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Preliminary Bedrock Geologic Map of the Chittenden Quadrangle Rutland County, Vermont

By

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INTRODUCTION

The bedrock of the Chittenden quadrangle consists of Middle Proterozoic through Cambrian metasedimentary and metaigneous rocks that lie along the western flank of the Green Mountain massif in south-central Vermont. The Green Mountain massif is cored by highly deformed and extensively retrograded schists and schistose gneisses derived from once high-grade gneisses that were intruded and originally metamorphosed during the Grenville orogeny prior to about 950 Ma. Upper Proterozoic through Cambrian metaclastic rocks, referred to as the western cover sequence, form a cover sequence that was deposited unconformably on the older schists and gneisses. The upper part of the cover sequence consists of marine-shelf carbonate rocks of the Vermont Valley sequence that developed on the stable Atlantic-type continental margin prior to the deformation in the Taconian orogeny during the Middle to Upper Ordovician.

In the Taconian orogeny, rocks of this area were thrust faulted and metamorphosed to biotite grade. The basement rocks were altered by low-grade remetamorphism and hydration to such an extent that the Grenvillian mineral assemblages, schistosity, and gneissosity are presently barely recognizable. As a result of the extensive alteration of the older gneisses and the remetamorphism to biotite-grade, many of the basement rocks contain abundant low-grade minerals such as chlorite, muscovite, albite, epidote, or clinozoisite. These minerals are in textural equilibrium with and define the strong Taconian foliations in both the cover rocks and the basement schists and gneisses. The textural and mineralogic changes in the basement rocks are most intense near major thrust faults where basement rocks are carried over cover rocks, thus making difficult the distinction between true basement (Middle Proterozoic) and cover rocks in many areas.

Previous work and current mapping

The Chittenden quadrangle forms the northwestern quarter of the Rutland 15 minute quadrangle, mapped by Brace (1953). This map was the primary reference for the geology of the Rutland area shown at 1:250,000 by Doll and others (1961) in the Vermont bedrock geologic map, although minor changes from Brace's map and stratigraphic usage were made in production of the Centennial map. Brace mapped a continuous unconformity along the west side of the Green Mountain massif from just south of Mendon, northward along the base of Blue Ridge Mountain to the northern edge of the 15 minute quadrangle. The rocks of his Mendon Formation here are separated by a thrust fault from valley carbonate rocks to the west. The Pine Hill thrust (Brace, 1953), located just west of the present map, carries the carbonate rocks, Cheshire Quartzite, the Mendon Formation, and underlying basement rocks westward over the Cambrian through Ordovician rocks of the adjacent West Rutland area. Karabinos (1987) placed another fault along the west front of the Green Mountain massif, in much the same location as Brace did but mapped this fault in a west stepping, folded pattern to the vicinity of Furnace Brook where the entire fault package was interpreted as riding on the younger Pine Hill thrust of Brace (1953). Karabinos also suggested that carbonate rocks of the Forestdale Member of the Mendon Formation of Brace (1953) in the northwest corner of the map are units of the Vermont Valley carbonate sequence. The present interpretation is similar to those of Brace and of Karabinos in many ways, but identifies several additional faults within and east of the Pine Hill thrust; these faults cross cut early metamorphic structure in all of the plates. In this report, rocks of the Forestdale Member are considered part of the Mendon Formation and not correlated with units in the Vermont Valley sequence. Several generations of thrust faults are required. In the western part of the map two new faults that are identified in this report are the Bald Peak and Burr Pond thrusts. The East Pittsford thrust of this report coincides approximately with a fault mapped by Brace (1953) and by Karabinos (1987). In addition, several thrust faults in the South Pond fault zone are mapped in the northeastern part of the map.

The ground water study of the Rutland area by Wiley and Butterfield (1983) contains detailed water well logs and a contoured depth-to-bedrock map that was particularly useful in helping define the location of the East Pittsfield thrust. Their data show that abundant surficial material at least 30 m in thickness underlies the area northeast of Rutland Town, the valley of East Creek near Chittenden, and the lowland west of Blueberry and Long Hills. Extensive glacial deposits occur in and around Chittenden Reservoir. Abundant outcrop occurs on most of the ridges with the notable exception of the south and southwest slopes of Blue Ridge Mountain where abundant thick glacial till is present. The lower slopes of the hills bounding Route 4 in the vicinity of Wheelerville and Elbow Roads contain thick deposits of sand and gravel in excess of 30 m in thickness (Wiley and Butterfield, 1983).

The present mapping, conducted in 1995 and 1996, was conducted in concert with studies in the Pico Peak, Killington Peak, and Rutland quadrangle completed since 1990. Some results of mapping in the Rutland and Killington Peak quadrangles may be found in Ratcliffe (1994).

MAJOR FAULTS AND FAULT SLICES

The area is transected by numerous east-dipping thrust faults that bound either entirely or partially the different fault slices. The stratigraphy of the cover rocks of the eastern and western cover sequences in each of these slices varies slightly because of rapid facies changes within the lower, clastic part of the cover section. From west to east these major fault and fault slices include:

1. North Chittenden slice, bordered on the east by the North Chittenden thrust.
2. Pine Hill slice that is imbricated by the Pine Hill and Bald Peak thrusts.
3. Burr Pond slice underlain by the Burr Pond thrust.
4. Green Mountain massif slice underlain by the East Pittsford thrust and overlain by the South Pond thrust.
5. Rocks above the South Pond thrust consist of imbricated Middle Proterozoic basement rock and basal clastic rocks on the eastern margin of the Green Mountain massif.

STRATIGRAPHY

Mount Holly Complex

The oldest rocks of the area belong to the Mount Holly Complex of Middle Proterozoic age. The complex is divided into a group of layered paragneisses, metaquartzite, marbles, and schist whose stratigraphic order is not known. The following discussion comes from the U-Pb zircon dating by John Aleinikoff and Paul Karabinos contained in Ratcliffe and others (1991). Throughout the massif, layered paragneisses are known to be older than intrusive granitoid gneisses that were dated by U-Pb zircon concordia studies at about 1.2 GA. Overgrowth on zircons contain rims that have U-Pb ages of about 1.1 Ga, and this is assumed to be the time of high-grade Grenvillian metamorphism. Thus, the paragneisses are known to be 1.2 Ga or older. A still older package of tonalitic and trondhjemitic gneisses, in part intrusive and in part metavolcanic, have U-Pb concordia ages of about 1.31 to 1.35 Ga and underlie the paragneiss units. These older gneisses are also intruded by the ~1.2 Ga granitic gneisses. None of these older intrusive rocks appear within this quadrangle.

Paragneiss of the Mount Holly Complex

An heterogeneous assemblage of well-layered biotite-quartz-plagioclase gneiss (Ybq) is interpreted to form the oldest rocks of the Mount Holly Complex in this quadrangle. These rocks include thin layers of hornblende amphibolite±garnet and hornblende-plagioclase gneiss and quartzite, as well as discontinuous layers of schists commonly are too thin to map. In addition, a fine-grained felsic gneiss (Yfg) occurs locally as mappable masses within the biotite-quartz-plagioclase gneiss.

Interlayered with, but generally overlying these gneisses, are mappable units of quartzite (Yq) schist (Ys), dolomite marble (Ydm), and calc-silicate rocks (Ycs). Dolomitic marble (Ydm) occurs as coarse-grained or fine-grained gray- to beige-weathering layers as much as 50 m thick but tapering to a feather edge. Commonly the dolomite marble contains layers rich in either fibrous or coarse tremolite, and passes laterally into massive tremolite rock and hornblende-diopside calc-silicate rock. The marbles are best exposed at the north end of Blue Ridge Mountain between the elevations of 2,400 and 2,600 feet. The finer-grained varieties are very pure dolomite marble, except for small black specks of pyrite that cause the rock to weather to a distinctive orangish-brown to beige color. These Proterozoic dolomitic marbles superficially resemble dolostone found in Forestdale Member of the Mendon Formation; however, the older marbles contain aplites (Yap), pegmatite (Yp), and the calc-silicate rocks mentioned previously that are absent in the Forestdale. These marbles (Ydm) also resemble coarse-grained dolomitic marble found within the Mount Holly Complex on Pine Hill within the Rutland and adjacent West Rutland quadrangles (Brace, 1953, p. 22). Similar beige-weathering dolomitic marbles also occur within the Mount Holly Complex in the southernmost part of the Mount Holly quadrangle and northern most part of the Weston Quadrangle (Ratcliffe, 1992, Ratcliffe and Burton, 1996).

The marble and calc-silicate rocks occur in contact with a schist and granofels unit (Ys) or quartzite (Yq); however, any one of the units (Ys, Yq, Ycs or Ydm) may be in contact with biotite-quartz-plagioclase gneiss (Ybq) or hornblende-garnet amphibolite or hornblende-plagioclase gneiss (Yhg). Multiple layers of paragneiss are interlayered throughout the Mount Holly Complex.

The quartzite unit (Yq) is highly variable in thickness and locally pinches out and passes laterally into the schist (Ys) unit. The quartzite is massive, highly jointed, and in many exposures otherwise structureless. Distinct, medium-grained quartz forms a mosaic of recrystallized grains, and original detrital grains are not discernable. The rock also contains patches of especially coarse muscovite, as much as 1 cm in diameter, and coarse-grained spangley muscovite-tourmaline-rich segregations. Veins and zones of disseminated coarse magnetite are common and locally can be mapped (Ymt) where the mineralization is associated with a coarse-grained tectonic breccia that resembles conglomerate. Beds of highly aluminous, fine-grained silvery-gray to light-greenish-yellow chlorite-muscovite phyllite occur within the quartzite. Locally, this phyllite contains relict garnet that is almost entirely chloritized. Small to large bodies of tourmaline-muscovite granite pegmatite intrude the quartzite (Yq) and schist (Ys). A magnetite-rich schist and plagioclase granofels (Ycms) occur locally at the upper and lower contacts of the quartzite where the quartzite grades into the schist (Ys) unit.

The schist and granofels unit (Ys) is highly variable in composition and structure. Overall, it is a light-gray to greenish-gray, lustrous, fine-grained chlorite-muscovite-albite-quartz schist±magnetite, or more feldspathic chlorite-biotite-muscovite-albite- (epidote or clinozoisite) quartz schist and granofels. The unit is almost always highly foliated by the regional S_2 foliation. This foliation contains the major retrograde lepidoblastic minerals in the rock, notably chlorite and muscovite. Coarse-grained plates of muscovite and coarse clots of chlorite derived from earlier garnet or biotite are common. Locally on Blue Ridge Mountain, the schist contains coarse rosettes of chloritoid growing in three dimensions across and into the retrogressive foliation. This rock was first reported by Whittle (1894a) and subsequently by Brace (1953, p. 26).

On Blue Ridge Mountain, the rock may contain as much as 40 to 50% chloritoid. The rock has a relict gneissic structure that is highly folded and strongly cross-foliated by ultrafine-grained muscovite and chlorite. Similar chloritoid rosette rock occurs as enclaves within the pegmatite shown along the northernwest border of the map. Chloritoid-bearing garnetiferous quartzite (Yq) is widespread in the Wallingford and Peru quadrangles west of the Devils Den, where chloritoid grows within the chloritized tails of large 2 cm-sized relict Proterozoic garnet. Beds of chloritoid-chlorite-muscovite-quartzite and schist are also widespread in schists of the Mount Holly Complex in the Weston (Ratcliffe and Burton, 1996), and Mount Holly quadrangles (Ratcliffe, 1992). These aluminous zones are commonly found near pegmatite-infiltrated contacts between Yq and Ys. Small pegmatites (Yp) occur throughout the schist and granofels unit. The schist, dolomite marble, and more feldspathic granofels units present at Blue Ridge Mountain resemble closely rocks of the Cavendish Formation in the core of the Chester dome (Ratcliffe, 1995a, b).

Two belts of poorly exposed schist and granofels (Ys) in the southern corner of the Chittenden quadrangle are continuous to the east with a large area of similar rock that caps Pico Peak in the adjacent Pico Peak quadrangle. In its fine-grained phyllitic appearance, and from the abundance of chlorite-muscovite-albite±magnetite, this schist and granofels unit could easily be mistaken for some chloritic schists in the Mendon Formation in the cover sequence.

Intrusive rocks of the Mount Holly Complex

The relative ages of the granitic intrusive rocks of the Mount Holly are uncertain; however, the granitic gneiss (Ygg) and aplite (Yap) are highly gneissic and infiltrate other gneissic units. On the other hand, the pegmatite (Yp) and a coarse-grained microcline-megacrystic augen gneiss (Ykg) are the least deformed and presumably the younger intrusive rocks. The pegmatite (Yp) clearly cross cuts relict gneissic layering and older folds in the Mount Holly. The microcline megacrystic gneiss (Ykg), although commonly strongly deformed by Paleozoic structures into an augen gneiss, locally does contain relict igneous flow layering. Large 2- to 4-cm-long rectangular microcline phenocrysts define these layers. Locally, pegmatoid microcline megacrystic rock (Ykg) passes along strike into large areas of pegmatite (Yp), and the two units may be coeval and perhaps cogenetic. A microcline megacrystic granite gneiss, like (Ykg) in the adjacent Pico Peak quadrangle, has given a discordant upper intercept U-Pb zircon age of about 1.1 Ga (Paul Karabinos, oral communication, 1987). Based on the observation above, the granitic gneisses (Ygg) are judged to be the oldest intrusive rocks.

Rocks of the western cover sequence

Mendon Formation of Brace (1953)

Whittle (1894a) originally applied the name Mendon Series to a tripartate collection of rocks that overlies his Mount Holly Series (Whittle, 1894a) along the west side of the Green Mountains. He cited the west slopes of Blue Ridge Mountain, in the present Chittenden quadrangle, as the best locality to find the various components of the Mendon. From the base upwards, he noted a collection of conglomerate, pebbly vitreous quartzite, and greenish magnetite schist. This is succeeded upwards in some localities by pebbly limestone, and limestone 16 to 130 m thick, and this is overlain on Nickwackett Mountain by pebbly feldspathic quartzite, which passes upwards into a dark micaceous and quartzose schist. He noted that the section nowhere is complete and that these lithologies laterally replace one another. The total thickness is estimated to be 400 m. The Mendon series of Whittle is overlain by vitreous quartzite of the Cheshire Quartzite, which contains the Lower Cambrian, Olenellus fauna.

Whittle (1984a) did not subdivide the Mendon series. It is clear from his discussions that chloritoid quartzites on Blue Ridge Mountain and some of the greenish schists exposed there (Whittle, 1894b) were inaccurately assigned by him to the basal Mendon. These rocks were mapped correctly by Brace (1953) as quartzite and schist and assigned to his Mount Holly Complex.

Keith (1932) did not adopt the term Mendon series but raised the main lithologic units of Whittle to formation status, as the basal Nickwackett Graywacke and the overlying Forestdale Marble. He applied the name Moosalamoo Phyllite to the overlying dark siliceous-rocks. This tripartate division follows closely the lithologic descriptions and sequence of Whittle (1894a); however, he incorrectly cited the beds of quartzite and feldspathic quartz conglomerate on Mount Nickwackett as the type locality for the Nickwackett Graywacke.

Unfortunately, the rocks on the top of Mount Nickwackett overlie stratigraphically excellent cliff exposures of Forestdale Marble (of Keith, 1932) as pointed out by Osberg (1959). For this reason, Osberg suggested abandoning the name Nickwackett. On the slopes of Mount Nickwackett and underlying the Forestdale Marble (of Keith, 1932), are thick lenses of conglomerate and magnetite-rich gritty graywacke, which closely resemble the rock Keith referred to as Nickwackett elsewhere.

Nowhere is this relationship so clear as on the slopes immediately south of route 4 and the town of Mendon, on the west slopes of East and Bald Mountain, and just north of route 4 at the town of Mendon. Here, coarse feldspathic conglomerate, white feldspathic quartzite, and greenish feldspathic granofels typical of the basal unit of Whittles' Mendon series are abundant and were so mapped by Brace (1953) as the Nickwackett Member of his Mendon Formation.

Brace's (1953) usage of the Mendon Formation and its three members of the Nickwacket Member, Forestdale Member, and Moosalamoo Member most accurately portrays the distribution of rocks in the Mendon and Rutland area, and therefore, his usage will be adopted as local usage for this area, despite Osberg's valid objection to the type section of the Nickwackett as inaccurately cited by Keith in the initial naming. Brace's (1953) redefinition is clear, and that is herein taken as the appropriate definition of the unit.

The Nickwackett Member (of Brace, 1953), of the Mendon Formation as used here refers to a collection of greenish albitic schist and granofels, greenish albitic grits, and white feldspathic quartzites and quartz conglomerate. These lithologic units are identified separately on the geologic map. The various lithologic units distinguished within the Nickwackett laterally replace one another. As here used, the greenish, feldspathic and gritty graywacke beds of the Nickwackett Member are the same as rocks Osberg (1959) mapped as the Pinnacle Formation.

The Nickwackett Member of the Mendon Formation (of Brace, 1953) consists of either a white-weathering, massive quartz-feldspar grit (or feldspathic quartzite) and conglomerate (ЄZmnc) or an albitic, greenish-gray, weathering magnetite granofels (ЄZmng). The two units interfinger and laterally replace one another. The overturned contact between coarse cobble and boulder conglomerate of the Nickwackett and microcline megacrystic granite gneiss of the Mount Holly is well exposed on the west facing cliffs 1 km southeast of North Chittenden. The basal contact is not well exposed anywhere else in the quadrangle, although it may be closely located in stream exposures 2 km north of Mendon at the base of Blue Ridge Mountain. In exposures south of Mendon, however, the contact is particularly unclear. There, a south plunging section of magnetite-rich albitic granofels (ЄZmng) overlies a granitic gneiss (Ygg). The contact between the two units appears to be more gradational than sharp, and it is uncertain whether the magnetite-rich granofels mapped as ЄZmng is depositionally above basement, or is altered basement. This magnetite-rich rock may be remetamorphosed lateritic soil and weathered rock (metasaprolite) developed on the rocks of the Mount Holly Complex. Erosion of iron-enriched residual soils could be the source for the iron-rich feldspathic quartzite and metasiltstones found higher up in the Forestdale Member.

The Forestdale Member of the Mendon Formation (of Brace, 1953) is best exposed in the fault sliver in the northwestern part of the map. Here, a very coherent stratigraphic section is preserved. Abundant cross beds indicate stratigraphic tops. The base of the unit (ЄZmfl) is a clean massive to well-bedded cream- to beige weathering dolostone as much as 100 m thick. The middle and upper part of the unit tends to be strongly colored, beige- to orangish-brown-weathering impure dolostone (ЄZmfu). Numerous lenses of white-weathering feldspathic quartzite (ЄZmfq) occur within the upper part of the Forestdale. This dolostone contains abundant dolomitic quartzite and quartzose, highly cross bedded dolostone (ЄZmfdq), having suspended grains of well-rounded bluish quartz. The upper unit (ЄZmfu) is 100 to 130 m in thickness. In and around Mount Nickwackett, in the adjacent Mount Carmel quadrangle, the Forestdale Member is as much as 260 m in thickness.

The top of the Forestdale Member is marked by a sharp contact with a greenish-gray or gray magnetite-rich metasiltstone (ЄZmmt) as much as 50 m thick. Locally, on Mount Nickwackett, a reddish-brown, 6-m-thick magnetite-bearing quartzite having trough cross beds as much as 1 m in amplitude occurs at or near the contact. These metasiltstones and magnetite-rich rocks are assigned to the Moosalamoo Member that generally consists of dark-gray- to medium-gray-weathering siliceous phyllite (ЄZmm) and phyllitic metaquartzites having a distinctive flaser bedding (ЄZmmq). This passes upwards into a gray-tan, well-bedded to laminated feldspathic quartzite (ЄZmmfq) that also contains rare beds of more vitreous quartzite.

On Blueberry Hill, in the Burr Pond slice, dark phyllites with interbedded quartzites (ꞒZmmfq) pass gradationally up into vitreous quartzite of the Cheshire Quartzite. The contact between black phyllite of the Moosalamoo (ꞒZmm) and Cheshire Quartzite is a much more abrupt transition on Bald Peak, in the Pine Hill slice.

The Cheshire Quartzite here is a massive vitreous quartzite that contains minor lenses of dark-gray siliceous phyllite like that typical of the Moosalamoo Member of the Mendon Formation. Near the top of the Cheshire, 1- to 2-meter-thick layers of intraformational conglomerate, consisting of angular to subrounded chips of dark siliceous quartzite and phyllitic quartzite, define bedding. The contact between the Cheshire Quartzite and the overlying Dunham Dolomite is exposed in outcrops by Cedar Avenue 400 m west of route 7. Thin beds of quartzite occur in medium-gray and dark-gray mottled dolostone for approximately 2 meters above the contact.

Carbonate rocks of the Vermont Valley sequence are very poorly exposed, except in the area immediately north of Rutland. The Dunham Dolomite (Ꞓd) contains several distinctive rock types: sedimentary breccia beds consisting of polymict (various types of dolostone clasts) breccia, as well as irregularly mottled gray and white dolostone, that is suggestive of soft-sediment slumps or bioturbated deposits. Excellent exposures of the coarse sedimentary conglomerate and breccia occur just south of the Chittenden quadrangle boundary and at the western border of the Rutland quadrangle, in an abandoned small quarry 500 m north of Otter Creek. The sedimentary breccia beds are concentrated in the lower third of the Dunham. Several distinctive lenses of very dark-gray dolostone (Ꞓdb_1 and Ꞓdb_2) can be mapped. The uppermost lense (Ꞓdb_2) is somewhat phyllitc and spheroidal weathering. Dolomitic quartzite and quartzose dolostone, having a distinctive brownish weathered hind and suspended quartz grains, characterize the Monkton Quartzite (Ꞓm) in this area.

Above this, occurs highly variegated dolostone of the Winooski Dolomite that is marked by abundant phyllitic and siliceous partings. There are no exposures of the Clarendon Springs Dolomite in the quadrangle; its presence is inferred from the structure of the older carbonate rocks, which suggests that a major overturned sycnline opening to the southeast is present.

Eastern cover sequence

Near the northeastern part of the map, three unnamed cover units enter the area based on extensive exposures in the adjacent Pico Peak quadrangle to the east. The correlation and identification of these units is uncertain, but they probably correlate with similar rocks of the Tyson Formation in the Mount Holly area (Ratcliffe, 1992). The structurally lowest unit is a dark-gray to black graphitic phyllite (ꞒZbs) that contain lenses 0.5 to 1 m thick of blue-gray to white graphitic calcite marble. Overlying this is a more lustrous greenish granofels and schist (ꞒZgs). The structurally uppermost unit (ꞒZcg) is a gneissose greenish albitic granofels that contain clots of chloritoid 0.5 cm in diameter. Locally the rock is permeated with brownish weathering ankerite. In some exposures what appears to be relict gneissosity is preserved. This unit may be an altered (weathered and remetamorphosed) basement gneiss. In the adjacent Pico Peak quadrangle to the east, black phyllite (ꞒZbs) is associated with conglomeratic feldspathic dolostone and dolostone that resembles closely beds of Forestdale Marble of this quadrangle.

STRUCTURAL GEOLOGY AND METAMORPHISM

East-dipping F_2 Taconian (Middle to Late Ordovician) thrust faults dominate the structure of the area, dividing the rocks into fault-bounded slices. The areas between the faults contain older folds, both Middle Proterozoic Grenvillian ones, as well as pre-thrust, F_1 early Taconian folds and foliations. Near the thrust faults, mylonitization becomes intense, and a prominent foliation (S_2) overprints both the Grenvillian and early Taconian S_1 foliation. A strong distinctive down-dip rodding and extension lineation characterizes these mylonites. Post-thrust deformation consists of several generations of crenulate cleavage and mild warping, termed F_3 and F_4 folds. These later fold events probably are Acadian and Late Devonian in age. The peak of the Paleozoic biotite-grade metamorphism is either pre S_2 and related to the F_1 fold event or synchronous with the F_2 and thrust events. Little mineralization accompanied the F_3 and F_4 fold events. Intrusion of mafic dikes in the Cretaceous was accompanied by abundant fracturing and the development of an extensive system of joints.

Grenvillian structures

Gneisses of the Mount Holly Complex contain relict folds and a coarse compositional layering expressed in outcrop and thin section by the parallel alignment and compositional segregation of high-temperature minerals. These include hornblende, garnet, biotite, diopside, and alkali feldspar or plagioclase. Gneissosity, indicated by a special symbol on the map, tends to be subvertical and trends northwest to southeast across the map. Several Middle Proterozoic folds have been identified in the Green Mountain massif slice from Blue Ridge Mountain south to the southern edge of the quadrangle. The fold plunges, where observed, are moderately inclined and the axial surfaces subvertical. Judging from the steep dips of gneissosity on the limbs, and from the abundant reversals of dip direction about the vertical, the Grenvillian folds have steeply dipping to vertical axial surfaces. This gneissosity and folded grain within the core of the Green Mountain massif serves as an excellent strain marker for subsequent shortening. Using the folded length of Grenvillian folds, as compared to the length of the folded belt normal to the dominant Paleozoic foliation, internal shortening is between 40 and 50 percent. Deformation in the cover rocks and translation on observed thrust faults probably greatly exceeds this value.

Paleozoic structures

F_1 folds and S_1 foliation in Late Proterozoic and Paleozoic cover rocks predate the thrust faults. S_1 foliation is axial planar to folds of bedding. These folds plunge in normal fashion, defining simple anticlines and synclines. S_1 foliation is expressed by oriented muscovite and biotite in the more phyllitic rocks, such as the Moosalamoo Member of the Mendon Formation. F_1 folds are identified within the North Chittenden slice, in the Pine Hill slice, and in the carbonate rocks of the Burr Pond slice. Two highly deformed F_1 folds occur within the cover rocks above the East Pittsfield slice. Importantly, in all these cases, the folds within the slices are truncated by the bounding faults of the slices.

F_2 folds and the S_2 foliation are spatially associated with the system of F_2 thrust faults. Near the thrust faults, and parallel to the trace of the thrusts, intense second generation foliation (S_2) forms the axial surface of numerous minor folds. The hingelines of the F_2 folds commonly plunge at high rake angles down the dip of the S_2 foliation. The prominent lineation defined by noses of minor folds of the S_1 foliation plunges east to southeast on the southeast dipping S_2 surfaces.

Locally, pebbles, augen of microcline, or clots of chlorite have a size-shape fabric or elongation direction to the east-southeast. Rotation sense of minor folds within the S_2-F_2 mylonitic domains reverse (clockwise to counterclockwise) within single outcrops, suggesting that the F_2 hingelines are sheath folds oriented approximately in the slip direction of the thrust faults. Locally, "c and s" mylonite structure, minor ramp- and flat-thrust structures and tails on microcline augen indicate an up-from-the-east sense of motion on the F_2 thrust faults. This pattern, the orientation of thrust fault and S_2-F_2, and the lineation is regionally consistent along the regional F_2 thrust faults throughout the Green Mountain Massif and in the eastern cover rocks throughout southeast Vermont. These structures are folded in the Acadian folds such as the Proctorsville and Spring Hill synclines and are arched over the Chester and Athens domes.

S_2 foliation within the fault slices east of the East Pittsford thrust is penetrative. Within the Green Mountain Massif slice, S_2 has an open left-stepping sigmoidal form. The foliation bends and steepens going into the bounding faults. The gross and detailed structure indicate that the F_2/S_2 and the faults are cogenetic. In the more western slices, internal F_2 type deformation is intense near the faults, but the internal cleavage is more of a crenulation type accompanied by more upright folds. Plunges of these folds, rather than plunging down the foliation, tend to plunge south or north depending upon the intersection angle with the older S_1 cleavage. Some of the deformation within the western slices appears to be the result of buckling coeval with strain-slip deformation within the fault zones. Therefore, some of the upright late folds of foliation described as "F_2 or younger" in the explanation, particularly in the zone between the East

Pittsford thrust and Blue Ridge Mountain, may actually belong to the F_2 fold- and thrust-event. The internal strain within slices appears to be less intense to the west.

The thrust direction of the F_2 thrust faults is approximated by the orientation of the prominent elongation lineation on the S_2 surfaces and the accompanying F_2 microfold hingelines. This direction ranges from about S60°E to east-west. This suggests that the thrusts are nearly pure thrust faults with perhaps a slight left-oblique movement. The total displacement on any of the faults cannot be determined from information in this quadrangle. However, the Pine Hill thrust and its associated faults are major faults that extend from north of Dorset Mountain, in the Dorset quadrangle (Shumaker and Thompson, 1967), to at least the northern end of the Mount Carmel quadrangle (Ratcliffe unpublished data, 1996). It and its splays undoubtedly dip under the Green Mountain massif. Much of the massif probably is underlain by carbonate rocks of the Vermont Valley sequence.

Relative age of the F_2 thrust faults

In general, the F_2 generation thrust faults form a normal set of overlapping east-dipping thrust faults, most of which could have formed simultaneously or in sequence. Some out-of-sequence faults are required in the western part of the map. Rocks of the North Chittenden slice are overlain to the east by rocks of the Pine Hill slice. A sliver of autochthonous carbonate (Ꞓd) is shown between these two slices. This wedge of underlying carbonate rocks is interpreted to have formed by out-of-sequence (younger) imbricate faulting also during the F_2 fold- and thrust-event. A similar out-of-sequence younger imbricate fault may also form the western border of the North Chittenden slice. If the interpretation is correct, the sole thrust under the North Chittenden slice may be a blind thrust that dies out upwards in overturned complex folds in the Vermont Valley sequence to the west.

The F_2-generation thrust faults of this area post-date regional F_1 folds and S_1 foliation and belong to the regional fold- and fault-event in the later part of the Taconian orogeny that was described by Stanley and Ratcliffe (1985). The intense zone of faulting associated with the South Pond fault system forms the base of an intensely developed zone of F_2 generation faulting that imbricates all of the eastern cover sequence rocks from the Tyson Formation through the Moretown Formation all along the eastern flank of the Green Mountain massif (Ratcliffe and others, 1992).

Cross folding younger than the F_2 structures is rather weak and only affects the map patterns of the rock units slightly. Northeast trending minor folds (F_3) are expressed by a weak crenulation cleavage. Northwest-trending crenulation cleavage and minor folds (F_4) appear to be due to the youngest structural event. The F_3 and F_4 folds are probably Acadian.

Mesozoic Dikes

Four alkaline mafic dikes (Kmd) of probable Cretaceous age cross cut all the above described features and appear to be the youngest event to have affected this area. These dikes are associated with plutons at Mount Ascutney, dated at 122 Ma (Foland and others, 1985) and at Cuttingsville, Vermont, that may be as young as 100 Ma (Eby and McHone, 1997). A prominent jointing subparallel to the walls of the dikes commonly marks distinct topographic lineaments near the dikes.

Late brittle faults

Brittle microfaults that have distinct slickensided surfaces were found at three localities. In addition, a zone of extensive brecciation was identified in the carbonate rocks near Rutland. A series of brittle oblique faults, trending northwest and dipping 55° to 60° to the northeast, occur in roadcuts of the Dunham Dolomite on route 7, 1 km northwest of the intersection with Chittenden Road. Slickensides plunge southeast, suggesting a high component of strike-slip motion; however, the actual sense of motion could not be determined.

An excellent exposure of microthrust faulting in the Moosalamoo Member of the Mendon Formation can be seen just south (BM761) on Parker Road, south of Long Hill. Subvertical bedding and S_1 foliation are cut by minor thrust faults that strike north-south and dip 32° east. Slickenlines on the faults plunge S.40°E. One- to 2-cm veins of quartz along the fault planes are also buckled by conjugate box folds, indicating general east-west shortening. The fault structures expressed here may be related to the latest, out-of-sequence thrust faulting mentioned previously. A late N-S striking 57° east-dipping slickensided fault also occurs in roadcuts on the south side of route 4, 1.7 km east of Mendon. A prominent spring is developed at this site, along the trace of a mapped thrust fault.

An extremely shattered zone, trending N.70°E. and marked by abundant closely spaced jointing, occurs along the north side of the stream draining Patch Pond. Solution cavities extend into the hillside to the north along the bedding that strikes northsouth and dips 31° to the east. Similar highly jointed rocks and solution-widened joints are present in the Dunham Dolomite in field exposures near the electric substation south of Post Road. The cause of the fracturing is unknown, but similar zones of late brittle, strike-slip faults are present west of the Otter Creek in the southwestern part of the Rutland quadrangle. Zones of fracture-induced permeability probably underlie much of the area northeast of Rutland Town, and there is the potential for finding high-yielding-bedrock water wells in the area, extending northeast from Patch Pond to the area of the Rutland City Reservoir.

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Description of Map Units

Kmd — Mafic dike--Cretaceous--Dark gray to black porphyritic, highly jointed, subvertical camptonite dikes as much as 1 m thick, found at four localities

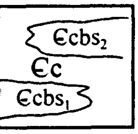
Oi — Ira Formation--Middle Ordovician--Dark gray carbonaceous phyllite (shown only on cross section)

Ꞓcs — Clarendon Springs Dolomite--Upper Cambrian--Steel-gray- to light-gray-weathering, calcitic dolostone, no exposures in quadrangle, presence inferred from structural data

Ꞓw — Winooski Dolomite--Lower Cambrian--Beige- to orangish gray-weathering, highly mottled, and well-bedded, dolostone, having thin siliceous and phyllitic partings, thin 1- to 2-cm-thick beds of dolomitic quartzite

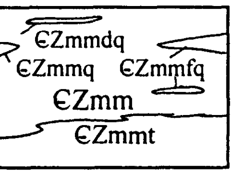
Ꞓm — Monkton Quartzite--Lower Cambrian--Medium-dark-gray- to light-brownish-gray-, deeply weathered, and pitted, dolomitic quartzite, and quartzose dolostone having suspended grains of quartz, locally cross bedded, associated beds of gray-weathering sedimentary dolostone breccia in beds as much as 1 foot thick

Ꞓdbs$_2$ / Ꞓd / Ꞓdbs$_1$ — Dunham Dolomite--Lower Cambrian--Light-gray- to cream-weathering, massive dolostone near the base, grades upwards into gray and white mottled dolostone and dolostone containing abundant layers of polymict matrix-supported sedimentary breccia consisting of subrounded cobbles of various types of dolostone; two lenses of dark gray, Ꞓdbs$_1$ and Ꞓdbs$_2$ weathering dolostone (Ꞓdb$_1$) occurs in the upper part of the formation, the uppermost Ꞓdb$_2$, has spheriodal weathering

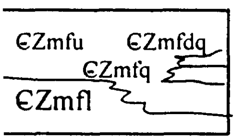


Cheshire Quartzite--Lower Cambrian--Light-gray to white, massive, highly jointed, vitreous quartzite, contains several lenses of dark-gray siliceous muscovite-quartz schist (Єcbs). Lower contact is drawn at the base of the lowest beds consisting of greater than 50 percent of massive vitreous quartzite; passes gradationally downward into feldspathic quartzite and phyllites the Moosalamoo Member of the Mendon Formation

Mendon Formation (Late Precambrian and Lower Cambrian)



Moosalamoo Member--Heterogeneous member consisting predominantly of dark-gray- to medium-gray-weathering, siliceous phyllitic metasiltstone, and dark-gray, flaser-bedded quartzite and interbedded dark-gray to locally tan-weathering phyllite (ЄZmm), near top contains lenses of gray-tan, well-bedded to laminated feldspathic quartzite (ЄZmmfq) and rare lenses of more vitreous quartzite and interbedded flaggy feldspathic quartzite (ЄZmmq) and interlayered dark schist; one lens of punky weathered, dolomitic quartzite (ЄZmmdq) occurs near the top on Bald Peak. Near base contains a prominent but discontinuous zone of magnetite-rich, cross bedded dolomitic quartzite, or gray-brown to greenish-gray-weathering magnetite metasiltstone (ЄZmmt)



Forestdale Member--Dolostone, dolomitic quartzite. Consists from the base up of a massive to well-bedded, cream- to beige-weathering dolostone (ЄZmfl), and an upper orangish-brown- weathering, impure dolostone (ЄZmfu) containing lenses of white-weathering quartz-feldspar grit, or pebbly dolomitic quartzite (ЄZmfq), and highly cross bedded quartzose dolostone (ЄZmfdq), having suspended grains of bluish gray quartz to3 mm in diameter. A thick section of

ЄZmfd

Forestdale occurs west of North Chittenden, elsewhere the dolostone ЄZmfd occurs as thin lens at or near the contact with the Nickwackett Member or is absent. A significant part of the Forestdale is characterized by grainstones consisting of mixture of detrital carbonate and quartz

ЄZmng
ЄZmnc

Nickwackett Member--Either white-weathering, massive quartz-feldspar grit and conglomerate (ЄZmnc) or greenish-gray weathering, chlorite muscovite-albite granofels commonly rich in magnetite (ЄZmng). The best exposures of conglomerate occur on the slopes on east side of the main road 1 km southeast of North Chittenden. Coarse boulder and cobble conglomerate there in inverted sequence unconformably underlies coarse potassium feldspar augen gneiss of the Mount Holly Complex. At other localities where the unconformity with the Mount Holly is exposed or nearly exposed, the basal beds of the Nickwackett Member may be magnetite-rich gritty granofels and or a gray-quartzose metawacke; the more massive, white feldspathic grit (ЄZmnc) may be absent

Eastern Cover Sequence

(Cambrian and Late Proterozoic)

ЄZgs

Green lustrous schist--Green lustrous chlorite-muscovite-albitic schist quartz schist

ЄZbs

Black phyllite--Dark gray to black, fine grained graphitic phyllite, with thin lenses of dark-blue-gray laminated beds of calcite marble

€Zcg	Green chloritoid schist and granofels--Green ankerite-albite-chlorite-muscovite quartz granofels, and chlorite-chloritoid-muscovite quartz granofels (rock of uncertain correlation perhaps altered basement gneiss)

unconformity

INTRUSIVE ROCKS OF THE MOUNT HOLLY COMPLEX

(Middle Proterozoic)

Yp	Pegmatite--Muscovite, tourmaline pegmatite containing large plates of muscovite as much as 4 cm in diameter, and biotite pegmatite, both occur as discrete bodies and as irregular masses enclosing tabular screens of quartzite (Yq) and aluminous chloritoid-bearing schist (Ys), spatially associated with the feather-edge contacts of coarse grained potassium feldspar augen gneiss in paragneiss units

Ykg	Microcline megacrystic gneiss and gneissic granite--Coarse-grained, biotite granitic gneiss having large augen of microcline as much as 5 cm in length, passes laterally into less foliated pegmatoid granite and biotite pegmatite, unit coeval with some or possibly all pegmatite (Yp)

Yap	Aplite--massive, white-weathering, fine-grained quartz-microcline-plagioclase aplite associated with pegmatite

Ygg	Granitic gneiss--Light-gray- to pinkish gray-weathering, biotite-plagioclase-microcline-quartz gneiss, ranges from granite to granodiorite, varies from medium-grained and well layered to more massive to coarse-grained, passes laterally into biotite-

muscovite-pegmatite granite where abundant discontinuous pegmatitic lenses occur. Coarser grained more pegmatitic varieties are found on the footwall of the Burr Pond thrust. Unit interpreted as intrusive granites or perhaps in part migmatitic gneisses of granitic composition

Paragneiss, schist of the Mount Holly Complex (relative tops not known, stratigraphic order uncertain)

Ys

Schist and granofels--Light-gray to greenish gray-weathering, lustrous to non-lustrous epidote-chlorite-muscovite-albite-quartz schist or granofels, lustrous chlorite-muscovite-quartz±chloritoid schist and chlorite-biotite-quartz-albite-epidote (or clinozoisite) quartz granofels, locally contains relict garnet replaced by chlorite or splotchs of biotite also replaced by chlorite. Unit contains rosettes of chloritoid on Blue Ridge Mountain at localities noted by Cht (chloritoid). Interpreted as highly retrograded and chemically altered biotite-garnet-muscovite-plagioclase (sillimanite?) quartz schist, or more aluminous sillimanite(?) muscovite-garnet-quartz schist

Ydm

Dolomite marble--White-gray to beige-tan-weathering coarse-grained to fine-grained dolomite marble, locally an extremely coarse-grained marble having pinkish gray to white zoned dolomite grains as much as 2 cm in diameter, the finer grained varieties are more common and contain accessory tremolite either in bundles of fibrous grains or in larger 5 mm tabular crystals. Passes laterally into calc-silicate rocks (Ycs)

Ycs

Calc-silicate rocks, an heterogeneous assemblage of highly magnesian rocks interfingering with Ydm, Yq or Ys consisting of white- to light-gray-weathering, coarse-grained tremolite±diopside dolomite rock, fibrous tremolite-talc-dolomite schist, or hornblende-diopside rock, exposed on Blue Ridge Mountain at or near the contact between Ys and or Yq

Yq

Quartzite--Massive, white-weathering, medium- to coarse-grained quartzite containing distinctive patches of coarse-grained muscovite, magnetite and tourmaline, locally contains deep-bluish-gray weathering more vitreous and layered quartzite commonly associated with zones of magnetite enrichment

Ycms

Magnetite schist and granofels--Light-green-weathering, lustrous magnetite-chlorite-muscovite-quartz-schist and albite-chlorite magnetite-muscovite-schist, a variant of Ys at or near the contact with Yq and association with Ymt

Yqmt

Magnetite-quartzite breccia and magnetite-rich quartzite--A magnetite-veined, tectonic breccia resembling a conglomerate, having subrounded blocks of quartzite 0.5 to 1 m in diameter surrounded by finer grained siliceous magnetite-rich microbreccia, or coarse-grained magnetite forming a network of veins and pods in fractured quartzite. Associated with pods 10 cm to a meter thick of muscovite-rich, tourmaline-magnetite schist resembling greisen within Yq. Magnetite mineralized zones occur in Yq or localized at the contact of Yq with Yb. Occurs 0.5 km south of Mendon, on the west side of the steep ravine in Yq 1 km northwest of Bald Peak and on the northeast slopes of Blue Ridge Mountain. Coarse-grained nature of the magnetite, the vein networks and irregular podiform masses suggest post-Grenville or late Grenvillian mineralization

Yhg

Hornblende garnet amphibolite--Medium-grained well foliated and well-layered, garnet-plagioclase-magnetite hornblende amphibolite and hornblende spotted plagioclase gneiss that contains pods of hornblende-diopside calc silicate rock to small to map

Yeg
Yegh

Epidote gneiss--Medium- to dark-gray-weathering, magnetite-biotite-epidote-plagioclase±quartz gneiss and interlayered hornblende amphibolite, locally interlayerd with dark gray fine-grained hornblende-diopside amphibolite (Yegh)

Ybg

Biotite-quartz-plagioclase gneiss--Heterogeneous, well-layered, dark-gray to medium-gray weathered biotite-quartz-plagioclase gneiss, hornblende amphibolite, minor lenses of schistose gneiss, quartzite and epidote-biotite quartz gneiss, and dark-green chloritic highly altered diopside(?) gneiss and quartzite having green layers rich in white mica possibly fuchsite

Yfg

Felsic gneiss--Either a light-gray fine-grained magnetite plagioclase-quartz gneiss or a felsic biotite gneiss, resembles aplite

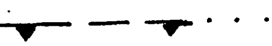
Yu

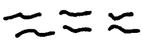
Middle Proterozoic rocks undifferentiated (shown only on cross sections)

EXPLANATION OF MAP UNITS

Contact--Solid where accurately located; dashed where approximately located; dotted where concealed by water

Major faults--Solid where accurately located; dashed where approximately located; dotted where concealed by water

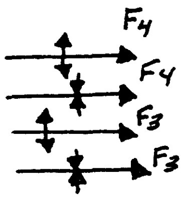

Thrust fault--Teeth on upper plate


Mylonite zone

FOLDS

Axial trace of major folds--Arrow shows approximate direction of plunge where known. Relative age identified by subscript; the greater the subscript, the younger the age

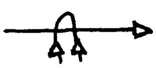
Upright Acadian(?) fold



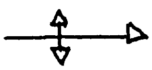
F_4 antiform
F_4 synform
F_3 antiform
F_3 synform

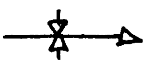

F_2 folds (Taconian ?)--Barb shows dip direction of axial surface. Arrow shows approximate plunge direction where known

F_1 folds (Taconian folds)


Overturned anticline


Overturned syncline


Upright anticline


Upright syncline

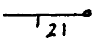
Middle Proterozoic Fold


Upright fold (original sense of closure uncertain)

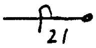
PLANAR STRUCTURES

(May be combined; joined at point of observation)

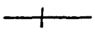
Strike and dip of bedding (ball on strike line indicates top know from sedimentary structures)



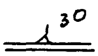
Inclined



Overturned


Vertical

Strike and dip of gneissosity in Middle Proterozoic rocks a Middle Proterozoic structure



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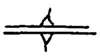
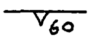

Vertical

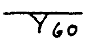
Strike and dip of S_1 foliation (Taconian)



Inclined


Vertical

Strike and dip of S_1 foliation and parallel bedding



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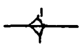

Vertical

Strike and dip of mylonite foliation (Taconian?) or second (S2) foliation; commonly associated with thrust faults and abundant reclined minor folds that plunge southeast subparallel to an elongation direction

Inclined

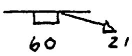

Vertical

Strike and dip of crenulation cleavage (Acadian?)

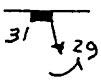
Inclined

Vertical

Axial planes of minor folds (combined arrow gives direction and plunge of hingeline of the fold; small arc shows sense of rotation given by asymmetric minor fold as view down plunge)

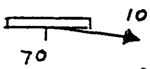


F_1 (Taconian fold, S_1 is axial surface)

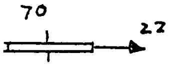


F_2 (Taconian?) fold, S_2 foliation as axial surface, many folds of this generation are reclined and plunge in the direction of dip of the axial surface

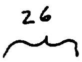
Late folds (F_2 or younger)



Inclined



Vertical

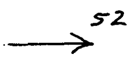


General strike and dip of highly folded gneissosity in Middle Proterozoic rocks, or of foliation in younger rocks

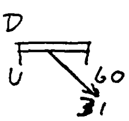
LINEAR FEATURE

(Azimuth and plunge of hingeline of folds or intersection lineation; open arrows indicate intersection with bedding, solid arrow indicates intersection with foliation or folds of foliation, shown joined with symbol for the planar feature in which the lineation lies)

F_2 or younger hingeline, or F_2 elongation lineation in S_2 foliation at or near thrust faults



Slickenline combine with symbol for brittle fault



Strike and dip of minor brittle fault and azimuth and plunge of slickenlines

Movement sense D (down) and U (up)

CORRELATION OF MAP UNITS