



INTRODUCTION TO GEOLOGY OF THE ORANGE AREA

Location and General Geologic Setting

The general location and geologic setting of the Orange area and adjacent areas is shown in Figure 1. The region lies to the east of the Connecticut Valley Triassic-Jurassic Extensional Basin. The older rocks (Hatch et al. 1984, Robinson et al. 1992, Robinson 1993) include the Late Proterozoic Dry Hill Gneiss and related rocks, and the Late Ordovician intrusions, volcanics and sedimentary strata belonging to the Bronson Hill Magmatic Arc, an arc terrane lying on the upper side of a subduction zone by which the east edge of Laurentia, now exposed in western Massachusetts was being subducted, leading to the Late Ordovician Taconian orogeny. After the Ordovician, the area lay near the boundary between two belts (Fig. 1) with very different Silurian sedimentation. The Connecticut Valley belt, to the west, was characterized by uplift and erosion with local deposition of the Early Silurian Clough Quartzite and Late Silurian Fitch Formation (Hatch et al. 1988). The Merrimac belt, to the east, was the site of more continuous sedimentation during much of the Silurian, largely derived by erosion of the Bronson Hill arc (Robinson and Goldsmith, 1991). Both the Connecticut Valley and Merrimac belts were then covered by early Devonian sandstone and shale spreading westward from a deformation front associated with arrival in the east of the 'Avonon' land mass, now exposed in the Boston area. The early Devonian strata, were then overthrust by this deformation front, typifying the Devonian Acadian orogen in the age range 420-385 Ma, and locally involving thrusting of the Merrimac sequence over the Connecticut Valley sequence on the Brennan Hill thrust (Fig. 2). The rocks were then subjected to two additional high-grade metamorphic and deformational events, unknown until 15 years ago (Robinson et al. 1992, 1998), in the time intervals, Late Devonian to Early Mississippian (Quabogon), 370-350 Ma, and Late Pennsylvanian (Northfieldian) 300-290 Ma. Acadian and Quabogon metamorphism and deformation had strong effects throughout the area, but the Northfieldian was confined to the western part, in addition there was a zone of retrograde metamorphism and deformation after the Northfieldian and before Mesozoic faulting.

Relations between Geology and Topography

The Orange area is central in the geologic picture of central Massachusetts (Fig. 1), containing parts of five domal areas of Ordovician and older gneisses. Much of the area is topographic lowland, eroded mainly in the area of the main body of Monson Gneiss, but also including low areas eroded in the Warwick Gneiss dome to the west by the Northfield, Wendell and Orcutt Hill synclines, all overturned to the west. The Pelham dome, Warwick dome, and Kempfield anticline are all normal antiform features surrounded by upward-facing stratigraphic sequences. The main body of Monson Gneiss, entirely in the Late Devonian - Early Mississippian deformation/metamorphism zone, is surrounded west, north and east by a coherent stratigraphic sequence, but structural observations show that the sequence dips and plunges BENEATH the stratigraphically lower Monson Gneiss, and rests ABOVE right-side-up sequences of the Warwick dome and the Keene dome in southern New Hampshire. (Fig. 1). The Main Body of Monson Gneiss is like an elongate gneiss dome, overturned on its end!! The south end of the Tully Body of Monson Gneiss (Fig. 2) has the shape of a steep-sided anticline plunging south, but the north end (Fig. 1) also plunges south (Pike 1968, Springston 1992), so the whole body has the shape of an enormous tongue extending upward to the north. These structures deform still older structures better known in the Mount Grace Quadrangle to the north (Robinson et al. 1991) that are involved in the deepest parts of the cross sections for the Orange area.

Introduction to Paleozoic Ductile Structural Features

The structural geology is complex (Figs. 1, 2). The Warwick Gneiss dome and the Kempfield Gneiss anticline are in the zone of Late Pennsylvanian deformation, and are separated by a cross syncline overturned to the south. These anticlinal features are separated from the Pelham Gneiss dome to the west by the narrow Northfield, Wendell and Orcutt Hill synclines, all overturned to the west. The Pelham dome, Warwick dome, and Kempfield anticline are all normal antiform features surrounded by upward-facing stratigraphic sequences. The main body of Monson Gneiss, entirely in the Late Devonian - Early Mississippian deformation/metamorphism zone, is surrounded west, north and east by a coherent stratigraphic sequence, but structural observations show that the sequence dips and plunges BENEATH the stratigraphically lower Monson Gneiss, and rests ABOVE right-side-up sequences of the Warwick dome and the Keene dome in southern New Hampshire. (Fig. 1). The Main Body of Monson Gneiss is like an elongate gneiss dome, overturned on its end!! The south end of the Tully Body of Monson Gneiss (Fig. 2) has the shape of a steep-sided anticline plunging south, but the north end (Fig. 1) also plunges south (Pike 1968, Springston 1992), so the whole body has the shape of an enormous tongue extending upward to the north. These structures deform still older structures better known in the Mount Grace Quadrangle to the north (Robinson et al. 1991) that are involved in the deepest parts of the cross sections for the Orange area.

Mesozoic Faulting

The Orange area is 10 km east of the Mesozoic Connecticut Valley border fault that marks the east side of the Deerfield Triassic-Jurassic basin (Fig. 1). Detailed mapping in the area has demonstrated the presence of three Mesozoic fault systems that offset stratigraphic units and locally are related to brittle fracturing, and production of fault breccias, both cemented and uncemented. The Bears Den fault (Fig. 2), the New Salem faults, and the Athol fault (Fig. 2) are all normal faults dipping steeply west or northwest. The Athol fault, exposed in a spectacular cut on Route 2 (Fig. 3), is downthrown 1000 feet on the west side based on detailed mapping of rock-unit contacts (Robinson 1963).

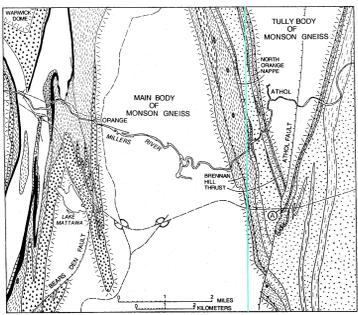


Figure 2. Generalized geologic map of the northern part of the Orange area, including parts of the Orange and Athol quadrangles. Key to patterns: Monson Gneiss - tick-marked border; Ammonoosuc Volcanics - triangles; Partridge Formation - fine dashes; Partridge Formation, ultramafic rocks - cross pattern; Clough Quartzite - black; Fitch Formation - brick pattern; Rangley Formation, gray schists - heavy dots; Rangley Formation, sulfide schists - dash-dot; Littleton Formation - not patterned; Devonian granite - uniform ticks. Blue line denotes boundary between quadrangles. 'X' indicates location of the Athol Road cut illustrated in Figure 3.

Orange Area - History of Investigations and Present Status

The long history of bedrock geologic investigations in the Orange area and adjacent areas has been reviewed, in the interests of space, to a telegraphic style with references:

- (1841) Edward Hitchcock, *Geology of Massachusetts* - earliest investigation.
- (1898) B. K. Emerson, *Geology of Old Hampshire County* - first portrait reflecting modern ideas of the distribution of rock types. Emerson was a scientist ahead of his time in his sense of continuity of stratigraphic rock units, quantitative stratigraphy, and petrographic observations in his sections. His collection of thin sections, many made in Europe in the 1880's, is now preserved in the Geological Museum at Amherst College.
- (1917) B. K. Emerson, *Geology of Massachusetts and Rhode Island* - synthesized much of the detail in the Old Hampshire County report accompanied by new ideas, some forward and some backward from before. Here again he was ahead of his time in recognizing the Late Ordovician age of rock units, whereas other sources claimed them to be Precambrian even as late as 1933. This was the last known geologic mapping in the Orange quadrangle until Robinson began again in summer 1959, but activity in adjacent areas was important.
- (1949) C. E. Moore, Jr., *Keene-Battleboro area, New Hampshire-Vermont* - last of a series of Harvard Ph. D. students who mapped southeast from Littleton, New Hampshire to the Massachusetts border, under Professor Maryland Billings.
- (1949) Jarvis B. Hadley, *Mount Grace Quadrangle, Massachusetts, north of Orange* - earlier, Hadley completed a Ph. D. Thesis at Harvard University, studying the bedrock geology of the Mount Grace Quadrangle, W. New Hampshire. He was thoroughly familiar with the bedrock and stratigraphic features of the region, thus, mapping of the Mount Grace area was the next natural step in carrying forward a rational regional correlation of Lower to Middle Paleozoic strata into Massachusetts, and Hadley did it very well, though leaving additional problems to be solved.
- (1956) Robert Balk, *Barnardston, Northfield and Millers Falls Quadrangles, northwest and west of Orange* - superb locations of outcrops and expert measurements of structural features, but poor concepts of the continuity of stratigraphy in metamorphic rocks and refusal to accept the well established correlations provided by Moore and Hadley to north and east. Balk died in an air crash in 1955 and maps were published posthumously, with some wrong contact adjustments made by U. S. Geological Survey personnel.

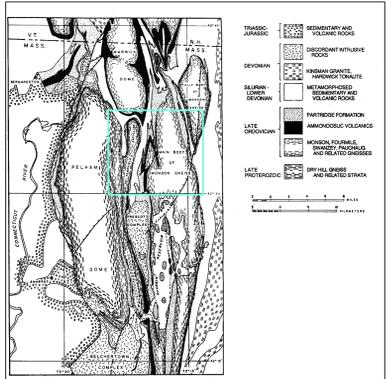


Figure 1. Generalized geologic map of north-central Massachusetts and adjacent states, showing gneiss domes of the Bronson Hill anticlinorium. Location of the Orange Area, consisting of the Orange quadrangle, the western part of the Athol quadrangle, and the eastern part of the Millers Falls quadrangle is shown in blue.

The areas between the lowlands are occupied by erosionally more resistant rocks (Figs. 1, 2), including Late Ordovician Ammonoosuc Volcanics, Late Ordovician Partridge Formation, Lower Silurian Clough Quartzite, Lower Silurian Rangley Formation, Upper Silurian - Lower Devonian Fitch Formation, Lower Devonian Littleton Formation and Lower Devonian Irving Formation, all showing definitive characteristics (Robinson 1963, 2003). During Triassic-Jurassic continental rifting that eventually created the present Atlantic Ocean, a large basin, in the Connecticut Valley to the west was filled with sedimentary rocks and basaltic lava flows. At this time there was active faulting in the Orange area with west-dipping normal faults (Fig. 2, 3), the largest with a displacement of at least 1000 feet.

Regional Metamorphism

The Paleozoic rocks were strongly metamorphosed, to staurolite-kyanite grade in the west, sillimanite-muscovite-staurolite grade in the center, and sillimanite-muscovite grade in the east (Robinson 1963, Robinson 1983). There is also a prominent zone of the retrograde chlorite-zone metamorphism in the southwest of the quadrangle (Hollocher 1981, 1997). Geochronologic work since 1988 demonstrates that little of the most intense metamorphism and deformation prominently in the rocks is 'Acadian', i.e. Lower Devonian, as formerly thought (Robinson et al. 1992, 1998). The most intense metamorphism and deformation is Late Devonian to Early Mississippian, 366-350 Ma (Quabogon), the western igneous staurolite zone is Late Pennsylvanian, 300-290 Ma (Northfieldian), and the southwestern retrograde zone is yet younger, probably 270-260 Ma (Alleghenian), but certainly older than the Mesozoic faulting.

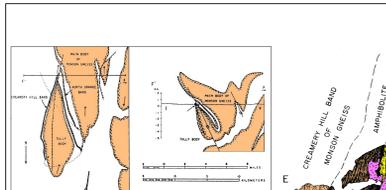
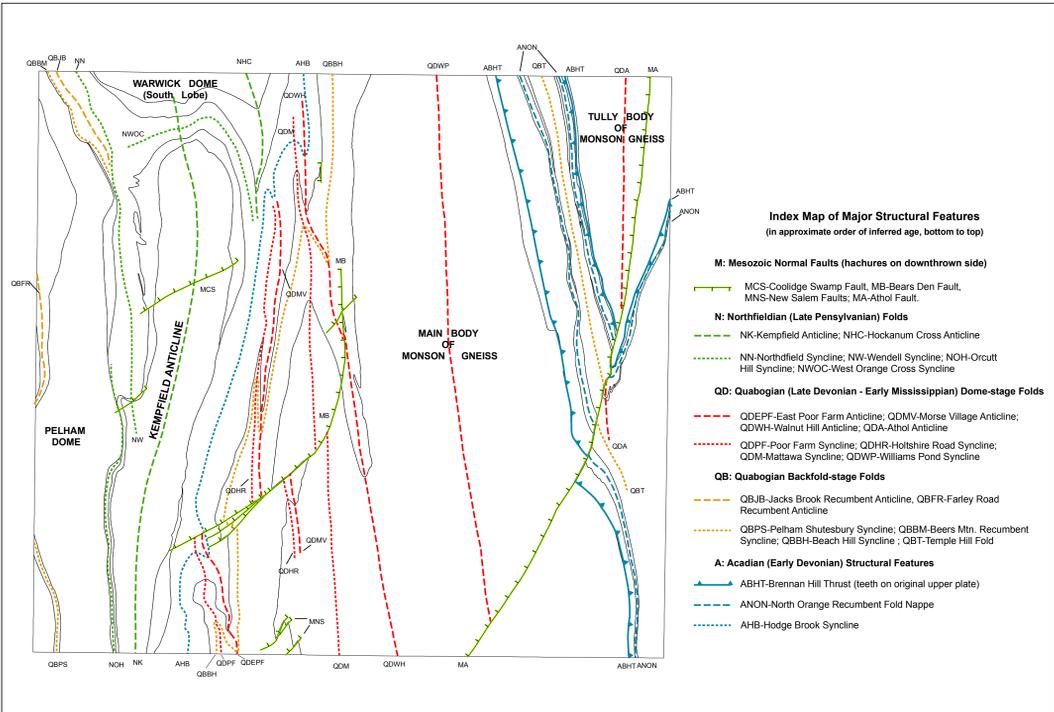


Figure 3. Sketch of south wall of rock cut on Route 2 at crest of the Athol anticline. Mesozoic Athol fault cuts the Quabogon anticlinal crest of the Tully body of Monson Gneiss. Approximate location of the cut is shown by nearly invisible stippled rectangle indicated by arrow in inset cross section. The major anticlinal dome and satellite folds of probable Quabogon age are parallel to a strong belt maximum (10% per 15' 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 Avonon-Bernardston Nappe. The North Orange nappe is interpreted as a fold of the same generation as the Avonon-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.



(1963) Peter Robinson, *Gneiss Domes of the Orange Area* - Ph. D. thesis at Harvard University with mapping in 1959-61, 62. Sought new stratigraphic and structural solutions. Included remapping of the Mount Grace Quadrangle, the eastern parts of the Northfield and Millers Falls Quadrangles, and new mapping in the Orange quadrangle and the western 1/3 of the Athol Quadrangle. Work built on four pillars of investigation: 1) Location of outcrops and contacts on quality topographic maps with walking of outcrops where exposed (not common 'traverse mapping'). 2) Detailed examination and description of rock types with precise stratigraphic correlation in mind (Billings was the founding scholar in the field of stratigraphic correlation of metamorphic rocks). 3) Detailed study of mineralogy both in hand specimen and in thin section to understand as precisely as possible the nature of the pre-metamorphic proclivity and the intensity of metamorphism. 4) Precise measurement and compiling of structural features with particular attention to relief primary structural features including bedding, and metamorphic structural features including tectonic foliation, mineral lineations of various kinds and minor fold axes. Structural data were then used quantitatively to construct large-scale cross sections by axial projection, illustrating the structure in three dimensions, both below the present land surface and above the present land surface where the geology has been removed by erosion. Brittle structural features were measured where appropriate and brittle fractures and stratigraphy were used in conjunction to map Mesozoic brittle faults associated with the Connecticut Valley Rift System. Robinson joined the faculty at University of Massachusetts in 1962, where he and students expanded research in the general region until his retirement in 1999, supported by grants from U. S. National Science Foundation, U. S. Geological Survey, Geological Society of America and University of Massachusetts. During all this time a share of energy was devoted to additional mapping and re-interpretation of the geology of the Orange area, with major accounts included in Thompson et al. 1968, Robinson 1977; Robinson et al. 1988; Robinson et al. 1991, Robinson and Elbert, 1992; Robinson et al. 1998 and Robinson 2002.

- Structural geology.** The area has been studied intensely. Abundant measurements of linear and planar structural features (Robinson 1963, 2003) have allowed quantitative modeling of structural geometry in three dimensions, as shown in a four quasi-parallel cross sections prepared by axial projection. Major features include:
 - a) North end of the 'zone' 'longitudinally overturned' main body of Monson Gneiss, with a complete inverted section of Ammonoosuc, Partridge, Clough, Fitch, Littleton dipping beneath stratigraphically lower Ordovician gneisses.
 - b) South-plunging hinge of the Tully body of Monson Gneiss, exposing the tectonic contact between Connecticut Valley and Merrimac sequences along the Brennan Hill thrust.
 - c) Northern hinge of Kempfield anticline and the south overturned corner of the Warwick dome.

Geochronology and metamorphic petrology. The area contains several sample locations forming the basis for the geochronology of the Late Ordovician Bronson Hill Magmatic Arc (Tucker and Robinson 1990), also much of the key geochronologic data demarcating the Late Devonian - Early Mississippian and Late Pennsylvanian zones of deformation/metamorphism (Robinson et al., 1992, 1998), as well as a chlorite-grade retrograde zone (Hollocher 1981, 1987; Hatch et al. 1986). The petrology of the metamorphic zones was studied in detail earlier (Hall 1970, Tracy et al. 1976, Robinson et al. 1989).

Mesozoic Normal Faults. Excellent rock stratigraphy of the area has allowed detailed mapping and quantization of Mesozoic normal faults. The Athol Fault is the best exposed Mesozoic normal fault in the region.

Bedrock Geology in Relation to Societal Needs

The bedrock geology of the Orange area, like most areas in New England, plays a crucial role in land-use planning, determining which areas are most and least suitable for agricultural land, industrial development, locations of homes, septic systems, public and private water supplies, and communication corridors, including railroads, highways and airports. Bedrock plays a stronger role in the Orange area than in many areas, because of the stark contrast between the lowlands, largely underlain by more easily eroded Late Ordovician gneisses, and uplands, largely underlain by more resistant Late Ordovician through Lower Devonian stratified rocks.

In the early 1800's the waters of the superimposed Millers River were harnessed to provide power for industries that led to the growth of the towns of Orange, Athol and Erving. These developments led population down from the more frost-free earliest upland settlements based on farming. The River also provided an east-west transportation corridor, soon occupied by early roads and Boston and Maine Railroad main line. Only in the mid 20th century were new highway corridors developed through uplands to bypass traffic congestion of the valley towns of Orange and Athol, and an upland bypass around Erving was only created in the 21st century. The quadrangle also provided the locations of new roads to bring to the north the side of Quabbin Reservoir, which began flooding in 1939. These developments provided fresh new exposures of bedrock geology and gave assistance to interpretation unavailable to earlier workers, though they enjoyed the benefit of much more open farmland and spent less time seeking exposures in deep forest. In addition, the lowland eroded in the Monson Gneiss provided the lowland location of the Orange Airport and the Quabbin Reservoir.

The topographic relationships are also why the area contains several glacial outwash gravel aquifers and water wells, public and private, and explains why there are concerns about groundwater contamination from old industrial developments in the valley, as well as investigations to be sure that contamination does not reach the Quabbin Reservoir watershed to the south. The recently mapped Mesozoic brittle normal faults, particularly at Bears Den and Athol, add a new dimension to the matter of subsurface water, both for potential sources, and for avenues of contamination.

One purpose of bedrock mapping is to provide details on the actual distribution of exposures for various societal uses. A very detailed record of these results is provided in the Orange area data base. For this, the coverage of the quadrangle is excellent, particularly where stratified rocks enter valleys, prompting intensive search for outcrops. Aside from highway exposures, outcrops were studied in a temporary trench created for the laying of a subsurface telephone cable across the northern part of the area February-March, 1965, and both outcrop and deep diamond drill cores were studied in detail in 1973-75, with David D. Ashenden, along the line of a proposed Northfield Mountain to Quabbin Reservoir water tunnel, since abandoned (Robinson et al. 1988). The map compilation 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 reviews based on stratigraphic relations, on new radiometric ages, and on quantitative petrology.

In its broadest outlines Massachusetts appears to be composed of 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 (450-440 Ma), the Late Silurian to Early Devonian Acadian (420-385 Ma), the Late Devonian to Early Mississippian Quabogon (370-350), the Late Pennsylvanian Northfieldian (305-285 Ma) and the Permian Alleghenian (270-260 Ma) (Robinson et al. 1998). The separation of the Late Devonian to Early Mississippian tectono-thermal events, now named Quabogon, from the Acadian is a significant change since 1993. The Late Pennsylvanian tectono-thermal events that were recognized then, are named Northfieldian. 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.

SETTING OF THE ORANGE AREA IN THE NORTHERN APPALACHIANS

The State of Massachusetts and adjacent New York contain a nearly complete section across the northern Appalachians. From the Presidential 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 Wachusett (2006') in the middle part of the State. This is a distance equivalent to that from Como south of the Alpine suite 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 a traverse of 2-3 days 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 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 reviews based on stratigraphic relations, on new radiometric ages, and on quantitative petrology.

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Importance of the Orange Area in Massachusetts Geology

Information provided above under Location and Geologic Setting, and History of Investigations shows why the Orange area is important. No modern bedrock map of the area has ever been published at 1:24,000 scale. The last previous map at a poorer scale was published by Emerson, 1898, with coarser upgrades at 1:250,000 in Bedrock Geologic Maps of Massachusetts (Emerson, 1917; Zen et al. 1983).

- Stratigraphic units.** The area contains exposures of stratigraphic units that are keys to the geology of the region, including but not limited to:
 - a) Ordovician Ammonoosuc Volcanics (Robinson 1963, 2003; Schumacher 1988) including Lower Member metamorphosed basalts, andesites and carbonate matrix volcanics, Middle Member garnet-cummingtonite-magnetite quartzite that is a metamorphosed volcanic exhalative crust; and Upper Member rhyolites, dacites and nodular sillimanite gneisses.
 - b) Lower Silurian Clough Quartzite and quartz pebble conglomerate unconformably resting on older Ordovician strata and Late Silurian - Early Devonian Fitch Formation calc-silicate and marble in much thicker sections than known elsewhere in central Massachusetts (Robinson 1963, 2003; Hatch et al., 1988).
 - c) Type area of the Lower Devonian Erving Formation (Emerson 1892, 1917; Thompson et al. 1968; Robinson, Hatch and Stanley, 1988; Robinson and Luttrell, 1985).

The western part of Massachusetts consists of rocks formed on or near the margins of Laurentia in Proterozoic through Late Ordovician time. Ample evidence indicates that Laurentia occupied the equatorial position in the early Paleozoic. The eastern part of the State consists of rocks formed on or near the Avalon plate. In earlier work it was supposed that this was collided with Laurentia during the Ordovician Taconian orogeny. However, more recent paleogeographic work as well as lithostratigraphic work suggests it was part of Gondwana to which Laurentia was added 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, including the Orange area, contains rocks formed on or near 'craton X' as described by Zen (1983) or 'medial New England' of Obereg (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/or 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.

The geology of the Orange area relates to 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, and a possible low-angle extensional fault, appear to be restricted to modest unconformities. The brittle faults that place in the Acadian and in the newly recognized Quabogon episodes, ranging from fold and thrust nappes to granulite facies metamorphism and gneiss domes. The Orange area also shows the well defined east boundary of the newly discovered Late Pennsylvanian ductile deformation and metamorphism. Here named Northfieldian, which is distinct from the early Paleozoic Alleghenian orogeny that deforms late Pennsylvanian fossiliferous sedimentary strata in Rhode Island and southeastern Massachusetts.

The major tectonostratigraphic units of the Orange area, from deepest to shallowest include the following: A) Late Proterozoic (613 Ma) alic volcanic, arkoses and quartzites of Avalon affinities with controversial contact relations with overlying rocks; B) A Late Ordovician (455-442 Ma) intrusive complex of felsic to mafic calc-aluminous rocks that may be the roots of a magmatic arc, that existed in the region at the peak of the Taconian collision and slightly after. C) A Late Ordovician cover sequence of tholeiitic arc volcanics ranging from basalts through andesites to rhyolites and overlying black shales, with controversial contact relations with the underlying Ordovician intrusive rocks; D) A Silurian cover in two facies, a thin western conglomerate and calcareous facies overlying the ruins of the Taconian arc, and a thicker eastern shale-gravels facies forming continental slope-rise or basin deposits on a post-Taconian North American margin, or the margin of a successor basin; E) A Lower Devonian cover that formed as a widespread spreading distal and proximal fan sequence-shale facies related to rising tectonic lands to the east associated with initial stages of Acadian Orogeny, overlain by a facies of felspathic siltstones and shales interleafed with basaltic tuffs and flows.

BRONSON HILL ANTICLINORIUM AND WESTERN PART OF THE MERRIMACK SYNCLINORIUM IN THE ORANGE AREA

Before 1965, and the application of plate tectonics, the Bronson Hill anticlinorium, especially in New Hampshire, 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 Matland P. Billings (1937), beginning in the Littleton-Merrimack 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 Hawthorn, N. H. where an eastward-sloping toward Sugarloaf Mountain and Bronson Hill, brought Billings the sudden realization of dome structures. Initially the domes were considered to be Devonian laccolitic intrusions, but Jarvis Hadley (1942) showed that they contain a tectonic fabric post-dating their igneous history. In 1969 Naylor proved that the granulite rocks in the domes are Ordovician, but the exact nature of the contact between the granulite 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-dipping Acadian fold nappes by J. B. Thompson, Jr. (Thompson et al., 1968); the recognition of low-angle extensional faults, some of high-grade metamorphic rocks (Boucot et al. 1958; Boucot and Thompson, 1963; Elbert et al., 1988); the recognition of metamorphic overthrust facies (Hess, 1969; Tracy et al., 1976; Hollöcher, 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 ductile deformation and metamorphism in part of the anticlinorium was Late Pennsylvanian (Tucker and Robinson, 1990; Gromet and Robinson, 1992) rather than Devonian. In addition, fairly recent geochronology (Robinson et al., 1998) indicates that the strong tectonic, plutonism and metamorphism of central Massachusetts occurs in three separate episodes, the Acadian from Late Silurian to Early Devonian, the Quabogon from Early to Early Mississippian and the Northfieldian in Late Pennsylvanian, whereas adjacent New Hampshire appears to be dominated by the earliest. Based on these results, the gneiss domes in the eastern part of the Orange area were produced during Quabogon tectonic deformation, whereas those in the western part were produced during the Northfieldian.

STRATIGRAPHY AND INTRUSIVE ROCKS

The rock layers and igneous intrusions of the Orange area are subdivided into seven subdivisions, each with problems of protoliths, plate-tectonic setting, and tectonic and metamorphic history, that will be discussed here, although outside the narrow realm of the Orange area, and older rocks have the most complex history and are the most difficult to put in context.

Late Proterozoic Basement: Dry Hill Gneiss (Zd), Poplar Mountain Gneiss (Zpm)

The Dry Hill microcline Gneiss, with its Pelham Quartzite Member, and the Poplar Mountain quartzite-biotite Gneiss, with its basal Poplar Mountain Quartzite Member in the core of the Pelham gneiss dome (Bedard, 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 Quabogon, east-directed recumbent fold nappe, that is both overturned and underlain successively by Poplar Mountain Quartzite and Poplar Mountain Gneiss. In the western part of the Orange area, only the upright part of this succession is exposed, with Poplar Mountain Gneiss overlying Dry Hill 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 zircon grains with a U-Pb age of 613±3 Ma. The Dry Hill Gneiss is considered to be a mafic to an 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 of the Poplar Mountain Gneiss and Quartzite, and Dry Hill Gneiss appear to be transitional or alkali basal compositions (Englander et al., 2002). An intrusive origin for the Dry Hill cannot be ruled out because the associated quartzites yielded detrital zircons only in the age range 280-930 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 (Hodgkins 1985), 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 zircon grains from the Pelham Quartzite Member are in three age groups that correspond to inheritance ages in one sample of Dry Hill Gneiss. These three 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 isochrones (Gromet and Robinson, 1990) showing that the last significant ductile deformation and metamorphism was Late Pennsylvanian (205-285 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 Quabogon 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, Quabogon 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 roughly in their present position in time to be involved in Quabogon east-directed recumbent folding.

Comments to the Map User

A geologic map displays information on the distribution, nature, orientation and age relationships of rock and deposits and the occurrence of structural features. Geologic and fault contacts are irregular surfaces that form boundaries between different types or ages of units. Data depicted on this geologic quadrangle map are based on reconnaissance field geologic mapping, compilation of published and unpublished work, and photogeologic interpretation. Locations of contacts are not surveyed, but are plotted by interpretation of the position of a given contact onto a topographic base map; therefore, the accuracy of contact locations depends on the scale of mapping and the interpretation of the geologist(s). Any enlargement of this map could cause misunderstanding in the details of mapping and may require other interpretations. Site-specific conditions should be verified by detailed surface mapping or subsurface exploration. Topographic and cultural changes associated with recent development may not be shown.

We recommend reading Reading Maps with a Critical Eye: Becoming an Informed Map Reader by the Maine Geologic Survey to make the best use of a geologic map. http://www.maine.gov/otrc/otrc/otrcmap/otrcmap_informed/informed.html

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This research was supported by U.S. Geological Survey, National Cooperative Geologic Mapping Program, under assistance Award Nos. 07HQAC0061. Citation: Robinson, P., 2008. Bedrock geologic map and cross sections of the Orange area, Massachusetts: Office of the Massachusetts State Geologist Open File Report 08-04. Scale: 1:24,000. 5 sheets and digital product. Adobe PDF files.

This map was produced on request directly from digital files (PDF format) on an electronic plotter.

A digital copy of this map (PDF format), including GIS datafiles, is available at <http://www.geo.umass.edu/stategeologist>

Bedrock Geologic Map and Cross Sections of the Orange Area, Massachusetts

Consisting of the Orange 7.5-Minute Quadrangle, the Western Part of the Athol 7.5-Minute Quadrangle and the Eastern Part of the Millers Falls 7.5-Minute Quadrangle

by Peter Robinson¹