U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Digital Bedrock Geologic Map of the Vermont Part of the Hartland Quadrangle, Windsor County, Vermont

by

Gregory J. Walsh

U.S. Geological Survey
P.O. Box 628
Montpelier, Vermont 05601
gwalsh@usgs.gov

Open-File Report 98-123

OF-98-123-A (paper map and text)
OF-98-123-B (diskettes)

1998

The text and map are part A and the database is part B of this report. Both parts are available from the Vermont Geological Survey, Waterbury, VT, telephone (802) 241-3608.

INTRODUCTION

The bedrock of the Hartland quadrangle consists primarily of Silurian and Devonian metasedimentary and metavolcanic rocks of the Waits River and Gile Mountain Formations. Regionally the formations lie within the Connecticut Valley - Gaspé synclinorium, locally referred to as the Connecticut Valley sequence (or trough, after Hatch, 1988). The metamorphic rocks are intruded by mafic and felsic Cretaceous dikes.

Recent work to the south in the Mount Ascutney and Springfield quadrangles (Walsh and others, 1996a, b) and the Bellows Falls quadrangle (Armstrong, 1997) has redefined the internal structure and stratigraphy of the Connecticut Valley sequence, and represents the first 1:24,000 scale mapping in the Vermont part of the trough. The purpose of this report is to present new results on the stratigraphic and structural relationships in the Connecticut Valley sequence rocks.

Previous work shown on the State map by Doll and others (1961) represents the most recent compilation of the bedrock geology of the Hartland quadrangle, and is based on work by Lyons (1955) in the Hanover, NH - VT 15 minute quadrangle. The earliest map of the Hartland quadrangle by Hitchcock (1908) divided the rocks into three groups: 1) Conway group - argillaceous mica schist and phyllite with beds of micaceous limestone, 2) Coös group - quartz-rich mica schist and quartzite, and 3) Argillite - fine grained slate.

The age of the Connecticut Valley sequence is based on limited fossil and isotopic evidence. The age of the rocks in the Hartland quadrangle is based on regional correlations with dated rocks because no fossils have been recognized and no isotopic evidence is available in this area. Aleinikoff and Karabinos (1990) and Hueber and others (1990) reported a U-Pb zircon age of 423$\pm$ 4 Ma from a sample of felsic rock from the Waits River Formation collected at a Route 11 roadcut just west of Goulds Mill in Springfield, Vermont. The sample is from a 50-cm-thick, light-gray, fine-grained epidote-chlorite-albite-quartz granofels layer within a coarser grained sequence of phenocrystic feldspathic schist and granofels. Aleinikoff and Karabinos (1990) interpreted the layer as a dike but left open the possibility that it was a volcanic layer. Walsh and others (1996a) and Armstrong and others (1997) interpreted the layer as a bed because of the lack of unequivocal cross-cutting relationships and the presence of many similar, yet thinner, layers within the feldspathic schist and granofels. The Silurian date either provides the age for the deposition of the felsic unit at that locality, and therefore the age of the Waits River, or a minimum age. Silurian (Llandoverian) fossils in the Shaw Mountain Formation, stratigraphically beneath the Waits River, provide a lower age limit for the Waits River Formation (Boucot and Thompson, 1963; Doll, 1984). Hueber and others (1990) reported Early Devonian (Emsian) plant fossils from the Compton Formation in Quebec, which is the northern correlative of the Gile Mountain Formation, and equivocal Silurian fossils in the Waits River Formation. For this report, the Waits River is assigned a Silurian and Lower Devonian age becuause the upper age limit is not unequivocally defined and it may range into Gile Mountain time. The mafic and felsic dikes are assigned a Cretaceous age on the basis of the 122.2 $\pm$2 Ma age of the intrusive complex at Ascutney Mountain (Foland and others, 1985) and on a regional summary by McHone (1984) for similar dikes throughout New England and Québec.

STRATIGRAPHY

Metasedimentary Rocks

The majority of the metasedimentary rocks in the Hartland quadrangle can be grouped into two lithologic categories: (1) gray carbonaceous schist and phyllite (DSw and Dgm) and (2) gray carbonaceous schist and phyllite with interbedded impure siliceous limestone (DSwl). A significant result of Walsh and others (1996a, b) is the separation of the carbonate-bearing from non-carbonate-bearing rocks in the Connecticut Valley sequence. This study uses the same criterion as Walsh and others (1996a, b) and maps the majority of the rocks on the presence or absence of the brown-weathering impure limestone beds, locally referred to as "punky" limestones. In addition to limestone beds, the DSwl rocks, and to a lesser extent the DSw rocks, locally contain rusty weathering, calcite-bearing schists. Trace limestone may be present in DSw rocks.

The major metasedimentary units mapped as Waits River Formation include the carbonate- and non-carbonate-bearing gray schists and phyllites (DSwl and DSw, respectively). Minor metasedimentary units in the Waits River include quartzite (DSwq), quartzose schist (DSwqs), and ankerite-biotite schist (DSwab). Previous interpretations (Doll and others,1961; Lyons, 1955) separated what now maps as one formation (Waits River) into two formations (Waits River and Gile Mountain). The assignment of rocks to the Gile Mountain Formation was based on the conclusion that rocks mapped as the Standing Pond volcanic member of Doll and others (1961) occur as a time-stratigraphic unit that separates older rocks with abundant limestone (Waits River) from younger rocks with little or no limestone (Gile Mountain). The new map of the Hartland quadrangle, in agreement with Walsh and others (1996a, b), indicates that limestones occur in roughly equal abundance on either side of the metavolcanic rocks and that it is not possible to separate two distinct formations based on the abundance of limestone-bearing rocks or the position of volcanic rocks. Volcanic rocks originally mapped as continuous are now mapped as discontinuous belts and lenses, making it impossible to assign different names where the volcanic rocks are absent. Lyons (1955) did note, however, that the Waits River and Gile Mountain Formations, as he defined them, could not be separated on a lithologic basis because the Gile Mountain became more calcareous and the Waits River became more arenaceous from north to south. Lyons (1955) did map one belt of black calcite-quartz schist in the Gile Mountain Formation in the area north and south of downtown Hartland, but this map makes no distinction between the limestone-bearing unit in this area versus other areas in the quadrangle. The new map supports Lyons' findings in the northern part of the quadrangle where the limestone-bearing units (DSwl) pinch out. The along strike variation within the Waits River is interpreted as a facies change. To his credit, Hitchcock (1908) also recognized the decrease in the amount of limestone beds to the north and mapped the area in the vicinity of Kent Hill as the Coös group.

Rhythmically bedded and graded sequences of gray phyllite and micaceous quartzite assigned to the Gile Mountain Formation, and reported by Fisher and Karabinos (1980) and Hatch (1988) from areas north of this study, are absent in the Hartland quadrangle. Feldspathic quartzite with dark-gray phyllite (Dgmf) and slate (Dgm) are present in the northeastern corner of the map and are assigned to the Gile Mountain Formation because they match descriptions of Hatch's (1988) major lithofacies in the Gile Mountain. The contact between the feldspathic quartzite unit (Dgmf) and the Meetinghouse slate (Dgm) is gradational by intercalation. Phyllite interbedded with the feldspathic quartzite and granofels is identical to the Meetinghouse slate. The contact between the two units is drawn where the pelite comprises approximately 90 percent or more of the unit and the thickness of feldspathic beds decreases to several cm or less. The western contact between Dgmf and the Waits River Formation rocks is not as gradational. The contact is drawn where the limestone beds are no longer present (in the case where DSwl is in contact with Dgmf) and where there is an abrupt increase in the occurrence of feldspathic quartzite beds. This contact is rather sharp on the southeastern slopes of Grout Hill but gradational on the eastern slopes to the north of the DSwl unit. The dark-gray schist or phyllite is very similar in both the Waits River and Gile Mountain formations, and without the feldspathic quartzite or limestone beds, the difference would not be mappable.

Metavolcanic Rocks

The metavolcanic rocks in the Connecticut Valley sequence consist of a heterogeneous assemblage of mafic and intermediate to felsic volcanic rocks interbedded with volcaniclastic sedimentary rocks. The rocks were previously mapped as the Standing Pond volcanic member of the Waits River Formation (Doll and others, 1961), Standing Pond amphibolite (Lyons, 1955), or hornblende schist within the Gile Mountain Formation (Lyons, 1955). New mapping indicates that all of the metavolcanic and metavolcaniclastic rocks are interbedded with the same metasedimentary rocks of the Waits River Formation and that they can not be assigned to separate formations. For this reason, the metavolcanic and metavolcaniclastic rocks are mapped as unnamed units of the Waits River Formation in accordance with Walsh and others (1996a, b) and Hatch (1991).

New mapping indicates that the volcanic rocks in the Connecticut Valley sequence can be subdivided into at eight different units: laminated schist and granofels (DSwv), large garnet and hornblende garbenschiefer schist (DSwg), porphyritic schist and granofels (DSwvp), amphibolite and greenstone (DSwa), hornblende-plagioclase gneiss (DSwhg), felsic gneiss and quartzose granofels (DSwf), sulfidic schist (DSwss), and hornblende fascicle schist (DSwh). Many of the units are similar to those mapped in the Mount Ascutney and Springfield quadrangles (Walsh and others, 1996a,b), with the following exceptions: (1) No felsic volcanic unit is mapped in the Hartland quadrangle (DSwvf in Mount Ascutney and Springfield), (2) the units DSwss and DSwvp are unique to this map, and (3) the amphibolite and greenstone are a single unit here (DSwa) but separate units to the south. Additionally, the proportion of mafic rocks to felsic rocks is greater in this quadrangle than it is to the south. This suggests an original compositional variation within the basin from more mafic rocks in the north to mixed mafic and felsic rocks to the south. These differences between the two areas highlight the considerable across strike and along strike variation in the units, which is consistent with a volcanic and volcaniclastic origin for these rocks.

The laminated schist and granofels (DSwv) is the most heterogeneous volcanic unit in the Waits River Formation. East of the garnet isograd, the unit maps as a single entity because it contains many rock types that are impossible to map separately at 1:24,000. In this area, porphyroblasts of biotite and ilmenite are the most conspicuous secondary minerals. West of the garnet isograd, hornblende fascicle schist and layers with conspicuously large porphyroblasts of garnet and hornblende are mappable (DSwhg). Slight differences in bulk composition, not readily separable at lower grades, are accentuated by the growth of large porphyroblasts west of the garnet isograd. This permits more detailed mapping of the subunits of the metavolcanic rocks at garnet grade. In the west, where the rocks are well within the garnet zone, only small amounts of the DSwv unit are mappable. The DSwv unit is interpreted as a heterogeneous assemblage of volcaniclastic and volcanic rocks.

The porphyritic schist and granofels unit (DSwvp) crops out in two belts from the west side of Grout Hill southward. The DSwvp unit is a porphyritic version of DSwv that is intercalated with DSwv and massive, thickly layered, hornblende-plagioclase gneiss (DSwhg). Quartz phenocrysts exhibit significant recrystallization and are deformed into lens-shaped porphyroclasts with the long axis parallel to the foliation. Euhedral to subhedral, blocky fractured, and partially recrystallized plagioclase phenocrysts outnumber quartz 5 to 1. The rock is interpreted as an intermediate volcanic rock.

The amphibolite and greenstone (DSwa) unit contains fine-grained mafic rocks that occur as both laminated and massive varieties. The more massive variety may be mafic flows and the laminated variety either mafic tuffs or volcaniclastic sediments. The large belt in the northwestern part of the map is mostly dark-green to black amphibolite, whereas the belt south of Hartland Four Corners contains an equal amount of greenstone and amphibolite. The difference is due to metamorphic grade.

The hornblende-plagioclase gneiss (DSwhg) is a medium- to very coarse-grained rock consisting of roughly equal percentages of hornblende and plagioclase. The large belt in the northwestern part of the map is generally a very massive black and white gneiss. Smaller belts south of Hartland Four Corners and south of Grout Hill are locally dark-green and less massive. The difference is due to metamorphic grade. In the more massive varieties, even at lower grade, intergrowths of hornblende with matrix plagioclase may indicate replacement of relict ophitic texture; if true the massive variety may be, in part, intrusive.

The felsic gneiss and quartzose granofels (DSwf) crops out mainly in the northwestern and west-central part of the map. The unit is interpreted as a volcaniclastic sedimentary and primary sedimentary rock. Similar felsic gneiss and quartzose granofels are reported to the south in the Saxtons River (Ratcliffe and Armstrong, 1995, 1996), Cavendish (Ratcliffe, 1995, in press), and Mount Ascutney quadrangles (Walsh and others, 1996a, b).

The sulfidic schist (DSwss) and hornblende fascicle schist (DSwh) are two minor units in the area. The sulfidic schist consists of 95 percent or more of muscovite and quartz in roughly equal abundance, with the remainder of the rock composed of sulfides (mostly chalcopyrite) and plagioclase. The schist varies from coarse grained to phyllonitic. A small prospect pit of uncertain age is located on Cobb Hill. The unit is interpreted as a hydrothermally altered stratiform sulfide deposit. The hornblende fascicle schist (DSwh) crops out in the northwestern part of the map, on Blake Hill. The rock contains conspicuous hornblende fascicles, but unlike the DSwg unit, contains no garnet porphyroblasts. The unit is interpreted as a volcaniclastic rock.

STRUCTURE

The oldest foliation in the Silurian and Devonian rocks is a bed-parallel schistosity (Acadian S1) containing rarely observed (four in the map area) refolded isoclinal folds with generally north or south gently plunging fold hinges (Acadian F1). Only in the hinge regions of these early F1 folds is it possible to see bedding that is not parallel to a foliation.

The second generation planar fabric in the Silurian and Devonian rocks (Acadian S2) varies from a non-penetrative cleavage in the west to a penetrative schistosity in the east. Folds associated with the second generation planar fabric (Acadian F2) vary from open to isoclinal with generally consistent shallow plunges to both the north and south, but locally the plunges are steep (fig. 1A). In the central and eastern part of the map, S2 generally strikes north and dips steeply to the east (fig. 1C). In the western part of the map the strike of S2 is deformed into more westerly orientations (fig. 1B).

S1 and S2 are the most dominant, or visibly conspicuous, planar fabrics in the Silurian and Devonian rocks. Locally, these two planar fabrics are parallel, and it is difficult to discern one from the other. In such places where only a single penetrative schistosity is observed, and no cross-cutting relative age relationships can be discerned, a dominant foliation symbol is used on the map. S1 and S2 are deformed by a minimum of one younger cleavage.

The next youngest generation of planar fabrics is broad to open folds with associated mm to cm spaced cleavage. These structures, shown as S3 on the map, have many different orientations, although they most commonly strike northeast and dip vertically to steeply northwest and southeast. These structures are related to the final phase of formation of the Chester dome (Walsh and others, 1996a; Ratcliffe and others, 1997a; Ratcliffe, in press), and the older Acadian S1 and S2 planar fabrics are deformed by them. In the western and northern part of the Hartland quadrangle, both S1 and S2 are deformed into sub-horizontal orientations producing a broad dome and basin pattern in the earlier foliations. It is not certain whether all of the "dome-related" cleavage shown on the map as S3 is coeval or not. The S1, S2, and "dome-related" structures are interpreted as Acadian.

To the south, Walsh and others (1996a) reported a younger generation of cleavage characterized by kink bands or low-amplitude, high-wavelength folds associated with Mesozoic deformation. Such structures were not readily identified in this study. It is possible, however, that some of the S3 cleavage show on the map may be related to this young deformation event, but could not be separated due to the lack of unequivocal cross-cutting relationships in the field.

Joints and brittle faults shown on the map include the most visibly conspicuous brittle features observed at the outcrop. Generally east-west striking joints are the most common in the area (fig. 1D). Some of the joint sets are associated with sub-parallel mafic and felsic dikes. These brittle features are Mesozoic or younger.

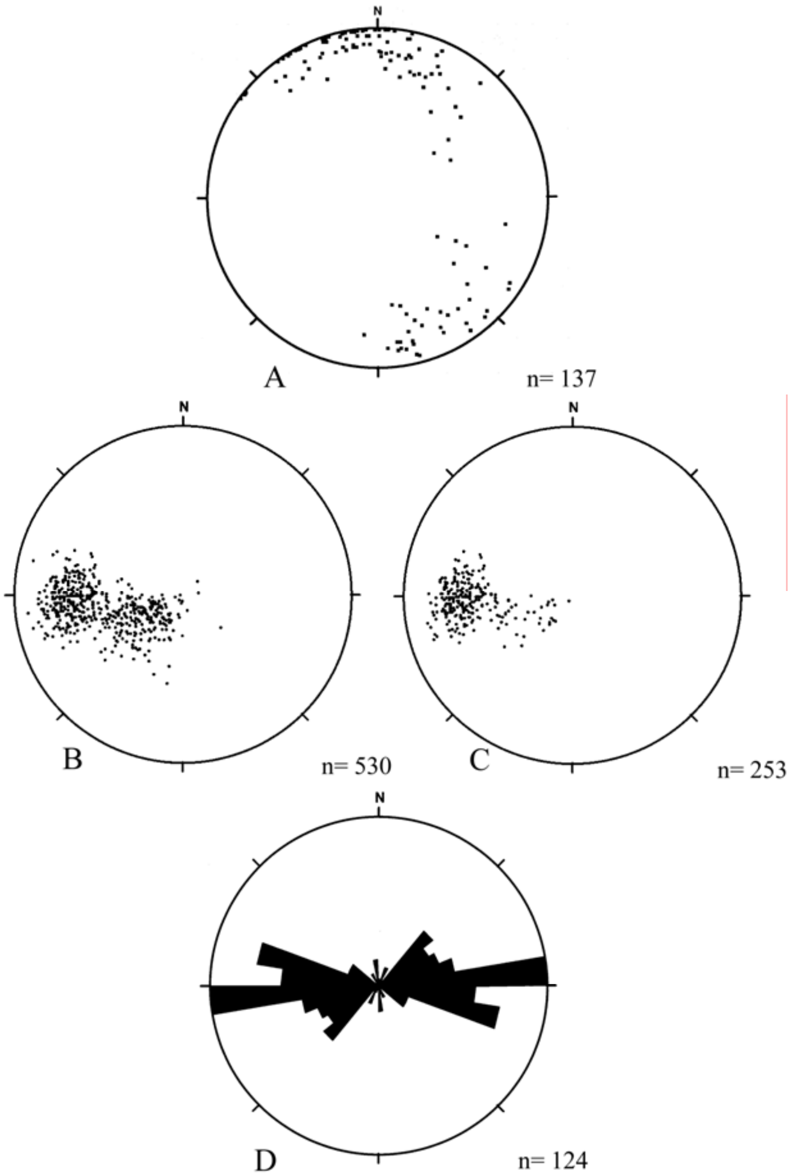


Figure 1. Lower hemisphere equal area projections (A-C) and rose diagram (D). North = N and the number of points in the dataset = n.

A) F2 fold hinges. B) Poles to all S2 measurements including schistosity and cleavage. C) Poles to S2 schistosity measurements from the eastern half of the quadrangle. D) Joints. Angular interval = 10°, maximum value = 21 percent.

METAMORPHISM

Paleozoic metamorphic grade within the Hartland quadrangle ranges from the chlorite and biotite zone to the garnet zone. Rocks in the western part of the map area are at garnet grade as evidenced by abundant garnet porphyroblasts in pelitic and semi-pelitic rocks. Large garnets are found sporadically within the gray schists in the western part of the Waits River Formation (DSw and DSwl). Large garnet and hornblende porphyroblasts are common within the western belts of volcanic lithologies in the Waits River Formation. The garnet isograd trends roughly north-northeast and cuts across several lithologies whose contacts are parallel to either S1 or S2. The garnet isograd, therefore, is not compositionally controlled and indicates increased pressure-temperature conditions to the west. Garnet porphyroblasts in this area grew syn- to post-S2 development.

DISCUSSION

The results of this mapping corroborate findings previously reported for the rocks in the Connecticut Valley sequence immediately to the south within the Mount Ascutney and Springfield quadrangles (Walsh and others, 1996a, b; Armstrong and others, 1997). The widespread distribution of similar metasedimentary and metavolcanic rocks throughout the sequence suggests a fairly uniform supply of pelitic, semi-pelitic, and volcaniclastic sediment and volcanic rock during the time of deposition. The distribution of interlayered limestone-bearing and non-limestone-bearing rocks across the Waits River belt is consistent with the distribution seen at the outcrop-scale. This suggests periodic influxes of carbonate sands into a dominantly pelagic sequence rather than transgressive and regressive cycles. Map scale lateral facies changes within the Waits River Formation are mapped here for the first time, and show a decrease in the amount of interlayered limestone to the north.

Rocks matching the lithologic description of the Gile Mountain Formation (Hatch, 1988) are present within the northeastern part of the map area, unlike in the quadrangles to the south (Walsh and others, 1996a, b; Armstrong and others, 1997; Armstrong, 1997; Ratcliffe and Armstrong, 1995). The gradation and intercalation of rock types along the mapped contact between the Waits River and the Gile Mountain Formations suggest a depositional relationship between the two formations. A low-angle discontinuity exists between the DSwl and Dgmf units southeast of Grout Hill, but there is no evidence for faulting along the contact. The discontinuity could be the result of a disconformity within the sequence. The relative age relationship between the two formations is based on regional correlations with fossiliferous strata because sedimentary criteria for stratigraphic tops were not observed along the formational boundary.

The four observed outcrop-scale refolded F1 folds in the area are not useful for determination of major regional folds because the folds are commonly rootless, show no asymmetry, and are too rare and widely distributed. Sedimentary criteria for stratigraphic tops are also rare and widely distributed, but the six measurements from graded beds in the western part of the map show upright tops. The application of topping criteria to regional structures is not well constrained, however, because it is not always apparent where the data are in relation to minor F1 and F2 folds. Recent analyses of sedimentary topping criteria to the northwest (Fisher and Karabinos, 1980; Hatch, 1988), in significantly less deformed rocks, provides evidence for the existence of map-scale F1 folds elsewhere in the Connecticut Valley sequence such as the Townshend-Brownington syncline. The lack of unequivocal fold and topping criteria means that interpretations as to the location of such folds in this area are conjectural. The map pattern provides the best evidence for F1 folds in this area. In the eastern part of the map, two belts of volcanic rocks can be traced from Grout Hill south to a point north of downtown Hartland. The two belts can not be mapped unequivocally into a fold closure due to a lack of exposure, but the encompassing DSw and DSwl units can. Outcrop scale refolded F1 folds in the area of the closure are deformed by F2 folds with a consistent east-over-west sense of asymmetry. This evidence suggests that the primary distribution of the units is related to an F1 fold that has undergone subsequent F2 refolding. The distribution of the volcanic rocks in the central and western part is the result of F1 and F2 folding. The along strike distribution occurs in a zone which is interpreted to be on the limb of a large F1 fold. The perturbations in the distribution of the volcanics on the F1 limb are due to subsequent F2 folding that decreases in intensity from east to west. The relationship between the western and eastern belts of volcanic rocks is unclear. The available evidence suggests that they are separate belts within the Waits River Formation, and there is no evidence indicating that the two belts are connected. Layers of limestone-bearing (DSwl) and non-limestone-bearing (DSw) rocks in the central part of the quadrangle show an intriguing map pattern, but it is unclear as to whether it is due to facies changes or early F1 fold closures. The asymmetric and discontinuous distribution of rock types in the sequence makes it difficult to place axial surfaces of such folds, if they exist, and would require significant lateral and vertical facies changes if certain volcanic horizons could be connected by such folds. If such folds account for the map pattern, the distribution of the units could be the result of a series of upward facing early (F1) folds in the synclinorium. This interpretation is simpler and provides an alternative to the downward facing folds presented on the State map by Doll and others (1961).

The new mapping, along with recent work to the south and west, make it possible to correlate regional structural relationships between the Connecticut Valley sequence and the pre-Silurian rocks to the west and south (table 1). The correlations provide a structural framework for Taconic and Acadian deformation in the Vermont Appalachians.

Table 1. Correlation of Taconic and Acadian deformational fabrics across southeast-central Vermont.

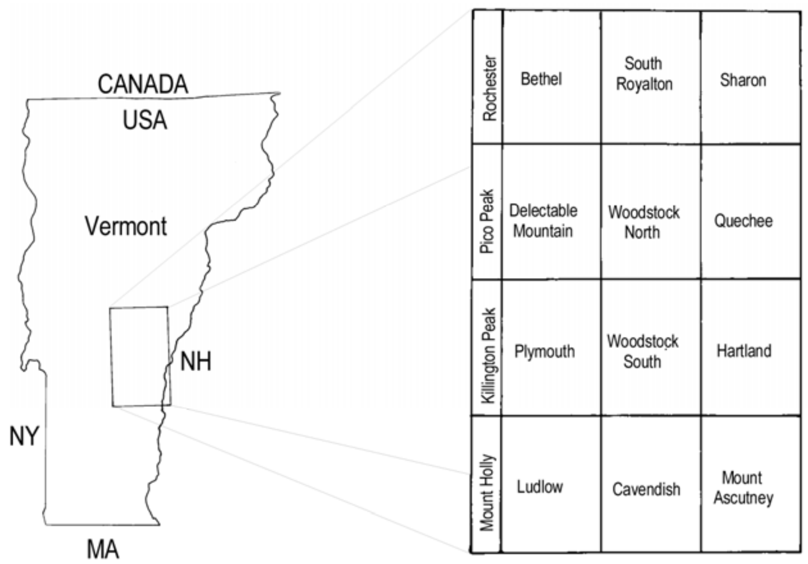
Planar Fabric in Pre-Silurian rocks	Planar Fabric in Silurian & Devonian rocks	Taconic Deformation Event	Acadian Deformation Event
S1	--	D1	--
S2	--	D2	--
S3	S1	--	D1
S4	S2	--	D2
S5	S3	--	D3

Within the pre-Silurian rocks, a penetrative schistosity is associated with reclined folds and a southeast to northeast trending elongation lineation and is interpreted as a fold-thrust fabric inherited from Taconian imbricate thrusting of basement and cover rocks (Walsh and others, 1996a; Ratcliffe and others, 1997b). These features are associated with Taconic D2 deformation and are absent from the Silurian and Devonian rocks. An upright cleavage to penetrative schistosity (S3 in the pre-Silurian rocks) deforms the Taconic D2 fabric and is associated with northeast trending lineations and fold hinges in the pre-Silurian rocks east of the Green Mountain anticlinorium (Walsh and Ratcliffe, 1994a; Walsh and Falta, 1996a, in press). These features can be traced into the Silurian and Devonian rocks where they represent the earliest phase of Acadian deformation (Walsh and Ratcliffe, 1994a; Ratcliffe and others, 1997b). Hinge lines of the first generation folds in the Silurian and Devonian rocks of the Proctorsville syncline (southern terminus of Silurian and Devonian rocks in the Townshend - Brownington syncline) plunge gently to the north approximately perpendicular to the general east-west trending hinge lines in the underlying pre-Silurian rocks (Ratcliffe, 1996). From this evidence it is possible to correlate D3 in the pre-Silurian rocks with D1 in the Silurian and Devonian rocks and attribute this to the first period of Acadian deformation. Northeast-striking and west-dipping cleavage in the pre-Silurian rocks (S4) deforms the earlier features and can be traced into the Silurian and Devonian rocks where it correlates with Acadian S2 (Walsh and Ratcliffe, 1994a; Walsh and Falta, 1996a, in press). In the eastern part of the Hartland quadrangle the S2 foliation is a penetrative schistosity to spaced cleavage, but in the western part of the map S2 is less penetrative. In the Mount Ascutney and Springfield quadrangles, along the eastern flank of the Chester dome, S2 is largely a penetrative schistosity that is locally associated with shear zones (Walsh and others, 1996a; Armstrong and others, 1997). Regionally, the distribution of pervasive S2 in the Silurian and Devonian rocks appears to be related to the Chester dome (fig. 2). If the relationship with the Chester dome is valid, then it is possible that the rocks within the dome had a buttressing effect on the development of the Acadian S2 cleavage to the west. Both the Acadian S1 and S2 fabrics are deformed by younger dome-related structures, which correspond to S3 in the Silurian and Devonian rocks and S5 in the pre-Silurian rocks.

Earlier work by White and Jahns (1950) to the north coined the phrase "cleavage arch" for the trace of the second generation cleavage across the Silurian and Devonian rocks and into the pre-Silurian rocks. White and Jahns' (1950) recognition of an earlier phase of deformation followed by a later phase corresponds to what is now called Acadian D1 and D2, respectively. White and Jahns (1950) subdivided the area into western, central, and eastern tectonic belts and noted that the second phase of deformation increased from west to east in the western domain and from east to west in the eastern domain. The new mapping agrees with their conclusions in the western belt but disagrees with their findings in the eastern belt. To explain the apparent increase in second generation deformation towards the central tectonic belt and the presence of a cleavage arch, White and Jahns (1950) proposed a period of thermal and tectonic uplift during the second phase of deformation. Later, Lyons (1955) suggested that the arching was due to the rise of granitic plutons in the core of the dome structures. Neither White and Jahns (1950) nor Lyons (1955) recognized a third phase of deformation. The new mapping indicates that the third phase of deformation is related to Acadian doming, and that the cleavage arch is simply deformed S2.

Figure 2 shows the regional distribution of Acadian S2 in southeast-central Vermont. Measured S2 in the area clearly defines the regional change in strike of S2. The "cleavage arch" is defined where S2 is extrapolated, or projected, across the belt. The decrease in intensity of D2 fabrics from east to west is apparent when comparing the amplitude of F2 folds along the Richardson Memorial Contact (RMC: the unconformity at the base of the Silurian and Devonian sequence) between Bethel and Ludlow with the F2 folds from the Hartland quadrangle. The F2 fold east of Bridgewater represents the only significant map-scale F2 fold along the RMC.

The regional correlation of Acadian and Taconic structures goes a long way in explaining an apparent structural paradox shown on the State map by Doll and others (1961). According to their map, the pre-Silurian rocks are part of a coherent eastward-dipping and -younging stratigraphic sequence. The younger Silurian and Devonian rocks, however, show significant structural complexity in cross-section involving two major phases of nappe folding. The older rocks, therefore, are less deformed than the younger rocks. The new mapping shows exactly the opposite C the younger rocks are the least deformed.



Area of figure 2 and index to 7.5' quadrangles

Figure 2. This and next page.

Figure 2. Map showing the regional distribution of Acadian S2 in southeast-central Vermont. Measured S2 data derived from this report, Walsh and Falta (1996a, b, in press) [Rochester], Walsh and Ratcliffe (1994a, b) [Plymouth], Walsh and others (1994) [Ludlow], Ratcliffe (1995) [Cavendish], Walsh and others (1996a, b) [Mount Ascutney]. Projected data compiled from unpublished reconnaissance mapping by Walsh in the Bethel, Delectable Mountain, Woodstock North, and Woodstock South quadrangles. Regionally, Acadian S2 correlates with S4 in the pre-Silurian rocks. The significant difference in amplitude between F2 folds along the RMC (i.e. east of Bridgewater) and the F2 folds shown on the geologic map of the Hartland quadrangle highlights the progressive decrease in Acadian D2 intensity towards the west. RMC = Richardson Memorial Contact, TBS = Townshend - Brownington syncline, K = Cretaceous White Mountain Plutonic - Volcanic Suite, Dg = Gile Mountain Formation, DSw = Waits River Formation.

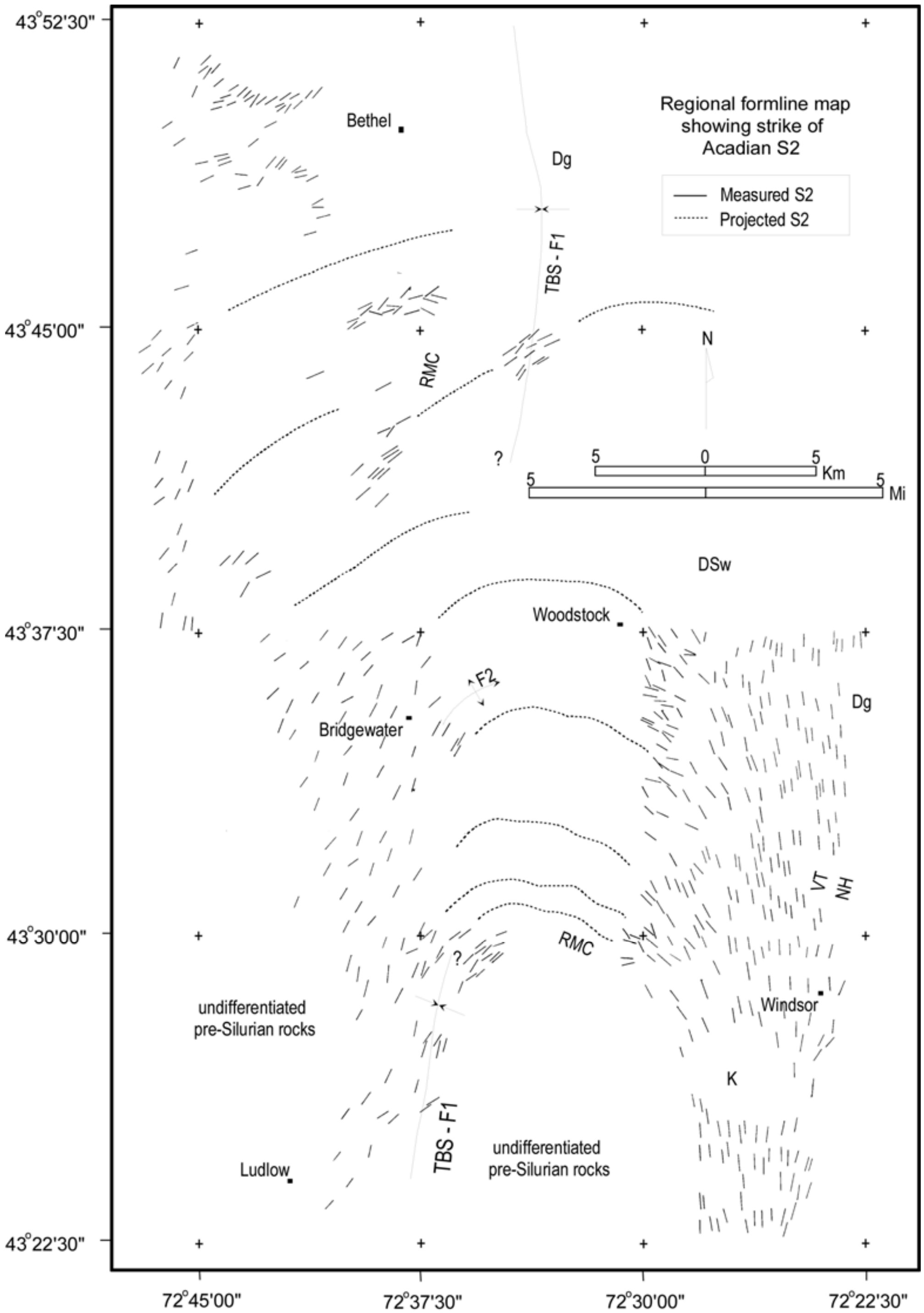


Figure 2. Continued.

REFERENCES CITED

Aleinikoff, J.N., and Karabinos, Paul, 1990, Zircon U-Pb data for the Moretown and Barnard Volcanic Members of the Mississquoi Formation and a dike cutting the Standing Pond Volcanics, southeastern Vermont, *in* Slack, J.F., ed., Summary Results of the Glens Falls CUSMAP Project, New York, Vermont, and New Hampshire: U.S. Geological Survey Bulletin No. 1887, p. D1-D10.

Armstrong, T.R., 1997, Preliminary bedrock geologic map of the Vermont part of the 7.5 x 15 minute Bellows Falls quadrangle, Windham and Windsor Counties, Vermont: U.S. Geological Survey Open-File Report 97-284, scale 1:24,000.

Armstrong, T.R., Walsh, G.J., and Spear, F.S., 1997, A transect across the Connecticut valley sequence in east-central Vermont: *in* Grover, T.W., Mango, H.N., and Hasenohr, E.J., eds., New England Intercollegiate Geological Conference: Guidebook to Field Trips in Vermont and adjacent New Hampshire and New York, 89th Annual Meeting, Castleton, Vermont, p. A6: 1-56.

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

Doll, C.G., 1984, Fossils from the metamorphic rocks of the Silurian-Devonian Magog belt in northern Vermont: Vermont Geology, v. 3, 16 p.

Doll, C.G., Cady, W.M., Thompson, J.B. Jr., and Billings, M.P., 1961, Centennial Geologic Map of Vermont: Vermont Geological Survey, Montpelier, Vermont, scale 1:250,000.

Fisher, G.W., and Karabinos, Paul, 1980, Stratigraphic sequence of the Gile Mountain and Waits River Formations near Royalton, Vermont: Geological Society of America Bulletin, Part I, v. 91, p. 282-286.

Foland, K.A., Henderson, C.M.B., and Gleason, Jim, 1985, Petrogenesis of the magmatic complex at Mount Ascutney, Vermont, USA, I. Assimilation of crust by mafic magmas based on Sr and O isotopic and major element relationships: Contributions to Mineralogy and Petrology, v. 90, p. 331-345.

Hatch, N.L., Jr., 1988, Some revisions to the stratigraphy and structure of the Connecticut Valley trough, eastern Vermont: American Journal of Science, v. 288, no. 10, p. 1041-1059.

Hatch, N.L., Jr., 1991, Revisions to the stratigraphy of the Connecticut Valley trough, eastern Vermont: Stratigraphic Notes, 1989-90, U.S. Geological Survey Bulletin 1935, p. 5-7.

Hitchcock, C.H., 1908, Geology of the Hanover, N.H., quadrangle: Vermont State Geologist 6th Report, 1907-1908, p. 139-186.

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

Lyons, J.B., 1955, Geology of the Hanover quadrangle, New Hampshire - Vermont: Geological Society of America Bulletin, v. 66, p. 105-146, scale 1:62,500.

McHone, J.G., 1984, Mesozoic igneous rocks of northern New England and adjacent Québec: Summary, description of map, and bibliography of data sources: Geological Society of America Map and Chart Series MC-49, scale 1:690,000.

Ratcliffe, N.M., 1995, Digital bedrock geologic map of the Cavendish quadrangle, Vermont: U.S. Geological Survey Open-File Report 95-203, scale 1:24000.

Ratcliffe, N.M., 1996, Preliminary bedrock geologic map of the Andover quadrangle, Windsor County, Vermont: U.S. Geological Survey Open-File Report 96-32, scale 1:24000.

Ratcliffe, N.M., in press, Bedrock geologic map of the Cavendish quadrangle, Windsor County, Vermont: U.S. Geological Survey Geologic Quadrangle Map GQ-1773, scale 1:24000.

Ratcliffe, N.M., and Armstrong, T.R., 1995, Preliminary bedrock geologic map of the Saxtons River 7.5 x 15 minute quadrangle, Windham and Windsor Counties, Vermont: U.S. Geological Survey Open-File Report 95-482, scale 1:24,000.

Ratcliffe, N.M., and Armstrong, T.R., 1996, Digital bedrock geologic map of the Saxtons River 7.5 x 15 minute quadrangle, Vermont: U.S. Geological Survey Open-File Report 96-52, scale 1:24,000.

Ratcliffe, N.M., Armstrong, T.R., and Aleinikoff, J.N., 1997a, Stratigraphy, geochronology, and tectonic evolution of the basement and cover rocks of the Chester and Athens domes, *in* Grover, T.W., Mango, H.N., and Hasenohr, E.J., eds., New England Intercollegiate Geological Conference: Guidebook to Field Trips in Vermont and adjacent New Hampshire and New York, 89th Annual Meeting, Castleton, Vermont, p. B6: 1-55.

Ratcliffe, N.M., Walsh, G.J., and Aleinikoff, J., 1997b, Basement, metasedimentary and tectonic cover of the Green Mountain massif and western flank of the Chester dome, *in* Grover, T.W., Mango, H.N., and Hasenohr, E.J., eds., New England Intercollegiate Geological Conference: Guidebook to Field Trips in Vermont and adjacent New Hampshire and New York, 89th Annual Meeting, Castleton, Vermont, p. C6: 1-54.

Walsh, G.J., Armstrong, T.R., and Ratcliffe, N.M., 1996a, Preliminary bedrock geologic map of the Vermont part of the 7.5 x 15 minute Mount Ascutney and Springfield quadrangles, Windsor County, Vermont: U.S. Geological Survey Open-File Report 96-719, scale 1:24,000.

Walsh, G.J., Armstrong, T.R., and Ratcliffe, N.M., 1996b, Digital bedrock geologic map of the Vermont part of the 7.5 x 15 minute Mount Ascutney and Springfield quadrangles, Vermont: U.S. Geological Survey Open-File Report 96-733, scale 1:24,000.

Walsh, G.J., and Falta, C.K., 1996a, Preliminary bedrock geologic map of the Rochester quadrangle, Rutland, Windsor, and Addison counties, Vermont: U.S. Geological Survey Open-File Report 96-25, scale 1:24000.

Walsh, G.J., and Falta, C.K., 1996b, Digital bedrock geologic map of the Rochester quadrangle, Vermont: U.S. Geological Survey Open-File Report 96-33, scale 1:24000.

Walsh, G.J., and Falta, C.K., in press, Bedrock geologic map of the Rochester quadrangle, Rutland, Windsor, and Addison counties, Vermont: U.S. Geological Survey Miscellaneous Investigations Map I-2626, scale 1:24000.

Walsh, G.J., and Ratcliffe, N.M., 1994a, Preliminary bedrock geologic map of the Plymouth Quadrangle and eastern portion of the Killington Peak Quadrangle, Windsor and Rutland counties, Vermont: U.S. Geological Survey Open-File Report 94-225, scale 1:24,000.

Walsh, G.J., and Ratcliffe, N.M., 1994b, Digital bedrock geologic map of the Plymouth quadrangle, Vermont: U.S. Geological Survey Open-File Report 94-654, scale 1:24,000.

Walsh, G.J., Ratcliffe, N.M., Dudley, J.B., and Merrifield, T., 1994, Digital bedrock geologic map of the Mount Holly and Ludlow quadrangles, Vermont and explanation of the bedrock geology database in the Vermont Geographic Information System: U.S. Geological Survey Open-File Report 94-229, scale 1:24,000.

White, W.S., and Jahns, R.H., 1950, Structure of central and east-central Vermont: Journal of Geology, v. 58, p. 179-220.

DESCRIPTION OF MAP UNITS

(Major minerals listed in order of increasing abundance)

POST-METAMORPHIC INTRUSIVE ROCKS

Dikes (Cretaceous)

Kd — Mafic dikes -- Aphanitic, dark-gray to black, lamprophyre, camptonite, or diabasic dikes. Dikes range in thickness from 0.1 to 2.5 m and may contain phenocrysts of biotite, amphibole, pyroxene, and olivine. May contain amygdules filled with dolomite or calcite. Generally, dikes intrude parallel to joint sets. Dikes are unfoliated but may be blocky jointed

Kt — Trachyte dikes -- Aphanitic, gray to light-gray, tan-weathering, trachyte dikes. Dikes are approximately 1 to 1.5 m thick and may contain quartz and feldspar phenocrysts. Generally, dikes intrude parallel to joint sets. Dikes are unfoliated but may be blocky jointed

SYN- TO POST-METAMORPHIC ROCKS

Quartz veins (Devonian and Cretaceous)

KDq — Quartz veins

ROCKS OF THE CONNECTICUT VALLEY SEQUENCE

Gile Mountain Formation (Lower Devonian)

Dgm — Meetinghouse Slate -- Dark-gray, lustrous, carbonaceous, plagioclase-quartz-chlorite-muscovite slate and phyllite locally rhythmically interbedded with lesser micaceous plagioclase-quartz granofels and micaceous quartzite similar to Dgmf. Quartzite and granofels beds generally range in thickness from 1-5 cm, and rarely exceed 10 cm thick

Dgmf — Feldspathic quartzite, granofels, and dark-gray slate -- Light-gray, massive, micaceous, feldspathic quartzite and micaceous plagioclase-quartz granofels interbedded with lesser dark-gray carbonaceous slate and phyllite. Quartzite and granofels comprise approximately 50 to 90 percent of the unit in beds that generally range in thickness from 2-30 cm

Waits River Formation (Silurian and Lower Devonian)

Metasedimentary Rocks

DSwl — Limestone and schist -- Dark- to light-gray, locally rusty weathering, lustrous, carbonaceous chlorite ±garnet ±biotite-plagioclase-quartz-muscovite schist and phyllite with interbedded dark-blue-gray, dark-brown weathering, siliceous limestone, quartz-rich calcareous schist, and gray calcareous to non-calcareous quartzite

DSw — Gray phyllite and schist -- Dark- to light-gray, lustrous, carbonaceous chlorite±garnet±biotite-plagioclase-quartz-muscovite schist and phyllite, locally interbedded with thin gray quartzite, tan to gray feldspathic quartzite, and gritty micaceous plagioclase-quartz granofels. Contains trace limestone

DSwq — Quartzite -- Gray micaceous quartzite and tan to gray feldspathic quartzite

DSwqs — Quartzose schist -- Dark-gray to blue-gray, carbonaceous muscovite-chlorite-plagioclase quartz-rich schist and micaceous quartzite. Crops out in the Connecticut River at Sumner Falls

DSwab — Ankeritic biotite schist -- Dark-gray, rusty spotted, ankerite-quartz-biotite schist with accessory plagioclase, epidote, chlorite, and garnet

Metavolcanic Rocks

DSwv — Laminated schist and granofels -- Heterogenous, laminated to layered, green and white, in places rusty weathering, fine- to medium-grained muscovite±biotite-chlorite-quartz-plagioclase schist; silvery-green, fine- to medium-grained muscovite±biotite-chlorite-quartz-plagioclase schist; gray-green, medium-grained muscovite±biotite-chlorite-quartz- plagioclase granofels; greenstone; and silvery gray, rusty weathering, carbonaceous calcite-plagioclase-quartz-chlorite-biotite-muscovite schist. Contains accessory calcite and ilmenite. Unit is interpreted as a heterogenous assemblage of volcaniclastic sediments and primary volcanic rocks

DSwvp — Porphyritic schist and granofels -- Gray-green to light-gray, medium-grained hornblende-muscovite-quartz-plagioclase-chlorite-biotite schist with quartz and plagioclase phenocrysts up to 1 cm long; contains accessory calcite, ilmenite, apatite, and idocrase. Unit is interpreted as a primary volcanic rock

DSwg — Large garnet and hornblende garbenschiefer schist -- Silvery gray to light-gray, in places rusty weathering, calcite-epidote-chlorite-garnet-hornblende-plagioclase- quartz-biotite-muscovite schist with distinctive sprays of hornblende and large-garnet porphyroblasts. Unit is interpreted as metamorphosed pelitic sediments with a volcaniclastic component

DSwa — Amphibolite and greenstone -- Massive, dark-green to green, fine-grained calcite- epidote-chlorite-biotite±hornblende±actinolite-plagioclase amphibolite and greenstone. Unit interpreted as mafic volcanic and volcaniclastic rock

DSwhg — Hornblende-plagioclase gneiss -- Medium- to very coarse-grained, black and white to dark-green, calcite-epidote±garnet-chlorite-biotite-hornblende-plagioclase amphibolite gneiss with roughly equal percentages of hornblende and plagioclase; contains accessory calcite and ilmenite

DSwf — Felsic gneiss and quartzose granofels -- Light-gray, biotite-quartz-plagioclase gneiss, and feldspathic biotite quartzite and granofels with accessory hornblende and garnet. Unit interpreted as a volcaniclastic sedimentary and primary sedimentary rock

DSwss — Sulfidic schist -- Silvery, rusty yellow weathering, sulfidic quartz-muscovite schist. Unit interpreted as a hydrothermally produced stratiform sulfide deposit

DSwh — Hornblende fascicle schist -- Silvery gray, medium- to coarse-grained calcite-hornblende-quartz-biotite schist with conspicuous hornblende fascicles; contains accessory muscovite and chlorite. Crops out on Blake Hill. Unit interpreted as a volcaniclastic rock