7 Turn left (north) on entrance ramp to Interstate 84 North and re-enter Massachusetts.
133.8 Take Exit 1, Mashpaug Road. Turn right (southwest) toward Southbridge.
134.2 Underpass beneath northbound lane of Interstate 84.
134.6 Turn left (south) into entrance of Sturbridge Isle Truck Stop and large outcrop at back.

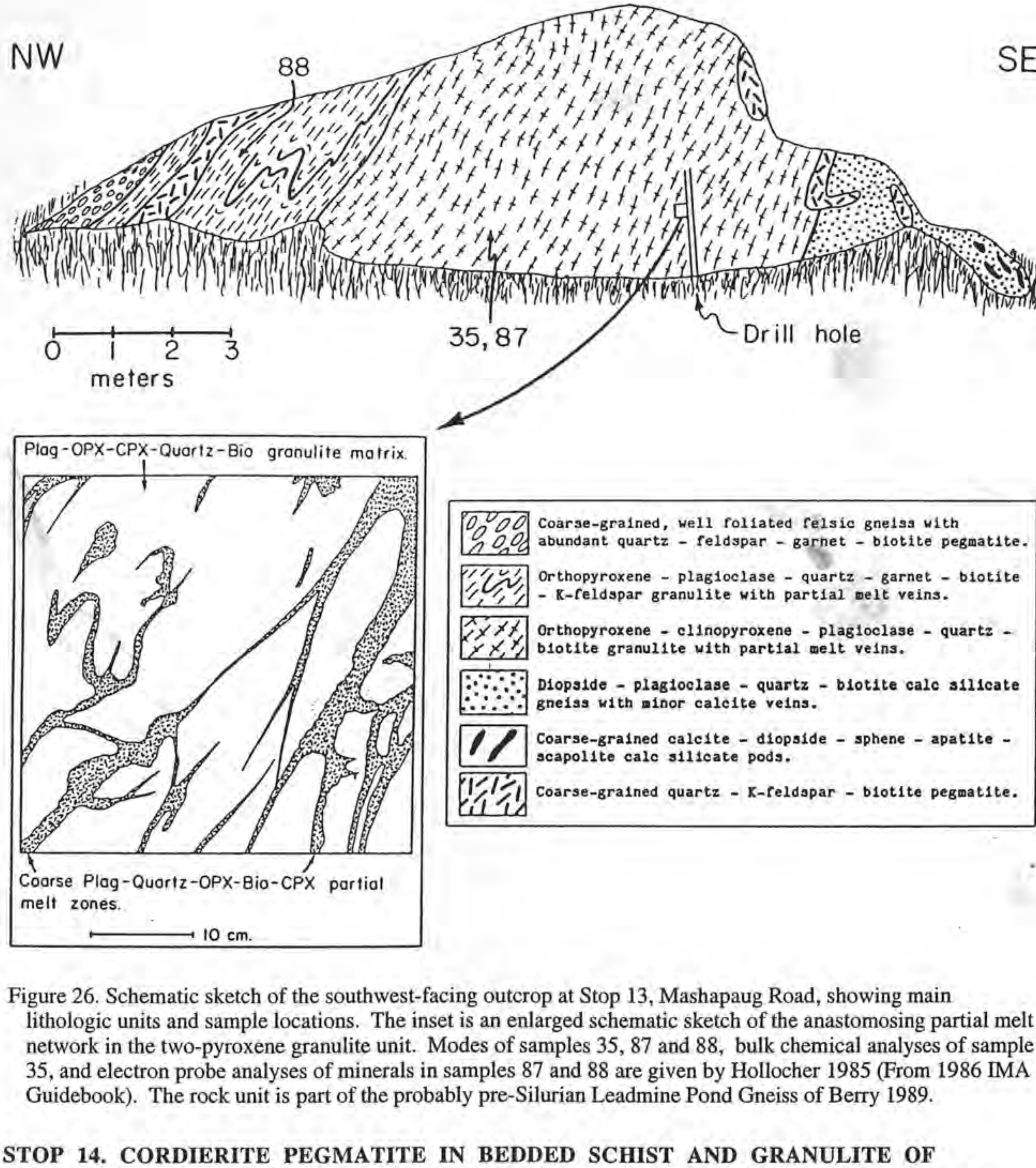


Figure 26. Schematic sketch of the southwest-facing outcrop at Stop 13, Mashapaug Road, showing main lithologic units and sample locations. The inset is an enlarged schematic sketch of the anastomosing partial melt network in the two-pyroxene granulite unit. Modes of samples 35, 87 and 88, bulk chemical analyses of sample 35, and electron probe analyses of minerals in samples 87 and 88 are given by Hollocher 1985 (From 1986 IMA Guidebook). The rock unit is part of the probably pre-Silurian Leadmine Pond Gneiss of Berry 1989.

STOP 14. CORDIERITE PEGMATITE IN BEDDED SCHIST AND GRANULITE OF PAXTON FORMATION AT STURBRIDGE ISLE (15 minutes) See Figures 21, 22. This outcrop was located by H. N. Berry in 1987; description is adapted from Thomson et al. (1992). It contains cordierite±garnet-bearing pegmatite resulting from fluid-absent, biotite-dehydration melting of surrounding gneisses. The host consists of quartz-sillimanite-garnet-cordierite schists and interbedded biotite and calc-silicate granulites of the Silurian (?) Paxton Formation. The pegmatite assemblage includes quartz, plagioclase, orthoclase, sillimanite, biotite, cordierite, and garnet. The cordierite is blue to dark lavender and up to 8 cm across, locally with large dark patches up to 15 cm across that are pinite alteration. Some samples show evidence of cordierite breakdown to aggregates of garnet, sillimanite, and quartz. Within 1 mm of these aggregates the cordierite is zoned from a normal XFe of 0.30-0.31 to as low as 0.22 near garnet. Garnet is also slightly zoned with pyrope content of 26-28%. Cordierite breakdown appears to have begun at 760°C and 5 kbar, and continued to 615°C and 6 kbar

134.9 Re-enter Mashpaug Road from truck stop and turn right (northeast).
135.5 Turn left into Interstate 84 East.
136.9 Take Exit 2, Old Sturbridge Village Road.
137.2 End of ramp. Turn left (west) on Old Sturbridge Village Road.
137.6 Wide space in road with outcrop on right at back gate to Village.

STOP 15. ISOCLINAL FOLDS IN BEDDED GRANULITE OF PAXTON FORMATION (10 minutes) See Figure 21, 22. Gray biotite-garnet granulites, and calc-silicate granulites of the Paxton Formation with abundant pegmatite and tight isoclinal folds.

After STOP 15 return to Interstate 84 East which leads to Massachusetts Turnpike Interstate 90 West or East. Take this 15 miles west to Palmer and then follow leader (not the signs) from Palmer through Bondsville and Belchertown and thence to Amherst along Route 9.

REFERENCES CITED

Ashenden, D. D., 1973, Stratigraphy and structure, northern portion of the Pelham Dome, north-central Massachusetts: Contribution No. 16 (M.S. thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 132 p., 3 plates.

Ashwal, L.D., Leo, G.W., Robinson, Peter, Zartman, R.E., and Hall, D.J., 1979, The Belchertown Quartz Monzodiorite pluton, west-central Massachusetts, a syntectonic Acadian intrusion: American Journal of Science, 279, 936-969.

Balk, Robert, 1956, Bedrock geology of the Massachusetts portion of the Northfield quadrangle, Massachusetts, New Hampshire and Vermont: United States Geological Survey Geological Quadrangle Map GQ-92.

Barker, Fred and Arth, J.G., 1984, Preliminary results, Central Gneiss Complex of the Coast Range batholith, southeastern Alaska: the roots of a high-K, calc-alkaline arc ?: Physics of the Earth and Planetary Interiors, 35, 191-198.

Barreiro, Barbara, and Aleinikoff, J. N., 1985, Sm-Nd and U-Pb isotopic relatonships in the Kinsman Quartz Monzonite, New Hampshire: Geological Society of America Abstracts with Programs 17, 3.

Berry, H.N., IV, 1989, A new stratigraphic and structural interpretation of granulite-facies metamorphic rocks, Brimfield-Sturbridge area, Massachusetts and Connecticut: Unpublished Ph.D. Thesis, Department of Geology and Geography, University of Massachusetts, Amherst, 330 p., 4 black and white plates, 2 color plates (bulletin in preparation).

Berry, H. N. IV, 1992, Stratigraphy and structural geology of the Acadian granulite facies: In Robinson, Peter and Brady, J. B., Editors, Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts, 84th Annual Meeting of the New England Intercollegiate Geological Conference, Amherst, Massachusetts, p. 95-119.

Berry, H.N., IV, and Robinson, Peter, 1989, The granulite-facies region of the Merrimack synclinorium in Massachusetts, U.S.A.: An open and shut case. TERRA Abstracts, 1, 359.

Billings, M. P., and Cleaves, A. B., 1934, Paleontology of the Littleton area, New Hampshire: American Journal of Science, 28, 5th series, 412-438.

Billings, M.P., 1937, Regional metamorphism of the Littleton-Moosilauke area, New Hampshire: Bulletin of the Geological Society of America, 48, 463-566.

Boucot, A. J., and Arndt, Robert, 1960, Fossils of the Littleton Formation (Lower Devonian) of New Hampshire: U.S. Geological Survey Professional Paper 334-B, 41-53.

Boucot, A. J., and Thompson, J. B., Jr., 1963, Metamorphosed Silurian brachiopods from New Hampshire: Geological Society America Bulletin, 74, 1313-1334.

Boucot, A. J., MacDonald, G. J. F., Milton, C., and Thompson, J.B., Jr., 1958, Metamorphosed middle Paleozoic fossils from central Massachusetts, eastern Vermont, and western New Hampshire: Geological Society of America Bulletin, 69, 855-870.

Browne, M. W., 1992, Vertebrates found to be much older: New York Times, May 29, 1992.

Chamberlain, C. P. and Sonder, L. J., 1990, Heat-producing elements and the thermal and baric patterns of metamorphic belts: Science, 250, 763-769.

Clark, R. G. and Lyons, J. B., 1986, Petrogenesis of the Kinsman intrusive suite: Peraluminous granitoids of western New Hampshire: Journal of Petrology, 27, 1365-1393.

Cornet, Bruce, 1977, The palynostratigraphy and age of the Newark Supergroup: Ph. D. dissertation, Pennsylvanian State University, University Park, Pennsylvania, 505 p.

Dalla Salda, L. H., Dalziel, I. W. D., Cingolani, C. A., and Varela, Ricardo, 1992, Did the Taconic Appalachians continue into southern South America?: Geology, 20, 1059-1062.

DelloRusso, Vincent, and Robinson, Peter, 1989, Late Acadian lineation in the gneiss domes of the Bronson Hill anticlinorium and the problem of the great swirl: Geological Society of America Abstracts with Programs, 21, A264.

Elbert, D. C., 1988, Tectonic and metamorphic evolution of the Bernardston nappe and the Brennan Hill thrust in the Bernardston-Chesterfield region of the Bronson Hill anticlinorium: New England Intercollegiate Geological Conference, 80th Annual Meeting, Keene, N. H., Guidebook, p. 70-102.

Elbert, D. C., Harris, A.G., and Denkler, K.E., 1988, Earliest Devonian Conodonts from marbles of the Fitch Formation, Bernardston nappe, north-central Massachusetts: American Journal of Science, v. 288.

Emerson, B.K., 1898, Geology of old Hampshire County, Mass., comprising Franklin, Hampshire, and Hampden Counties: United States Geological Survey Monograph 29, 790 p.

Englander, Leah, Hollocher, Kurt, and Robinson, Peter, 2002, Geochemical affinities of intermediate to mafic layers in metamorphosed Late Proterozoic sedimentary and rhyolitic strata, Pelham dome, Massachusetts: Geological Society of America Abstracts with Programs, 34, A19.

Eusden, J. D., and Barreiro, B., 1988, The timing of peak high-grade metamorphism in central-eastern New England: Maritime Sediments and Atlantic Geology, 24, 241-255.

Finkelstein, D. B., 1987, Sense of shear in a major mid-Acadian mylonite zone in a granulite-facies metamorphosed tonalite and Rangeley Formation of the Merrimack Belt, northeastern Connecticut: Geological Society of America Abstracts with Programs, 19, 14.

Fitzpatrick, J. C., 1978, Interpretation and significance of a major positive gravity anomaly in central Massachusetts: M.S. thesis, University of Massachusetts, Amherst, 45 p. 3 plates.

Gromet, L. P., and Robinson, Peter, 1990, Isotopic evidence for Late Paleozoic gneissic deformation and recrystallization in the core of the Pelham dome, Massachusetts: Geological Society of America Abstracts with Programs, 22, A368.

Guthrie, J. O., 1972, Geology of the northern portion of the Belchertown Intrusive Complex, west-central Massachusetts: Contribution No. 8 (M.S.Thesis), Department of Geology, University of Massachusetts, Amherst, Mass., 110p., 3 plates.

Hadley, J. B.,1942, Stratigraphy, structure and petrology of the Mt. Cube area, New Hampshire: Geological Society of America Bulletin, 53, 113-176.

Hall, B. A., Pollock, S. G., and Dolan, K. M., 1976, Lower Devonian Seboomook Formation and Matagamon Sandstone, northern Maine: A flysch basin-margin delta complex. In Page, L. R. ,Editor, Contributions to the Stratigraphy of New England, Geological Society of America Memoir 148, 57-63.

Halpin, D. L., M.S., 1965, The geometry of folds and style of deformation in the Quabbin Hill area, Massachusetts: M.S.thesis, University of Massachusetts, Amherst, Massachusetts, 93 p.

Hames, W. E., Tracy, R. J., Ratcliffe, N. M., and Sutter, J. F., 1991, Petrologic, structural, and geochronologic characteristics of the Acadian overprint on Taconian assemblages in southwestern New England: American Journal of Science, 291, 887-913.

Hamilton, W. B., 1988, Plate tectonics and island arcs: Geological Society of America Bulletin, 100, 1594-1615.

Harris, A.G., Hatch, N.L., Jr., and Dutro, J.T., Jr., 1983, Late Silurian conodonts update the metamorphosed Fitch Formation, Littleton area, New Hampshire: American Journal of Science, 283, 722-738.

Harrison, T. M., Spear, F.S. and Heizler, M. T., 1989, Geochronologic studies in central New England II: Post-Acadian hinged and differential uplift: Geology, 17, 185-189.

Harwood, D. S., and Berry, W. B. N., 1967, Fossiliferous Lower Paleozoic rocks in the Cupsuptic quadrangle, west-central Maine: U. S. Geological Survey Professional Paper 575-D, p. D16-D-23.

Hatch, N.L., Jr., Zen, E-an, Goldsmith, Richard, Ratcliffe, N.M., Robinson, Peter, Stanley, R.S., and Wones, D.R., 1984, Lithotectonic assemblages as portrayed on the new bedrock geologic map of Massachusetts: American Journal of Science, 284, 1026-1034.

Hess, P.C., 1969, The metamorphic paragenesis of cordierite in pelitic rocks: Contributions to Mineralogy and Petrology, 24, 191-207.

Hess, P.C., 1971, Prograde and retrograde equilibria in garnet-cordierite gneisses in south-central Massachusetts: Contributions to Mineralogy and Petrology, 30, 177-195.

Hitchcock, C. H., 1871, Helderberg corals in New Hampshire: American Journal of Science, 3rd Series, 2, 148-149.

Hodgkins, C.E., 1985, Major and trace element geochemistry of the Late Precambrian Dry Hill Gneiss, Pelham Dome, Massachusetts: Contribution No. 48 (M.S. Thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 135p.

Hollocher, K.T., 1985, Geochemistry of metamorphosed volcanic rocks in the Middle Ordovician Partridge Formation, and amphibole dehydration reactions in the high-grade metamorphic zones of central Massachusetts: Contribution No. 56 (Ph.D. thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 275p.

Hollocher, Kurt, 1987, Petrology and geochemistry of the Monson Gneiss and related rocks, Bronson Hill anticlinorium, Massachusetts: Geological Society of America, Abstracts with Programs, 19, 19.

Hollocher, Kurt, 1988, Geochemical comparisons of the Monson Gneiss and associated tonalitic Acadian plutons, and overlying Ordovician volcanics, Massachusetts: Geological Society of America Abstracts with Programs, 20, 28.

Hollocher, K. T., 1991, Prograde amphibole dehydration reactions during high-grade regional metamorphism, central Massachusetts, U. S. A: American Mineralogist, 76 (J.B.Thompson Volume), 956-970.

Hollocher, Kurt, Bull, Jon and Robinson, Peter, 2002, Geochemistry of the metamorphosed Ordovician Taconian Magmatic Arc, Bronson Hill anticlinorium, western New England: Physics and Chemistry of the Earth 27, 5-45.

Hueber, F. M., Bothner, W. A., Hatch, N. L. Jr., Finney, S. C., and Aleinikoff, J. N., 1990, Devonian plants from southern Quebec and northern New Hampshire and the age of the Connecticut Valley trough: American Journal of Science, 290, 360-395.

Karabinos, Paul, Samson, S. D., Hepburn, J. C., Stol, H. M., and Aleinikoff, J, N, 1998, Taconian orogeny in the New England Appalachians: collision between Laurentia and the Shelburne Falls arc: Geology 26, 215-218.

Karabinos, Paul, Samson, S. D., Hepburn, J. C., Stol, H. M., and Aleinikoff, J, N, 1998, Taconian orogeny in the New England Appalachians: collision between Laurentia and the Shelburne Falls arc: Reply. Geology 27, 382.

Kick, J. F., 1975, A gravity study of the gneiss dome terrain of north-central Massachusetts: Ph.D. thesis, University of Massachusetts, Amherst, Massachusetts, 179 p., 4 plates.

Laird, H. S., 1974, Geology of the Pelham Dome near Montague, west-central Massachusetts: Contribution No. 14 (M. S. thesis), Department of Geology and Geography, University of Massachusetts, Amherst, Massachusetts, 84 p., 5 plates.

Leo, G. W., 1991, Oliverian domes, related plutonic rocks, and mantling Ammonoosuc Volcanics of the Bronson Hill anticlinorium, New England Appalachians: U. S. Geological Survey Professional Paper 1516, 92p.

Maczuga, D. E., 1981, Petrology and geochemistry of the Devonian Fitchburg plutonic complex, central Massachusetts: Contribution No. 36 (MS. Thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 127 p.

Makower, Jordan, 1964, Geology of the Prescott Intrusive Complex, Quabbin Reservoir Quadrangle, Massachusetts: M.S. Thesis, Department of Geology and Geography, University of Massachusetts, Amherst, Massachusetts, 91 p.

McEnroe, S. A., 1989, Paleomagnetism and geochemistry of Mesozoic diabase dikes and sills in west-central Massachusetts: Contribution No. 64 (MS thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 169 p.

McEnroe, S.A. and L.L. Brown, 1992, Mesozoic paleomagnetism and diabase petrography and geochemistry in central Massachusetts: In Robinson, Peter and Brady, J.B., Editors, Guidebook for Field Trips to the Connecticut Valley Region of Massachusetts and Adjacent States. New England Intercollegiate Geological Conference, 84th Annual Meeting, Amherst, Massachusetts, p. 358-379.

McEnroe, S.A. and L.L. Brown, 2000, Juarassic paleomagnetism: A view from New England, U. S. A. Geophysical Journal International, 143, 22-38.

McEnroe, S.A., Robinson, Peter., Brown, L.L., and Foland, K.A., 1987, Paleomagnetic discovery of Cretaceous diabase dikes in central Massachusetts: Geological Society of America Abstracts with Programs, 19, 765.

Moench, R. H., and Aleinikoff, J. N., 2003, Stratigraphy, geochronology, and accretionary terrane settings of two Bronson Hill arc sequences, northern New England: Physics and Chemistry of the Earth, 28, 113-160.

Naylor, R.S., 1969, Age and origin of the Oliverian domes, central-western New Hampshire: Geological Society of America Bulletin, 80, 405-428.

Naylor, R.S., Boone, G.M., Boudette, E.L., Ashenden, D.D., and Robinson, Peter, 1973, Pre-Ordovician rocks in the Bronson Hill and Boundary Mountains anticlinoria, New England, U.S.A. (abstract): Transactions of the American Geophysical Union, 54, 495.

Onasch, C. M., 1973, Analysis of the minor structural features in the north-central portion of the Pelham dome: Contribution No. 12 (M.S. Thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 87 p., 6 plates.

Oxboel, Lisa, Robinson, Peter and Tucker, R. D., 1997, Transition between Acadian and Late Pennsylvanian ductile structural features and regional metamorphism, west limb of the Pelham dome, west-central Massachusetts: Geological Society of America Abstracts with Programs 29, 72.

Peterson, V. L., 1992a, Structure, petrology, and tectonic implications of highly strained rocks along the west margin of the Acadian granulite-facies high, south-central Massachusetts: Ph. D. thesis, University of Massachusetts, Amherst, Massachusetts, 283p.

Peterson, V. L., 1992b, The Conant Brook shear zone: An Acadian high strain zone along the Bronson Hill - Merrimack boundary in southern Massachusetts. In Robinson, Peter and Brady, J. B., Editors, Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts, 84th Annual Meeting of the New England Intercollegiate Geological Conference, Amherst, Massachusetts, p. 1-26.

Peterson, V. L., and Robinson, Peter, 1993, Progressive evolution from uplift to orogen-parallel transport in a late-Acadian, upper amphibolite- to granulite-facies shear zone, south-central Massachusetts: Tectonics, 12, 550-567.

Peterson, V. L., Robinson, Peter, and Tucker, R. D., 1993, Rotated lineations in a metamorphic and geochronologic transition zone, central Massachusetts: Implications for Late Pennsylvanian transport: Geological Society of America Abstracts with Programs, 25, 69.

Pomeroy, J.S., 1977, Bedrock geologic map of the Warren quadrangle, Worcester, Hamden, and Hampshire Counties, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map GQ-1358.

Ratcliffe, N. M., Hames, W. F., and Stanley, R. S., 1999, Taconian orogeny in the New England Appalachians: collision between Laurentia and the Shelburne Falls arc: Comment. Geology 27, 381.

Reed, R. M. and Williams, M. L., 1989, Petrofabric kinematic indicators in the northern portion of the Pelham dome, western Bronson Hill anticlinorium, central Massachusetts: Geological Society of America Abstracts with Programs, 21, 60.

Reed, R. M.,1993, Microfabric analysis of the northern part of the Pelham dome: M. S. thesis, University of Massachusetts, Amherst, Massachusetts.

Robinson, Peter, 1963, Gneiss domes of the Orange area, west-central Massachusetts and New Hampshire: Ph.D. thesis, Harvard University, Cambridge, Massachusetts, 253 p.

Robinson, Peter, 1967. Geology of the Quabbin Reservoir area, central Massachusetts: In Robinson, Peter and Drake, D. P., Editors, Field Trips in the Connecticut Valley Massachusetts: New England Intercollegiate Geological Conference 59th Annual Meeting, Amherst, Massachusetts, p. 114-127.

Robinson, Peter, 1979, Bronson Hill anticlinorium and Merrimack synclinorium in central Massachusetts: In Skehan, J.W., S.J., and Osberg, P.H., Editors, The Caledonides in the U.S.A., geological excursions in the northeast Appalachians, Project 27, Caledonide Orogen 1979, Weston Observatory, Weston, Massachusetts, p. 126-150.

Robinson, Peter, 1981, The basement-cover enigma in the gneiss domes of central New England, U.S.A. (abstract): Uppsala Caledonide Symposium, Terra Cognita, 1, 70.

Robinson, Peter,1991, The eye of the petrographer, the mind of the petrologist: American Mineralogist, 76, 1781-1810.

Robinson, Peter and Brady, J. B., Editors, 1992, Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts and Adjacent States: Annual Meeting New England Intercollegiate Geological Conference, Contribution No. 66, Department of Geology and Geography, University of Massachusetts, Amherst, 535 p.

Robinson, Peter and Elbert, D. C., 1992, The Bernardston nappe and Brennan Hill thrust in the Connecticut Valley and their root zones east of the Bronson Hill anticlinorium: In Robinson, Peter and Brady, J. B., Editors, Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts, 84th Annual Meeting of the New England Intercollegiate Geological Conference, Amherst, Massachusetts, p. 27-47.

Robinson, Peter and Jaffe, H. W. 1969a, Aluminous enclaves in gedrite- cordierite gneiss from southwestern New Hampshire: American Journal of Science 267, 389- 421.

Robinson, Peter, and Jaffe, H. W., 1969b, Chemographic exploration of amphibole assemblages from central Massachusetts and Southwestern New Hampshire: Mineralogical Society of America, Special Paper No. 2, p. 251-274.

Robinson, Peter, and Peterson, V. L., 2002, Lineation patterns and associated kinematics in central New England: Under-reported resource for interpretation of orogenic evolution. Geological Society of America Abstracts with Programs 34, A29.

Robinson, Peter, and Tucker, R. D., 1992, A traverse across the "wild unknowns" of North-Central Massachusetts from the Bronson Hill anticlinorium to the Fitchburg plutons: In Robinson, Peter and Brady, J. B., Editors, Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts, 84th Annual Meeting of the New England Intercollegiate Geological Conference, Amherst, Massachusetts, p. 424-445.

Robinson, Peter, Field, M. T., and Tucker, R. D., 1982a, Stratigraphy and structure of the Ware-Barre area, central Massachusetts: Guidebook New England Intercollegiate Geological Conference, 74th Ann. Meeting, Storrs, Connecticut, p. 341-374.

Robinson, Peter, Spear, F.S., Schumacher, J.C., Laird, Jo, Klein, Cornelius, Jr., Evans, B.W., and Doolan, B.L., 1982b, Phase relations of metamorphic amphiboles: natural occurence and theory: In Veblen, D.R., and Ribbe, P.H., Editors, Amphiboles: petrology and experimental phase relations, Reviews in Mineralogy, 9B, 1-227, Mineralogical Society of America, Washington, D.C.

Robinson, Peter, Tracy, R.J., Hollocher, K.T., and Dietsch, C.W., 1982c, High grade Acadian regional metamorphism in south-central Massachusetts: Guidebook New England Intercollegiate Geological Conference, 74th Ann. Meeting, Storrs, Connecticut, p. 289-339.

Robinson, Peter, Tracy, R. J., Hollocher, K. T., Schumacher, J. C. and Berry, H. N. IV, 1986, The central Massachusetts metamorphic high: In Robinson, Peter and Elbert, D. C., Editors, Field Trip Guidebook: Regional Metamorphism and Metamorphic Phase relations in Northwestern and Central New England. IMA Meeting Stanford, Contribution No. 59, Department of Geology and Geography, University of Massachusetts, p. 195-283.

Robinson, Peter, Hatch, N. L., Jr., and Stanley, Rolfe S., 1988, The Whately Thrust: A structural solution to the statigraphic dilemma of the Erving formation: In Hatch, Norman L.(Ed.), The Bedrock Geology of Massachusetts. U.S. Geological Survey Professional Paper 1366-D, p.D1-D23.

Robinson, Peter, Tracy, R.J., Hollocher, Kurt, Berry, H.N., IV, and Thomson, J.A., 1989, Basement and cover in the Acadian metamorphic high of central Massachusetts: In Chamberlain, C. Page and Robinson, Peter (Editors), Styles of Metamorphism with Depth in the Central Acadian High, New England: A Field Trip Honoring J.B. Thompson, Jr.: Contribution No. 63, Department of Geology and Geography, University of Massachusetts, Amherst, p. 69-140.

Robinson, Peter, Thompson, P. J. and Elbert, D. C., 1991, The nappe theory in the Connecticut Valley region: thirty-five years since Jim Thompson's first proposal: American Mineralogist, 76, 689-712.

Robinson, Peter, Tucker, R. D., Gromet, L. P., Ashenden, D. D., Williams, M. L., Reed, Robert, and Peterson, V. L., 1992, The Pelham dome, central Massachusetts: Stratigraphy, geochronology, , and Acadian and Pennsylvanian structure and metamorphism: In Robinson, Peter and Brady, J. B., Editors, Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts, 84th Annual Meeting of the New England Intercollegiate Geological Conference, Amherst, Massachusetts, p. 132-169.

Robinson, Peter, Tucker, R. D., Bradley, Dwight, Berry, H. N. IV, and Osberg, P. H., 1998. Paleozoic orogens in New England: GFF (Journal of Geological Society of Sweden), 120, 119-148.

Roll, Margaret A., 1987, Effects of Acadian kyanite-zone metamorphism on relict granulite-facies assemblages, Mount Mineral Formation, Pelham dome, Massachusetts: Contribution No. 60 (M.S. Thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 202 p.

Schumacher, J. C., 1988, Stratigraphy and geochemistry of the Ammonoosuc Volcanics, central Massachusetts and southwestern New Hampshire: American Journal of Science 288, 619-663.

Schumacher, J. C. and Robinson, Peter, 1987, Mineral chemistry and metasomatic growth of aluminous enclaves in gedrite-cordierite gneiss, southwestern New Hampshire: Journal of Petrology, 28, 1033-1073.

Schumacher, J. C., Hollocher, K. T., Robinson, Peter and Tracy, R. J., 1990, Progressive reactions and melting in the Acadian metamorphic high of central Massachusetts and southwestern New Hampshire, U. S. A.: In Ashworth, J. R., and Brown, M. (Editors), High Temperature Metamorphism and Crustal Anatexis, Unwin Hyman, London, p. 198-234.

Schumacher, J. C., Schumacher, Renate, and Robinson, Peter, 1989, Acadian metamorphism in central Massachusetts and southwestern New Hampshire: Evidence for contrasting P-T trajectories: In Daly, J.S., Cliff, R.A., and Yardley, W.D. (Eds.), Evolution of Metamorphic Belts, Geological Society Special Publication No. 34, London, p. 453-460.

Schumacher, Renate, 1986, Petrology and geochemistry of epidote- and clinopyroxene-bearing amphibolites and calc-silicate rocks from central Massachusetts, USA: Ph. D. Dissertation, University of Bonn, Germany, 233p.

Shearer, C. K., 1983, Petrography, mineral chemistry, and geochemistry of the Hardwick Tonalite and associated igneous rocks, central Massachusetts: Contribution. No. 51 (Ph.D. Thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 210 p.

Shearer, C. K., and Robinson, Peter, 1988, Petrogenesis of metaluminous and peraluminous tonalites within the Merrimack synclinorium: Hardwick Tonalite, central Massachusetts. American Journal of Science, 288-A, 148-196.

Spear, F.S. and Chamberlain, C. P., 1986, Metamorphic and tectonic evolution of the Fall Mountain nappe complex and adjacent Merrimack synclinorium: In Robinson, Peter, and Elbert, D. C., Editors, 1986, Field trip guidebook: regional metamorphism and metamorphic phase relations in northwestern and Central New England: Field Trip B-5, International Mineralogical Association, 14th General Meeting at Stanford University, Contribution No. 59, Department of Geology and Geography, University of Massachusetts, Amherst, Massachusetts, p. 121-144.

Spear, F. S., Hickmott, D. D. and Selverstone, Jane, 1990, Metamorphic consequences of thrust emplacement, Fall Mountain, New Hampshire: Geological Society of America Bulletin, 102, 1344-1360.

Thompson, J.B., Jr., 1954, Structural geology of the Skitchewaug Mountain area, Claremont quadrangle, Vermont-New Hampshire: Guidebook, New England Intercollegiate Geological Comference, 46th Annual Meeting, Hanover, New Hampshire, p. 93-174.

Thompson, J.B., Jr., Robinson, Peter, Clifford, T. N., and Trask, N. J. Jr., 1968, Nappes and gneiss domes in west-central New England: In Zen E., and W.S. White, Editors, Studies of Appalachian Geology: Northern and Maritime, John Wiley & Sons, New York, p. 203-218, 2 color plates.

Thompson, P. J., 1985, Stratigraphy, structure, and metamorphism in the Monadnock quadrangle, New Hampshire: Contribution No. 58 (Ph.D. thesis), Department of Geology and Geography, University of Massachusetts, Amherst, 255 p., 8 plates.

Thomson, J. A., 1992, Petrology of high-grade schists, gneisses, and cordierite pegmatites in south-central Massachusetts: Ph. D. thesis, University of Massachusetts, Amherst, Massachusetts.

Thomson,m J. A., Peterson, V. L., Berry, H. N. IV, and Barreiro, Barbara, 1992, Recent studies in the Acadian metamoprhic high, south-central Massachusetts: In Robinson, Peter and Brady, J. B., Editors, Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts, 84th Annual Meeting of the New England Intercollegiate Geological Conference, Amherst, Massachusetts, p. 229-255.

Tracy, R. J., 1975, High grade metamorphic reactions and partial melting in pelitic schist, Quabbin Reservoir area, Massachusetts: Contribution No. 20 (Ph. D. Thesis), Department of Geology and Geography, University of Massachusetts, Amherst, Mass. 127p.

Tracy, R. J., 1978, High grade metamorphic reactions and partial metling in pelitic schist, west-central Massachusetts: American Journal of Science, 278, 150-178.

Tracy, R.J., and Dietsch, C.W., 1982, High temperature retrograde reactions in pelitic gneiss, central Massachusetts: Canadian Mineralogist, 20, 425-439.

Tracy, R.J., and Robinson, Peter, 1988, Silicate-sulfide-oxide-fluid reactions in granulite-grade pelitic rocks, central Massachusetts: American Journal of Science, 288-A, 45-74.

Tracy, R. J. and Robinson, Peter, 2002, Monazite microprobe ages from a structurally complex outcrop, central Massachusetts: Exploration of "Acadian" tectonothermal events. Geological Society of America Abstracts with Programs, 34, A10.

Tracy, R.J., and Rye, D.M., 1981, Origin and mobility of sulfur in graphitic schists, central New England: Geological Society of America Abstracts with Programs, 13, 569.

Tracy, R. J., Robinson, Peter, and Thompson, A. B., 1976, Garnet composition and zoning in the determination of temperature and pressure of metamorphism, central Massachusetts: American Mineralogist, 61, 762-775.

Tracy, R. J., Robinson, Peter, and Wolff, Robert A., 1984, Metamorphosed ultramafic rocks in the Bronson Hill anticlinorium, central Massachusetts: American Journal of Science, 284, 530-558.

Trzcienski, W. E., Jr., Thompson, J. B., Jr., Rosenfeld, J. L. and Hepburn, J. C., 1992, The Chicken Yard line / Whately Fault debate: From Springfield Vermont to Whately, Massachusetts. In Robinson, Peter and Brady, J. B., Editors, Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts, 84th Annual Meeting of the New England Intercollegiate Geological Conference, Amherst, Massachusetts, p. 291-304.

Trzcienski, W. E., Jr., Thompson, J. B., Jr., Hepburn, J. C., and Rosenfeld, J. L., 1993, Reinterpretation of the "Chicken Yard Line" (CYL)- Whately Pound Channel Deposit (WPCD) relationship: Geological Society of America Abstracts with Programs 25, 85.

Tucker, R. D. and Robinson, Peter, 1990, Age and setting of the Bronson Hill magmatic arc: A re-evaluation based on U-Pb zircon ages in southern New England. Geological Society of America Bulletin, 102, 1404-1419.

Tucker, R. D., and Robinson, Peter, 1991, Age of inherited components in composite single zircons from the Dry Hill Gneiss, central Massachusetts: evidence concerning the "basement" of the Bronson Hill magmatic arc. Geological Society of America Abstracts with Programs, 23, 141.

Tucker, R.D., Robinson, Peter and Hollocher, K.T., 1988, U-Pb zircon, titanite and monazite dating in "basement" rocks of the Bronson Hill anticlinorium, central Massachusetts. Geological Society of America Abstracts with Programs, 20, A216.

Tucker, R. D., Bradley, D. C., Ver Straeten, Harris, A. G. Ebert, J. R., and McCutcheon, 1998, New U-Pb zircon ages and the duration and division of Devonian time scale: Earth and Planetary Science Letters 158, 175-186.

Tucker, R. D., Osberg, P. H., and Berry, H. N., IV, 2001, The geology of a part of Acadia and the nature of the Acadian orogeny across central and eastern Maine: American Journal of Science 301, 205-260.

Zartman, R. E. and Marvin, R. F., 1991, Radiometric ages of rocks in Massachusetts: In Hatch, Norman L.(Ed.), The Bedrock Geology of Massachusetts. U.S. Geological Survey Professional Paper 1366-E-J, p.J1-J19.

Zen, E-an, 1983, Exotic terranes in the New England Appalachians - Limits, candidates, and ages: A speculative eassy. In Hatcher, R. D. et al., Editors, Geological Society of America Memoir 158, p. 55-81.

Zen, E-an, Goldsmith, Richard, Ratcliffe, N.L., Robinson, Peter, and Stanley R.S., 1983, Bedrock geological map of Massachusetts, Scale 1/250,000 (two sheets in color, with cross sections, tectonic map, metamorphic map, explanation, black and white reference sheet): U.S. Geological Survey, Washington, D.C.