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# Preliminary bedrock geologic map of the Andover quadrangle, Windsor County, Vermont

BY

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## Introduction

The Andover Quadrangle contains Middle Proterozoic through Devonian igneous, metaigneous and metasedimentary rocks. The oldest rocks, Middle Proterozoic gneisses of the Mount Holly Complex, occur in the western part of the quadrangle, along the east margin of the Green Mountain massif, and also in the Butternut Hill fold, a major south-closing appendage of the Chester dome. Core gneisses of the Chester dome occur at the eastern edge of the quadrangle. Late Proterozoic through Ordovician cover rocks dip to the east off of the Green Mountain massif and flank the Butternut Hill fold. Two tightly pinched synforms, the Proctorsville syncline and the Spring Hill fold contain rocks of Silurian and/or Devonian age and therefore must be Acadian structures. Rocks of the Spring Hill fold dip steeply to the west off the west flank of the Chester dome, which also is an Acadian structure. The pre-Silurian rocks contain abundant thrust faults and complex reclined folds that probably are Taconian. These have been refolded by intense Acadian deformation.

Previous investigations in the Andover Quadrangle include the unpublished Ph.D. thesis of J.B. Thompson, Jr. (1950) and his subsequent studies that were incorporated in the Centennial Geologic Map of Vermont at 1:250,000 (Doll and others, 1961). More recent compilations include Thompson, McLelland and Rankin (1990) and Thompson, Rosenfeld, and Chamberlain (1993). Regional structural studies include Rosenfeld (1968), Ratcliffe, Armstrong, and Tracy (1992), and Ratcliffe and Armstrong (1995). Recent geologic maps of the adjacent quadrangles are: Cavendish (Ratcliffe, 1995a), Chester (Ratcliffe, 1995b), Saxtons River 7.5x15 minute quadrangle (Ratcliffe and Armstrong, 1995), the Mount Holly and Ludlow quadrangles (Ratcliffe, 1992; and Walsh and others, 1994), and the Jamaica-Townshend area (Karabinos, 1984 and Ratcliffe, in press).

In previous interpretations of the geology, the Butternut Hill fold was viewed as an inverted anticline (synform) cored by Middle Proterozoic rocks, and the complimentary Spring Hill fold (the Star Hill fold of Thompson, 1950) was viewed as antiformal. The Spring Hill fold according to Rosenfeld (1954,

1968) and Thompson (1950) plunges to the north underneath core gneisses of the Chester dome. Subsequent work by Ratcliffe (1994a) showed that such an interpretation was not supported by the mapping at Star Hill in the Cavendish Quadrangle. Likewise at the southern closure of the Butternut Hill fold in the Saxtons River Quadrangle (Ratcliffe, 1993; Ratcliffe and Armstrong, 1995), cover rocks overlie, not underlie, the gneisses in a southwest plunging fold. Based on these observations the Butternut Hill and Spring Hill folds are interpreted as antiformal and synformal folds respectively.

In addition to the differences of interpretation of the major structures in the quadrangle, there are differences of opinion regarding the assignment of stratigraphic units and their interrelationships. The Tyson, Plymouth, Pinney Hollow, Ottauquechee, Stowe, and Moretown Formations have classically been interpreted as a single continuous stratigraphic section that tops eastward away from basement rocks of the Green Mountain massif. Recent studies in southern Vermont, however have indicated that these formations are either fault bounded or highly heterogeneous to the point that a coherent stratigraphic succession is not determinable (Ratcliffe, 1994b; Walsh and Ratcliffe, 1994). The basal unit, the Tyson Formation rests unconformably on the Mount Holly Complex and interfingers with the Hoosac Formation in the southwest corner of the map. The Hoosac Formation appears on the Butternut Hill fold where it is interpreted to unconformably overlie the Mount Holly Complex.

Within this quadrangle, an additional complication involves the age and correlation of the cover rocks in the Steadman Hill area east to the west flank of the Butternut Hill fold. Doll and others (1961) showed these rocks as units of the Moretown member of the Missisquoi Formation (of Doll and others, 1961) of Ordovician age. Subsequently the bulk of these rocks were assigned to the Cambrian Ottauquechee Formation by Thompson, Rosenfeld, and Chamberlain (1993). I conclude, for reasons explained later, that the older assignment is more nearly correct, and that the bulk of these rocks belong to the Moretown Formation and the Cram Hill Formation. The cover rocks above the Middle Proterozoic basement rocks of the Butternut Hill fold are interpreted as units of the Moretown Formation that, in many places, are in fault contact with the basement rocks. As a result, correlatives of the Hoosac, Pinney Hollow and Ottauquechee Formations are largely absent. Limited exposures of garnetiferous schists, possibly correlative with the Stowe Formation, may be present but also are largely absent in the cover sequence of the Butternut Hill fold and in that of the western flank of the Chester dome.

All the rocks in the quadrangle except for Devonian granite dikes are highly metamorphosed, having been subjected in part to Middle Proterozoic, Ordovician (Taconian), or Middle Devonian (Acadian) metamorphism and deformation. The latest Acadian metamorphism varies from perhaps garnet grade in the west to kyanite-staurolite grade in the east. Almost certainly the older Taconian metamorphism was garnet grade or higher throughout the area but vestiges of older metamorphism are rare and may only exist as the cores of some garnets as described by Rosenfeld (1968) and by Karabinos (1984).

Previous plate tectonic interpretations of the pre-Taconian, Taconian and Acadian tectonism can be found in Stanley and Ratcliffe (1985). In broad general terms, the rocks of the Andover Quadrangle can be assigned to the following mega-lithotectonic assemblages:

(1) Rocks of the Laurentian plate. These include the Mount Holly Complex and its immediate unconformable cover of the Tyson and Hoosac, and Plymouth Formations that together formed the basement and cover affected by ancient Late Proterozoic rifting leading to formation of the Laurentian passive continental margin in the Cambrian and Ordovician.

(2) Rocks of the late-rift and oceanic-drifting stage. These include the Pinney Hollow, Ottauquechee, and Stowe Formations. Although these rocks were deposited in a deepening and widening Iapetan ocean basin, sediment polarity was largely from the Laurentian margin and these rocks are not therefore truly exotic rocks.

(3) Rocks of the oceanic arc and fore-arc accretionary prism. These include the rocks of the Moretown Formation, and the Cram Hill Formation and may include felsic and mafic volcanic or intrusive rocks of the Barnard Gneiss of Richardson (1929). These rocks and the contained ultramafic rocks are exotic to the Laurentian plate.

(4) Post-accretionary Taconian or late Taconian metasedimentary and volcanic rocks. In the Andover Quadrangle these may include some rocks of the Cram Hill Formation and the Silurian and Devonian rocks of the Waits River Formation.

(5) Acadian granite dikes and sills formed late in the Acadian orogeny and following much of the doming but not before all of the tightening of the Acadian folds marginal to the Chester dome.

(6) Outside the Andover Quadrangle abundant Cretaceous lamprophyre, diabase and syenitic dikes are present and are related to a major episode of intraplate alkaline plutonism.

## Stratigraphic Problems of Special Note

Middle Proterozoic units of the Mount Holly Complex in the Green Mountain massif, exposed in the western part of the map, consist of metasedimentary rocks, schists, calc-silicate rock, quartzites and biotite-quartz-plagioclase paragneiss that contains layers of amphibolite. The complex also contains intrusive granite gneiss, pegmatite, hornblende diorite gneiss and trondhjemitic rocks that may or may not be intrusive. The trondhjemite gneisses, in adjacent areas yield U-Pb zircon upper intercept ages of about 1.35 to 1.3 Ga (Ratcliffe and others, 1991). Elsewhere, post-tectonic granites of the Cardinal Brook Intrusive Suite have been dated at about 0.95 Ga (Karabinos and Aleinikoff, 1990). These data suggest that rocks in the Mount Holly Complex, which are defined (Ratcliffe, 1991) as older than the Cardinal Brook Intrusive Suite, range in age from greater than 1.35 to 0.95 Ga.

Very similar rocks of the Mount Holly Complex reappear in the Butternut Hill fold. A trondhjemitic gneiss there is known informally as the Felchville gneiss (unit Ygp on this map). $^{207}Pb/^{206}Pb$ ages as great as 1.4 Ga have been determined for the cores of zircons from the Felchville gneiss in the Cavendish Quadrangle, suggesting ages in excess of 1.4 Ga for the Mount Holly Complex in the core of the Chester dome (written communication from John Aleinikoff, 1994; Ratcliffe, Aleinikoff and Hames, 1996). Except for the much greater deformation of the Mount Holly Complex of the Butternut Hill fold, the rocks are approximately correlative and lithically very similar to rocks in the Green Mountain massif.

Cover sequence rocks above the Hoosac Formation on the west flank of the Chester dome and adjacent Butternut Hill fold are typical of the Moretown Formation rather than the Pinney Hollow, Ottauquechee and Stowe Formations. Along the eastern side of the Chester and Athens domes, from a point north of Cambridgeport in the Saxtons River 7.5x15 minute quadrangle, feldspathic granofels and hornblende-fascicle schist and granofels typical of the Moretown Formation occur within 100 meters of the basement rocks. From this point northward and around the north end of the Chester dome the cover rocks resting directly on the basement rocks, are typical of either feldspathic granofels of the Moretown or possibly schists and coticule of the Stowe Formation. Stratigraphic units typical of the Hoosac, Pinney Hollow, and Ottauquechee are largely absent along the west side of the Chester dome south to the northern border of the Saxtons River Quadrangle, where some exposures of Hoosac-like rocks exist along the Moretown-basement contact.

In the Andover Quadrangle, the Moretown Formation is exposed in three different belts. The eastern belt in the core of the Spring Hill fold, consists of the pinstriped granofels member (Oml) and a greenish chlorite-muscovite schist and hornblende-fascicle schist (Omhfs) that contains beds of typical pinstripe granofels. Only minor areas of black schist (Ombs) associated with talc deposits and amphibolite are present.

The Moretown units of the Steadman Hill area consist predominantly of dark gray, slabby weathering schist (Ombs) that locally is carbonaceous but which is distinctly quartzose and which contains abundant discrete flakes of biotite. Beds of typical feldspathic pinstripe granofels are common throughout, as well as dark-gray to black vitreous quartzite in beds 1 to 5 m thick. Overall this black schist is much more quartzose and coarser grained than black schist of the Ottauquechee Formation and the two units are quite dissimilar. A very feldspathic granofels (Omfgc), either gray or greenish that contains thin beds or laminae of garnet-rich, fine-grained quartzite or true coticule is interbedded within the Ombs member and is easily separable. This granofels appears at different structural positions within the Steadman Hill and Proctorsville folds. This member and the Ombs member are involved in folds that are discordant to the lower contact of the Moretown. The map pattern suggests that an older generation of pre-Acadian folds may have formed within the Moretown during emplacement perhaps in the Taconian orogeny. The Omfgc unit resembles both the pinstripe granofels member Oml and the green granofels unit exposed in the belt of Moretown that extends south from Whetstone Hill.

On Whetstone Hill, and in the strike belt to the south, a fine-grained carbonaceous gray to papery tan garnet or biotite porphyroblastic phyllite (Omws) is exposed. Associated with this phyllite are magnetite-bearing coticule beds (Omwc) and dark-gray quartzite and epidotic quartzite (Omwq), as well as a very minor but distinctive volcaniclastic breccia (Omwv). Associated with these rocks and underlying them at Whetstone Hill, is a greenish-gray to gray feldspathic metasiltstone (Omwg). All the units above were previously mapped as the Whetstone Hill Member of the Missiquoi Formation of Doll and others (1961). Distinctive interbeds of pinstriped granofels (Oml) are common near the border of the schists and it is quite clear that the schists are interbedded with rocks typical of the Moretown Formation. These schists (Omws, Omwg) and associated coticule (Omwc) do resemble schists above the Moretown Formation in the core of the Spring Hill syncline, and along the eastern margin of the Chester dome in the Saxtons River quadrangle (Ratcliffe and Armstrong, 1995). The schists at Spring Hill correlate closely with rocks east of the Chester dome that contain abundant mafic to intermediate amphibolites, quartz-pebble conglomerate, and felsic and mafic volcanic rocks that are traceable into the Hawley Formation of Massachusetts (Ratcliffe and Armstrong, 1995). The rocks of the Whetstone area, however, both in the Andover quadrangle and further north in the Ludlow quadrangle (Walsh and Ratcliffe, 1994), lack the abundant mafic volcanic rocks and felsic volcanic rocks characteristic of the Hawley. I conclude that the rocks on Whetstone Hill are not correlative with rocks of the Hawley, but are part of the Moretown Formation as originally determined by Thompson (1950). The recent correlation of the Whetstone Hill phyllite member with the Hawley by Thompson, Rosenfeld and Chamberlain (1993) is therefore not accepted here.

Although the three outcrop belts of the Moretown in this quadrangle seemingly contain quite different stratigraphies, there is an overall similarity in the lithologies present in each belt and it is the proportions that vary. Map relations throughout southern Vermont indicate that the Moretown Formation is very heterogeneous and that rock units as well as structures within the Moretown are discordant to basal thrusts that underlie the Moretown (Ratcliffe and Armstrong, 1995). Numerous large to small ultramafic bodies, now converted to talc or talc-carbonate schists, are found within the Moretown Formation. At some localities the talcose rock appears bedded within schists of the Moretown, and at other places blocks of ultramafic rock 0.2 m to 0.5 m in diameter appear within otherwise normal metasedimentary rock. A particularly coarse-grained, gritty feldspathic quartzite (Omgrt) is spatially associated with zones of talc schist and complex sedimentary(?) breccias along the base of the Ombs unit on the Potash Brook fault.

The belt of ultramafic rocks that extends from near Proctorsville in the Ludlow Quadrangle to the center of the Townshend Quadrangle is spatially associated with the black schist (Ombs) of the Moretown. The close association of the ultramafic rocks with the Ombs unit and the presence of sedimentary blocks or "bedded" ultramafic rock suggests that the ultramafic rocks may be olistoliths.

The differences in the stratigraphy of the Moretown Formation from the Whetstone Hill and Steadman Hill areas and from the Spring Hill fold, are exaggerated by the close distinctions made between similar different facies described above. In part these subtly different packages may be the result of early, unrecognized faulting in the Moretown basin during subduction and formation of an accretionary prism in the Taconian orogeny (Stanley and Ratcliffe, 1985). The association of the ultramafic rocks with the black schist (Ombs) unit is very strong and suggests, along with the olistolithic features, slumping of large to small blocks of serpentinized oceanic mantle into a euxinic part of the Moretown basin.

The faults shown on the map that floor the Moretown Formation are, however, syn- to post-metamorphic faults and formed well after accretionary processes ended, probably during collision and emplacement of the accretionary wedge onto the Taconian-deformed continental Laurentian plate. Because the Moretown accretionary rocks began their emplacement from an oceanward and lower structural position than the Laurentian crust (represented by the Mount Holly Complex) the younger Moretown could be emplaced by thrust faulting over older cover rocks of the Laurentian plate (Stanley and Ratcliffe, 1985).

Dark schists (Ombs) of the Moretown are indistinguishable from similar schists mapped elsewhere as the Cram Hill Formation and it is possible that all or part of what is mapped here as Ombs correlates with Cram Hill as mapped elsewhere by Currier and Jahns (1941). In this quadrangle and to the north in the Ludlow Quadrangle, these dark schists are interbedded with felsic metavolcanic rocks of the Barnard Gneiss of Richardson (1929). At the type locality of the Barnard Gneiss in Bethel, Vermont, layers of felsic granofels, and ankeritic greenstone occur interbedded with rocks of the Moretown Formation. Similar relations occur in the Ludlow Quadrangle (Walsh and Ratcliffe, 1994). The bulk of the Barnard Gneiss in the Ludlow Quadrangle, however, appears to be metatrondhjemite that intrudes the contact between Ombs and typical feldspathic pinstripe granofels of the Moretown (Oml). Therefore the type Barnard Gneiss of Richardson (1929) may include both intrusive rocks as well as layered volcanic rocks. The intrusive units should be singled out and assigned to a named intrusive suite. East of the Chester dome these intrusive rocks, previously referred to as the Barnard volcanic member of the Missisquoi

Formation (of Doll and others) have been termed the North River Intrusive Suite (Armstrong, 1994). Where the volcanic rocks can be mapped as a part of another recognizable formation, they should be referred to as volcanic or volcaniclastic members; here they would be members of the Moretown or Cram Hill Formations.

In this map, units thought to be volcanic and volcaniclastic units above the Moretown Formation are informally referred to as the Barnard member of the Cram Hill Formation and the base of the Cram Hill is drawn at the base of the lowest and predominantly felsic member (Obf). A mixed unit (Obm) contains layered felsic and mafic layers, 10 cm to 1 m thick, interspersed with feldspathic granofels, and this is overlain by a unit consisting predominantly of amphibolite (Oba). Locally dark biotitic schist overlies the amphibolites and is assigned to the Cram Hill Formation (Och).

At the base of the Waits River Formation, in the Proctorsville syncline, is a thin, less than 10-m-thick unit of well-laminated epidote-hornblende amphibolite, granofels, and quartz-rich granofels that passes along strike into limey phyllite or thinly laminated felsic and mafic volcaniclastic beds (DSvc). In the adjacent Cavendish Quadrangle, this unit (DScv) is clearly interbedded at the base of the Waits River Formation. The felsic and mafic laminated rocks resemble the Obm unit of the Barnard, and are interpreted as recycled volcaniclastic rocks derived by erosion of the underlying Barnard Gneiss (of Richardson, 1929). The Moretown in the core of the Spring Hill fold is overlain by a well laminated, felsic to intermediate volcaniclastic rock and amphibolite (Ochv) and feldspathic granofels (Ochq). Both units are assigned to the Cram Hill Formation and may correlate with the Obm unit of the Proctorsville syncline.

## Structural Geology

### Introduction

Middle Proterozoic rocks of the Green Mountain massif trend east-southeast and occur in the western part of the quadrangle, where they are unconformably overlain by rocks of the Hoosac and Tyson Formations. Above these, is the foliated, east-dipping and thrust-faulted sequence of Pinney Hollow, Ottauquechee and Stowe Formations, exposed in the central part of the quadrangle. Rocks of the Moretown Formation, including the Whetstone Hill member of the Moretown Formation, overlie the Stowe Formation, perhaps on a thrust fault. The dominant structure within this section as far east as Whetstone Hill, is a moderately steeply east-dipping Taconian schistosity. This schistosity everywhere contains macroscopic hooks and noses of strongly deformed folded foliation. These folds plunge steeply to the southeast nearly down the dip of the foliation in reclined folds. This structure is known regionally to be the second generation or $F_2$ folding event in the pre-Silurian rocks and is interpreted as a Taconian fabric. This fabric is most intense at or near contacts between units which are mapped as Taconian thrust faults.

East of Whetstone Hill, Acadian folds increase in intensity and plicate the older Taconian foliation and $F_2$ folds in upright to overturned folds; these folds are complimented by development of an intense crenulation cleavage. The eastern half of the map is dominated by intense Acadian plications especially in the Proctorsville fold system. Middle Proterozoic rocks of the Mount Holly Complex reappear in the antiformal Butternut Hill fold. Rocks of the Moretown Formation occur in a folded thrust sheet, and are down-folded into the basement rock along the Acadian Spring Hill syncline. Middle Proterozoic rocks reappear at the easternmost edge of the quadrangle on the west limb of the Chester dome.

In the eastern part of the quadrangle, where Acadian structures are dominant, relict Taconian structure and the reclined $F_2$ folds are best preserved on the limbs of Acadian folds. Well developed $F_2$ folds appear along both limbs of the Butternut Hill fold and along the west dipping contact between cover rock and gneisses of the Chester dome. Here the older $F_2$ lineations plunge steeply to the northwest. In the center part of the Proctorsville fold system, where the older $S_2$ foliation is very tightly folded into subvertical Acadian folds, the older $F_2$ lineations are nearly destroyed or obscured by the intensity of the later folding.

Pre-Acadian (Taconian) deformation probably affected all the pre-Silurian rocks of the quadrangle. The Taconian events appear to be responsible for large-scale imbrication of basement and cover rocks originally on gently east-dipping faults. Strong transposition accompanied formation of a regionally important set of reclined folds whose hingelines are approximately parallel to the elongation or emplacement direction of the faults. These thrust faults and the foliation were subsequently folded to form the Acadian Chester dome.

The contact between basement gneisses and the Moretown Formation indicate that the Moretown was emplaced on and truncated earlier folds and thrust-faulted rocks in the hanging wall. On a regional scale, the fault contacts with basement rocks now exposed in the Chester and Athens domes (of Acadian age) represent the down dip parts of the Moretown faults, that to the north and west climb up section across the earlier, accumulated thrust faults in the Tyson, Plymouth, Pinney Hollow, Ottauquechee, and Stowe Formations. The contacts at the base of the Moretown Formation are therefore interpreted as Taconian faults resulting from up thrusting of the exotic accretionary rocks onto the Laurentian or continental block. The metamorphic fabrics and lineations associated with these faults are comparable to those early structures (Taconian) found in the thrust-faulted cover rocks older than the Moretown Formation. This structure is folded over the domes, and is highly folded in Acadian folds elsewhere.

Three major Acadian folds dominate the structure in the eastern half of the map. From east to west these are: the Spring Hill syncline, the Butternut Hill fold, and the Proctorsville fold system, which contains Devonian and Silurian rocks of the Waits River Formation. The tightly appressed pre-Silurian rocks in these folds contain relict Middle Proterozoic and, Ordovician (Taconian) folds, gneissosity and schistosity. Because of these pre-Acadian features, the Acadian folds are highly irregular both in plunge direction and in amount of plunge. In particular, plunges of folds in pre-Silurian rocks reverse from northeast to southwest along the axial trace of the Acadian folds. Commonly these folds plunge very steeply, either to the northeast or to the southwest or in some cases, down the dip of the Acadian foliation. This contrasts markedly with the plunge of folds in the Silurian and Devonian rocks, which is consistently to the northeast at about 15 degrees.

The dominant and oldest foliation in the Silurian and Devonian rocks of the Waits River Formation dips steeply northwest and is subparallel to the limbs of isoclinal folds of bedding. The hinge lines of these folds plunge northeast. In pre-Silurian rocks, the first generation Acadian folds are expressed by tight, nearly isoclinal, subvertical to southeast overturned folds of schistosity or gneissic layering. Commonly a strong to moderately strong crenulation cleavage is parallel to the axial surface of these folds. On the limbs of these folds the older, pre-Acadian schistosity and the Acadian crenulation cleavage are parallel or intersect at small angles of strike or dip.

In the Proctorsville, Butternut Hill, and Spring Hill folds, two later and apparently conjugate crenulation cleavages are present. These crenulation cleavages dip moderately east and west and fold the oldest foliation in the Silurian and Devonian rocks and both the pre-Acadian schistosity and first-stage Acadian crenulation cleavage in pre-Silurian rocks. Very commonly, these oppositely dipping crenulation cleavages produce opposed asymmetric minor folds in the same outcrop. The folds have opposite rotation senses but a common orientation of their hinge lines. The obtuse bisectrix of the two late crenulation cleavages is subhorizontal and the acute bisectrix subvertical. This configuration suggests an important component of flattening related to later tightening of the main Acadian folds. This characteristic pattern is especially well developed in the Waits River Formation and older rocks in the core of and on the steep west-dipping limb of the Butternut Hill fold.

## Rotation sense of minor folds

The rotation sense of Acadian minor folds is highly variable and depends entirely upon the intersection relationship between the dip direction of the folded foliation and the dip direction of the axial surface of the folds. Likewise the direction of plunge is governed by the general strike of the foliation or gneissosity and the strike of the axial surface of the later folds. Because of the control that orientation of the older foliation or gneissosity exerts, the rotation sense and plunge direction of minor folds has only local significance. A previous interpretation of the major folds, based on the plunge and rotation sense of minor folds, indicated that the Proctorsville and Butternut Hill folds plunged to the northeast (Thompson, 1950; Rosenfeld, 1954), however re-examination of minor folds on the limbs of the Butternut Hill fold by Nisbet (1976) suggested that neither the rotation sense or plunge directions of minor folds were consistent with such an interpretation. Examination of the plunge and rotation senses of minor folds observed in this study support the observations of Nisbet. Observations along the southern closure of the Butternut Hill fold in the Saxtons River Quadrangle (Ratcliffe, 1993; Ratcliffe and Armstrong, 1995) indicates that the regional plunge is to the southwest. Therefore, we interpreted the Butternut Hill fold as antiformal and the structural compliment to the Spring Hill syncline on the east, and to the Proctorsville fold on the west.

## Spring Hill syncline

Metavolcanic and metasedimentary rocks of the Cram Hill Formation lie in the core of the Spring Hill syncline (as defined by Ratcliffe and Armstrong, 1995). At the northern closure of the Cram Hill, plunges of Acadian minor folds are consistently to the south as they are in the northern half of the syncline in the Saxtons River Quadrangle. These observations do not support the northerly plunges and inverted rocks as suggested by Rosenfeld (1954). At the northern closure of the Spring Hill syncline, in the Chester Quadrangle, (Ratcliffe, 1995b) northerly plunges are not present and the folds plunge either southwest or west.

Acadian plunges tend to be subhorizontal throughout most of the syncline in this map because the strike of the crenulation cleavages and the strike of the older schistosity (Taconian) are commonly parallel. However, the minor folds do not plunge uniformly in one direction and the average fold plunge probably is subhorizontal.

Butternut Hill fold

The Butternut Hill fold, like the Proctorsville fold to the west, appears to be a composite of several smaller en echelon and doubly plunging folds. The tight folding exhibited by units of the Mount Holly Complex suggest intense plication rather than folding in a single highly attenuated isoclinal fold. The highly variable plunges reflect variations in the dip direction of gneissosity prior to Acadian folding, resulting from a combination of Middle Proterozoic, and Taconian folding. The axial surfaces of the dominant minor folds trend northeast and are vertical or dip steeply to the northwest or to the southeast. Very commonly, the plunges of hingelines in a single outcrop are quite variable. Complex interference folds having lunate- or anchor-shaped outlines are common. These forms suggest intersection of folds having nearly orthogonal axial traces. Excellent exposures of folds of this kind may be seen in the bed of the Williams River from near route 103 westward to the contact with the Moretown Formation on the west limb of the Butternut Hill fold.

Along the length of the Butternut Hill fold and extending northwestward on the limb of the Proctorsville fold, a prominent northwest-striking, northeast dipping crenulation cleavage is well developed. This cleavage is younger than the main-phase folding of the Butternut Hill and Proctorsville folds. Because of its oblique orientation, relative to the northeast-striking, northwest-dipping gneissosity or schistosity, minor folds tend to plunge northeast and have a rather consistent up-from-the-west sense of rotation. This is true regardless of where the folds are located: either on the east, center, or west limb of the Butternut Hill fold. This illustrates how misleading minor folds might be in interpreting regional plunges and form of larger folds.

Proctorsville fold system

The Proctorsville fold system consists of four subparallel en echelon folds. The Proctorsville syncline proper is a tightly appressed, northeast-verging fold cored with Devonian and Silurian phyllites of the Waits River Formation. Bedding and foliation intersections plunge horizontally to as much as 15 degrees north. The axial trace is reasonably well defined to the southern closure of the Waits River Formation. From that point southward the fold appears to bifurcate into several smaller folds expressed in the underlying Cram Hill and Barnard gneiss. As a result, the amplitude of the Proctorsville syncline decreases and the amplitude on the western unnamed fold appears to increase.

A well-developed crenulation cleavage forms the axial surface of folds in the pre-Silurian rocks. Plunges of folds of foliation within these rocks are irregular and locally are very steep to the northeast or to the southwest. The plunges which are to the northeast probably reflect the pre-Acadian easterly dip of the Taconian foliation. Acadian axial traces trend approximately 25 degrees east of the more northerly striking Taconian foliation. This in conjunction with the vertical or even west-dipping Acadian crenulation cleavage, creates a regional bias towards north or northeast plunging folds in the pre-Silurian rocks.

The northeast-striking crenulation cleavage associated with the main-phase Acadian folds trends diagonally across the belt of Moretown and is responsible for numerous folds in the Steadman Hill area. South of this hill, the belt of Moretown narrows and an antiformal exposure of Stowe appears east of the axial trace of the main synform. A similar and well-developed north-plunging antiform, the Proctor-

Piper fold, occurs west of the Proctorsville syncline. It is clear that the widest part of the Moretown belt occurs where the four en echelon Acadian folds are present. These plications cut obliquely from northeast to the southwest across the more northerly trending belt of Moretown.

Discussion of Cross Sections

Both cross sections A-A' and B-B' extend from the basement rocks of the Green Mountain massif to the western flank of the Chester dome. The structural arguments made previously support the synformal nature of the Moretown rocks in the Whetstone Hill and Steadman Hill areas. In section A-A' Silurian and Devonian rocks of the Proctorsville syncline are projected on rather shallow $\approx 10°$ northerly plunges into the line of section. The uncomplicated stratigraphy and synclinal cross section of the Devonian and Silurian Waits River Formation contrasts markedly with the complicated refolded folds in the underlying Cambrian and Ordovician rocks. Near the contact of the Moretown and the basement rock the Omfgc and Omgs members of the Moretown Formation form a steeply west-dipping reclined $F_2$ isoclinal fold with a hinge line that plunges to the northwest. This fold projects upward into the line of section and closes in the air above the crest of the Butternut Hill fold.

Plunge reversals of folds in the core gneisses of the Butternut Hill fold are abundant, suggesting that Yrg unit projects above the Earth's surface in the rather simple folds illustrated. The tightly folded Spring Hill fold appears to be synform as shown, however an abundance of northwest-plunging reclined minor folds, like those along the west limb of the Butternut Hill fold, are present. A more complex geometry involving major reclined folds is possible. The dominant folding however, folds the schistosity that is the axial surface of the reclined folds, and amplitude of the fold seems to be largely the result of Acadian shortening.

In section B-B', the south-plunging rocks of the Cram Hill in the keel of the Spring Hill fold, are projected upwards into the line of section. These plunge data support the overall synformal pattern of the

Spring Hill fold. In the Saxtons River Quadrangle, the Cram Hill rocks in the core of the fold occupy a doubly plunging Acadian syncline. In the core of the Butternut Hill fold, the axial trace of an upright Middle Proterozoic fold has been refolded. The isolated repeats of Ya and Ybg within the Ymig unit, shown above the ground, are the expression of steeply dipping east-west-trending layering controlled by the subvertical older axial surface and the intersection of the units with the vertical section. Minor folds in this area exhibit steep plunges both to the north and to the south suggesting refolding of subvertical rocks.

In both A-A' and B-B' a folded thrust fault is shown within the Mount Holly Complex that extends downward from the east side of the sections. This fault is the down-dip projection of the Hawks Mountain fault, that in the Chester Quadrangle to the east, thrusts rocks of the Cavendish Formation over tonalitic gneisses in the core of the Chester dome. This fault is interpreted as a pre-dome thrust fault that roots within the core of the dome and which passes up section to the west (Ratcliffe, 1995b). It is interpreted as a Taconian thrust that imbricated basement and cover rocks and which subsequently was folded. To the west, this fault is shown as merging with the $F_2$ generation Andover thrust, that places Pinney Hollow over the underlying Plymouth and Tyson Formations.

The Moretown Formation is shown as floored by thrust faults that cut down to and across the basement rocks of the Chester dome. These same faults are interpreted to pass up section to the west, cutting across older thrust faults in the Tyson through Stowe section to the west. All these faults are interpreted as Taconian. The connection between these faults is highly interpretive. As shown on section B-B' the Nancy Brook fault may connect in the subsurface with a Taconian master, but hypothetical fault that carries the core gneisses of the Butternut Hill fold of the Chester dome over an unknown thickness of cover sequence rocks. These faults are all interpreted to have formed in the Taconian orogeny and were subsequently folded in the Acadian orogeny.

## Economic Geology

Talc and serpentinite were quarried extensively in the Andover area. The least extensive talc and talc-carbonate deposits in Spring Hill fold are associated with amphibolite (Oma), laminated granofels (Oml), and dark schist (Ombs) of the Moretown Formation. Three small abandoned quarries are located along a strike-distance of 1.5 km. The southernmost, water-filled quarry, is located south of Reservoir Road. A small opening in a layer of talc schist about 5 m thick is located on the south facing slopes 0.2 km northeast of the active gravel pit on the east side of Reservoir Road. The third small area consists of a series of small pits on the ridge 0.5 km east of Chester Reservoir, where there are the remains of a quarry mast and crane.

Much more extensive quarrying was associated with the major belt of serpentinite and talc that extends from the Proctorsville area south into the Andover Quadrangle. Prospecting and coring has taken place at a few localities south of the Williams River, but there is no evidence of active quarrying. An adit at the 1300 foot level extends northward into the south facing slopes above the Williams River toward the large abandoned quarry 0.5 km to the north, where a layer of talc schist approximately 10 to 15 m thick was quarried extensively. To the north of this quarry, numerous abandoned quarries exist. At the present time the slopes above the 1500 feet elevation, southeast of the landing strip are being cleared for open-pit mining of talc and talc-carbonate rock. The once extensive underground workings in this area have in part, been re-excavated by surface mining and this area is currently being quarried. There is no evidence that the small occurrence of ultramafic rock in the Proctor Piper State Forest near the northeastern corner of the map has ever been either prospected or quarried. To the north and south of this quadrangle talc and talc-carbonate rocks occur within the Stowe Formation but there are no such exposures in this quadrangle. At the present time the talc quarried here and from the Hamm Pit in the adjacent Saxtons River Quadrangle is being used as commercial filler for strengthening and adding flexibility to plastics.

Aside from abandoned and active sand and gravel pits in the area many of which are shown on the topographic base, the author is not aware of any other economic geologic materials that have been exploited. There is potential for small scale mining of well- foliated gneiss and schists for flagstone, especially in the highly foliated gneisses along the east side of the Butternut Hill fold from the Middle Branch of the Williams River northward. Similarly, highly foliated amphibolite of the Cram Hill Formation, on the east side of the Proctorsville syncline, could be used for flagstone or facing stone.

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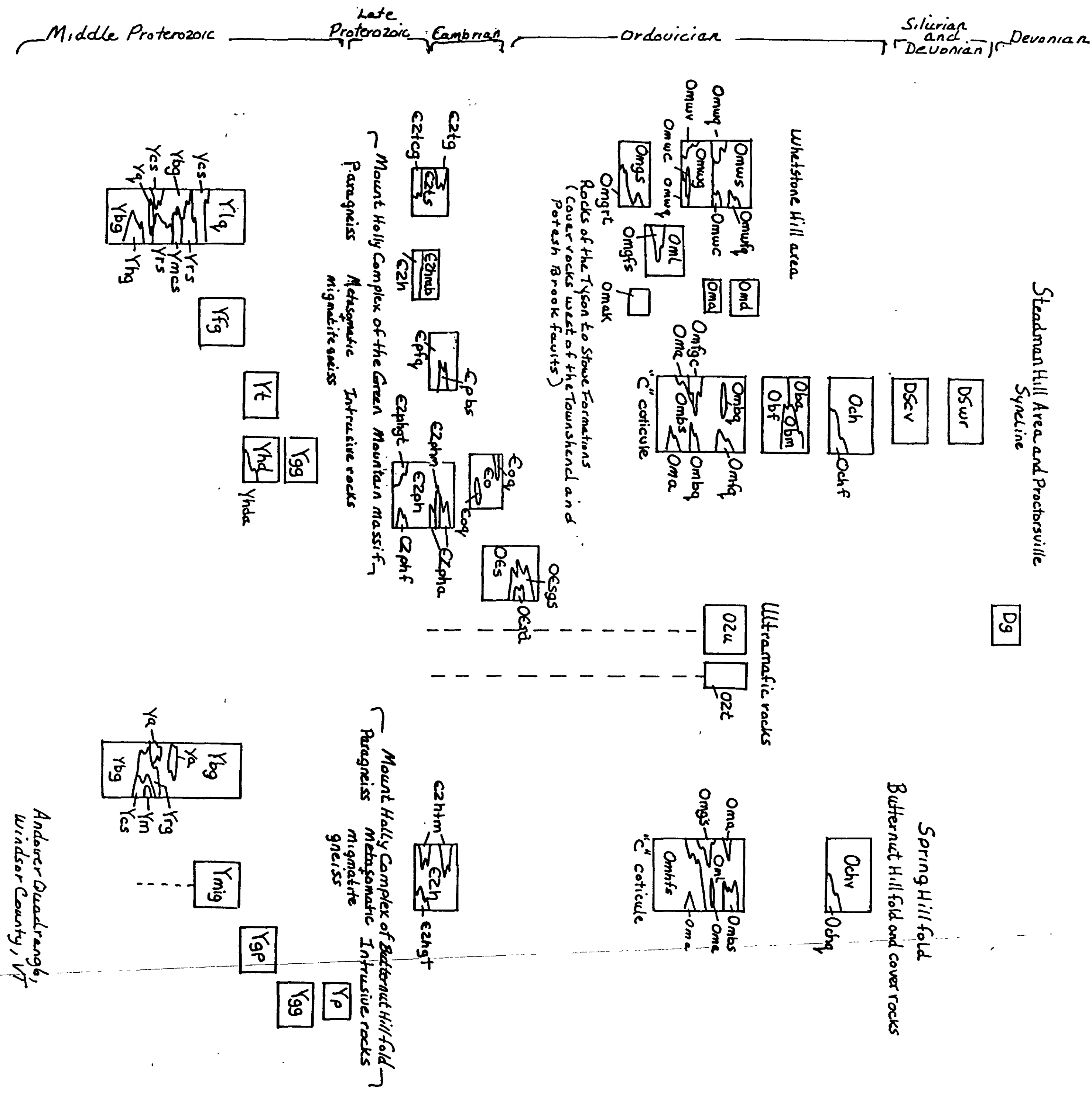


Middle Proterozoic
Late Proterozoic
Cambrian
Ordovician
Silurian and Devonian
Devonian
Steadman Hill Area and Proctorsville Syncline
Whetstone Hill area
Rocks of the Tyson to Stowe Formations (cover rocks west of the Townshend and Potash Brook faults)
"C" coticule
Mount Holly Complex of the Green Mountain massif
Paragneiss
Metasomatic + migmatite gneiss
Intrusive rocks
Ultramafic rocks
Spring Hill fold
Butternut Hill fold and cover rocks
Mount Holly Complex of Butternut Hill fold
Andover Quadrangle, Windsor County, VT
DSwr
DScv
Dg
Och
Ochv
Ozu
Ozt
Yfg
Yt
Yhd
Ygg
Ymig
Ygp
Yp

# DESCRIPTION OF MAP UNITS

(major minerals listed in order of increasing abundance)

## ACADIAN INTRUSIVE ROCKS

**Dg** Granite (Devonian)--Massive to weakly-foliated, muscovite-biotite-microcline-plagioclase-quartz granite to granodiorite dikes and sills, that cross cut highly foliated country rocks. May be shown by symbol only; locally weakly folded and foliated but commonly straight-walled and only weakly foliated

## COVER SEQUENCE ROCKS OF THE SPRING HILL FOLD AND STEADMAN HILL AREA AND THE PROCTORSVILLE SYNCLINE

### Waits River Formation (Lower Devonian and Silurian)

**DSwr** Dark-gray to black to lustrous-silvery gray, fine-grained, carbonaceous garnet-biotite-muscovite-quartz schist containing punky-brown-weathering limestone and quartz-rich limey schist in beds as much as 2 m thick

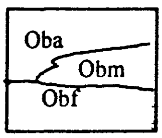
**DScv** Amphibolite and quartzite member--Heterogeneous unit consisting of well-layered biotite-epidote-hornblende-plagioclase amphibolite, gray to dark-gray quartzite, and well-laminated biotite-plagioclase-quartz±hornblende granofels. Unit 5 to 10 meters thick, and poorly exposed; may disconformably overlie the Cram Hill Formation

### Cram Hill Formation (Ordovician)

**Och** Black biotite schist member--Dark-gray to steely gray, muscovite-biotite-plagioclase-quartz schist and quartz-rich granofels; characterized by distinct porphyroblasts of biotite in a slabby, well-foliated rock, locally slightly sulfidic and rust-stained

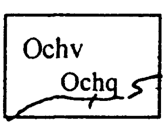
Ochf

Felsic volcaniclastic member--Finely laminated, dark-gray to light-gray, biotite-plagioclase-quartz and hornblende-biotite-plagioclase-quartz granofels; layers 1 cm to as much as 10 cm thick. A thin poorly exposed unit less than 10 m thick. Unit may correlate with Ochv member in the Spring Hill syncline




Barnard gneiss member--Consists of three units that are gradational. Amphibolite (Oba) dark-gray-green to black, fine-grained, slabby, well-foliated biotite-plagioclase-hornblende amphibolite, lacking beds of more felsic rocks; (Obm) mixed unit consisting of very well layerd biotite-hornblende-amphibolite and light-gray- to white-weathering, fine-grained and internally laminated biotite±hornblende-quartz-plagioclase granofels, interpreted as interbedded felsic (dacitic) and basaltic or andesitic volcanic and volcaniclastic rocks; Felsic volcanic unit (Obf), predominantly light-gray- to whitish-gray-weathering, medium- to fine-grained, biotite-quartz-plagioclase granofels having minor layers of amphibolite or quartz-rich granofels; interpreted as dacitic volcaniclastic rocks, or possibly fine-grained intrusive trondhjemite. Lower contact with Ombs is locally gradational

Cram Hill Formation in the Spring Hill Fold




Volcaniclastic and quartzite member--Principally well-layered, felsic to intermediate biotite-quartz-plagioclase and biotite-hornblende-quartz-plagioclase granofels in layers 0.5 to 3 m thick, locally contains thin layers of amphibolite and quartz-rich, plagioclase granofels. Unit may be correlative with unit Obf of the Proctorsville syncline. Underlain by a relatively persistent zone of steel-gray to white-weathering muscovite-plagioclase quartzite or conglomerate (Ochq) that is interlayered at its base with laminated feldspathic-muscovite-plagioclase-quartz granofels typical of the Moretown Formation. Quartzite unit is as much as 5 meters thick

Moretown Formation (Ordovician)

(Exposed in three separate and fault-bounded areas; members may be mapped separately in each area, but only subtle differences exist among probable correlatives in each of the three areas)

Moretown Formation of the Spring Hill fold

| Oml |

Pinstripe granofels member--Light-gray- to pinkish-gray-weathering, pinstriped, biotite-plagioclase-quartz granofels and quartzite. Granofels layers contain abundant fascicles of hornblende, or layers of hornblende-plagioclase granofels 1 to 5 cm thick; where these hornblende fascicles and granofels layers predominate unit passes into Omhg

| Ombs |

Black schist member--Dark-gray to silvery-gray, garnet-biotite-muscovite carbonaceous schist, and associated rusty-weathering muscovite-biotite-quartz schist. Passes laterally into more muscovite-rich, lustrous, dark-gray quartz schist, very locally exposed and associated with amphibolite (Oma), and talc deposits that were locally mined. Occurs in the core of the Spring Hill fold where it is as much as 10 m thick, may correlate with the Ombs member exposed near the ultramafic rocks in and along the Potash Brook fault

| Omgs |

Garnet schist and granofels member--Light-greenish gray-weathering, chlorite-muscovite-plagioclase-quartz granofels and schist containing feldspathic and well-laminated garnet-rich granofels layers 0.5 to 1 m thick, unit is gradational with Oml, which it closely resembles, except for the higher proportion of muscovite-rich schist in Omgs

| Oma |

Amphibolite member--Dark-green to black, well-foliated, fine-grained hornblende and epidote-plagioclase amphibolite, occurs as discontinuous layers in Oml, and in Omhfs as several more continuous units

Omhfs

Hornblende fascicle schist member--Light-gray to gray-green, chlorite-muscovite-biotite-plagioclase-quartz schist and granofels marked by conspicuous sprays of hornblende and distinctive, large, 5 mm to 1 cm porphyroblasts of cross-foliation biotite, abundant irregular layers of coticule 1 to 2 cm in thickness, and abundant layers of pinstriped light-gray biotite-quartz granofels like Oml. Unit closely resembles the Omfgc unit exposed west of the Butternut Hill fold, with which it is correlated

Moretown Formation of the Steadman Hill area west of the Butternut Hill Fold

Ombs

Black schist member--A very extensive unit consisting of dark-gray to rusty gray-brown weathering slabby, muscovite-biotite-plagioclase-quartz schist, quartz-knotted schist, and slabby gray, biotite porphyroblastic, siliceous schist and granofels. Unit is distinguished by abundant layers of gray or green feldspathic granofels resembling Oml and Omfgc, as well as abundant layers of quartzite and by gray, slabby to splintery outcrops that weather to a dull- brownish gray rind. Unit locally carbonaceous. Distinct porphyroblasts of biotite 2 to 3 mm in diameter are common

Omfq

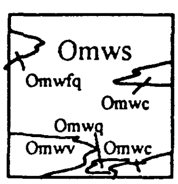
Feldspathic quartzite member--Light-gray- to yellow-tan-weathering, pitted quartzite in beds as much as 5 m thick, interspersed with dark-gray schist (Ombs) or more feldspathic granofels like Oml or Omfgc. Occurs within Ombs or near the contact with Omfgc

Ombq

Black quartzite member--Dark-gray to jet-black vitreous quartzite in beds as much as 10 m thick but commonly occurs as 1- to 2-m-thick beds in predominantly black schist. Many of these quartzites occur at or near the contact with Omfgc and pass laterally into more feldspathic quartzite (Omfq)


Feldspathic granofels and coticule member--Either a light-green-, to greenish-gray-weathering, well-laminated chlorite-biotite-plagioclase-quartz granofels and pinstriped granofels, or a light-gray biotite-plagioclase-quartz granofels and pinstriped granofels. Both varieties contain layers of light-brownish-gray-weathering schist and thin layers of pinkish gray garnetiferous quartzite containing abundant minute garnets less than 0.5 mm in diameter or finely laminated layers of ultrafine grained quartz-garnet rock (coticule). Unit closely resembles the pinstriped granofels member (Oml), but contains abundant layers of muscovite-chlorite-quartz schist. Interpreted as a lateral equivalent of Oml as mapped elsewhere. Near the Townshend thrust, layers of amphibolite (Oma), garnet schist (Omgs) and abundant 1-cm-thick layers of pinkish gray coticule are present. Amphibolite (Oma) occurs within Omfgc near exposures of ultramafic rock (Ozu) in the northern part of the map

Moretown Formation of the Whetstone Hill area




Carbonaceous schist member--Either a dark-gray to black, fine grained, garnet-biotite-muscovite-quartz phyllite or a whitish-tan, papery thin muscovite phyllite containing distinct porphyroblasts of biotite 2 to 3 mm in diameter, contains discontinuous layers of black vitreous quartzite (Omwq), or more feldspathic quartzite (Omfq). The quartzites pass laterally into zones of tan- to rusty-weathering feldspathic schist having distinct laminae of pinkish gray coticule, in layers 1 cm thick, and magnetite quartzite collectively mapped as Omwc, or separately mapped lens of gray, slabby biotite schist or granofels that contain elliptical fragments of fine-grained, felsic (dacitic) volcanic rock mapped as Omwv. These distinctive beds of volcaniclastic rock occur in two places at or near the base(?) of the carbonaceous schist member.

Omd

Hornblende-plagioclase granofels--Medium-gray, medium- to coarse-grained hornblende amphibolite consisting of equally abundant plagioclase and hornblende intergrown in distinctive metamorphic habit, resembling the dioritic texture of intrusive rocks

Omwg

Metasiltstone member--Light-green- to dull-gray-green-, weathered well-laminated, chloritic metasiltstone, underlies Omws; contains deeply weathered, dark-brown lenses, 5 cm wide and 10 cm long, that may have been calcareous nodules, or altered fragments of volcanic rocks. Omgs and Omws were previously mapped as the Whetstone Hill Member of the Missisquoi Formation of Doll and others (1961), they also contain irregularly distributed amphibolite (Oma) and pinstriped granofels (Oml), especially near the base

Oml

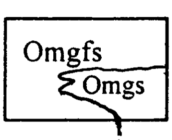
Pinstripe granofels member--Light-gray- to pinkish-gray-weathering, pinstriped, biotite-plagioclase-quartz granofels and quartzite; unit passes laterally into Omgfs by increase in muscovite and chlorite

Omgrt

Gritty feldspathic quartzite--Light-gray to greenish gray, chlorite-muscovite-quartzite and small-pebble conglomerate or grit in beds 0.25 to 0.5 m thick, associated with beds of ankeritic greenstone, and pinstriped to laminated quartzite, unit less than 20 m thick associated with zones of talcose schist (OZt) near the Potash Brook fault

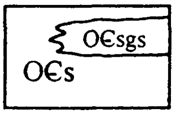
Omak

Ankeritic greenstone member--Pale green, deeply weathered, ankerite-chlorite-muscovite-plagioclase greenstone, contains layers having as much as 15 percent ankerite



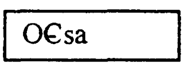

Green feldspathic schist member--Light-green to gray-green, muscovite-rich, chlorite-quartz schist, and chlorite-biotite-muscovite plagioclase-quartz granofels. Unit resembles Oml, and passes laterally into garnet schist (Omgs) and both contain beds of ankeritic greenstone (Omak)

Stowe Formation (Ordovician and Cambrian)



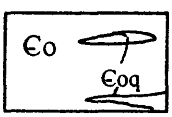

Schist member--Principally a light-green to gray-green lustrous biotite-chlorite-muscovite-quartz schist that contains abundant beds of gray to white feldspathic granofels or garnet-bearing granofels. Unit typically contains porphyroblasts of biotite and abundant elliptical pods of granular quartz; is distinguished from the Pinney Hollow Formation, which it resembles superficially, by having flakes of biotite and abundant feldspathic layers

Garnet schist and granofels member (OЄsgs)--Tan to greenish gray, pinstriped feldspathic, chlorite-muscovite-garnet-plagioclase-quartz schist and granofels marked by abundant large garnets as much as 1 cm in diameter that overgrow and include the strongly foliated pinstriped matrix



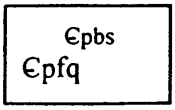

Amphibolite member (OЄsa)--Dark green, well foliated hornblende and epidote-plagioclase-hornblende amphibolite

Ottauquechee Formation (Cambrian)



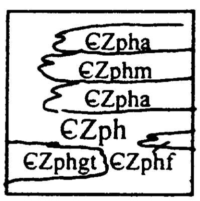

Schist member (Єo)--Dark gray to black, slightly rusty weathering, fine-grained, carbonaceous, biotite-muscovite-quartz phyllite; very finely foliated; commonly contains no recognizable porphyroblasts of biotite and is uniformly fine grained. Unit is distinguished from dark biotite schists of the Cram Hill and Moretown Formations by the coarse biotite and abundant slabby quartzitic layers in the latter. Contains beds of black to whitish gray, fine-grained vitreous quartzite (Єoq) in beds as much as 1 m thick. The upper contact with the Stowe Formation is sharp and is interpreted as a fault

## Plymouth Formation (Cambrian)




Feldspathic quartz-schist member (Єpfq)--Gray-tan to dark-gray, pinstriped, feldspathic biotite quartzite and quartz schist; distinctive tectonic laminae 0.5 cm thick that are biotite-rich or quartz-rich poor are characteristic. Dark-gray to black, thinly layered, graphite-biotite-muscovite-quartz schist (Єpbs) locally contains 0.1 to 0.5 m-thick layers of gray dolomitic quartzite at or near the contact with the upper lens of feldspathic quartz schist. Contact with the underlying Tyson Formation is not exposed in this quadrangle but is interpreted as a fault based on information from the Mount Holly (Ratcliffe, 1992a) and Plymouth (Ratcliffe, 1992b) areas to the north

## Pinney Hollow Formation (Cambrian and Late Proterozoic)




Schist member (ЄZph)--Principally fine grained, lustrous, light green, chlorite-magnetite-muscovite-quartz schist, containing knots of fine grained milky-white quartz; overall member is finer grained, more muscovitic, and more chloritic than similar appearing schists of the Stowe Formation. Contains layers of dark-green, laminated to well-foliated hornblende and epidote-hornblende-plagioclase amphibolite (ЄZpha), that is interbedded with dull-greenish gray, medium- to fine-grained, metasiltstone or metatuffaceous rock (ЄZphm). The bedded nature of the amphibolites and the metasiltstone suggest a protolith of mafic volcaniclastic and perhaps more felsic volcanogenic metasediments. White to light-gray, very feldspathic quartz granofels (ЄZphf) occurs near the base of the amphibolite and may be a felsic volcaniclastic rock similar to that described by Walsh (1996) from the Pinney Hollow Formation in the Rochester Quadrangle, Vermont. Greenish gray, medium-grained, muscovite-chlorite-plagioclase-quartz pebble grit (ЄZphgt) occurs as a 10-m-thick lens. The base of the formation is strongly sheared along the Boynton Hill fault

Tyson Formation (Late Proterozoic? and Lower Cambrian)

€Zts

Schist member--Light-gray- to tannish-gray-weathering, fine-grained, well-laminated, biotite or chlorite-muscovite-quartz phyllite and schist, locally albitic; contains distinctive beds as much as 1 m thick of blue-quartz-pebble quartzite

€Ztg

Green schist member--Light- to medium-dark-green, chlorite-muscovite-quartz±magnetite schist, locally contain white-weathering small albite porphyroblasts 1 to 2 mm in diameter

€Ztc

Conglomerate member--Coarse-grained, tan to gray, well-bedded quartz- and gneiss-cobble conglomerate, and well-bedded blue-quartz pebble quartzite and feldspathic grit in beds 1 to 2 m thick

Hoosac Formation (Late Proterozoic and Cambrian)

Hoosac Formation on the Green Mountain massif

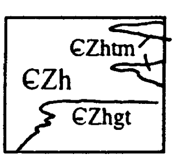
€Zhrab

Rusty albitic schist member--Light-tan to yellowish brown, albite-studded, biotite-muscovite-albite-quartz schist

€Zh

Hoosac Formation undifferentiated--Poorly exposed gray, albite-studded biotite-albite-quartz granofels and tan weathering feldspathic muscovite quartz schist, passes laterally into similar rocks mapped as the Tyson Formation, which it replaces

Hoosac Formation in the Butternut Hill Fold




Schist and granofels member (€Zh)--Medium-gray, slabby well-foliated, biotite-plagioclase quartz schist and granofels, locally containing black, well-layered hornblende amphibolite (€Zhtm) and a basal garnet-rich biotite-muscovite-plagioclase-quartz schist (€Zhgt)

## MOUNT HOLLY COMPLEX (MIDDLE PROTEROZOIC)

### Intrusive Rocks of the Mount Holly Complex

Yp

Pegmatite--Highly deformed, well-foliated, light-gray to pinkish-gray, biotite-hornblende(?)-muscovite pegmatite commonly altered to chlorite, epidote, albite and sericite and containing large plates of ilmenite and locally diopside crystals as long as 30 cm. Forms small 1- to 2-meter-thick pods to masses as much as 1 km long, most abundant in or near rusty weathering schist and quartzite units (Yrg, Yrs, Yrq). Occurs as thin nonmappable pods, stringers or layers in all units of the Mount Holly Complex

Ygg

Granitic and migmatitic gneiss--Light-gray to pinkish-tan weathering, fine-grained, ropy or knotted-structured to well foliated, biotite-quartz-microcline-plagioclase granite gneiss, commonly having indistinct layers and or augen of microcline and intergrown plagioclase as much as 2 cm in diameter. Unit resembles Ygp but contains abundant fine-grained, 1 to 2 mm grains of microcline subequal in abundance to plagioclase, which commonly form larger 3-5 mm diameter grains. Accessory metamorphic muscovite and coarse epidote common. Finer-grained varieties may contain abundant scattered magnetite. Unit interpreted as original feldspathic volcanic rock migmatized in the Middle Proterozoic. Unit may correlate with Yfg unit of the Mount Holly complex, as mapped in the Green Mountains massif

Ygp

Felchville trondhjemite gneiss--Light-gray- to whitish-gray-weathering, medium- to medium-coarse-grained, magnetite-biotite-microcline-quartz-plagioclase gneiss, having indistinct layering near contacts with adjacent units but massive elsewhere. Large conspicuous augen of well-twinned plagioclase, as much as 1 cm in diameter are common, whereas matrix feldspar is less than 1 mm in diameter, and consists of sparing amounts of microcline to as much as 25 percent. Overall unit a granodiorite to trondhjemite. Unit is intrusive into all units of Mount Holly including the Cavendish Formation. $^{207}Pb/^{206}Pb$ SHRIMP data indicate an intrusive age of approximately 1.4 Ga (John Aleinikoff, personal communication, 1994). May be correlative with Yt in the Green Mountain massif

Yhd Yhda

Hornblende diorite-gneiss--Medium-gray to greenish-gray weathering, coarse-grained biotite-hornblende-plagioclase metadiorite or mafic tonalite. Contains approximately 25 percent hornblende and 65 percent plagioclase and locally large retrograded metamorphic garnets as much as 2 cm in diameter, but most commonly only scattered small garnet. Gneissic rock has a relict diabasic to allotriomorphic granular texture, and passes gradationally along its contact with Yrs on Terrible Mountain into a very fine grained, dark-green to gray, hornblende plagioclase amphibolite (Yhda) that contains irregular patches and clots rich in plagioclase. Interpreted as fine-grained and perhaps more mafic border facies of Yhd. Unit may have genetic and temporal affinities with tonalites and trondhjemites (Yt) described below

Yt

Trondhjemite gneiss--Light-gray to chalky-white weathering, medium- to coarse-grained biotite trondhjemite commonly containing minor 0 to 10 percent microcline, to as much as 20 percent. Interpretated as a metaintrusive younger than some of the layered gneisses. U-Pb zircon ages of 1.3 to 1.35 Ga have been determined for similar rocks in the Londonderry quadrangle (Ratcliffe and others, 1991) and $^{207}Pb/^{206}Pb$ SHRIMP ages of about 1.4 Ga (John Aleinikoff, written communication, 1995) for cores of zircons in the Felchville trondhjemite gneiss of the Chester dome and the Butternut Hill fold (Ygp)

## METASOMATIC OR MIGMATITIC ROCK

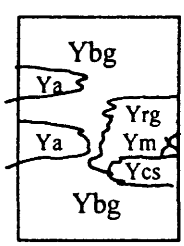
Yfg

Felsic magnetite-biotite gneiss--Massive to gneissic, white- to pinkish gray-weathering, fine-grained, biotite-magnetite-microcline-quartz-oligoclase-gneiss, distinguished by scattered octahedra of magnetite and only minor amphibolite or biotite. Strongly foliated varieties contain prominent muscovite and epidote and albite. Resembles Yap but is better layered and contains a higher percentage of magnetite and/or biotite. Subordinate microcline commonly ranges from about 5 to as much as 25 percent. Unit may represent an altered felsic volcanic rock or a contact phase of the trondhjemite gneiss (Yt)

Ymig

Migmatite gneiss--Coarse-grained pinkish gray, epidotic-biotite-plagioclase-quartz-microcline gneiss; massive in outcrop but well-foliated and marked by distinct clots, stringers and lenses of microcline-rich granite. Interpreted as a metamorphosed and anatectic rock produced by partial melting of a felsic volcanic or intrusive rock. May be correlative of Yfg unit of the Green Mountain Massif

## PARAGNEISS OF THE MOUNT HOLLY COMPLEX IN THE CHESTER DOME AND BUTTERNUT HILL FOLD




Biotite-quartz-plagioclase gneiss (Ybg)--A heterogeneous assemblage of dark- to medium-gray, nonrusty-weathering, quartz-rich biotitic gneisses, all characterized by having abundant plagioclase, epidote and little or no microcline. Other distinctive rocks include: light-gray-weathering, magnetite-muscovite-biotite-plagioclase-quartz gneiss containing thin layers of hornblende-spotted gneiss; a very dark-gray, biotite-rich plagioclase-quartz gneiss commonly associated with epidotic quartzite, and medium- to dark-gray, white-albite-spotted-biotite-quartz gneiss. Muscovite is a common accessory in most rocks and small amounts of garnet may be present as well. The biotite-quartz-plagioclase gneiss unit contains numerous layers of other distinctive rocks interlayered throughout, where thick enough to map, these units, listed below, are mapped separately

Ya Amphibolite--Dark-green- to dull-gray-weathering, fine- to coarse-grained, biotite-hornblende and hornblende-garnet-plagioclase amphibolite, commonly associated with Yrg or Ycs, or isolated within Ybg

Yrg Rusty muscovite-biotite-plagioclase-quartz gneiss--Dark-brown to gray, rusty-weathering gneiss and schist containing abundant layers of schistose quartzite, biotite-garnet quartzite, and rusty sulfidic amphibolite, passes laterally into a muscovite-rich schist: locally very rich in garnet too small to map separately. Unit is correlative with units Yrq, Yrs, Ycms of the Green Mountain massif

Ycs Calc-silicate gneiss--Commonly coarse-grained, hornblende-plagioclase-calcite $\pm$ diopside $\pm$ actinolite calc-silicate knotted rock, as pods, stringers or lenses in other rock types, interlayered with beds of coarse- grained calcite, calcite-diopside-actinolite marble or amphibolite. Many bands of calc-silicate gneiss occur with the Ybg unit or in Yrg

Ym Marble--Consists of a variety of marbles intimately associated with calc-silicate gneiss and or beds of actinolitic quartzite, including, whitish-gray weathering, medium- to coarse-grained, phlogopite-calcite-dolomite and quartz-knotted marble; greenish actinolite-rich dolomitic marble; fine-grained yellow-gray weathering, highly foliated phlogopite-talc(?)-tremolite-dolomite marble

### Paragneiss in the Green Mountain Massif

Ycs Calc-silicate rocks--Consists of one or more of the following rock types, often occurring in close proximity and interlayered: Light-green, coarse-grained, diopside-hornblende calc-silicate rock variably altered to actinolite-tremolite or talc; coarse-grained calcite marble;

calcite-diopside (±actinolite) marble; massive coarse-grained, white, calcite- or dolomite-tremolite; marble, beige- to orange-tan-weathering medium-grained, dolomite-phlogopite±scapolite marble; light-gray to pinkish-green plagioclase microcline-diopside-quartz-calcite granofels or gneiss

**Yrs**
**Ymcs**

Rusty muscovite quartz schist--Rusty-brown- to yellowish-gray-weathering, coarse-grained, garnet-muscovite-spangled schist, commonly lustrous and ultrafine-grained where highly foliated; contains layers of muscovite-biotite±garnet quartzite (Yq) and muscovite-biotite-plagioclase±garnet-schist, highly altered to chlorite, sericite, albite, clinozoisite or epidote and veins of abundant albite-quartz and tourmaline. Ranges from coarse-grained garnetiferous and biotitic schist to a highly retrograde rock containing clots of chlorite after biotite and garnet. Unit passes gradationally into a lighter colored, yellowish-greenish gray, lustrous chlorite and muscovite rich schist (Ymcs) that may contain abundant deep-blue- green chloritoid. Clots of chlorite and muscovite as much as one cm in diameter are set in a very fine-grained matrix of muscovite±paragonite±ilmenite

**Yq**

**Ylq**

Quartzite on Ludlow Mountain--Massive, white weathering, vitreous, highly jointed quartzite, contains scattered magnetite, and lenses of chloritoid-muscovite-chlorite-ilmenite quartz schist grades into Yrs outside the quadrangle

**Yq**

Quartzite--Thinly bedded, light-gray to white vitreous quartzite, muscovite-garnet-quartzite interbedded in Yrs or Ycms

**Yhg**

Hornblende-plagioclase gneiss--Dark-greenish gray to medium-dark-gray, hornblende-streaked to hornblende-spotted well-layered gneiss; commonly consists of alternating dark- (hornblende-rich) and light-colored (plagioclase-rich) layers 1 to 5 cm thick. Contains layers of massive, dark-green amphibolite. Passes laterally into a more plagioclase-rich gneiss having approximately 25 percent hornblende and biotite as porphyroblasts as much as 1 cm in length

Ya

Amphibolite--Dark-green, well-foliated, medium-grained, hornblende amphibolite, garnet-hornblende-plagioclase amphibolite, interlayered with biotite-quartz-plagioclase gneiss (Ybq), rusty-muscovite-quartz schist (Yrs)

ULTRAMAFIC ROCKS

(Late Proterozoic to Ordovician)

OZu

Serpentinite--Massive to well-foliated highly jointed serpentinite or serpentine-talc rock; occurs as large exposures of metamorphosed, ultramafic rocks originally peridotite, or harzburgite and smaller bodies of serpentinite, largely within the Moretown Formation or in the Stowe Formation near the contact with the Moretown. Interpreted as tectonic blocks or slide blocks of oceanic mantle deposited within the Moretown Formation or as fragments of ophiolite sheets tectonically intercalated within the Taconian accretionary prism. Commonly are associated with amphibolites of basaltic composition that occur within the enclosing metasedimentary rocks. The age of the rock may range from the Late Proterozoic to the Ordovician corresponding to a period of extraction of oceanic basalt which formed the basaltic layer of the Iapetan Ocean basin, and the depleted mantle rock

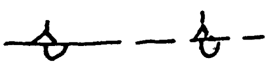
OZt

Talc schist and talc-carbonate schist--Highly foliated, fine-grained talc schist and talc carbonate rock occurs as selvages and tails of larger serpentinites and as apparent beds of talc schist within metasedimentary rocks of the Moretown Formation. May in part, be ultramafic slide breccias and submarine debris flows

## EXPLANATION


Contact; solid accurately located; dashed approximate; dotted concealed under water


Thrust fault, teeth on upper plate; solid accurately located, dashed approximate; dotted concealed under water


Overturned thrust fault, teeth on present upper surface; dashed where approximate

**AXIAL TRACES OF MAJOR FOLDS (GENERALIZED PLUNGE SHOWN BY ARROW)**


Middle Proterozoic fold (dip direction uncertain, commonly subvertical)

Taconian $F_1$ fold, rectangle shows dip direction

Taconian $F_2$ fold (commonly reclined folds)

Acadian folds, rectangle shows dip direction; A indicates Acadian, generations of folds not ditinguished

## PLANAR FEATURES

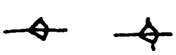
Strike and dip of gneissosity in Middle Proterozoic rocks (relict Middle Proterozoic gneissosity)

Inclined


Vertical

Strike and dip of $S_1$ Taconian schistosity or foliation in pre-Silurian rocks; Acadian in Silurian and Devonian rocks, tick mark indicates parallel bedding and foliation

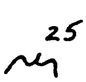
Inclined; bedding parallel


Vertical; bedding parallel

Strike and dip of Taconic $S_2$ foliation or spaced cleavage prevalent near thrust faults; tick mark indicate parallel bedding

Inclined


Vertical



Highly crenulated schistosity, gneissosity or foliation showing general strike and dip

Crenulation cleavage--Acadian (individual phases not distinguished separately, varies from weakly to non-mineralized and having no new oriented minerals in the west to a moderately well-developed foliation in the east)


Inclined

Vertical

Strike and dip of axial surface of macroscopic fold (plunge of hingeline may be shown by arrow; sense of rotation given by small arc indicating either counter-clockwise or clockwise rotation, as viewed down plunge)


Middle Proterozoic fold; inclined


Taconian $F_2$ fold (multiple plunge arrows indicate multiply plunging folds in a single outcrop)


Inclined open to tight Acadian fold


Vertical open to tight Acadian fold

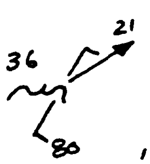
## LINEAR FEATURES

Azimuth and plunge of hinge line of minor fold (attached to planar symbol of the same generation

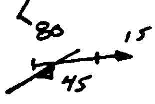

Taconian $F_2$ fold (commonly very tiny folds lying in the $S_2$ foliation)


Acadian fold, commonly the intersection between Taconian $S_1$ or $S_2$ foliation and Acadian crenulation cleavages, or second or third generation Acadian folds in Silurian and Devonian rocks

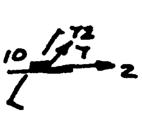
## SYMBOLS MAY BE COMBINED (JOINED AT POINT OF OBSERVATION)



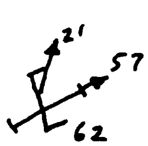

Highly plicated gneissosity, schistosity or foliation, intersecting Acadian crenulation cleavage, and plunge of hingeline of minor fold




Inclined Taconian $S_2$ foliation, intersected by vertical Acadian crenulation cleavage and plunge of hingeline of Acadian minor folds

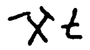



Inclined Taconian $F_2$ axial surface having east-plunging $F_2$ folds, intersected by inclined Acadian crenulation cleavage and plunge (to northeast) of Acadian plication of the Taconian $F_2$ axial surface

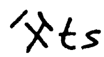



Multiple intersecting Acadian crenulation cleavages, arrows show plunge of hingelines of minor folds in these clevages

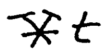
## OTHER SYMBOLS




Active quarry (t, talc)




Area of active strip mining for talc




Abandoned quarry (t, talc)