ROAD TO THE KINGDOM: A BEDROCK TRANSECT ACROSS THE PRE-SILURIAN ROWE-HAWLEY BELT IN CENTRAL VERMONT

Jonathan Kim[1], Marjorie Gale[1], Ray Coish[2], Jo Laird[3], and Greg Walsh[4]

[1]Vermont Geological Survey, 103 South Main St., Logue Cottage, Waterbury, VT 05671
[2]Dept. of Geology, Middlebury College, Middlebury, VT 05753
[3]Dept. of Earth Sciences, University of New Hampshire, Durham, N.H. 03824
[4]U.S. Geological Survey, 87 State St., Montpelier, VT 05601

TRIP SUMMARY

The 101st NEIGC is being held at Lyndon State College in Lyndonville in the heart of the "Northeast Kingdom" (NEK) of Vermont. The NEK is primarily underlain by Silurian and Devonian metasedimentary rocks of the Connecticut Valley Belt/Synclinorium (CVB) that were intruded by Late Devonian granitoids of the New Hampshire Plutonic Series. Although most bedrock trips will focus on various aspects of the CVB, the "Road to the Kingdom" field trip will traverse the eastern half of the Pre-Silurian bedrock section (Rowe-Hawley Belt (RHB)) between the Green Mountain Belt and CVB. In general terms, the RHB is a lithotectonic assemblage of Laurentian continental margin, oceanic, and suprasubduction zone rocks that were first juxtaposed during the Ordovician Taconian Orogeny, but were also deformed and metamorphosed during the Devonian Acadian Orogeny. We will begin in the Green Mountain Belt (transitional rift clastic rocks of the Hazens Notch Formation) and work our way through metasedimentary and meta-igneous slices of the Rowe-Hawley Belt that contain rocks of the Ottauquechee, Stowe (including the garnet amphibolites and muscovite-garnet-kyanite schists) of the Worcester Complex) and Moretown, and Cram Hill formations. Metamorphic grade for most slices is muscovite-biotite grade with the Worcester slices being garnet-kyanite grade. The framework for this trip will be 1: 24,000 scale maps and cross sections constructed during the 2002-2006 field seasons by the Vermont Geological Survey (Kim and Gale). A tectonic story will be proposed by integrating new igneous geochemical data from Middlebury College (Coish and students) and petrological data from the University of New Hampshire (Laird and students) with this framework. When combined with trip C3: Bedrock Geology of the Montpelier Area, Central Vermont (Walsh et al., this volume), the participant will get a detailed transect across the RHB and the CVB along with the abrupt transition between them marked by the Richardson Memorial Contact (RMC).

INTRODUCTION

The Pre-Silurian RHB was originally defined in Massachusetts by Stanley and Ratcliffe (1985) and Stanley and Hatch (1988) to include the Rowe (undifferentiated Pinney Hollow, Stowe, and Ottauquechee formations and ultramafic slivers (Taconian accretionary wedge), Moretown (forearc basin fill), and Hawley (metavolcanics from the western edge of a Taconian arc) formations. Although the Hawley Formation was originally proposed to be a distal part of the Bronson Hill Arc of New Hampshire, Massachusetts, and Connecticut (Stanley and Ratcliffe, 1985; Stanley and Hatch, 1988), later workers suggested that it was actually part of an older and independent Shelburne Falls Arc that collided with the Laurentian margin prior to the accretion of the Bronson Hill Arc (Karabinos et al., 1998); this hypothesis was built in part on U/Pb isotopic data from zircons that indicated that the Bronson Hill Arc was too young to be the colliding body for the Taconian Orogeny (Tucker and Robinson, 1990). In the Karabinos et al. (1998) model, the collision of the Shelburne Falls Arc (SFA) "caused" the Taconian Orogeny whereas Ratcliffe et al. (1998) maintained that the SFA was a stage in the protracted evolution of the Bronson Hill Arc system. Hibbard et al. (2006) include the RHB in New England as being related to a peri-Laurentian arc system whereas the Bronson Hill Arc is a peri-Gondwanan arc system. Recent isotopic work, however, indicates that this scenario may be more complicated (Dorais et al., 2008).

In southern Quebec, the RHB generally correlates with parts of the Internal Humber and Dunnage zones. The Internal Humber Zone represents strongly metamorphosed rocks of the Laurentian Margin whereas suprasubduction and oceanic rocks comprise the Dunnage Zone (e.g., Castonguay et al., 2001; Castonguay et al., 2007). Metasedimentary and meta-igneous rocks of the Stowe and Ottauquechee formations correlate respectively with Caldwell and Rosaire group rocks of the Internal Humber Zone that structurally overlie the Sutton-Bennett Schist (Green Mt. Belt correlative of Hazens Notch and Fayston formations) and structurally underlie the Thetford Mines

Ophiolite, St. Daniel Mélange, and Magog Group of the Dunnage Zone (e.g., Kim et al., 2003c). Although the Moretown Formation has no southern Quebec analogue, it fits with the Dunnage Zone because it contains Late Cambrian and Ordovician suprasubduction zone intrusives and volcanics (e.g., Ratcliffe et al., 1997; Kim et al., 2003a; Hibbard et al., 2006). The fragmentary ophiolite represented by the Belvidere Mountain Complex and blueschists and eclogites of the Tillotson Peak Complex are part of the RHB and are also Dunnage correlatives (Kim et al., 2001; Kim et al., 2003c). In northern Vermont, some thrust sheets of Stowe Formation contain metadiabasic intrusives with suprasubduction zone tectonic affinity (Stanley et al., 1984; Mount Norris Intrusive Suite of Kim et al., 2003a).

The RHB in central and northern Vermont occupies a critical transition zone that occurs between the Pre-Silurian portions of the western New England and southern Quebec Appalachians. This zone occurs between the New York Promontory and the Quebec Reentrant. Several significant along-strike changes that occur in this zone are: 1) disappearance of the regionally extensive, bimodal forearc and arc meta-igneous rocks of the Hawley Formation/Barnard Gneiss as a mappable unit in the eastern RHB - vestiges of Hawley suprasubduction zone meta-igneous rocks continue northward to the Quebec border as mafic dikes within slices containing the Moretown and Cram Hill formation lithologies; 2) the appearance of mafic complexes that Kim et al. (2001, 2005) have correlated with those of southern Quebec (e.g. Worcester, Belvidere Mt.); and 3) the thickening and eventual along-strike termination of the Moretown Formation. This trip will focus on structural, petrologic, geochemical, and tectonic elements of the RHB in central Vermont.

REGIONAL GEOLOGY

Vermont can be divided into a number of north-northeast trending bedrock belts of generally similar age and tectonic affinity. To provide context for this trip, these belts are shown in Figure 1 and described below: From west to east the belts are:

1) <u>Champlain Valley:</u> Cambrian – Ordovician carbonate and clastic sedimentary rocks deposited on the eastern (present coordinates) continental margin of Laurentia. This continent was left behind as the Rodinian supercontinent rifted apart in the Late Proterozoic and an intervening Iapetus Ocean formed.

2) <u>Taconic</u>: Late Proterozoic- Ordovician clastic metasedimentary rocks of oceanic and continental margin affinity that were thrust onto the Laurentian margin during the Taconian Orogeny.

3) <u>Green Mountain:</u> Late Proterozoic- Cambrian rift and transitional rift related metasedimentary and meta-igneous rocks originally deformed and metamorphosed during the Taconian Orogeny (also during the Acadian Orogeny).

4) <u>Rowe-Hawley:</u> Metamorphosed continental margin, oceanic, and suprasubduction zone rocks of Late Proterozoic-Ordovician age assembled in the suture zone for the Taconian Orogeny (also deformed and metamorphosed during the Acadian Orogeny). Arc components may be part of an older Shelburne Falls Arc.

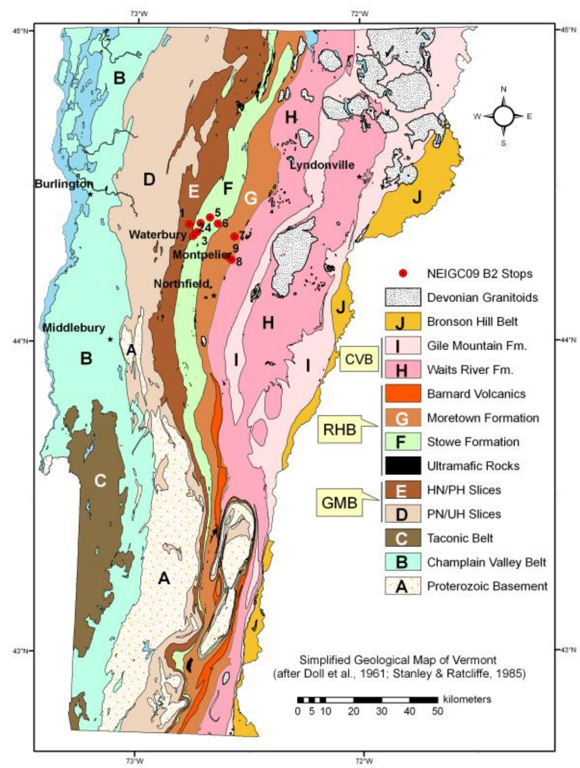


Figure 1: Simplified geology of Vermont showing locations of stops for this trip. GMB – Green Mountain Belt, RHB – Rowe-Hawley Belt, CVB – Connecticut Valley Belt, PN – Pinnacle, UH – Underhill, HN – Hazens Notch, PH – Pinney Hollow.

5) <u>Connecticut Valley:</u> Silurian and Devonian metasedimentary and meta-igneous rocks deposited in a post-Taconian marginal basin. First deformed and metamorphosed during the Acadian Orogeny.

6) Bronson Hill: Ordovician meta-igneous and metasedimentary rocks of arc affinity and the underlying metasedimentary rocks that the arc was built on. Current debate focuses on whether this arc had Laurentian or Gondwanan arc affinity.

The bedrock map of the field trip area was assembled from three separate STATEMAP funded (1:24,000 scale) mapping projects: 1) Montpelier Quadrangle (Kim et al., 2003a; Walsh et al., in press), 2) Southern Worcester Mountains (Gale et al., 2006), and 3) Western Worcester Mountains (Kim et al., 2007). These maps span from (from west to east) the eastern Green Mountain Belt (GMB), the Rowe-Hawley Belt, and the westernmost part of the Connecticut Valley Belt (Figure 2). Since deformation and metamorphism of these belts occurred during the Taconian and Acadian orogenies, discerning tectonic stratigraphy from original stratigraphy is often difficult. Each of the Pre-Silurian belts is composed of fault-bounded lithotectonic slices that often contain lithologies from more than one formation and identical lithologies are also found in more than one formation. In spite of the tectonic dismemberment, intact stratigraphy can be found within the slices. Although mapping the rocks and making cross sections establish a valuable framework, it is the integration of petrology and igneous geochemistry that allows us to infer the tectonic history of each slice and belt.

Figure 2 shows the major bedrock belts in the field area as well as the lithotectonic slices within the RHB. To supplement the map, more detailed descriptions and general association of the lithologies (and their formations) in each slice follow. The ages of each of the lithologies are also shown in the key for Figure 2.

Green Mountain Belt (Thompson et al., 1999; Thompson and Thompson, 2003)

- Rusty weathering gray-black graphitic albite porphyroblast schists interlayered with laminated black quartzites (Hazens Notch Formation)
- Greenstones (mafic metavolcanics)

Rowe-Hawley Belt

Prospect Rock Slice (Thompson et al., 1999; Thompson and Thompson, 2003)

- Rusty weathering gray-black graphitic phyllites (Ottauquechee Formation)
- Silvery gray phyllitic granofels +/- smoky quartz pebbles (Ottauquechee Formation)
- Rusty weathering gray-black graphitic phyllites interlayered with grayish-green phyllites (Ottauquechee Formation if black phyllites are dominant and Stowe Formation if grayish-green phyllites are dominant)
- Greenstones (mafic metavolcanics)

Hyde Park Slice (Kim et al., 1999; Thompson et al., 1999; Thompson and Thompson, 2003)

- Rusty weathering gray-black graphitic phyllites (Ottauquechee Formation)
- Silvery gray phyllitic granofels +/- smoky quartz pebbles (Ottauquechee Formation)
- Grayish-green phyllites (Stowe Formation)
- Rusty weathering gray-black graphitic phyllites interlayered with grayish-green phyllites ((Ottauquechee Formation if black phyllites are dominant and Stowe Formation if grayish-green phyllites are dominant)
- Greenstones (mafic metavolcanics)

Worcester Complex (Stowe Formation) (Kim et al., 2001, Laird et al., 2007)

- Amphibolites +/- garnet
- Muscovite-quartz-garnet +/- kyanite schist

Dumpling Hill Slice (Moretown Formation) (Kim et al., 2003b, Walsh et al., *in press*)

- Interlayered green and black phyllite/granofels
- Phyllite, granofels, and pinstriped granofels
- Interlayered black phyllite and quartzite.

Wrightsville Slice (Moretown Formation) (Kim et al., 2003b; Walsh et al., *in press*)

- Greenish-gray phyllite, granofels, and pinstriped granofels
- Greenstone and metadiabase occur **throughout** and are characteristic of this slice.

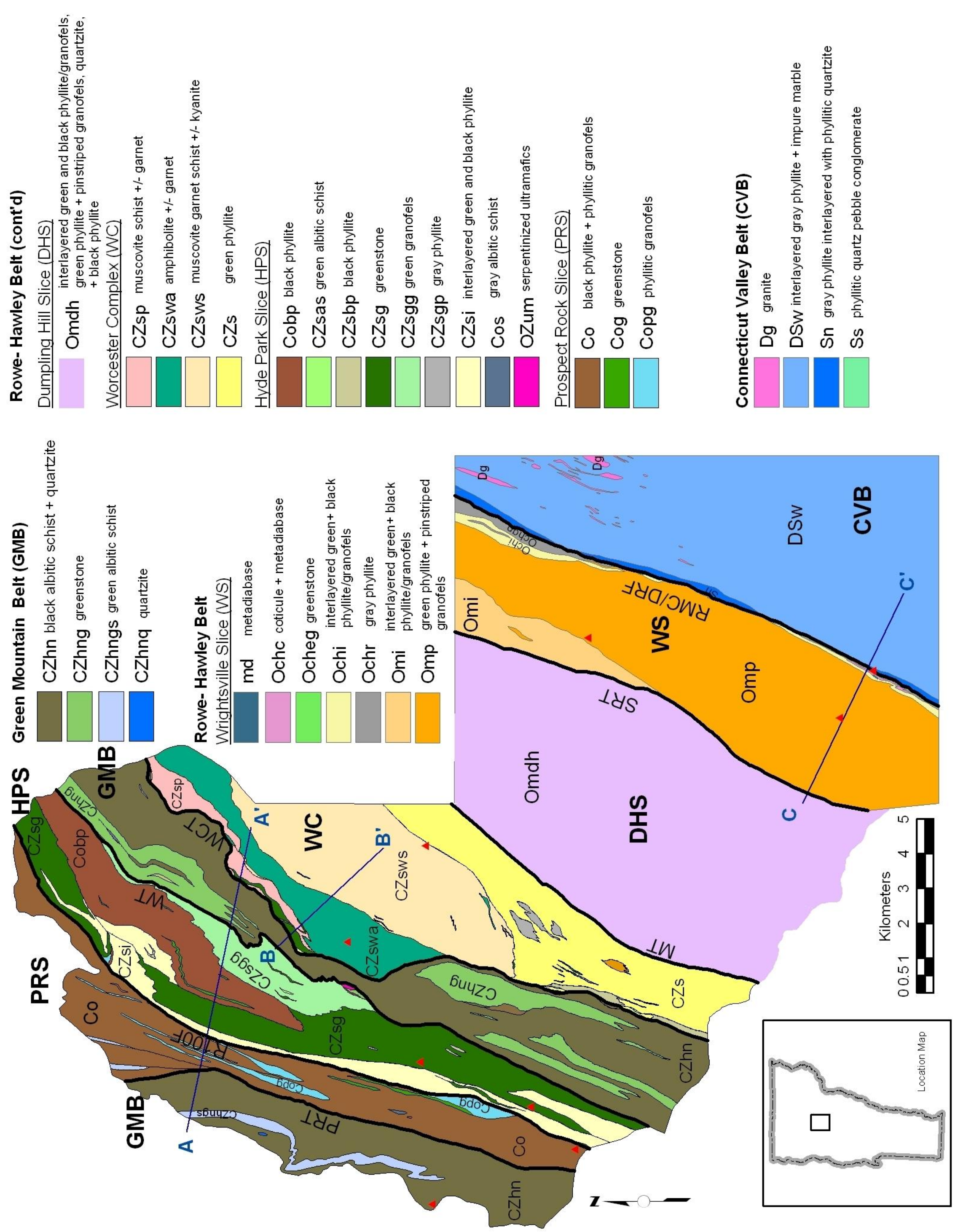


Figure 2: Geological map of Waterbury-Montpelier area (Kim et al., 2003b; Gale et al., 2006; Kim et al., 2007).

GEOCHRONOLOGY

Igneous

There are no igneous crystallization ages for any unit within the Pre-Silurian study area so extrapolation to other areas along strike is necessary for age control. The minimum age for the Moretown Formation in southern Vermont was established by 486 Ma and 496 Ma U/Pb zircon ages on metafelsite intrusions (Ratcliffe et al., 1997). Similarly, the age of the Cram Hill in southern Vermont is constrained by a 484 Ma U/Pb zircon age on a felsic metavolcanic (Ratcliffe et al., 1997).

In the Dunnage Zone of southern Quebec, the U/Pb age on zircons in the Thetford Mines and Mt. Orford ophiolites are 479 Ma (Dunning and Pedersen, 1988) and 504 Ma (David and Marquis, 1994), respectively. Other granitoids in the Thetford Mines Ophiolite are 469-470 Ma (Whitehead et al., 2000). Metarhyolites from the Ascot Complex gave U/Pb zircon ages of 441 and 460 Ma (David and Marquis, 1994).

Metamorphic

In the northern Vermont RHB, $^{40}Ar/^{39}Ar$ total fusion ages on amphiboles give Taconian ages that range from 460 to 471 Ma whereas total fusion ages on muscovite and biotite give Acadian ages of 355-386 Ma (Laird et al., 1984; Laird et al., 1993). A 505 Ma $^{40}Ar/^{39}Ar$ plateau age on barroisitic amphibole from the Belvidere Mt. Complex amphibolite was obtained by Laird et al. (1993). Glaucophane from the Tillotson Peak Complex yielded an $^{40}Ar/^{39}Ar$ total fusion age of 468 Ma (Laird et al., 1984).

In the Dunnage and Internal Humber zones of southern Quebec (RHB equivalents collectively), $^{40}Ar/^{39}Ar$ studies established discrete Middle Ordovician (ca. 470-460 Ma), Silurian-Lower Devonian (431-411 Ma), and Devonian (ca. 380 Ma) events (Whitehead et al., 1996; Tremblay et al., 2000; Castonguay et al., 2001; Castonguay and Tremblay, 2003; Castonguay et al., 2007). These metamorphic events are associated with west directed ophiolite emplacement and thrusting during the Taconian Orogeny, southwest-directed reverse faulting and normal faulting in the Salinian “Orogeny”, and folding during the Acadian Orogeny, respectively.

STRUCTURAL GEOLOGY

Folding Events and Associated Fabrics

The field area for this trip lies in the overlap zone between Taconian and Acadian deformation. Five phases of ductile deformation are recognized in this field area with the first two being Taconian and the last three Acadian. Block diagrams of these fold generations are shown in Figure 3.

- <u>F1 and F2 (Taconian)</u> Isoclinal folds that are frequently rootless and intrafolial. When observed at a single outcrop, F1 and F2 may have axial surfaces that are coplanar, but their fold axes are not coaxial. Relative orientation is variable. F2 folds are reclined, as are some F1 folds. S1 and S2 are spaced cleavages that are axial planar to these folds. Isolated sheath folds occur locally. Well developed down-dip stretching lineations (primarily quartz rods) define these fold axes and suggest rotation of these axes into the transport direction of the slices. When marker lithologies are present, F1 and F2 folds are recognizable at the map scale.

- <u>F3 (Acadian)</u> Open to tight asymmetric folds with sub-horizontal fold axes that frequently change plunge direction. S3 is an axial planar penetrative

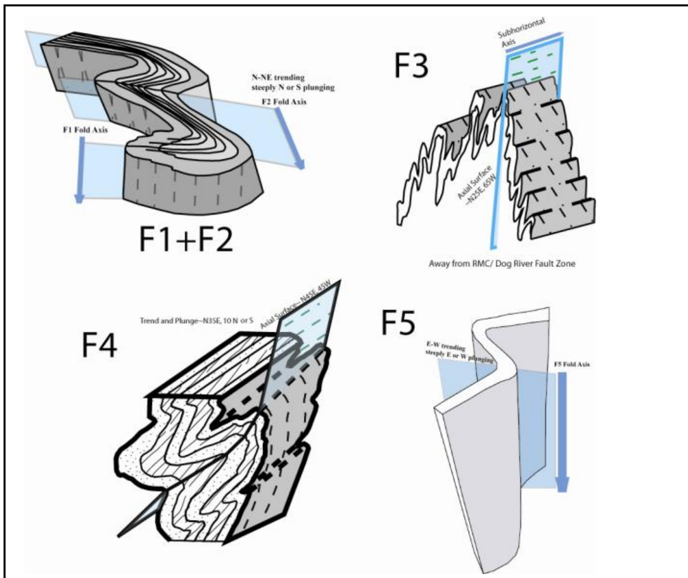


Figure 3: Styles of fold generations observed in the area.

to irregularly developed crenulation cleavage. The intensity of S3 increases eastward in the RHB and in the vicinity of D3 fault zones. S3 is the first foliation to affect the Silurian and Devonian rocks of the Connecticut Valley Belt and can easily be traced across strike to the west into Pre-Silurian rocks. Crenulate lineations occur where F3 fold axes intersect S1/S2. In the vicinity of the RMC/Dog River Fault Zone, sub-horizontal F3 fold axes are reoriented by this Acadian fault to plunge steeply down dip.

- F4 (Acadian) Locally developed tight asymmetric folds with sub-horizontal fold axes that occur in the eastern part of the RHB and in the CVB; these folds clearly deform S3. S4 is a crenulation cleavage that occurs irregularly. F4 folds deform the RMC/Dog River Fault Zone. When S3 and S4 occur together, S4 generally trends more to the northeast and dips more shallowly to the west.

- F5 (Acadian) Open folds with a sporadically developed axial planar crenulation cleavage. These folds deform all earlier fabrics and are seen at the outcrop and map scale.

Cross Sections

Although the Acadian Orogeny had a pronounced effect on the field area in terms of folding and retrogressive metamorphism, the current architecture of slices is largely due to Taconian thrusting. This thrusting produced the F1+F2 isoclinal folds and was followed by Acadian F3 asymmetric folding. Acadian faults formed in locations where the limbs of F3 folds sheared out; however, some later faulting resulted from the reactivation of Taconian faults. The structural level of the slices increases from east to west (see cross sections A-A’ and B-B’ in Figure 4). The map is essentially a cross section for Taconian structures since they plunge downdip whereas the cross sections themselves are better for looking at the modification of the Taconian structures by the Acadian deformation(s). From west to east across the field area, there is general intensification of the F3 folding which first steepens the east dipping S1/S2 composite foliation and ultimately overturns it to the west.

In the Green Mountain Belt, the dominant foliation is an S1/S2 composite that is rumpled by F3 folds. The S1/S2 foliation generally dips gently-moderately to the east depending on the position on F3 folds. After crossing into the Rowe-Hawley Belt, the dominant S1/S2 foliation becomes steeper due to intensification of F3 and S3 becomes more penetrative. Cross-section B-B’ shows that the axial surfaces of F3 folds rotate from east dipping to west dipping as the Worcester Mountains are crossed; because of this, the dip of the dominant S1/S2 fabric and S3 also change from east to west. In cross section C-C’, the dominant foliation is tightly folded by the F3 folds and S3 also dips steeply to the west.

Although the strike of the lithotectonic slices in the RHB is generally to the N-NE, the isoclinal map pattern in the northern half of the Hyde Park Slice is worthy of note. A series of nested southward closing isoclinal folds are defined by lithologic markers; these F2 structures plunge downdip. Vestiges of similar structures are observed in the neighboring Prospect Rock Slice at the map scale through the disarticulated limbs of the phyllitic granofels (Copg) unit.

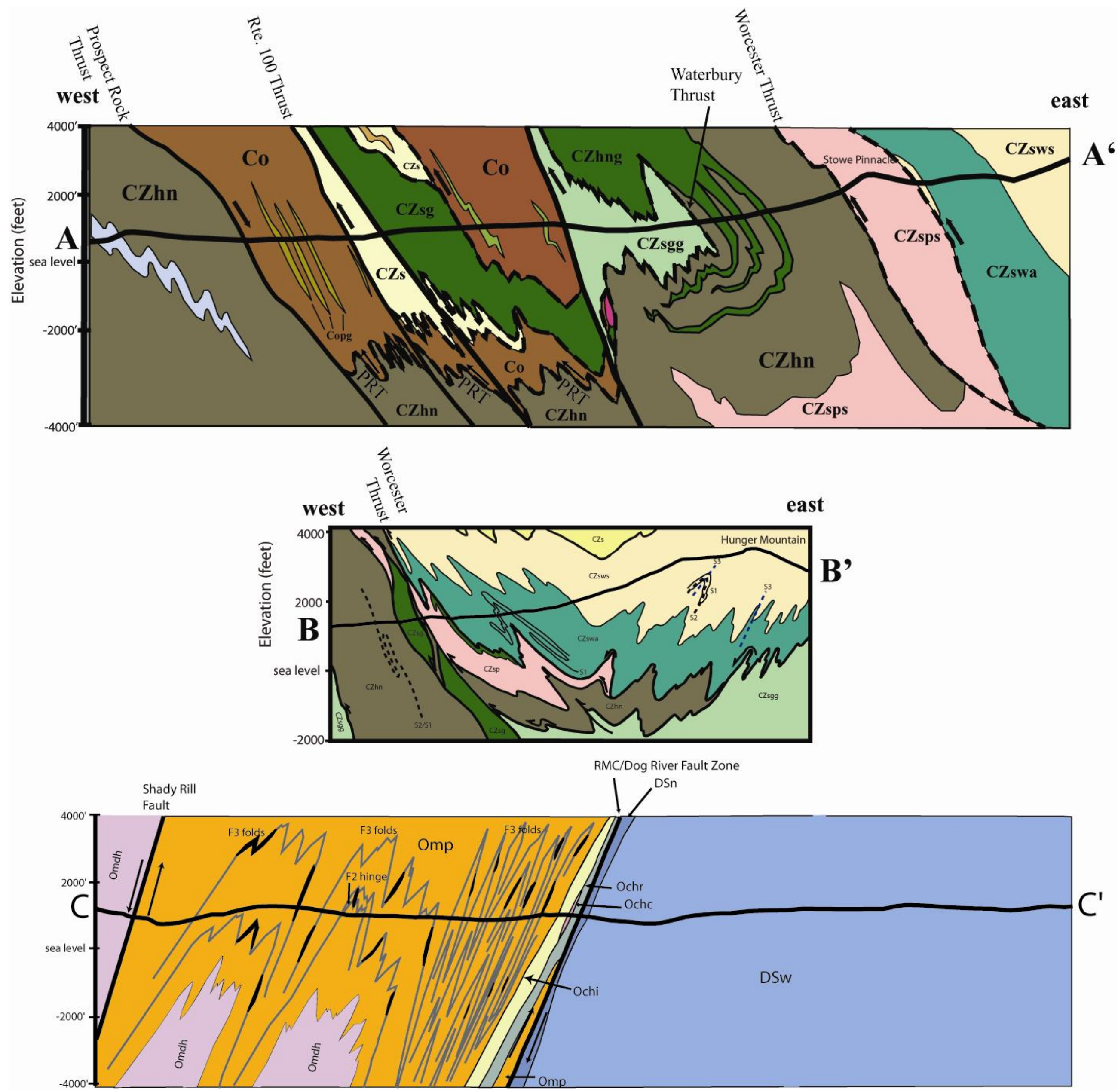


Figure 4: Cross sections A-A', B-B' and C-C' as shown on map in Figure 2.

Faults

The following informally-named major faults are shown on the Figure 2 base map and the cross sections in figure 4. Brief descriptions and the significance of these faults follow:

Taconian

- Prospect Rock Thrust (reactivated) - East dipping fault that separates the RHB from the GMB. This fault generally coincides with the folded Prospect Rock Fault (see cross-section A) of Thompson and Thompson (2003). However, at this latitude the papery schist in the fault zone suggests the PRF was reactivated and the displacement of the folded PRF is down to the east, similar to the Burgess Branch Fault further north. Timing of the fault reactivation may be late Taconian to early Acadian.

- Rte. 100 Thrust – East-dipping fault that separates the Hyde Park Slice from the underlying Prospect Rock Slices.

- Waterbury Thrust – East-dipping thrust that places an out-of-sequence thrust of the Green Mountain Belt (Hazens Notch Formation and associated greenstone) on top of the Hyde Park Slice.

- Worcester Complex Thrust – East-dipping fault that juxtaposes the schists and amphibolites of the Worcester Complex with the previously mentioned out-of-sequence thrust of the Green Mt. Belt. Cross sections A-A' and B-B' show that this thrust has a composite history. The Stowe Pinnacle Slice is a part of the western part of the Worcester Complex.

Acadian (or Salinian)?

- Middlesex Thrust - A steeply west-dipping overturned fault that places the Dumpling Hill Slice on the Hyde Park Slice and the Worcester Complex. Marked by a phyllonitic zone. We cannot discount the possibility that this is a Taconian fault that was reactivated during the Acadian.

- Shady Rill Thrust - A steeply west-dipping overturned fault that places the Wrightsville Slice bearing abundant metadiabasic intrusions on the Dumpling Hill Slice. This slice also truncates isoclinal fold structures (not shown on map) in the Dumpling Hill Slice.

- RMC/ Dog River Fault Zone - At the latitude of this trip and trip C3, this fault is a discontinuous Acadian (F3/S3) fault (Westerman, 1987) with west side up kinematics (Walsh et al., in press). This fault is intermittently coincident with the major Upper Silurian unconformity represented by the RMC.

PETROLOGY AND THERMOBAROMETRY

Participants on this trip will notice the obvious contrast between the amphibolite facies metamorphism of the Worcester Complex (garnet-kyanite schist and garnet amphibolite) and the greenschist facies metamorphism (maximum of biotite grade) of the other slices. However, what meets the eye in the field is only a small part of the petrologic story. Based on the detailed examination of amphibole compositions in mafic rocks in the central and northern Vermont RHB, a complex spectrum of amphibole compositions are proxies for metamorphic pressures and temperatures during the Taconian and Acadian orogenies (Laird and Albee, 1981; Laird et al., 1984; Laird et al., 1993; Laird et al., 2007). New bedrock geologic maps produced by the Vermont Geological Survey of the central Vermont RHB (Kim et al., 2003b; Gale et al., 2006; Kim et al., 2007) provide a detailed framework in which to place the work of Laird et al. (1984, 1993, 2007).

As summarized by Laird et al. (1984; 1993), the major changes in mode and mineral chemistry in mafic rocks in Vermont occur among the phases amphibole, chlorite, epidote, plagioclase, and quartz and these phases can be shown in three-dimensional reaction space. There are two specific reactions that stand out in the metamorphism and dictate the NaSiCa-1Al-1 (PL) substitution in amphibole and plagioclase and the Al2Mg-1Si-1 (TK) substitution in amphibole and chlorite. PL increases with the pressure of metamorphism whereas TK increases with the temperature of metamorphism. Both PL and TK were determined from the cores and rims of amphiboles from mafic metaigneous rocks in the field area. By plotting PL vs TK, Laird et al. (1984) were able to delineate envelopes that represent *Pressure Facies Series* (Figure 5A).

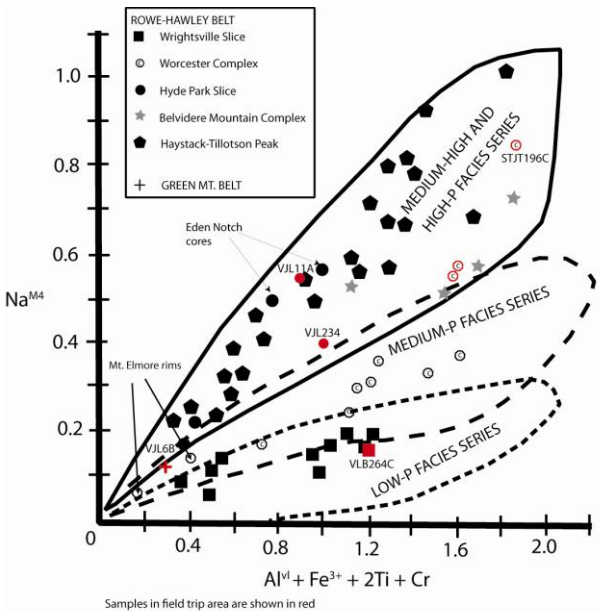


Figure 5A: Metamorphic facies series for mafic rocks in the area, as determined from amphibole chemistry (Ferguson, 2003; Laird et al., 2007). X axis = TK, Y axis = PL.

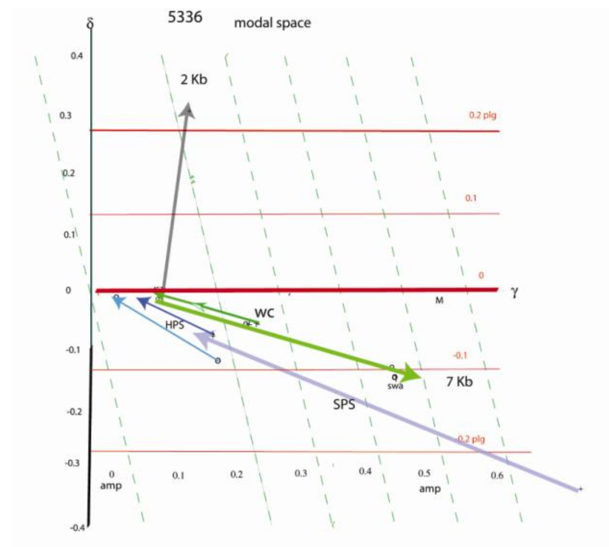


Figure 5B: Modal space for Stowe Formation amphibolite showing core to rim arrows for the Stowe Pinnacle Slice (SPS), Hyde Park Slice (HPS), and Worcester Complex (WC) relative to 2 Kb and 7 Kb whole rock reactions in mafic schist. Isopleths are for modal amphibole (amp) and plagioclase (plg). X and Y axes are the reactions γ and δ as given in the text. The symbol M is for the Wrightsville Slice.

Amphibole core compositions indicate that the Stowe Pinnacle Slice (STJL196C) and Hyde Park Slice (VJL11A) were metamorphosed at the greatest pressure with the former at greater temperature. The Wrightsville slice was metamorphosed at the lowest pressure, and the Worcester Complex was metamorphosed at medium pressure. Rims on amphiboles from all slices are actinolite and show low temperature metamorphism.

Metamorphism of samples in the field area from the Stowe Formation is examined in modal space (Figure 5B) relative to whole rock experiments at 2 Kb and 7 Kb (Thompson and Laird, 2005). On this diagram increasing TK and modal amphibole are explained by reaction γ (epidote + chlorite + quartz → amphibole + TK + H_2O), while increasing modal plagioclase *and decreasing PL* are explained by reaction δ (chlorite+epidote +PL+ quartz → plagioclase + amphibole + H_2O).

Figure 5B supports the conclusion that before retrogradation to greenschist facies metamorphism in the field area decreased in pressure from the SPS and HPS to the WC to the Wrightsville Slice. SPS and HPS were initially metamorphosed at pressures greater than 7 Kb, with the former at greater temperature, while the Wrightsville Slice was initially metamorphosed at a pressure less than 7 Kb. WC was initially metamorphosed at about 7 Kb.

IGNEOUS GEOCHEMISTRY

Overview

Metamorphosed mafic volcanic and volcaniclastic rocks, locally known as greenstones, occur throughout the western tectonic slices of the Vermont Appalachians (e.g., Coish et al., 1985; Coish et al., 1986; Coish, 1997). Chemical variations in principally titanium and the rare earth elements, along with stratigraphic and structural information, have been used to distinguish four geochemical zones of mafic magmatism within the Green Mountain and Stowe slices of the Vermont Appalachians (Coish et al., 1991). From west to east, Zone 1 greenstones are represented by dikes mainly found in the Adirondack basement; Zone 2 greenstones occur in the Pinnacle and Underhill slices; Zone 3 greenstones crop out in the Hazens Notch and Pinney Hollow slices; and Zone 4 greenstones are in the Stowe slice. While the division into zones is somewhat arbitrary, the differences in chemistry among the zones reflect different sources available for melting during continental breakup to form the Iapetus Ocean.

Zones 1 and 2 in westernmost Vermont formed by partial melting of plume or enriched lithospheric mantle, often the primary source of magma during early stages of continental rifting. Zone 3 greenstones seem to have had enriched sources as well as more depleted mantle sources available for melting and Zone 4 greenstones are dominated by more depleted sources. This is interpreted to mean that as continental rifting proceeded, the influence of the plume or mantle lithosphere source waned and the influence of the depleted (mid-ocean ridge type) mantle waxed (Coish, 1997). Thus, westernmost greenstones are mostly, but not exclusively, “enriched” basalts whereas easternmost greenstones (Stowe slices) are mostly, but not exclusively, more depleted basalts.

Remnants of mafic magmatism subsequent to Iapetan rifting volcanism are preserved in the Rowe-Hawley Belt of north-central Vermont as metadiabasic intrusions of the Mount Norris Igneous Suite (MNIS) (Kim et al., 2003a). Whole rock chemistries of these greenschist facies rocks show that they were subalkaline, tholeiitic basalts. Furthermore, rare earth element contents, Ta/Yb and Th/Yb ratios suggest that the basalts were formed in an extensional volcanic arc environment, perhaps a back-arc basin (Kim et al., 2003a).

On this trip, we will visit outcrops exposing metamorphosed mafic rocks that represent late-stage Iapetan rift magmatism in the Stowe tectonic slices and extensional arc magmatism one of the lithotectonic slices containing Moretown Formation rocks (Wrightsville Belt).

Greenstone and Amphibolite from Hyde Park Slice and Worcester Complex

Geochemical evidence suggests that both greenstone and amphibolite represent mafic magmatism as shown by their basaltic compositions. Compositions of the greenstone and amphibolite indicate they were mostly tholeiitic basalt with a small subset containing alkali basalt (Fig. 6). Samples of greenstone are divided into three geochemical types based on their rare earth element patterns (Fig. 6). Type 1 greenstone has light-rare earth element (LREE) depleted patterns ($(La/Yb)_n < 1$) and total abundances of the rare earths (as represented by the sum of La, Sm and Yb) from 5 to 10. Type 2 greenstone has slightly enriched LREE patterns ($(La/Yb)_n \sim 1$ to 2) with total rare earth element abundances from 10 to 17. Type 3 greenstone has highly enriched LREE patterns ($(La/Yb)_n \sim 5$ to 10), with total abundances from 25 to 40; they represent the alkalic basalt subset. Types 1 and 2 are not separable spatially; however, type 3 greenstone samples occupy a distinct geographical area. Amphibolite samples fall into type 1 (mainly) and type 2 geochemical categories.

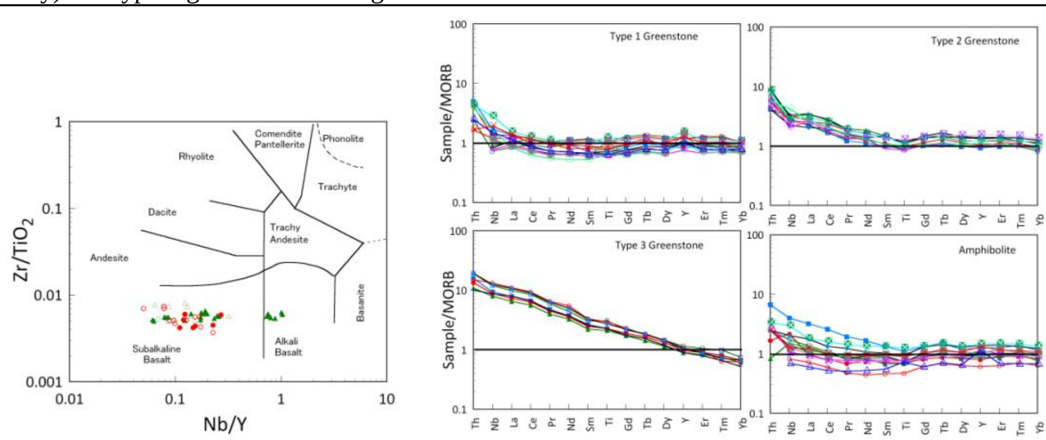


Figure 6: Classification and trace element compositions of greenstone and amphibolite samples from the Stowe Formation (Worcester Mountains area, Vermont). Most samples are subalkaline basalt; a few plot as alkali basalt.

Precursors of the types 1 & 2 greenstone and amphibolite samples are like mid-ocean ridge basalts in many chemical characteristics. However, their slightly elevated LREE and Nb/Y contents suggest they most closely match very late rift basalts (magmatism transitional from continental rift to oceanic ridge). Thus, they are interpreted as the final stages of rift magmatism related to the opening of the Iapetan Ocean (Coish et al., in review). Type 3 greenstone samples were alkali basalts - either tectonically incorporated early-rift rocks or rocks formed co-magmatically with subalkaline basalts.

Dikes and Greenstones from Wrightsville Slice

Samples from the Moretown and Cram Hill Formations are subalkaline basalts that plot close to the andesite field in classification schemes (Fig. 7). Chemical variations are also well shown in an extended rare earth element plot (Fig. 7). Samples from both formations show some common features: flat patterns (near-zero slope) from Ti to Yb and negative Nb anomalies accentuated by relatively high Th contents. There are also some differences between formations: patterns in samples from the Moretown Formation have slightly higher overall abundances and higher negative slopes for elements in the range from La to Ti. Samples from both formations have *patterns* similar to those seen in metadiabasic dikes of the Mount Norris Igneous Suite (MNIS) in northwestern Vermont (Kim et al., 2003a), although samples from the Moretown greenstones most closely match *abundances* in the MNIS. Basalts from a modern-day environment in the Marianas back-arc are similar chemically to the Moretown/Cram Hill greenstones.

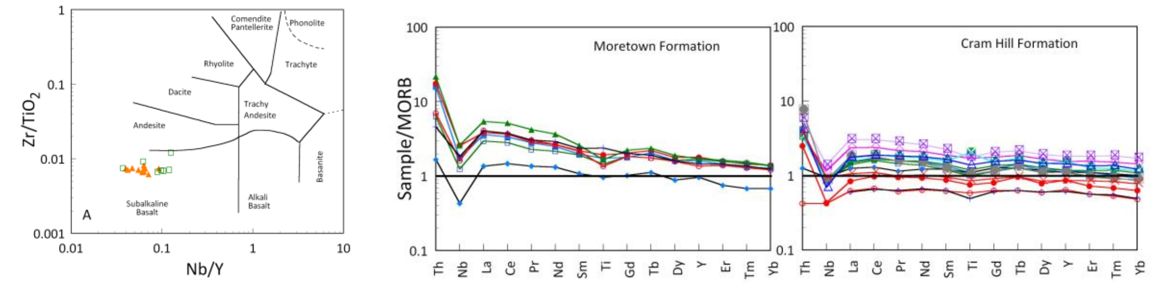


Figure 7: Classification and trace element compositions of greenstone samples the Cram Hill (▲) and Moretown Formations (□). Note negative Nb anomaly in samples from both formations.

The negative Nb anomalies and high Th contents shown by the Cram Hill and Moretown Formation rocks indicate their precursor magmas were affected by a crustal or subduction component. This, used along with other geochemical data, suggests that the magmas could have formed in an extensional environment associated with a subduction zone, i.e., a back-arc or interarc basin (Coish et al., in preparation).

TECTONIC SYNTHESIS

Detailed bedrock geologic mapping and cross section construction indicates that the RHB in central Vermont is composed of a series of thrust bounded lithotectonic slices of metasedimentary and meta-igneous rock that were assembled during the Taconian (and Acadian?) orogeny from west to east. The RHB is separated from the structurally underlying Green Mountain Belt by the Taconian Prospect Rock Thrust of Thompson and Thompson (2003).

The earliest ductile structures are two generations of Taconian isoclinal folds (F1 and F2): F2 folds are reclined with stretching lineations parallel to their fold axes; F1 folds are frequently rootless and intrafolial, may be reclined, and locally have sheath geometry. The identification of both isoclinal fold generations is easiest in the Green Mountain Belt where the Acadian deformation is not as severe. Axial planar spaced cleavages are associated with both fold sets. Open to tight asymmetric F3 Acadian folds with sub horizontal fold axes and an axial planar crenulation (S3) cleavage deform the S1/S2 composite foliation. The effects of F3/S3 increase from west to east such that a moderately east dipping S1/S2 in the Green Mountain Belt steepens on the western side of the RHB and is overturned (west dipping) in the Moretown Formation slices. The age designations of the fold generations and associated fabrics are based on their presence or absence in the Silurian and Devonian rocks of the Connecticut Valley Belt. The F3/S3 deformation is the first in the CVB.

Laird et al. (1984; 1993; 2007) demonstrated that the major metamorphic changes in mode and mineral chemistry in mafic rocks in Vermont occur among amphibole, chlorite, epidote, plagioclase, and quartz. There are two specific reactions that stand out in the metamorphism and dictate the NaSiCa-1Al-1 (PL) substitution in amphibole and plagioclase and the Al2Mg-1Si-1 (TK) substitution in amphibole and chlorite. PL and TK increase with the respective pressures and temperatures of metamorphism. By plotting the PL vs TK of amphiboles (cores and rims) in central and northern Vermont, Laird et al. (1984; 1993; 2007) delineated *Pressure Facies Series* envelopes (Figure 5A). We assigned each lithtectonic slice in the field area the *Pressure Facies Series* of the amphiboles in the mafic rocks in the slice. We assumed that the cores in all of the amphiboles in these Pre-Silurian lithotectonic slices are Taconian whereas the rims are Acadian. Figure 8 shows the *Pressure Facies Series* of each slice based on the PL and TK in amphibole cores.

Figure 8 shows that the structurally lowest slices (west) were at the highest pressure (medium-high) (Green Mt.1, Prospect Rock, Hyde Park, Green Mt. 2, and the Stowe Pinnacle Slice of the Worcester Complex), the slice in the middle (remainder of Worcester Complex) was at intermediate (medium) pressure, and that the Dumpling Hill and Wrightsville slices were at the lowest (low) pressure. As a calibration for Medium Pressure Facies Series metamorphism, thermobarometric data from the Worcester Complex (Laird et al., 2007) show pressures (MABS) of ~7-8 kb and temperatures (garnet-biotite, Ferry and Spear, 1978) of ~590-670 C. Low Pressure Facies series metamorphism was calibrated using the actinolite-chlorite geobarometer (Laird et al., 1993) at 3-6 kb. Using reaction space calculations, Laird et al. (2007) suggested that the upper end of medium-high pressure was approximately equivalent to 9 Kb (Belvidere Mt. Complex). Metadiabasic intrusions within the Wrightsville Belt have hornblende cores and actinolite rims and reaction space calculations for the cores indicates ~5 Kb.

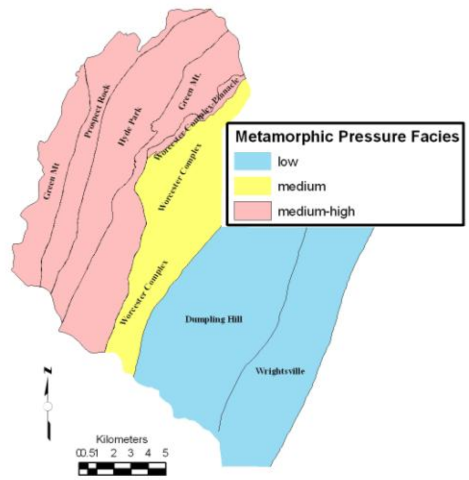


Figure 8: Pressure facies series for rocks of area.

By integrating the $^{40}Ar/^{39}Ar$ ages from the previous geochronology section, a pressure vs. time diagram was constructed (Figure 9) that gives a regional sequence for the assembly of slices in central and northern Vermont:

1) metamorphism of amphibolite in Belvidere Mountain Complex (BMC) at 505 Ma (~9 kb)
2) metamorphism of blueschist- grade mafic schist in Tillotson Peak Complex (12-14 kb)(~468 Ma)
3) emplacement of BMC and TPC on Hazens Notch Slice (Green Mt. Belt)
4) emplacement of Prospect Rock and Hyde Park slices at med-high pressure
5) emplacement of Worcester Complex on Hyde Park Slice at medium pressure (460-471 Ma)
6) emplacement of Dumpling Hill and Wrightsville slices on the Worcester Complex.

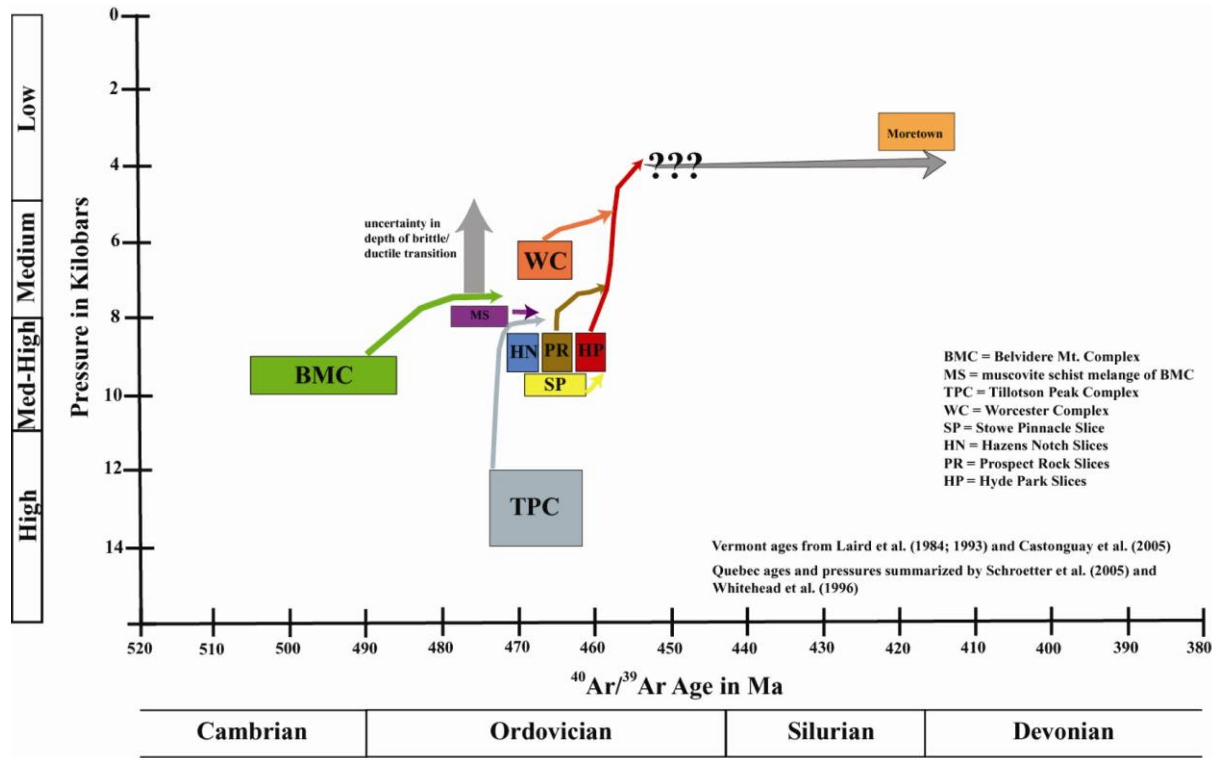


Figure 9: Pressure – time diagram for slices in central and northern Vermont.

Major, trace, and REE geochemistry were used to discriminate the tectonic environment of mafic rocks in the lithotectonic slices in the RHB. There are two basic tectonic environments represented in the field area: transitional/late- rift metabasalts in the Prospect Rock, Hyde Park, and Worcester Complex slices and suprasubduction zone basin (backarc) metabasalts in the Wrightsville Slice (Figure 10). It is important to note that Transitional/late Rift environment mafic rocks have not been reported in the RHB of central Vermont and this implies that the slices that contain these mafic rocks have more of a continental margin affinity than oceanic affinity. In addition, the slices containing T-Rift margin rocks were metamorphosed at significantly higher pressure than the suprasubduction zone slices. This is consistent with the Moretown slices being accreted last and at the highest structural level along a suture zone.

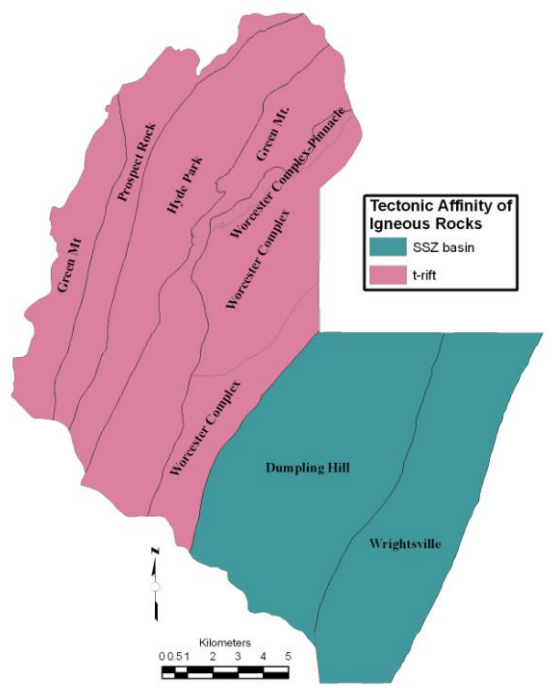


Figure 10: Tectonic affinity of mafic igneous rocks in area.

REGIONAL TECTONIC CORRELATIONS

In the central and northern Vermont RHB, $^{40}Ar/^{39}Ar$ total fusion ages on amphibole indicate that Taconian metamorphism generally corresponds to the 471-460 Ma interval whereas $^{40}Ar/^{39}Ar$ total fusion ages on muscovite and biotite suggest Acadian metamorphism ranges in age from 386 -355 Ma (Laird et al., 1984, 1993). $^{40}Ar/^{39}Ar$ plateau ages on micas and amphiboles from southern Quebec by Castonguay et al. (2001, 2007) suggest three distinct ranges 470-460 Ma, 431-411 Ma, and ~380 Ma. The Ordovician and Devonian metamorphic age ranges essentially match between Vermont and southern Quebec, but there appears to be no Silurian component in Vermont. However, new $^{40}Ar/^{39}Ar$ ages on muscovite from the Green Mt Belt indicate a Silurian metamorphic event (Castonguay et al., 2005).

In southern Quebec, the Becancour Dome and Carineault Antiform are Acadian antiformal structures in the Dunnage Zone cored by Pre-Silurian metamorphic rocks of the Internal Humber Zone that structurally underlie the Thetford Mines Ophiolite (e.g., Castonguay et al., 2001; Schroetter et al., 2005). The 470-460 Ma $^{40}Ar/^{39}Ar$ ages described above are from the cores of these Acadian structures. Similar 470-460 Ma $^{40}Ar/^{39}Ar$ ages are preserved in tbe Worcester Complex. Based on structural position, lithologic similarity and age, Kim et al., (2001, 2005) suggested a possible tectonic correlation between the Worcester Complex and the Internal Humber Zone rocks in the cores of the Becancour Dome and Carineault Antiform.

The fragmental ophiolite of the Belvidere Mountain Complex lies tectonically above the Hazens Notch Formation schists of the Green Mountain Belt (Gale, 1980; Doolan et al., 1982; Gale, 1986) and structurally below the Prospect Rock Thrust of Thompson and Thompson (2003). Laird et al. (1993) obtained a 505 Ma $^{40}Ar/^{39}Ar$ plateau age on barroisitic amphibole from the Belvidere Mt. Complex which is considerably older than either the 478-480 Ma formation age (U/Pb zircon age, Whitehead et al., (2000)) or the 477 Ma $^{40}Ar/^{39}$ emplacement age (amphibole from dynamothermal sole) of the Thetford Mines Ophiolite of southern Quebec (Whitehead et al., 1995).

The Pennington Sheet is an ultramafic body in southern Quebec that is caught along an Ordovician fault (Vermont F1 equivalent) within metasedimentary rocks of the Internal Humber Zone (Castonguay et al., 2006). Whitehead et al. (1996) proposed that a 496 Ma $^{40}Ar/^{39}$ age on amphibole from an amphibolite sliver associated with the Pennington Sheet represented an ophiolitic decoupling event that preceded the development of the Thetford Mines Ophiolite. Since this part of the Pennington sheet lies at a deeper structural level than the Thetford Mines Ophiolite and is associated with older metamorphic ages and correlative metasedimentary rocks, Kim et al. (2003c) correlated it with the ultramafic and amphibolite portions of the Belvidere Mountain Complex.

Using a one to one correlation of the lithologies and structural positions of slices in the central and northern Vermont RHB and the Internal Humber and Dunnage zones of southern Quebec, Kim et al. (2003c) suggested that the Thetford Mines Ophiolite would root beneath the Moretown Formation and thus structurally overlie the Worcester Complex, Hyde Park, and Prospect Rock slices. The contact between the Moretown and Worcester Complex slices represents a Taconian suture.

Mafic lavas are found in Caldwell Group (Stowe Formation equivalent) metasedimentary rocks of southern Quebec (Bédard and Stevenson, 1999). These rocks structurally underlie the Thetford Mines Ophiolite and have geochemical signatures very similar to the T-rift mafic rocks in the Hyde Park and Worcester Complex slices.

FIELD TRIP ROAD LOG

0 Starting Point- Montpelier Park and Ride near Exit 8 off of Interstate 89 (I-89). Make right out of Park and Ride onto Dog River Road (Our cell phone numbers: Jon Kim 802/249-0596, Marjie Gale 802/338-0324)

0.05 Bear right onto access road for I-89 (Memorial Drive).
0.20 Bear right onto entrance ramp for I-89 North towards Burlington.
10.5 Take Exit 10 on I-89 for Stowe-Waterbury.
10.9 Turn left at the end of the exit ramp onto Route 100 South.
11.3 Turn right at stop sign onto U.S. Route 2 West.
12.6 Turn right onto Little River Road.
16.8 Park on the right just past the Waterbury Dam on the road going down to the boat ramp. Walk Across the dam and down the south face to Stop 1.

Stop 1 A) Overview of Field Area, and B) Hazens Notch Schist and Black Quartzite of the Green Mountain Belt; Taconian F1/F2 isoclinal folds and F3 Acadian Tight Asymmetric Folds at Waterbury Dam (UTM NAD83 coordinates: X- 677728, Y- 4916589) (40 minutes).

Lithology: Rusty-weathering gray and black albitic schists interlayered with black laminated quartzites of the Hazens Notch Formation.

Structure: Reclined F1/F2 isoclinal folds in black quartzite layers with fold axes colinear with downdip quartz rodding. We have discussed whether there is more than one generation of isocline here, but if so, their axial surfaces must be ~coplanar and axes ~colinear. Although cryptic in the schist, the same fold generation usually appears as rootless isoclines. The preservation of the folds in the quartzite reflects the ductility contrast between the schist and quartzite. Open F3 Acadian folds deform the isoclines in the quartzite whereas tight asymmetric F3 folds affect the schist.

Petrology: Amphiboles from greenstone in parts of the Green Mountain Belt outside this field area have cores that fall in the medium-high pressure facies series of Laird et al. (1984, 1993, 2007).

Tectonics: This stop is the only one in the Green Mountain Belt and is at the lowest structural level of the trip. This is the best stop to observe the Taconian isoclinal structures. Note that the S1/S2 composite foliation dips moderately to the east at this stop as this will change at the following stops as F3 intensifies to the east.

Return to vehicles, turn around near end of boat ramp road, return to Little River Road and make a left.
19.6 Turn left at Stop Sign onto U.S. Route 2 East.
20.9 Turn left onto Vermont Rte.100 North.
21.5 Pull over onto right shoulder just past I-89 exit ramp.

Stop 2 Ottauquechee Formation Black Phyllites of Prospect Rock Slice of the Rowe-Hawley Belt at former I-89 Exit Ramp (X- 679434, Y- 4912542) (20 minutes).

Lithology: Rusty weathering, gray to black, graphitic, sulfidic, phyllites with thin interlayers of gray phyllitic quartzites. Cubic molds are after pyrite.

Structure: Steeply east-dipping composite S1/S2 foliation tightly folded by F3 and overprinted by an S3 crenulation cleavage. Tight asymmetric folds of variable plunge are F3. Multiple F3 folds are visible in the outcrop on the north side of Route 100. Isolated steeply plunging rootless F2 folds are defined by thin disarticulated quartzite layers. Steeply plunging lineations are intersections between F2 fold axes and either S3 or S1/S2. Crenulate lineations are intersections of F3 fold axes on S1/S2.

Tectonics: These Ottauquechee Formation phyllites are part of the Prospect Rock Slice of the Rowe-Hawley Belt. They were emplaced on the Hazens Notch Formation schists of Stop 1 along the Taconian Prospect Rock Thrust of Thompson and Thompson (2003).

Return to vehicles and continue north on Rte. 100

22.6 Turn right onto Guptil Road.

22.7 Turn right onto Country Club Road (Vermont National Country Club) and park on the right side of the driveway.

Stop 3 Greenstone and Grayish-Green Phyllites of the Hyde Park Slice at Entrance to the Country Club of Vermont (X-680617, Y-4913838) (30 minutes)

Lithology: Dark green, fine-grained foliated greenstone interlayered with grayish-green phyllites (Stowe Fm.). Interlayering of phyllites and greenstones is both stratigraphic and tectonic within this slice.

Structure: Greenstone outcrop at country club entrance exhibits F2 isoclinal folds that do not have a well developed S2. F2 fold axes plunge moderately to the south.

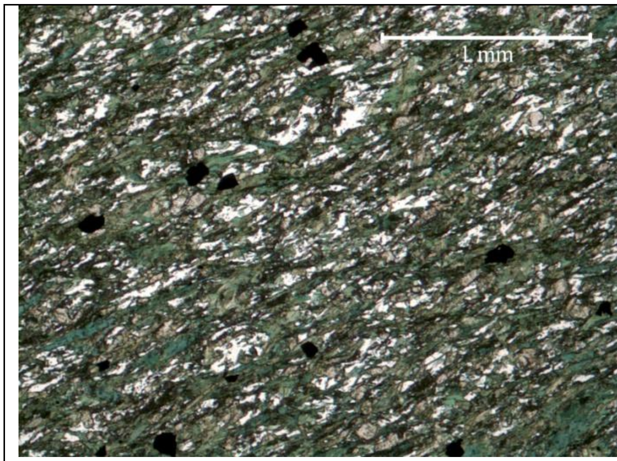
Interlayered greenstone and grayish-green phyllite outcrops along grassy path to the right of the driveway have a steeply east dipping S1/S2 composite fabric with downdip stretching lineations that are colinear with F2 fold axes. Sub-horizontal crenulate lineations represent intersections of S3 on S1/S2. S3 can be seen transecting S1/S2 and strikes NNE and dips moderately westward.

Petrology: These greenstones can be chlorite or actinolite rich. Some chlorite-rich but actinolite-poor samples have a general paragenesis of 30% chlorite, 40% epidote, 28% quartz and albite and trace amounts (<2%) of white mica, sphene and opaque minerals whereas actinolite-rich/ chlorite-poor samples have 30-40% actinolite, 25-40% epidote, 30-40% quartz and albite and trace amounts of sphene and opaques. Samples from some areas are especially rich in epidote, with assemblages of 70-80% epidote, 10% chlorite, 5-15% amphibole, 5% quartz and albite and trace amounts of sphene.

Laird et al. (2007) sample VJL11rep is from the same greenstone body, but 1.8 km. to the northeast. Cores in amphiboles from this sample fall in the medium-high pressure facies series (Figure 4).

Geochemistry: This greenstone is spatially part of Zone 4 greenstones within the Hyde Park Slice. Although most greenstones in Zone 4 are “MORB-like” tholeiites, this outcrop is part of a small area of “enriched” basalts within Zone 4 (see text for further discussion).

Tectonics The Hyde Park Slice was emplaced on the Prospect Rock Slice by the Taconian Route 100 Thrust. The Green Mountain Belt and Prospect Rock slice also fall in the medium high pressure facies series.



Foliated albite-actinolite-chlorite-epidote greenstone (NM05-25)

Chlorite-calcite-quartz crenulated phyllite (5219)

Return to vehicles, turn around, and turn left onto Guptil Road.

22.9 Turn right at Stop Sign onto Rte. 100 North.

25.1 Turn right onto Suss Drive

25.4 Stop at the loading dock area.

<u>Stop 4</u> Massive Greenstone of the Hyde Park Slice behind the Suss Microtec Loading Dock (X-681791, Y-4917048) (20 minutes).

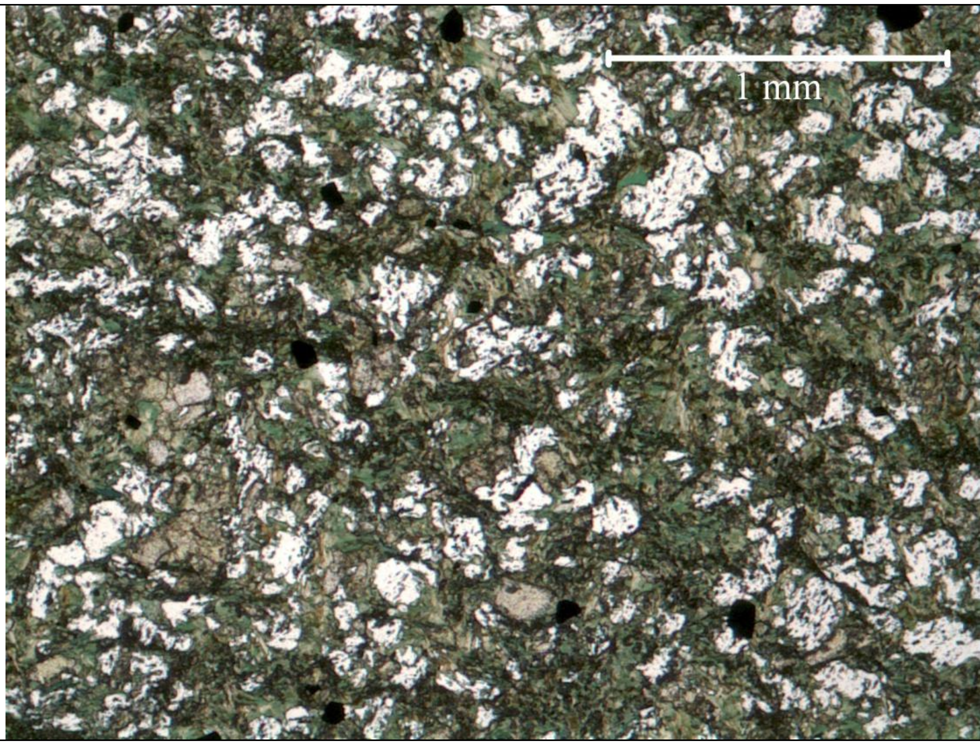
<u>Lithology:</u> Massive albite-epidote-chlorite greenstone.

<u>Structure:</u> F2 tight to isoclinal asymmetric folds with steeply east dipping axial surfaces and moderate northward plunges; stretching lineations collinear with the F2 axes are well developed on S1.. The rotation sense of these folds is clockwise looking down plunge (top to the north). Subhorizontal crenulate lineations represent intersections of F3 fold axes with S1 (S2 is not well developed in this greenstone). F3 folds can be observed at the south end of the outcrop. A steeply east dipping late shear zone (“papery” schist) with west side up sense of shear offsets the northernmost portion of the outcrop from the rest and deflects the dominant foliation (S1). Open F5 folds have E-W trending axial surfaces.

<u>Petrology:</u> Laird et al. (2007) sample VJL11rep is from the same greenstone body, but 1.9 km. to the south. Cores in amphiboles from this sample falls in the medium-high pressure facies series (Figure 4).

<u>Geochemistry:</u> Although no geochemical analyses exist on samples from this outcrop, there were 3 samples analyzed from this same greenstone body within 2 kilometers of this location; the tectonic affinity of these samples is late stage rift greenstones (types 1 and 2)(see text for further discussion).

<u>Tectonics:</u> The Hyde Park Slice was emplaced on the Prospect Rock Slice by the Taconian Route 100 Thrust. The Green Mountain Belt and Prospect Rock slice also fall in the medium high pressure facies series.



Massive albite-epidote-chlorite greenstone in Stowe Formation (NM05-26)

Return to vehicles and turn around.

25.7 Turn right at Stop Sign onto Rte. 100 North.
26.5 Turn right onto Guild Hill Road
27.0 Turn right at Stop Sign onto Maple Street.
27.8 Turn left onto Loomis Hill Road.
29.7 Pavement changes to dirt/ Loomis Hill Road becomes Sweet Road.
31.2 Turn right into parking lot for Mt. Hunger Trail OR park on the right side of the road beyond (this lot will probably be full during foliage season).
Walk up the trail and make a left onto the second trail to the amphibolite quarry.

Stop 5 Epidote Amphibolite of the Worcester Complex at Inactive Quarry near Hunger Mountain Trailhead (X-685177, Y-4919250) (20 minutes + Lunch)

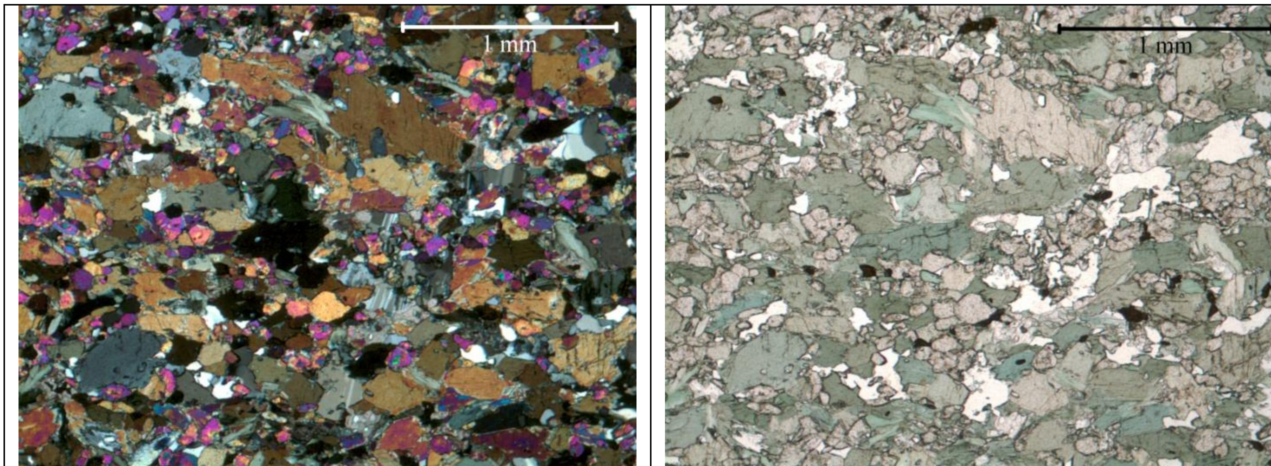
Lithology: This exposure shows medium to fine-grained amphibolite, typical of the Worcester Complex (see Figure 2). The mineralogy is dominated by epidote, plagioclase, and blue-green hornblende +/- garnet. Patches of coarse-grained amphibole and plagioclase along with fine-grained epidote mark hydrothermally altered areas.

Structure: Rootless F2 and F1 isoclinal folds are defined by transposed feldspathic and epidosite layering and quartz veins. The dominant foliation is a NE trending moderately east dipping S1/S2 composite that is deformed by subtle open F3 folds with shallowly south plunging fold axes. The general southward dip of the outcrop surface is approximately parallel to the F3 fold axes.

Petrology: Typical mineral assemblages in the amphibolite are: 54-59% blue-green hornblende, 25-35% epidote, 10-15% plagioclase & quartz, and trace amounts (<1%) of sphene and opaque minerals. PL and TK values from amphibole cores from this amphibolite place this part of the Worcester Complex in the medium- high pressure facies series.

Geochemistry: Chemistry of the amphibolite indicates that it is similar to late stage rift greenstones (types 1 and 2) seen within the Hyde Park Slice – (see text for further discussion)

<u>Tectonics:</u> The Worcester Complex was emplaced onto an out of sequence slice of the Green Mountain Belt by the Taconian Worcester Complex Thrust. Maps and cross sections suggest that motion along the Worcester Complex Thrust occurred during 2 episodes. As mapped, the WC includes schists and amphibolite of both the medium (Hunger Mtn slice) and medium-high (Stowe Pinnacle slice) pressure facies series. These internal slices are separated by an early, folded thrust. Although the amphibolite falls near the medium-high/medium pressure overlap zone it is interpreted as part of the medium pressure facies series as it is east of the early internal thrust.



Photomicrographs of epidote amphibolite (NM0505)

Return to vehicles, turn around, and follow Sweet Road-Loomis Hill Road back to Barnes Hill Road.

34.1	Turn left at Stop Sign onto Maple Street.
34.3	Bear left onto Guptil Road.
36.3	Turn left at Stop Sign onto Rte. 100 South.
37.4	Bear right onto entrance ramp for I-89 South towards Montpelier.
42.7	Take Exit 9 for Middlesex-Moretown.
47.0	At stop sign, bear left at intersection with Brook Road onto Center Road
43.0	Turn left at Stop Sign onto Center Road.
47.3	Turn right onto Swamp Road.
47.9	Turn left onto Molly Supple Hill Road.
48.5	Molly Supple Hill Road becomes Shady Rill Road.
49.4	Turn left onto Story Road.
50.0	Bear left onto Chase Road.
50.1	Turn left onto Bear Swamp Road.
51.6	Turn left onto unnamed dirt road in front of huge brown log house.
52.1	Turn right into parking lot for Middlesex Trail to Mount Hunger.

Proceed up the trail for approximately 20 minutes.

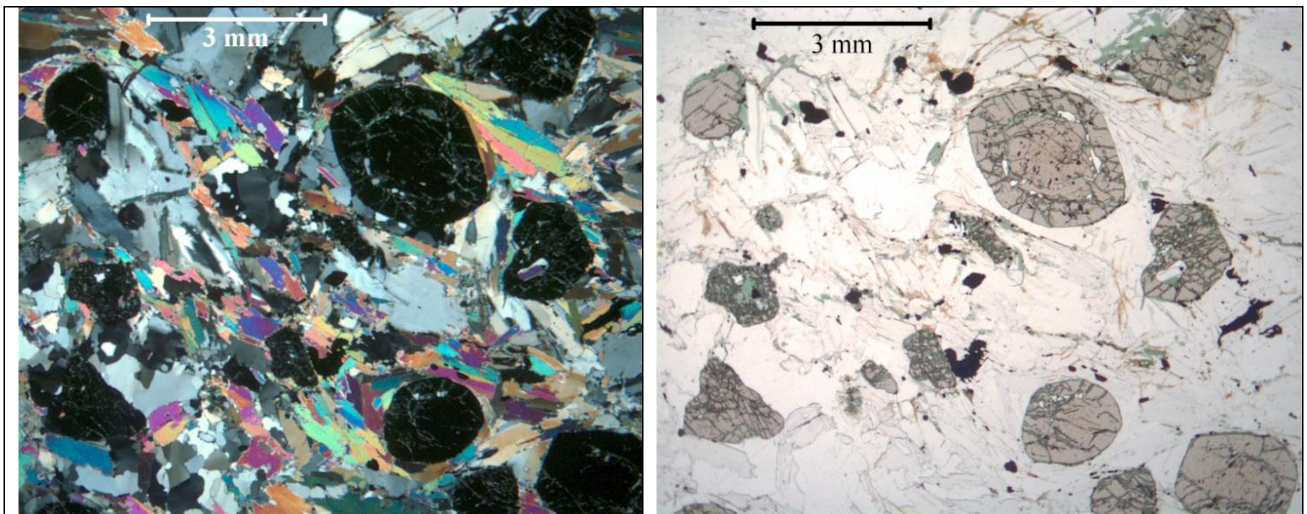
<u>Stop 6</u> Garnet-Kyanite Schist of the Worcester Complex along the trail to Mt. Hunger from the Middlesex side (X-688002, Y- 4917082) (1 hour).

<u>Lithology:</u> Muscovite-quartz-kyanite-garnet schist with disarticulated coticule layers and abundant isoclinally folded and transposed vein quartz layers.

Structure: NE trending moderately west dipping S1/S2 composite foliation overprinted by a steeper (also west dipping) S3 cleavage. South verging open folds with ~E-W west trending axial surfaces deform everything. Kyanites appear to grow within or at a slight angle to the S1/S2 foliation.

Petrology: Lanphere and Albee (1974), Laird et al. (1984; 1993) have shown that the kyanite grade metamorphism in the Worcester Mountains is Taconian. Coarse grained muscovite from the Worcester Schist gave 451-457 Ma cores and 400-430 Ma rims using $^{40}Ar/^{39}Ar$ laser dating (Hames, 1992). Amphiboles dated by Laird et al.(1984; 1993) gave $^{40}Ar/^{39}Ar$ ages of 460-470 Ma.

Tectonics: The Worcester Complex structurally overlies an out of sequence slice of the Green Mountain Belt and underlies the Dumpling Hill Slice that contains Moretown Formation rocks. East of the muscovite-garnet-kyanite schist of this stop, are grayish green phyllites (CZs) of the Stowe Formation. We believe that the change from the grayish green phyllites to the muscovite-garnet-kyanite schists is transitional and represents a series of faulted Taconian isograds. Therefore, we include these phyllites with the Worcester Complex. The overturned Acadian Middlesex Thrust separates the Worcester Complex from the Dumpling Hill Slice and is marked by an intense zone of S3 shear bands. We believe that this thrust may have reactivated a Taconian Thrust.



Muscovite-garnet-quartz in the Worcester schist (7659). Kyanite is not present in this section.

Return to vehicles and make a left onto unnamed road.
52.6 Turn right onto Bear Swamp Road.
54.1 Bear right onto Chase Road.
54.2 Turn right onto Story Road.
54.6 Turn left at Stop Sign onto Shady Rill Road.
56.7 Turn left at Stop Sign onto Rte. 12 North.
57.8 Turn right onto Norton Road in Putnamville.
Park on right side of the road just past first house on the right and walk up driveway.

Stop 7 Moretown Formation and Metadiabase Dikes of the Wrightsville Slice at Putnamville Waterfall (X-694105, Y-4912614) (30 minutes).

Lithology: Pinstriped granofels of the Moretown Formation intruded by Ordovician? metadiabasic dikes and a Mesozoic lamprophyre dike.

Structure: The dominant pinstriped foliation (S1) is cut by metadiabase dikes. Some intrafolial F2 isoclinal folds are seen on the western side of this outcrop. In the eastern part of the outcrop, tight asymmetric F3 and F4 folds and their associated crenulation cleavages fold and overprint the metadiabase/ pinstriped granofels contact. Although some of the smaller metadiabase dikes in the eastern half of this outcrop cut across the pinstriped foliation at a high angle, there is a foliation within these dikes that is generally parallel to the pinstriped layering; we do not know for certain which foliation this is, but its age has important implications for the age of the dikes. The lamprophyre generally follows the dominant foliation in the pinstriped granofels.

Petrology: Dikes such as those exposed at Stop 7 vary in terms of degree of alteration and proportion of principal minerals, but most consist of chlorite, albite, epidote, quartz, and calcite – a typical assemblage in the greenschist metamorphic facies. Lesser amounts of actinolite, biotite, and titanite occur; magnetite and muscovite occasionally occur. Albite is often twinned and usually altered to saussurite. In some samples, epidote is abundant and has replaced much of the plagioclase.

The diabasic dikes, despite their greenschist facies mineralogy, have well preserved igneous textures. Some samples show remnant diabasic texture of interlocking plagioclase laths and chlorite (from pyroxene). In foliated greenstone samples, the foliation is usually defined by the alignment of chlorite and/or actinolite grains.

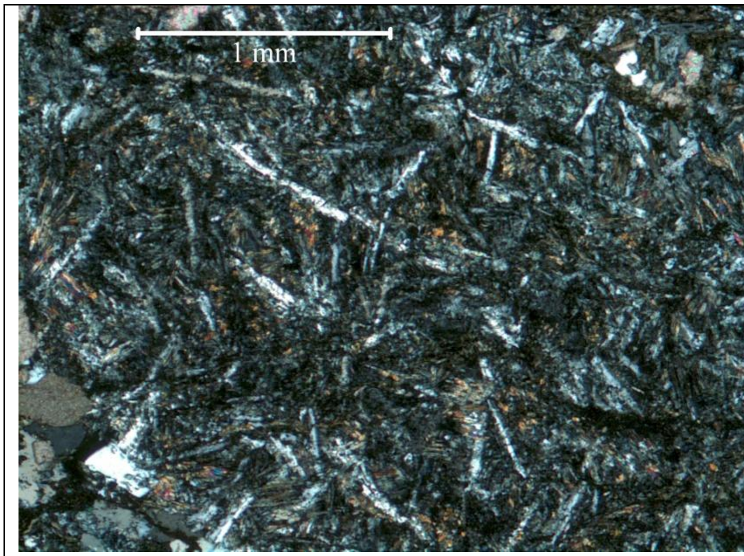
No amphibole analyses were conducted on metadiabases from this outcrop, but other nearby metadiabases were analyzed by Laird et al. (1984; 1993). These analyses indicated that amphiboles within the metadiabases had hornblende cores and actinolite rims. The PL vs. TK values for these amphiboles plot in the low pressure facies series. Although actinolite rims on amphiboles are characteristic of the Acadian retrograde metamorphism across the RHB, the hornblende cores may be Taconian.

Geochemistry: The chemistry of the mafic dikes (see text for more discussion) indicates they were crystallized from tholeiitic magmas with chemical characteristics indicative of formation in an extensional subduction environment such as a back-arc basin.

Tectonics: The age of the metadiabase dikes is problematic and all tectonic models are based on this. Metadiabase dikes in the Moretown Formation in northern Vermont were associated with the Ordovician Mt. Norris Intrusive Suite by Kim et al. (2003). Because these dikes cut Taconian fabrics and are clearly folded by Acadian F3 folds, it is also possible that they are Silurian in age and correlative with the Comerford dikes of Rankin et al. (2007).

From amphibole chemistry, we see a west to east decrease in the metamorphic pressure of the slices (pressure was highest in the structurally lowest slices to the west and lowest in the structurally highest slices to the east). If the metadiabase dikes are Ordovician, this order could be related to thrust stacking in the Taconian. If the dikes are Silurian, the accretion of the Wrightsville and Dumpling Hill slices could be Silurian or Devonian.

The rocks in the Moretown Formation are extremely quartz rich and suggest derivation from a cratonic source. Stanley and Ratcliffe (1985) suggested the Moretown Formation represented forearc basin fill derived from erosion of the outer arc high of the accretionary wedge (Taiwan model). If one is to invoke an eastern source (present coordinates), Waldron and van Staal (2001) proposed the existence of a Dashwoods Block which was a piece of Laurentia that was rifted out into Iapetus during the Proterozoic. Such a block could have supplied quartz rich sediment from the east to form the Moretown Formation. Based on geochronology by Ratcliffe et al. (1997), any tectonic model involving the Moretown Formation must accommodate the fact that the Moretown was intruded by Late Cambrian and Early Ordovician felsic suprasubduction zone magmas from an east dipping subduction zone.



Plagioclase laths in metadiabase (sample 7582)

Return to vehicles, turn around, and make a left onto Russell Road.
58.0 Turn left at Stop Sign onto Rte. 12 South towards Montpelier.
63.9 Turn right onto Spring Street
64.0 Bear sharply to the left onto Park Way which will take you into Hubbard Park.
64.4 Bear left onto unnamed road in Hubbard Park.
64.5 Pass road to Fire Tower on right and park on right side of road.

Stop 8 Gray Phyllite, Coticule, and Metadiabase Dikes of the Wrightsville Slice (Cram Hill Formation) in Hubbard Park (X-693417, Y- 4904404) (30 minutes).

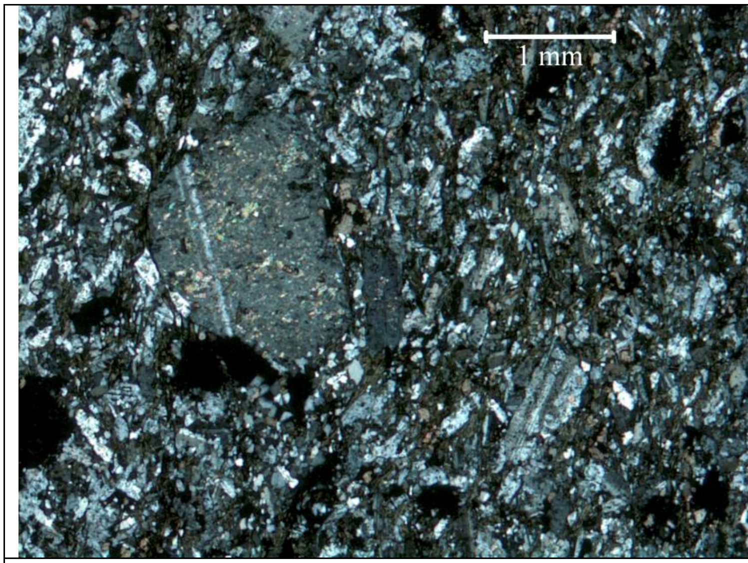
Lithology: Gray phyllites, coticule (quartz-spessartine garnet rock), and plagioclase phenocryst-bearing metadiabases and greenstones.

Structure Composite S1/S2 fabric tightly folded by F3 folds and overprinted by S3. Rootless F2 folds defined by coticule with downdip stretching lineations (L2). Upright open folds with subhorizontal axes (F4).

Petrology: The mineralogy of dikes from the Cram Hill Formation is similar to those of the Moretown, except that the Cram Hill exposes samples with abundant plagioclase (now albite) phenocrysts. This is apparent in the outcrops of Stop 8 and in the photomicrograph below. Amphiboles within the Wrightsville Slice have cores that fall in the low pressure facies series.

Geochemistry: The chemistry of metadiabase dikes from the Cram Hill is similar to dikes in the Moretown and thus, they are also interpreted as having been formed in an extensional arc environment (see text for more discussion).

Tectonics: See stop 7 discussion.



Plagioclase phenocrysts in plag-rich metadiabase (sample 7583)

Return to vehicles and continue straight on park road**.**

64.8 Make sharp left onto Cliff Street (this road is narrow and steep (~15 % grade) so be careful!).

65.0 Turn right onto Court Street (unmarked).

65.1 Turn left onto Govenor Davis Street.

65.2 Turn right onto State Street and pass Vermont Statehouse (The RMC is just to the east of the Statehouse).

65.5 Turn right at stoplight onto Bailey Avenue.

65.6 Bear left onto Terrace Street.

66.6 Turn right onto Ledgewood Terrace and park on the right side of the road.

<u>Stop 9</u> "Pinstriped" Moretown Formation Granofels and Metadiabase dike of the Wrightsville Slice at Terrace St./Ledgewood Terrace Intersection(X-692043, Y-4905325) (15 minutes).

<u>Lithology:</u> Moretown granofels with spectacular pinstriped foliation. Sharp contact with metadiabase dike.

<u>Structure:</u> Composite S1/S2 foliation deformed by tight F3 folds with refracted S3 crenulation cleavage; fold axes plunge moderately to the north. Look for rootless isoclinal folds internal to this composite foliation.

<u>Petrology:</u> See stops 7 and 8.

<u>Geochemistry:</u> See stops 7 and 8.

Return to vehicles, turn around, and turn left onto Terrace Street.

67.6 Bear right onto Bailey Avenue.

67.7 Go straight through stoplight at State Street

67.8 Make right at stoplight onto I-89 access road (Memorial Drive).

68.3 Bear right onto Dog River Road

68.5 Turn left into Montpelier Park and Ride where trip began.

References Cited

Bédard, J. H., and Stevenson, R., 1999, The Caldwell group lavas of southern Quebec: MORB-like tholeiites associated with the opening of Iapetus ocean: Canadian Journal of Earth Sciences, v. 36, no. 6, p. 999-1019.

Castonguay, C., Doolan, B., Gale, M., Kim, J., Ruffet, G., Thompson, P., Tremblay, A., and Villeneuve, M., 2005, 40Ar/39Ar geochronological data from the Sutton/Green Mountains Anticlinorium, southern Quebec-northern Vermont Appalachians: episodic and diachronous tectonism from Middle Ordovician to Middle Devonian: Geological Society of America Abstracts with Programs, v. 37, no. 1, p. 30.

Castonguay, S., Ruffet, G., and Tremblay, A., 2007, Dating polyphase deformation across low-grade metamorphic belts: An example based on 40Ar/39Ar muscovite age constraints from the southern Quebec Appalachians, Canada: Geological Society of America Bulletin, v. 119, no. 7-8, p. 978-992, doi: 10.1130/b26046.1.

Castonguay, S., Ruffet, G., Tremblay, A., and Féraud, G., 2001, Tectonometamorphic evolution of the southern Quebec Appalachians: 40Ar/39Ar evidence for Middle Ordovician crustal thickening and Silurian-Early Devonian exhumation of the internal Humber zone: Geological Society of America Bulletin, v. 113, no. 1, p. 144-160.

Castonguay, S., Pinet, N., Tremblay, A., and Brisebois, D., 2006, A foreland to hinterland structural transect across the Humber Zone south of Quebec City, southern Quebec Appalachians, in Corriveau, L., Malo, M., and Clark, T. editors, Guidebook for Field Trips in Southern Quebec, New England Intercollegiate Geological Conference, p. 87-107.

Castonguay, S., and Tremblay, A., 2003, Tectonic evolution and significance of Silurian-Early Devonian hinterland-directed deformation in the internal Humber Zone of the southern Quebec Appalachians: Canadian Journal of Earth Sciences, v. 40, no. 2, p. 255-268.

Coish, R., Kim, J., Morris, N., and Johnson, D., in review, Late stage rifting of the Laurentian continent: evidence from the geochemistry of greenstone and amphibolite in the central Vermont Appalachians.

Coish, R., Kim, J., and Twelker, E., in preparation, Paleozoic back-arc volcanism in the western New England Appalachians: evidence from the geochemistry of metamorphosed mafic rocks in central Vermont.

Coish, R. A., 1997, Rift and ocean floor volcanism from the Late Proterozoic and early Paleozoic of the Vermont Appalachians, *in* Sinha, A. K., Whalen, J. B., and Hogan, J. P., eds., The Nature of Magmatism in the Appalachian Orogen: Boulder, Colorado, Geological Society of America, p. 129-145

Coish, R. A., Bramley, A., Gavigan, T., and Masinter, R. A., 1991, Progressive changes in volcanism during Iapetan rifting; comparisons with the East African Rift-Red Sea system: Geology, v. 19, no. 10, p. 1021-1024.

Coish, R. A., Fleming, F. S., Larsen, M., Poyner, R., and Seibert, J., 1985, Early rift history of the proto-Atlantic ocean: Geochemical evidence from metavolcanic rocks in Vermont: American Journal of Science, v. 285, p. 351-378.

Coish, R. A., Perry, D. A., Anderson, C. D., and Bailey, D., 1986, Metavolcanic rocks from the Stowe Formation, Vermont: Remnants of ridge and intraplate volcanism in the Iapetus ocean: American Journal of Science, v. 286, p. 1-28.

David, J., and Marquis, R., 1994, Géochronologie U-Pb dans les Appalaches du Québec: application aux roches de la zone de Dunnage: La Revue géologique du Québec, v. 1, p. 16-20.

Doolan, B. L., Gale, M. H., Gale, P. N., and Hoar, R. S., 1982, Geology of the Quebec Reentrant: possible constraints from early rifts and the Vermont-Quebec serpentine belt, *in* St. Julien, P., and Beland, J., eds., Major Structural Zones and Faults of the Northern Appalachians, Geological Association of Canada, Special Paper 7, p. 87-115

Dorais, M. J., Workman, J., and Aggarwal, J., 2008, The petrogenesis of the Highlandcroft and Oliverian Plutonic Suites, New Hampshire: Implications for the structure of the Bronson Hill terrane: Am J Sci, v. 308, no. 1, p. 73-99, doi: 10.2475/01.2008.03.

Dunning, G. R., and Pedersen, R. B., 1988, U/Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonides; implications for the development of Iapetus: Contributions to Mineralogy and Petrology, v. 98, no. 1, p. 13-23.

Ferguson, E. W., 2003, Temperatures and pressures of peak metamorphism of the Stowe Formation in the Worcester Mountains, North-Central Vermont, [MS thesis]: University of New Hampshire, 152 p.

Ferry, J. M., and Spear, F. S., 1978, Experimental calibration of the partitioning of Fe and Mg between biotite and garnet: Contrib. Mineral Petrol., v. 66, p. 113-117.

Gale, M., Kim, J., King, S., Montane, P., and Orsi, C., 2006, Bedrock Geologic Map of the Southern Worcester Mountains Watershed, Middlesex and Stowe 7.5' Quadrangles, Vermont: Vermont Geological Survey, scale 1:24,000, 1 sheet(s).

Gale, M. H., 1980, Geology of the Belvidere Mountain Complex, Eden and Lowell, Vermont, [Masters of Science thesis]: University of Vermont, 169 p.

-, 1986, Geologic map of the Belvidere Mountain area, Eden and Lowell, Vermont: United States Geological Survey, scale 1:24,000, 3 sheet(s).

Hibbard, J. P., van Staal, C. R., Rankin, D. W., and Williams, H., 2006, Lithotectonic map of the Appalachian Orogen: Geological Survey of Canada, Map 2096A, scale 1:1,500,000, 2 sheet(s).

Karabinos, P., Samson, S. D., Christopher Hepburn, J., and Stoll, H. M., 1998, Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls arc: Geology, v. 26, no. 3, p. 215-218.

Kim, J., Coish, R., Evans, M., and Dick, G., 2003a, Supra-subduction zone extensional magmatism in Vermont and adjacent Quebec; implications for early Paleozoic Appalachian tectonics: Geological Society of America Bulletin, v. 115, no. 12, p. 1552-1569.

Kim, J., Gale, M., King, S. M., Orsi, C. M., and Pascale, L., 2003b, Bedrock Geologic Map of the Montpelier Quadrangle: Vermont Geological Survey Open File Map VG03-1, scale 1:24,000, 1 sheet(s).

Kim, J., Castonguay, S., Tremblay, A., Thompson, P., and Bedard, J., 2003c, Comparative Structural, Metamorphic, and Geochemical Transects across the Dunnage and Internal Humber zones in the Northern Vermont and Southern Quebec Appalachians: Geological Society of America Abstracts with Programs, v. 35 #3, p. 97

Kim, J., Gale, M., and Laird, J., 1999, Lamoille River Valley Bedrock Transect #2; in Wright, S.F. ed., New England Intercollegiate Geologic Conference Guidebook #91, p. 213-250.

Kim, J., Gale, M., Laird, J., Thompson, P. J., and Bothner, W. A., 2001, Mafic complexes in northern Vermont and Quebec correlatives: Geological Society of America, Abstracts with Programs, v. 33, no. 1, p. A-20.

Kim, J., Gale, M. H., and Springston, G., 2007, Bedrock Geologic Map of the Western Worcester Mountain Watersheds, Waterbury and Stowe, Vermont: Vermont Geological Survey Open File Map VG07-6, scale 1:24,000, 3 plates.

Laird, J., and Albee, A. L., 1981, High-pressure metamorphism in mafic schist from northern Vermont: American Journal of Science, v. 281, p. 97-126.

Laird, J., Kim, J., and Gale, M., 2007, Integration of amphibole composition data and mafic schist modal data with recent geologic maps and cross-sections from the pre-Silurian lithotectonic belts of central and northern Vermont: Geological Society of America, Abstracts with Program, v. 39, no. 1, p. 50.

Laird, J., Lanphere, M., and Albee, A., 1984, Distribution of Ordovician and Devonian metamorphism in mafic and pelitic schists from northern Vermont: American Journal of Science, v. 284, p. 376-413.

Laird, J., Trzcienski Jr, W. E., and Bothner, W. A., 1993, High-pressure, Taconian, and subsequent polymetamorphism of southern Quebec and northern Vermont: Field trip guidebook for the northeastern United States, p. 1–32.

Ratcliffe, N. M., Walsh, G. J., and Aleinikoff, J. N., 1997, 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., Guidebook to Field Trips in Vermont and Adjacent New Hampshire and New York, New England Intercollegiate Geological Conference, p. C6 1-54

Schroetter, J.-M., Tremblay, A., and Bédard, J. H., 2005, Structural evolution of the Thetford Mines Ophiolite Complex, Canada: Implications for the southern Québec ophiolitic belt: Tectonics, v. 24, no. 1, p. 1-20.

Stanley, R. S., and Hatch, N. L., Jr., 1988, The pre-Silurian geology of the Rowe-Hawley Zone, *in* Hatch, N. L., Jr., ed., The bedrock geology of Massachusetts, U. S. Geological Survey Professional Paper P 1366 A-D, p. A1-A39

Stanley, R. S., and Ratcliffe, N. M., 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, no. 10, p. 1227-1250.

Stanley, R. S., Roy, D. L., Hatch, N. L., and Knapp, D. A., 1984, Evidence for tectonic emplacement of ultramafic and associated rocks in the pre-Silurian eugeoclinal belt of western New England; vestiges of an ancient accretionary wedge: American Journal of Science, v. 284, no. 4-5, p. 559-595.

Thompson, A. B., and Laird, J., 2005, Calibrations of modal space for metamorphism of mafic schist: American Mineralogist, v. 90, no. 5-6, p. 843-856.

Thompson, P., and Thompson, T., 2003, Prospect Rock thrust: western limit of the Taconian accretionary prism in the northern Green Mountain anticlinorium, Vermont: Canadian Journal of Earth Sciences, v. 40, p. 269-284.

Thompson, P. J., Thompson, T. B., and Doolan, B. L., 1999, Lithotectonic packages and tectonic boundaries across the Lamoille River Transect in northern Vermont, *in* Wright, S. F., ed., Guidebook to Field Trips in Vermont and adjacent regions of New Hampshire and New York, New England Intercollegiate Geological Conference, p. 51-94

Tremblay, A., Ruffet, G., and Castonguay, S., 2000, Acadian metamorphism in the Dunnage zone of southern Québec, northern Appalachians: 40Ar/39Ar evidence for collision diachronism: Geological Society of America Bulletin, v. 112, no. 1, p. 136-146.

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

Walsh, G. J., Kim, J., Gale, M. H., and King, S. M., in press, Bedrock geologic map of the Montpelier and Barre West quadrangles, Washington and Orange Counties, Vermont: U.S. Geological Survey, scale 1:24,000, 1 sheet(s).

Westerman, D. S., 1987, Structures in the Dog River fault zone between Northfield and Montpelier, Vermont, *in* Westerman, D. S., ed., Guidebook for Field Trips in Vermont, New England Intercollegiate Geological Conference 79th Annual Meeting, p. 109-132

Whitehead, J., Dunning, G. R., and Spray, J. G., 2000, U-Pb geochronology and origin of granitoid rocks in the Thetford Mines ophiolite, Canadian Appalachians: Geological Society of America Bulletin, v. 112, no. 6, p. 915-928, doi: 10.1130/0016-7606.

Whitehead, J., Reynolds, P. H., and Spray, J. G., 1995, The sub-ophiolitic metamorphic rocks of the Québec Appalachians: Journal of Geodynamics, v. 19, no. 3-4, p. 325-350.

-, 1996, $^{40}Ar/^{39}Ar$ age constraints on Taconian and Acadian events in the Quebec Appalachians: Geology, v. 24, no. 4, p. 359-362.