BEDROCK GEOLOGY OF THE MONTPELIER AREA, CENTRAL VERMONT

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INTRODUCTION

The bedrock geology of the Montpelier area consists of metamorphic and igneous rocks that range in age from Cambrian to Cretaceous. New mapping in the Montpelier and Barre West quadrangles shows that the rocks consist of Silurian to Devonian metasedimentary rocks of the Connecticut Valley – Gaspé synclinorium (CVGS) and metamorphic rocks of the Cambrian to Ordovician Moretown and Cram Hill Formations (figs. 1 and 2). The pre-Silurian rocks to the west are separated from the rocks of the CVGS to the east by the informally named "Richardson Memorial contact" (RMC), historically interpreted as either an unconformity (Cady, 1956; Doll and others, 1961) or fault (Westerman, 1987; Hatch, 1988). Rocks east of the RMC occur in the CVGS and include the metasedimentary Shaw Mountain, Northfield, Waits River, and Gile Mountain Formations.

The Moretown and Cram Hill Formations occur west of the RMC (figs. 1 and 2). In southeastern Vermont, metasedimentary and metavolcanic rocks of the Moretown Formation are cut by calc-alkaline arc-related tonalite and trondhjemite gneisses that yield Cambrian to Ordovician U-Pb zircon ages of ca. 496 – 462 Ma (Ratcliffe and others, 1997). The Late Cambrian to Early Ordovician ages from the intrusive rocks provide an upper age limit for deposition of the metasedimentary and metavolcanic rocks of the Moretown Formation, and here we assign a Cambrian to Ordovician age to these rocks, in accordance with the time scale of Gradstein and others (2004). In Springfield, Vermont, the Cram Hill Formation contains felsic volcanic rocks that yield an Early Ordovician U-Pb zircon age of 484 ± 4 Ma (Ratcliffe and others, 1997), thus we assign an Ordovician age to these rocks. Mafic rocks in the Wrightsville belt (fig. 1) include greenstone and metadiabase. The mafic rocks occur as layers, interpreted as metabasalts or metamorphosed volcaniclastic rocks, and as dikes. The dikes may be correlative in age with similar mafic dikes found in the Comerford Intrusive Suite (CIS) on the east side of the CVGS where gabbro-diorite rocks are dated at 419 ± 1 Ma (Rankin and others, 2007). Biotite-hornblende monzodiorite of the Braintree pluton in central Vermont has the same age (419.26 ± 0.39 Ma, Black and others, 2004) and appears to have the same relative age of the dikes in the Montpelier area, but differs petrographically and chemically from the greenstones and mafic dikes in the Moretown Formation (Ratcliffe and Aleinikoff, 2000; Ratcliffe, 2006). The mafic dikes and the rocks of the CIS and the Braintree pluton do not cross the RMC into the rocks of the CVGS suggesting a Pridolian age limit for the base of the CVGS in some places.

The age of CVGS metasedimentary rocks is based on limited fossil and isotopic data and regional correlations. The depositional age of sediments in the CVGS is considered to be Silurian to Devonian (Doll and others, 1961; Boucot and Drapeau, 1968; Hatch, 1988; Lyons and others, 1997). Correlative rocks in southern Québec, where the rocks are lower grade and less deformed, have yielded better fossil control. Lavoie and Asselin (2004) report Late Silurian (Pridolian) to early Devonian (Lochkovian) fossil ages. Early Devonian (Emsian) plant fossils from the Compton Formation in Québec, the northern correlative of the Gile Mountain Formation, provide age control for the upper part of the CVGS (Hueber and others, 1990). Aleinikoff and Karabinos (1990) and Hueber and others (1990) reported a U-Pb zircon age of 423 ± 4 Ma from a felsic rock from the Waits River Formation 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 a felsic volcaniclastic map unit. The Late Silurian date provides either the age of deposition of the felsic unit at that locality, and therefore the age of the Waits River there, or an upper age limit on deposition.

The stratigraphy of the area is summarized in Figure 3. The metamorphic rocks are cut by Devonian granite dikes and quartz veins and Cretaceous diabase or lamprophyre dikes. This trip will highlight the results of new bedrock geologic mapping in the Montpelier and Barre West quadrangles (Walsh and others, in press), and address the tectonic evolution of the rocks across the RMC, with specific emphasis on the rocks of the CVGS. This trip will follow up on discussions presented in Saturday's trip B2 across the pre-Silurian rocks by Kim and others (this volume).

Walsh, G.J., Kim, J., and Gale, M.H., 2009, Bedrock geology of the Montpelier area, central Vermont, in Westerman, D., and Lathrop, A., editors, New England Intercollegiate Geological Conference: Guidebook for Field Trips in the Northeast Kingdom of Vermont and Adjacent Regions, 101st Annual Meeting, Lyndonville, Vermont, Trip C4, p. 243-260.

PREVIOUS WORK

Previous mapping in the area includes the earliest work by Richardson (1916) in the towns of Calais, East Montpelier, Montpelier, and Berlin. Cady (1956) mapped the 15-minute Montpelier quadrangle and his work represents the first published geologic map on a topographic base in the capitol region. Unpublished mapping by Richard Jahns from 1937-1940 in the 15-minute Barre quadrangle was subsequently described in Currier and Jahns (1941) and White and Jahns (1950), and used by Doll and others (1961) on the State bedrock map. An unpublished reconnaissance map of the 7.5-minute Barre West quadrangle dated 1984 by Norman Hatch, USGS, contained compilation information that was subsequently published in a regional paper on the CVGS (Connecticut Valley trough of Hatch, 1988). Maps of adjacent areas include preliminary 1:24,000-scale work in the Northfield (Westerman, 1994) and Middlesex quadrangles (Gale and others, 2006), and 1:62,500-scale work in the East Barre (Murthy, 1957) and Plainfield (Konig, 1961) 15-minute quadrangles.

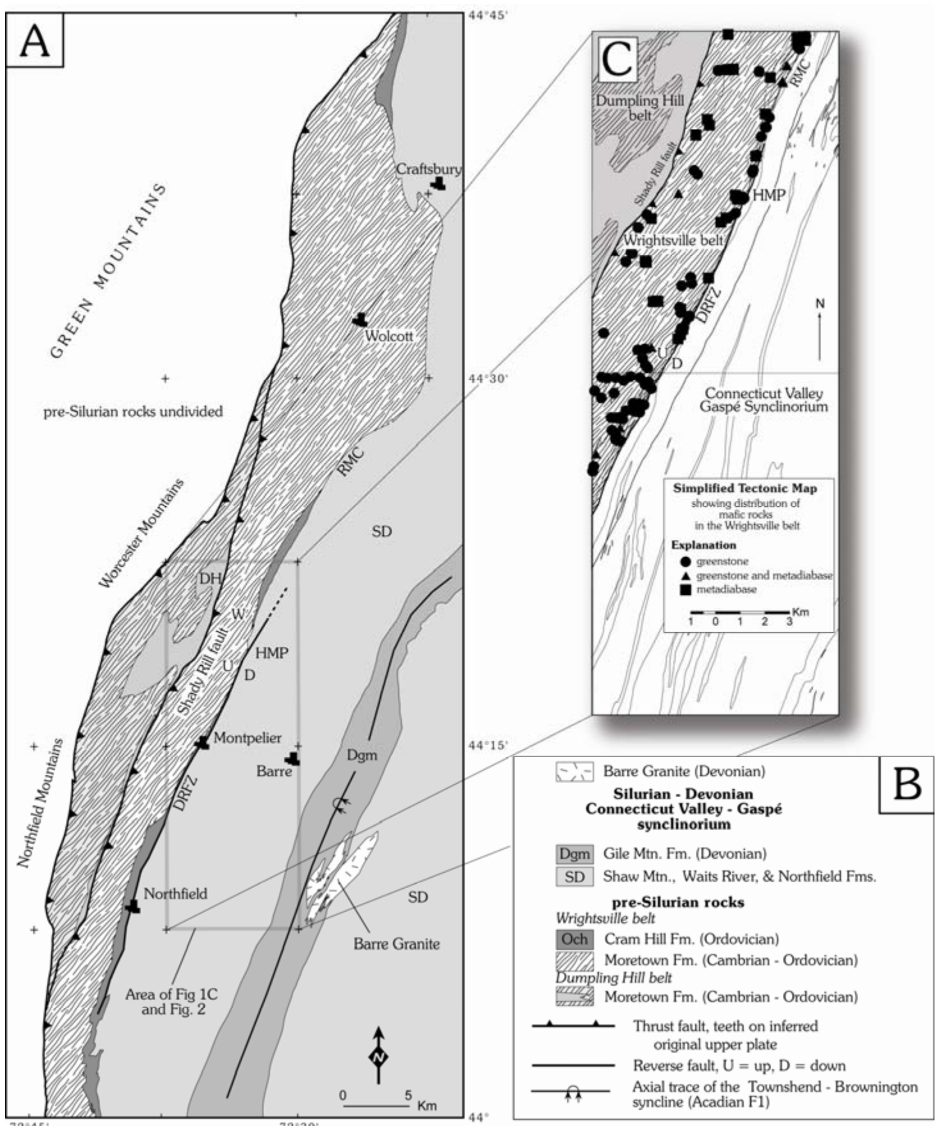

Figure 1. A) Simplified regional geologic map showing the setting of the Montpelier and Barre West quadrangles (outlined in gray). B) Explanation for map. C) Simplified tectonic map of the Montpelier and Barre West quadrangles. Abbreviations: RMC – Richardson Memorial Contact, DH – Dumpling Hill, W – Wrightsville, DRFZ – Dog River fault zone, and HMP – Horn of the Moon Pond.

Walsh, G.J., Kim, J., and Gale, M.H., 2009, Bedrock geology of the Montpelier area, central Vermont, in Westerman, D., and Lathrop, A., editors, New England Intercollegiate Geological Conference: Guidebook for Field Trips in the Northeast Kingdom of Vermont and Adjacent Regions, 101st Annual Meeting, Lyndonville, Vermont, Trip C4, p. 243-260.

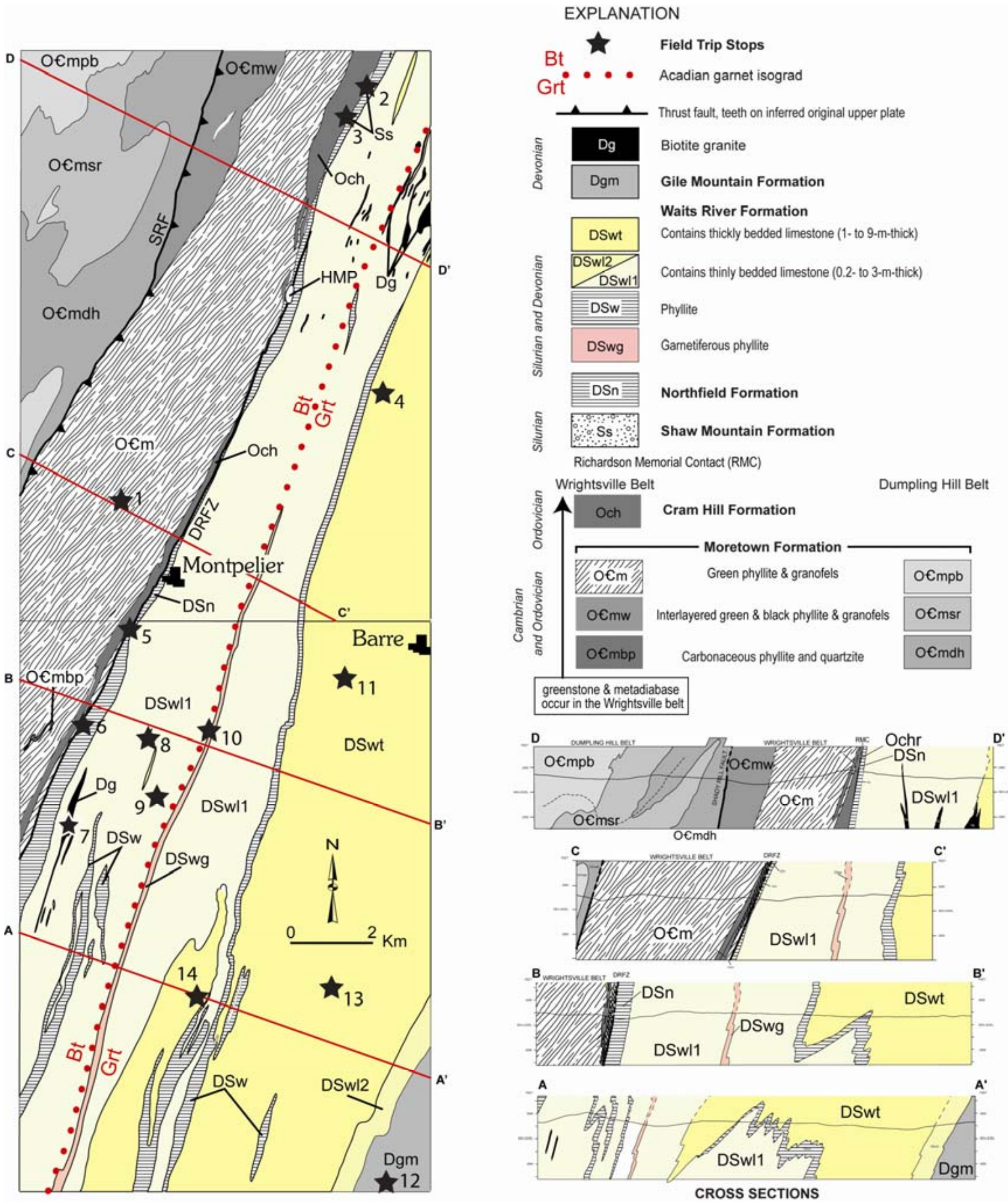

Figure 2. Simplified geologic map of the Montpelier and Barre West quadrangles showing field trip stops 1-14; modified from Walsh and others (in press); DRFZ – Dog River fault zone, and HMP – Horn of the Moon Pond.

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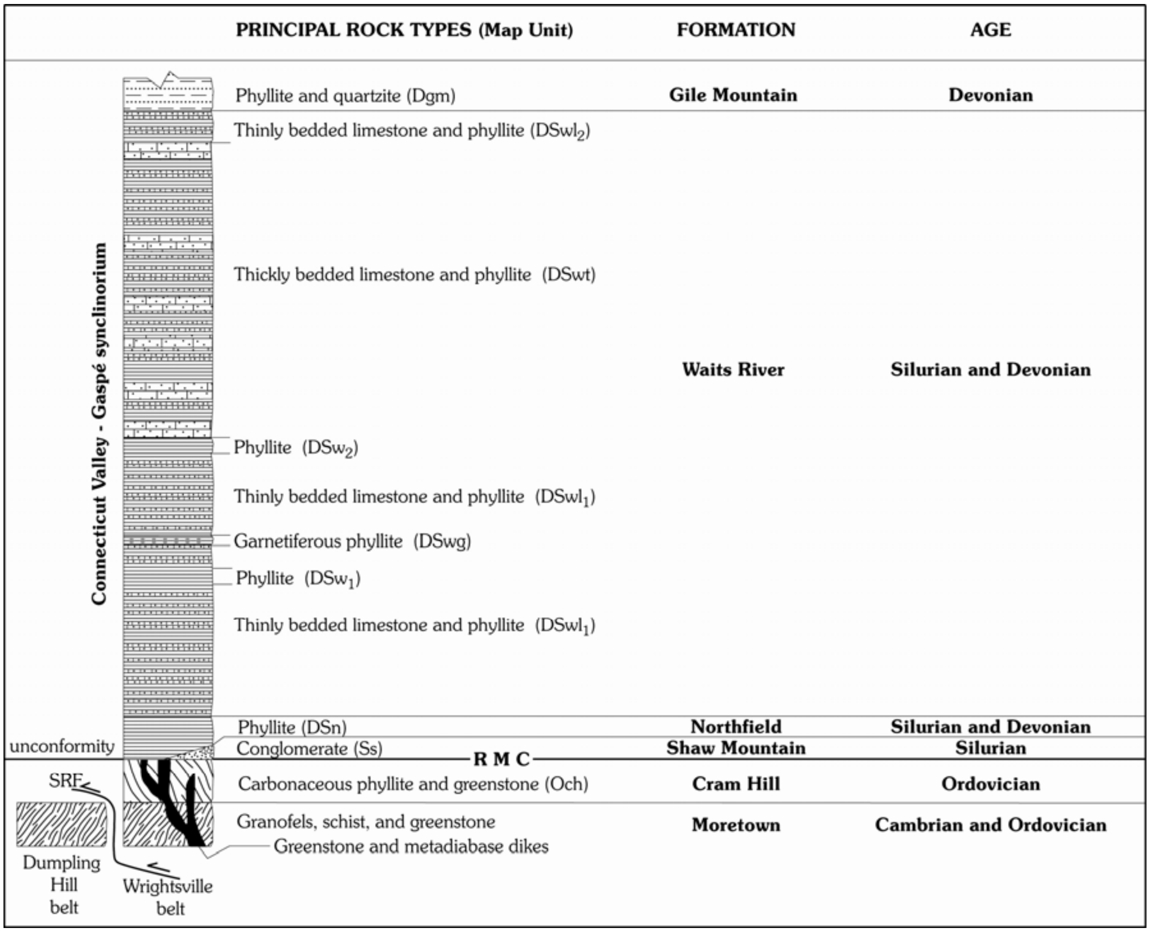

Figure 3. Simplified stratigraphic section for the Montpelier and Barre West quadrangles; RMC – Richardson Memorial Contact, SRF – Shady Rill fault.

THE RICHARDSON MEMORIAL CONTACT (RMC) AND DOG RIVER FAULT ZONE (DRFZ)

In central Vermont, the origin of the RMC is controversial as it has been interpreted as both tectonic and stratigraphic. The RMC separates pre-Silurian rocks to the west (Cram Hill and Moretown Formations) from Silurian and Devonian rocks to the east (Shaw Mountain, Northfield, and Waits River Formations). Richardson (1919) thought that the quartz-pebble conglomerates of the Shaw Mountain Formation sat unconformably on the Moretown and Cram Hill Formations and later work supported this interpretation (Currier and Jahns, 1941; White and Jahns, 1950; Doll and others (1961). On the basis of mapping along the RMC in the Northfield-Montpelier area, Westerman (1987) suggested that the RMC corresponds to the “Dog River fault zone” along which pre-Silurian and Silurian rocks were juxtaposed. In central and southern Vermont, the RMC has been mapped as an unconformity, with only localized offset along syn-tectonic Acadian faults (Currier and Jahns, 1941; White and Jahns, 1950; Armstrong, 1994; Martin, 1994; Walsh and others, 1994, Walsh and Ratcliffe, 1994a,b; Walsh and others, 1996a,b; Ratcliffe, 1996, 2000a,b; Ratcliffe and Armstrong, 1999, 2001). In Massachusetts, Hatch and Stanley (1988) interpreted the RMC equivalent as a décollement called the “Surface of Acadian Structural Disharmony” (SASD). This interpretation was primarily based on the disparity in size and amplitude of first generation Acadian large high-amplitude isoclinal folds found in Silurian rocks versus small low-amplitude folds in the underlying pre-Silurian rocks. In addition, the SASD was rarely deformed by these isoclinal folds. Cross sections by Hatch and Hartshorn (1968) and Hatch and Stanley (1988) portray the isoclinally folded Silurian and Devonian rocks as a crumpled rug above a décollement at the top of the pre-Silurian section. Kim (1996) noted a thin (~5 cm) highly fissile, papery schist zone in the Devonian Goshen Formation garnet schist and lithologic truncations along the SASD in northwestern Massachusetts.

This field trip will present evidence that the boundary is a faulted unconformity in the Montpelier area. In some places it is a fault and in other places it is an unconformity, in agreement with findings reported in Québec (ie. Lavoie and Asselin, 2004). The boundary corresponds to the Dog River Fault zone from about Horn of the Moon Pond southward (figs. 1 and 2). To the north, the boundary is mapped as an unconformity, and the Dog River Fault zone, if present, is located somewhere to the east in the CVGS. Our findings support the work by Westerman (1987) for the Dog River fault zone at the latitude of Montpelier. In Québec, the La Guadeloupe fault separates pre-Silurian rocks to the west from Silurian-Devonian metasedimentary rocks of the CVGS to the east (Cousineau and Tremblay, 1993; Tremblay and others, 1989, 2000; Lavoie and Asselin, 2004), and represents a possible along-strike correlative to the Dog River fault zone because it occurs at the same stratigraphic boundary, the RMC. We will see at Stop 2, however, that the RMC is not a fault in all places.

STRUCTURAL EVOLUTION

Five generations of ductile deformation and associated structures are recognized in the area. The five generations are designated D1 through D5, and their associated fabrics are summarized in Table 1. The oldest two periods of deformation (D1 and D2) are interpreted to be the result of the Ordovician Taconian orogeny, and the youngest three periods of deformation (D3 through D5) the result of the Devonian Acadian orogeny. It is possible that the dome stage deformation (D5) is related to the Alleghanian orogeny. D1 and D2 occur only in the pre-Silurian rocks and D3 produced the oldest fabric in the CVGS. This field trip will discuss the structural evolution as it relates to rocks on both sides of the RMC, with particular emphasis on rocks in the CVGS.

This Study				Kim and Gale (2004)	Walsh & Falta (2001)	Ratcliffe (2000a,b)	Walsh (1998)	Offield and others (1993); Woodland (1977)
	Deformation	**Foliation**	**Relative Timing of Paleozoic Intrusive Rocks**					
D5	Weak dome-stage cleavage	S5 (Acadian S3) or Alleghanian		na	S5	F4 & F5	S3	F3
D4	NE striking - NW dipping and lesser NW striking - NE dipping cleavage and folds	S4 (Acadian S2)	Granite dikes	S3	S4	Acadian F2	S2	F2
D3	Dominant schistosity with tight-isoclinal folding in SD rocks Cleavage to fault-related fabric along Dog River fault zone	S3 (Acadian S1)	Metadiabase and greenstone dikes	S2	S3	F3 or Acadian F1	S1	F1
D2	Dominant schistosity and pinstripe in Moretown Fm., to relict foliation where overprinted by Acadian S1	Taconian S2		S1	S2	F2	na	na
D1	Relict layer-parallel foliation in Moretown and Cram Hill	Composite Taconian S1/S0			S1	F1 Taconian?	na	na

Table 1. Regional correlation of deformational fabrics, central Vermont.

Walsh, G.J., Kim, J., and Gale, M.H., 2009, Bedrock geology of the Montpelier area, central Vermont, in Westerman, D., and Lathrop, A., editors, New England Intercollegiate Geological Conference: Guidebook for Field Trips in the Northeast Kingdom of Vermont and Adjacent Regions, 101st Annual Meeting, Lyndonville, Vermont, Trip C4, p. 243-260.

ROAD LOG

STARTING POINT. Meet at 09:00 AM on Sunday September 27, 2009 at the Montpelier Park & Ride commuter parking lot. Take Exit 8 off I-89 and proceed northeast for 1/3 mile towards Montpelier. Make your first left onto Dog River Road towards Montpelier Junction and the railroad station. The parking lot is on the left. Latitude and Longitude: 44°15'19"N, 72°35'41"W (WGS84 datum). Please bring your lunch, a hard hat, and a safety vest. Stop coordinates are given for outcrop locations in UTM meters (Easting and Northing), Zone 18, NAD27 datum, unless stated otherwise. Minerals in rock descriptions are listed in order of increasing abundance.

Mileage
0.0 Turn right out of Park & Ride
0.1 At stop sign turn left onto Memorial Drive towards Montpelier
0.6 At light turn left onto Bailey Ave. Ext.
0.7 At light proceed straight onto Bailey Ave.
0.9 Turn left onto Terrace St.
1.9 Turn right onto Ledgewood Terrace and park for Stop 1

STOP 1. Moretown Formation at Ledgewood Terrace, Montpelier (692000 E 4905130 N)

This roadcut contains interlayered light-green and silvery green to gray-green chlorite-plagioclase-quartz-muscovite phyllite, schist, and chlorite-muscovite-plagioclase-quartz granofels and "pinstriped" granofels of the Moretown Formation in the Wrightsville belt. The tectonic pinstriping is the dominant foliation in this rock at this outcrop and is regionally associated with the Taconian S2 fabric. Upright F3 folds with north plunging fold axes deform the S2 foliation and have the same relative age as the Acadian F1 folds that we will see in the Silurian – Devonian rocks later today. A metadiabase dike on the west end of the roadcut truncates the S2 foliation but contains a weak S3 foliation. Metadiabase dikes, greenstone dikes, and greenstone layers are typical of the Wrightsville belt of the Moretown Formation (fig. 1). Trace element geochemistry shows that these mafic rocks have tholeiitic basalt signatures (Twelker, 2004). Previous workers in this and adjacent areas also recognized both older greenstone layers and younger greenstone or metadiabase dikes in the eastern part of the Moretown Formation (Cady, 1956; Cua, 1989; Westerman, 1987, 1994). The dikes and mafic rocks are truncated by the RMC. See Kim and others (this volume, Trip B2) for a regional discussion of the mafic rocks.

Mileage
0.0 Turn right off Ledgewood Terr. onto Terrace St. heading north
0.7 Turn right onto Portal Rd.
2.4 Bear right onto Bolduc Rd.
2.7 At stop sign turn left onto Route 12 North
3.2 Turn right onto Horn of the Moon Rd.
3.3 Wrightsville Dam and Reservoir
3.5 Outcrops of Moretown Formation at spillway
5.0 Bear right at fork in road
5.6 Proceed straight at 4-way intersection
6.7 Turn left onto County Rd.
9.1 Turn left onto Longmeadow Hill Rd. (see green and black mailboxes)
9.8 Turn right onto Robinson Hill Rd.
10.3 Park in vicinity of the gate on the left for Stop 2. Do not block the gate.

STOP 2. Hersey Hill traverse, Calais (697830 E, 4915190 N at parking area start of traverse)

This stop will include a traverse up to the north peak of Hersey Hill. One way, the traverse is 350 m at a bearing of 295° with a steep elevation gain of about 60 m (200 feet). This traverse will go down-section and we will cross the Waits River and Northfield Formations to arrive at the Shaw Mountain Formation at the RMC.

Along the road, about 10 m north of the gate, you will see pavement outcrops of dark gray slate with thin interbedded punky weathering limestone (or marble). From the gate proceed uphill and you will see better-exposed outcrops of interbedded sulfidic slate and marble typical of the western, lower part of the Waits River Formation where marble beds generally measure 0.2- to 3.0-m-thick. Once you achieve the crest of the first hill, descend on the same bearing and cross a small valley. This valley marks the contact between the Waits River and Northfield Formations and is expressed as a pronounced topographic lineament that extends southward to Horn of the Moon Pond. This valley may mark the northern continuation of the Dog River fault zone (DRFZ), however, structural evidence in the valley is limited as the outcrop is quite poor. The next outcrops on the steep slope will be slate of the Northfield Formation; note that marbles are absent or very rare. Near the hill crest you will find outcrops of ankeritic greenstone and interbedded gray to silvery green muscovite-chlorite-albite-quartz schist with calcite-ankerite porphyroblasts. These rocks are mapped as the easternmost part of the Cram Hill Formation because these rocks are similar to those in the Cram Hill and Moretown Formations farther west. We place them in the pre-Silurian section and not in the Shaw Mountain Formation as Cady (1956) did. Alternatively, these rocks may be stratigraphically above the conglomerate but below the Northfield Formation, and similar to rocks mapped as "Unnamed calcareous volcaniclastic and feldspathic granofels" in the Cavendish quadrangle (Ratcliffe, 2000a). West of the ankeritic green schist you will see rusty weathering quartzite, quartz-rich schist, and quartz pebble conglomerate of the Shaw Mountain Formation. An excellent exposure is located at 697540 E, 4915190 N. Note that the pebbles are only weakly deformed. The conglomerate marks the location of the RMC here. The relatively weak deformation in the conglomerate suggests that the RMC is an unconformity here, which sharply contrasts with the evidence for high strain to the south in the DRFZ. The contrast in deformation suggests that if the DRFZ exists at this latitude it is located to the east of the RMC.

Mileage

0.0	Make a U-turn and drive south on Robinson Hill Rd.
0.4	Turn right onto Longmeadow Hill Rd.
0.5	Cross swamp at contact between the Waits River and Northfield Formations
0.6	Turn right and park in driveway for Stop 3. Do not block the driveway.

STOP 3. Hersey Hill south slopes, Calais (697270 E, 4914700 N at destination Shaw Mountain outcrop)

This is an optional stop if we do not make it up the Hersey Hill traverse at Stop 2. Here outcrops along the driveway are dark gray sulfidic slate of the Northfield Formation. Walk behind the house and to the west into the meadow and you will find closely spaced outcrops of both Northfield Formation slate and Cram Hill Formation ankeritic green schist. There is no conglomerate exposed in the meadow so walk north, uphill, into the woods along strike until you find some low outcrops of rusty weathering quartz-rich schist and small pebble conglomerate of the Shaw Mountain Formation. This outcrop is not as nice as the exposure at Stop 2, but the access is easier.

Mileage

0.0	Make a U-turn and drive east Longmeadow Hill Rd.
0.9	At stop sign turn right onto County Rd.
3.5	Turn left onto Templeton Rd.
4.7	At stop sign turn right onto Center Rd.
5.1	Park on right for Stop 4

STOP 4. Fossil locality No. 7 of Cady (1950, p. 492), East Montpelier (698270 E, 4908010 N)

From the road, walk east along the East Montpelier Trails footpath. You will cross over outcrops of interbedded dark gray slate and punky weathering marble of the Waits River Formation. After a short distance, proceed south to a small meadow. On the west side of the meadow along the tree line, you will see an outcrop of dark gray phyllite with quartz pebbles showing graded beds overturned to the east. Graded bedding in the Waits River Formation was rarely seen during mapping, but the majority of observed topping criteria suggest that the Waits River is steeply overturned toward the east-southeast. The relationship of bedding steeper than cleavage, with both dipping steeply to the west, is widespread in the CVGS in the Montpelier area and is consistent with the generally overturned nature of the bedding on the western limb of the Townshend – Brownington syncline (fig. 1).

The western part of the formation is dominated by thinly bedded limestone and phyllite or slate (see Stop 9) and the eastern belt is dominated by thickly bedded rocks seen here and especially at Stop 11. Most of the clasts in the graded beds here appear to be quartz, but some fragments appear to be fossil cup corals as Cady (1950) reported. Hatch (1988, p. 1056) and Hueber and others (1990, p. 363) reported that, based on a study of slides and slabs by William A. Oliver, Jr., "None of the specimens at hand appear to be corals and none have any markings or structure that suggest an organic origin, although this is a possible origin of the objects." This locality has yet to be re-examined by another paleontologist. We welcome your opinion.

Mileage

0.0 Continue south on Center Rd.
3.3 At stop sign turn left onto County Rd. (County Rd. turns into Main St. in Montpelier)
5.0 At rotary bear left onto Route 12 South (Main St.)
5.3 At light proceed straight through the junction of State St. and Main St. in downtown Montpelier
5.5 At light proceed straight through the junction of Route 12 and U.S. 2, continue on Route 12 South
6.5 Park on right under the I-89 overpass for Stop 5.

STOP 5. Dog River fault zone at Exit 8 on I-89 northbound, Berlin (692310E, 4902040N)

Hard hats and safety vests required. Written permission from the Vermont Agency of Transportation is required. Walk west up the hill to the north of the northbound overpass. Stay on the grass at the top of the hill and do not walk on the roadway. This stop is also described by Westerman (1987; Stop 1).

This roadcut marks the best known exposure of the RMC in Vermont, and here it corresponds to the Dog River fault zone (DRFZ). You can put your finger on the steeply west dipping contact near the southeast end of the cut where light-green muscovite-quartz-calcite-chlorite-plagioclase granofels with minor greenstone that we map as Moretown Formation occur to the west, and dark-gray carbonaceous phyllite of the Northfield Formation occur to the east. The contact between the two formations is sharp and parallel to the S3 foliation (Acadian S1). A strongly developed penetrative S3 fabric is the dominant foliation in all the rocks at this roadcut. Across the outcrop, however, the S3 fabric shows varying degrees of transposition of bedding and older fabrics. A zone of high strain and intense transposition associated with S3 extends from about 10 m east of the RMC to approximately 80 m west of the RMC, and this is the Dog River fault zone. In the Northfield and Waits River Formations more than 10 m east of the RMC, bedding is deformed into isoclinal F3 folds, but it is not transposed. As the RMC is approached from the east, bedding in the Northfield Formation is progressively transposed. From the western edge of the Northfield Formation to a point approximately 80 m west of the RMC, bedding and at least one, perhaps two, older schistosities in the Cram Hill and Moretown Formation are transposed and quartzite layers are preserved only as tectonic slivers. Thus, the RMC at this location is a faulted surface within an approximately 90-m-wide fault zone, and the original unconformity is not preserved. In the vicinity of the Dog River fault zone, L3 lineations consisting of quartz rods, stretched pebbles, and F3 fold axes are sub-parallel, indicating high strain, and plunge moderately to the northwest. Away from the DRFZ, the L3 lineations and F3 fold axes show greater variability, and locally much shallower plunges to the north-northwest and south.

Kinematic analysis of three oriented thin sections from this roadcut shows west-side-up reverse relative motion. Type II S-C mylonitic fabrics (Lister and Snoke, 1984) in all three samples show S-surfaces that correspond to the S3 fabric and microscopic C-surfaces that were not recognized in the field. Two samples collected from a muscovite-carbonate-plagioclase-chlorite-quartz granofels at the RMC and a muscovite-quartz-carbonate-chlorite-plagioclase granofels 2-m-west of the RMC, display Type II S-C fabrics, mica fish, and slightly asymmetric porphyroclasts with consistent west-side-up relative motion. The asymmetric fabrics are overprinted by late, post-tectonic carbonate and lesser muscovite porphyroblasts. The third sample, a micaceous quartzite from a tectonic sliver about 8 m west of the RMC, shows similar microstructures with the same relative displacement, but also contains many symmetrical fabrics indicative of flattening. Combined with the consistent northwest trending lineations, the overall sense of displacement of the DRFZ is reverse, left-lateral oblique, in agreement with the findings of Westerman (1987). Since the RMC currently dips steeply to the west, these kinematics either support west-side-up reverse motion or initial east-side-down normal motion along an east-dipping normal fault followed by folding of the fault plane through the vertical by subsequent D4 or D5 deformation.

Mileage

0.0 Continue south on Route 12 South
1.4 Turn left onto Browns Mill Rd.
1.5 Cross bridge and bear right
1.8 Park on right near mailbox 493 for Stop 6.

STOP 6. Northfield Formation conglomerate on the Dog River, Berlin (691200E, 4899670N)

Walk down the bank to the outcrop on the river. This outcrop exposes conglomerate near the base of the Northfield Formation. The matrix consists of dark-gray phyllite similar to the Northfield Formation phyllite. Clasts consist of tabular, tectonically elongated rock fragments of light-gray to white ankerite-spotted phyllite and quartzite measuring as much as approximately 10 cm thick by 50 cm long. The conglomerate is intraformational within the

Northfield Formation near its base, and approximately 2-3 m thick. This conglomerate occurs within the Northfield Formation, not at the contact between the Northfield and Cram Hill Formations as does the Shaw Mountain Formation. The rock was described and seen elsewhere by Currier and Jahns (1941). In fact, the outcrop at this stop was photographed and appears as figure 1 in Currier and Jahns (1941, p. 1494). The outcrop is more overgrown now, but tectonically elongated clasts are still visible in the phyllitic matrix. Currier and Jahns (1941) report that the clasts consist of rocks found in the Cram Hill and Shaw Mountain Formations, and our observations support their findings for Cram Hill Formation clasts, but not the Shaw Mountain probably because the outcrop is so poorly exposed now and because their usage of Shaw Mountain included rocks that we map as Moretown Formation or Cram Hill Formation. This outcrop is just east of the DRFZ; note the difference between the deformation experienced by the clasts here compared to the Shaw Mountain Formation conglomerate at Stop 2.

Mileage

0.0	Make a U-turn and return to Route 12
0.4	At stop sign turn left onto Route 12 South
1.9	Turn left onto Rowell Hill Rd.
3.0	At stop sign turn right onto Crosstown Rd.
3.5	Park on right for Stop 7

STOP 7. Granite quarries at Crosstown Road, Berlin (691000 E, 4897700 N at road)

Walk south up the footpath to the abandoned granite quarries. The first quarry (691000 E, 4897700 N) along the trail is approximately 350 m southwest of the trail junction with Crosstown Road. If time permits, continue up the trail to additional quarries. The granite here is a dike that is approximately 150 m thick. The country rock is Waits River Formation, and the contacts are visible east and west of the first quarry.

Granitic dikes in the area range in composition from trondhjemite, to granodiorite, to muscovite-biotite granite. The dikes are part of the Devonian New Hampshire Plutonic suite. Although not dated in the map area, similar correlative rocks occur throughout Vermont. A U-Pb zircon age by sensitive high resolution ion microprobe (SHRIMP) for the nearby Barre Granite (Murthy, 1957) is 368 ± 4 Ma (Ratcliffe and others, 2001). Ratcliffe and others (2001) report a similar U-Pb zircon age of 366 ± 4 Ma for the Black Mountain Granite in southern Vermont. Structurally, the dikes cut the bedding in the Silurian-Devonian rocks and generally intruded sub-parallel to the dominant foliation (S3 or Acadian S1) in these rocks. Locally the dikes contain the S3 foliation, especially in thin bodies or along the margins of larger dikes, suggesting that some may pre-date or be synchronous with foliation development. Other dikes without a foliation post-date the S3 foliation, but may have experienced subsequent flattening along their margins during continued regional deformation. The generally massive texture of the dikes makes it difficult to assess whether they pre- or post-date the weakly developed S4 (Acadian S2) cleavage in this area. In thin section, however, the granite in the core of the dike here at Crosstown Road contains no foliation or even preferred fracture orientation, suggesting that its central core post-dates both S3 and S4. The structural relationships combined with the regional zircon ages and similar regional $^{40}Ar/^{39}Ar$ metamorphic ages (Laird and others, 1984; 1993; Spear and Harrison, 1989), clearly suggests that the granites are related to Acadian deformation and metamorphism. See Westerman (this volume, Trip A6) for a regional discussion of the Acadian plutons.

Building stone from the Crosstown road quarries was used to build the Christ Episcopal Church at 64 State Street and the old post office (since torn down) in downtown Montpelier (Richard Turner, written commun., 2006). These quarries, which have no formal name, were owned by C.M. Ayers and opened sometime after 1858 according to records of the Berlin Historical Society (Richard Turner, written commun., 2006). The quarries were in operation in the 1870s (Collier, 1872). Unpublished documents on file at the Vermont Geological Survey indicate that the quarries also went by the name of “S. Fruchter quarry”. These granite quarries were abandoned by the time of Richardson’s (1916) mapping in 1914-1915, and probably sometime before then as Dale (1909) did not include them in his study.

Mileage

0.0	Carefully make a U-turn and travel north on Crosstown Rd.
1.4	At yield sign proceed straight onto Hill St. Ext.
1.9	Park on left before the overpass for Stop 8

STOP 8. Hill Street Extension overpass on I-89, Berlin (692800 E, 4899310 N)

Hard hats and safety vests required. Written permission from the Vermont Agency of Transportation is required. Walk north through the woods and meadow along the west side of the I-89 southbound lane. Stay on the grass at the top of the hill and do not walk on the roadway.

The roadcut, approximately 100 m north of the overpass, exposes a light gray calcareous quartzite in the Waits River Formation. These quartzites are relatively rare compared to the marbles in the Waits River. The quartzite here contains about 80 percent quartz, 10 percent calcite, 6 percent plagioclase, and 3 percent muscovite. Accessory minerals include pyrite, graphite, tourmaline, zircon, and monazite. The quartzite consists of an individual bed about 2-m-thick. Look across the highway along strike to the north and you will see the rock exposed on the opposite side of the highway. The quartzite is interlayered with dark-gray sulfidic quartz-muscovite phyllite and impure siliceous marble. Analysis of detrital zircons from this rock contain three age populations: 1) 415-500 Ma, 2) 550-615 Ma, and 3) 925-2120 Ma, with three grains >2600 Ma (McWilliams and others, in press). Detrital zircon ages from this sample and three other samples from the Waits River and Gile Mountain Formations support a Silurian to Devonian depositional age range and support the stratigraphic topping criteria that show the Waits River is older than the Gile Mountain (McWilliams and others, in press).

Mileage

0.0 Carefully make a U-turn and travel south on Hill St. Ext.
0.6 At stop sign turn left onto Crosstown Road
1.0 Turn right onto Paine Turnpike and immediately park along the right side of the road for Stop 9

STOP 9. Intersection of Paine Turnpike and Crosstown Road, Berlin (693000 E, 4898030 N)

These roadcuts expose interbedded limestone and phyllite or slate of the Waits River Formation. Limestone beds are generally < 3 m thick. This exposure is typical of the western, or lower part, of the formation in the Montpelier area. Two Cretaceous lamprophyre dikes also occur at these roadcuts.

The most distinctive aspect of the Waits River Formation is the presence of metamorphosed impure limestone or marble. Historically, workers have used both the terms “marble” and “limestone”. White and Jahns (1941, p. 187) noted that the term limestone was, “long-established local usage”. Cady (1956, footnote 1) provides a possible explanation as follows:

“Though the crystalline limestones are strictly marbles, the geologists who have studied these rocks have long referred to them as limestone rather than marble, probably because of their poor commercial qualities compared to the marbles of western Vermont.”

Doll and others (1961) also used the term “limestone” on the State map, and we continue the traditional usage here. The limestone is considered siliceous and impure because it typically contains 50-75 percent calcite, 50-25 percent quartz, and less than 5 percent muscovite and/or biotite. The protolith of this rock was probably sandy limestone according to the classification of Williams and others (1954) and Compton (1962).

Initial reports of Ordovician graptolites from this exposure, referred to as Berlin Corners, by Bothner and Berry (1985) and Bothner and Finney (1986) were re-evaluated and reported to be plant fragments and not graptolites by Hueber and others (1990). Hueber and others (1990) also found crinoid and echinoderm fragments from this Berlin Corners exposure, but the fragments did not provide specific age constraints. Look along the base of the limestone beds for mm-scale clasts; this is where the fossil fragments were found.

A gamma ray spectrometer survey in the Barre West quadrangle (Walsh and Satkoski, 2005) shows that the carbonaceous metapelites are the primary source for naturally occurring radionuclides in these rocks; the limestones contain considerable less radioactivity. A detailed survey at Exit 7 was conducted in this belt of Waits River Formation about 0.5 km north of this stop.

Note also the lithologic control on joint patterns in the limestone versus the phyllite, and the abutting terminations. Fracture analysis shows that the principal trends in the area are dominated by north-northeast trending foliation-parallel parting both east and west of the RMC, and this topographic grain is clearly visible on digital elevation model (DEM) shaded relief maps. West of the RMC, kilometer-scale west-northwest drainage patterns and valleys are probably associated with the principal trends of crossing joints measured during mapping. East of the RMC, however, the west-northwest trends are not as prominent and we speculate that the more subdued topographic expression is the result of the abutting nature of the joints. Thus the distinct layering in the Silurian and Devonian rocks, and especially the well-layered Waits River Formation, inhibits the formation of kilometer-scale crossing joints and joint sets.

Mileage

0.0 Carefully make a U-turn and turn right onto Crosstown Road
0.3 At stop sign turn left onto Paine Turnpike N.
0.6 At light and junction with Route 62 proceed straight on Paine Turnpike N.
1.9 Turn right and carefully make a U-turn at the City of Montpelier Water Treatment Facility
2.4 Pull over and park on the right for Stop 10. Caution this is a busy road!

STOP 10. Garnetiferous phyllite in the Waits River Formation, Berlin (694300 E, 4899410 N)

Outcrops on the west side of the road are garnetiferous phyllite of the Waits River Formation. This unit was mapped continuously for approximately 18 km and measures as much as 200 m wide, or about 185 m thick. The rock is dark-gray, garnet-chlorite-quartz-muscovite phyllite with distinctive abundant small (0.1 – 2.0 mm) euhedral garnet porphyroblasts or chlorite pseudomorphs after garnet. The unit defines the western Acadian garnet isograd; west of this limit the rocks experienced sub-garnet grade metamorphism during the Acadian (east of the RMC) or during both the Acadian and Taconian orogenies (west of the RMC). In the garnet zone, inclusion patterns in garnet and biotite porphyroblasts indicate that both minerals grew after the development of the S3 foliation, but prior to or during the early stages of S4 cleavage development. Microscopic study shows that the S4 foliation wraps around garnet porphyroblasts in most samples indicating that cleavage development or modification continued after porphyroblast growth. One sample shows deformed S3 inclusion trails in garnet indicating that porphyroblast growth began after the onset of D4 deformation. During D4, quartz pressure shadows formed around biotite and garnet, and the pressure shadows are aligned with the L4 crenulation lineation. These findings indicate that peak metamorphic conditions occurred after D3 but prior to the completion of D4 deformation. Subsequent to D4, some garnet porphyroblasts exhibit static retrogression to chlorite. In these places, chlorite formed euhedral, undeformed pseudomorphs after garnet and locally, some chlorite grew in sheets with the basal 001 cleavage sub-parallel to the shape of the original garnet crystal faces. Because the chlorite in the garnet pseudomorphs is undeformed, this period of retrogression occurred after D4 and possibly after D5, although no fabrics associated with D5 were observed microscopically.

Mileage

0.0 Proceed south on onto Paine Turnpike N.
0.1 Turn left onto Fisher Rd.
0.5 At light turn left onto Route 62 East
0.6 Bear right towards Montpelier and go down the hill
1.6 At light at bottom of hill turn left onto U.S. 302 West
2.7 At rotary bear right onto U.S. 2 East
4.2 Pull over and carefully park on the right for Stop 11. Caution this is a busy road!

STOP 11. Winooski 1 Power Co. dam, U.S. Route 2, Berlin (697580 E, 4900980 N)

This stop shows the thickly bedded Waits River Formation typical of the eastern, or upper part, of the formation. The unit contains thick beds of limestone (> 8 m) and phyllite (0.5 – 1.0 m). Carefully cross the road and look at the exposure at the base of the dam on the Winooski River where bedding is clearly visible. Note the thick bed of limestone at the base of the dam. At the roadcut on the south side of the highway you can see an east verging, tight Acadian F1 anticline that is the height of the outcrop . Note the refraction of the S3 (Acadian S1) cleavage from the phyllite to the limestone. Many large roadcuts in the Waits River Formation in the Barre West quadrangle exhibit these outcrop-scale F1 folds.

Mileage

0.0 Proceed straight continuing on U.S. 2 East
0.4 Pull off to the right and carefully make a U-turn onto U.S. 2 West
2.4 At rotary bear left onto U.S. 302 East
3.5 At light turn right uphill towards Route 62 East and I-89
4.5 At light at top of hill turn left onto Airport Rd.
5.9 At the airport you might get a view of the Green Mountains to the west and peaks of the Knox Mountain pluton to the east
8.1 At stop sign turn right onto Miller Rd.
9.6 At stop sign turn left onto Route 63 East

10.3 Large roadcut of thickly bedded Waits River Formation
10.8 View of Spruce Mountain at 12 O'clock
11.7 At light turn right onto Route 14 South
12.5 Turn left onto Holden Rd.
13.0 Turn right on Peloquin Rd.
13.4 At stop sign turn right onto Orchard Terr.
13.5 Bear left. Orchard Terr. becomes McLeod Rd.
13.8 At gravel McLead Rd becomes McGlynn Rd.
15.4 Pull over and park on the right before crossing the stream for Stop 12

STOP 12. Gile Mountain Formation on McGlynn Road, Williamstown (698910 E, 4888740 N)

This stop shows a typical exposure of the Devonian Gile Mountain Formation quartzofeldspathic granofels and micaceous quartzite. The rock contains porphyroblasts of garnet and biotite. Note that some of the biotite porphyroblasts are aligned parallel to the intersection lineation between the dominant foliation (S3, Acadian S1) and the younger cleavage (S4, Acadian S2). Graded beds show that the Gile Mountain Formation is above the Waits River Formation. The outcrop in the driveway across the street shows interbedded quartzofeldspathic granofels and micaceous quartzite with punky brown weathering calcareous phyllite -- a relatively rare rock type in the Gile Mountain Formation. Limestones more typical of the underyling Waits River Formation do occur in the Gile Mountain, but are equally rare.

Mileage

0.0 Proceed straight on McGlynn Rd.
0.1 At stop sign turn right onto Graniteville Rd.
1.5 Turn right onto Route 14 North
5.6 At light turn left onto Route 63 West
6.8 Turn right onto Cheney Rd.
7.0 Turn left onto Apple Blossom Rd. and park on the right for Stop 13

STOP 13. Folds in the Waits River Formation on Apple Blossom Road, Barre (697500 E 4893350 N)

This stop shows complex folding in the thickly bedded part of the Waits River Formation (fig. 4). This exposure contains massive siliceous limestone with interbedded calcareous schist. Dark gray to black sulfidic schist occurs at the west end of the roadcut. The folds are the result of interference between F3 (Acadian F1), F4 (Acadian F2), and upright F5 (Acadian F3). Ptygmatically folded quartz veins show complex and variable deformation. The best F3 folds are tight to isoclinal folds of laminations in the limestone. The trace of S4 is warped across the exposure by the upright S5 cleavage. Note that S5 occurs in discrete zones and is not penetrative. Regionally F5 is associated with dome stage folds (table 1), and in many places throughout the Montpelier area there is little or no expression of the S5 cleavage.

Figure 4. Photograph of folds at Stop 13. S0 – bedding, S3 – Acadian S1, S4 – Acadian S2, S5 – Acadian S3, and pty – ptygmatically folded quartz veins.

Mileage

0.0	Proceed straight uphill on Apple Blossom Rd.
0.1	Carefully make a U-turn at the junction with Crab Apple Ln.
0.2	At stop sign turn right onto Cheney Rd.
0.4	At Stop sign turn right onto Route 63 West
1.6	Large roadcut of thickly bedded Waits River Formation
2.8	Pull over and carefully park on the right. Caution this is a busy road!

STOP 14. Folds in the Waits River Formation on Route 63, Berlin (694180 E, 4893160 N)

This stop is a good place to see how the style of deformation in the limestone contrasts with deformation in the metapelite of the Waits River Formation. Bed-parallel foliation defined largely by aligned quartz is present as thin laminations in the impure limestone (fig. 5). This fabric is not tectonic, but rather diagenetic (Passchier and Trouw, 2005) as there are no axial planar folds associated with the alignment of these grains which are deformed by the first period of folding recognized in these rocks (F3, Acadian F1). These laminations are, therefore, considered primary (S0) with enhancement due to subsequent recrystallization and growth of metamorphic minerals.

F3 (Acadian F1) folds are well preserved in the limestone (fig. 5A). The folds deform bedding laminations in the limestone but are generally invisible in the slate (fig. 5B). Deformation in the slate is dominated by the S3 (Acadian S1) slaty cleavage here (S3; fig. 5A, B), however, the folds can be seen in thin section (fig. 5C). Bain (1931) and Ern (1963) called the folds in the limestone "flow" or "flowage" folds, because they clearly exhibit plastic deformation typical of calcite marbles at greenschist facies conditions. The contact between limestone and slate also exhibits slip parallel to Acadian S2 (S4). The S4 cleavage is not developed in the limestone in the photograph (fig. 5B), but is locally well-developed in the limestone just above the location of the photograph (fig. 5A).

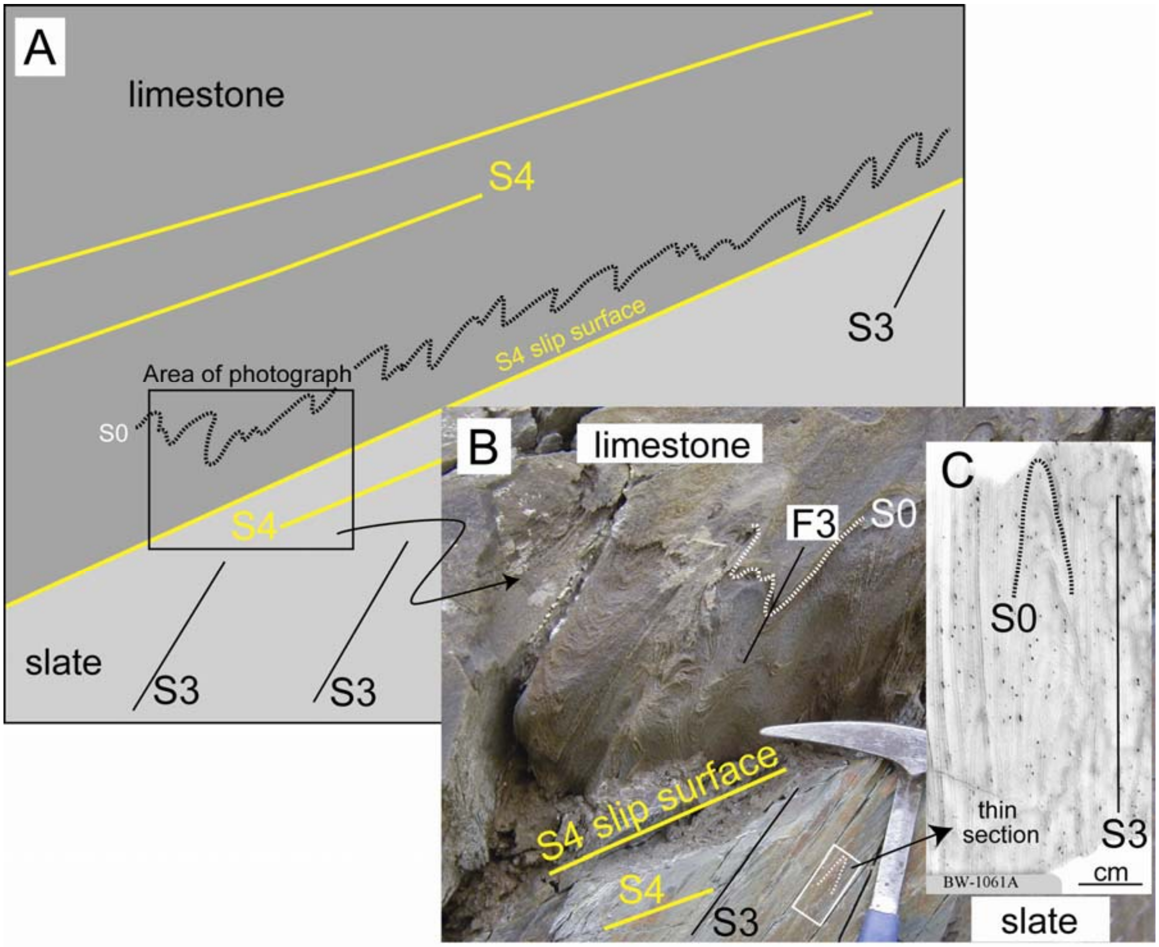

Figure 5. Sketch (A), photograph (B), and photomicrograph (C) of outcrop at Stop 14. White rectangle on the photograph (B) shows the location of the photomicrograph (C).

END OF TRIP

If you parked your car at The Montpelier Park & Ride at Exit 8, proceed straight to the Interstate and get on I-89 North. The interchange just to our west is Exit 6.

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