

CURRENT RESEARCH IN STRUCTURE, STRATIGRAPHY, AND HYDROGEOLOGY IN THE CHAMPLAIN VALLEY BELT OF WEST- CENTRAL VERMONT

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INTRODUCTION

Over the past four years, the Vermont Geological Survey and professors and undergraduate students from the University of Vermont, Middlebury College, and SUNY at Plattsburgh geology departments have formed a multidisciplinary fractured bedrock consortium. This consortium integrates varying expertise and resources to comprehensively address applied geologic issues in Vermont, such as groundwater quality (i.e. radionuclides, arsenic, nitrates, fluoride, and manganese), groundwater quantity of domestic and public wells, groundwater-surface water interaction, and shallow geothermal energy. The purpose of this trip is to visit field sites in the Champlain Valley Belt of west-central Vermont that illustrate our group's current research efforts in fractured bedrock hydrogeology. At each site, we will discuss how structural geology, stratigraphy, and hydrogeology (including geophysical well logging) bear on a specific environmental issue. This trip will not only visit classic sites such as the Champlain Thrust at Lone Rock Point and the Hinesburg Thrust at Mechanicsville, where we will discuss refined structural chronologies, but also locations that exhibit a strike-slip fault zone in the Winooski River Spillway (Williston), a well-described wrench fault site in Shelburne, phosphorite layers that explain elevated radioactivity in the bedrock aquifer (Milton), and a site in Hinesburg where field mapping of fractures has been correlated with those in geophysical logs. The following Bedrock Geology of Vermont, Field Area Geology, Structural Geology, Metamorphism, and Geochronology sections are modified from Kim et al. (2011).

BEDROCK GEOLOGY OF VERMONT

Vermont can be divided into several north-northeast trending bedrock belts of generally similar age and tectonic affinity (Figure 1). From west to east the belts are;

- 1) Champlain Valley: Cambrian – Ordovician carbonate and clastic sedimentary rocks deposited on the eastern (present coordinates) continental margin of Laurentia (e.g., Stanley and Ratcliffe, 1985). This continent was left behind after the Rodinian supercontinent rifted apart during the Late Proterozoic and the intervening Iapetus Ocean formed between it and Gondwana (e.g., van Staal et al., 1998). The margin was deformed and weakly metamorphosed during the Ordovician Taconian Orogeny. It was deformed again during the Devonian Acadian Orogeny.
- 2) Taconic Allochthons: Late Proterozoic- Ordovician slices of clastic metasedimentary rocks of oceanic and continental margin affinity that were thrust onto the Laurentian margin (Champlain Valley Belt) by arc-continent collision during the Taconian Orogeny (e.g., Stanley and Ratcliffe, 1985).
- 3) Green Mountain: Late Proterozoic–Cambrian rift- and transitional rift-related metasedimentary and meta-igneous rocks that unconformably overlie Mesoproterozoic basement rocks. These assemblages were deformed and metamorphosed during the Taconian Orogeny (also during the Acadian Orogeny) (e.g., Thompson and Thompson, 2003).
- 4) Rowe-Hawley: Metamorphosed continental margin, oceanic, and suprasubduction zone rocks of Late Proterozoic-Ordovician age that were assembled in the suture zone of the Taconian Orogeny. These rocks also were deformed and metamorphosed during the Acadian Orogeny. Arc components are part of a Shelburne Falls Arc that collided with the Laurentian margin, causing the Taconian Orogeny (Karabinos et al., 1998). Recent detrital zircon work by McDonald et al. (2014) indicates that the Moretown Formation, the central member of the Rowe-Hawley Belt, had a Gondwanan rather than Laurentian source.
- 5) Connecticut Valley: Silurian and Devonian metasedimentary and metaigneous rocks deposited in a post-Taconian marginal basin. Tremblay and Pinet (2005) and Rankin et al. (2007) suggested that this basin formed from lithospheric extension associated with post-Taconian collisional delamination processes. These rocks were first deformed and metamorphosed during the Acadian Orogeny.
- 6) Bronson Hill: Ordovician metaigneous and metasedimentary rocks of magmatic arc affinity and the underlying metasedimentary rocks on which the arc was built (e.g., Stanley and Ratcliffe, 1985). Recent studies show that this is a composite arc terrane with juxtaposed components of Laurentian and Ganderian/ Gondwanan arc affinity (e.g., Aleinikoff and Moench, 2003; Aleinikoff et al., 2007; Dorais et al., 2008; 2011). Accretion of the arc terranes onto the composite Laurentia occurred during the latest stage of the Taconian Orogeny and Silurian Salinian Orogeny (van Staal et al., 2009).

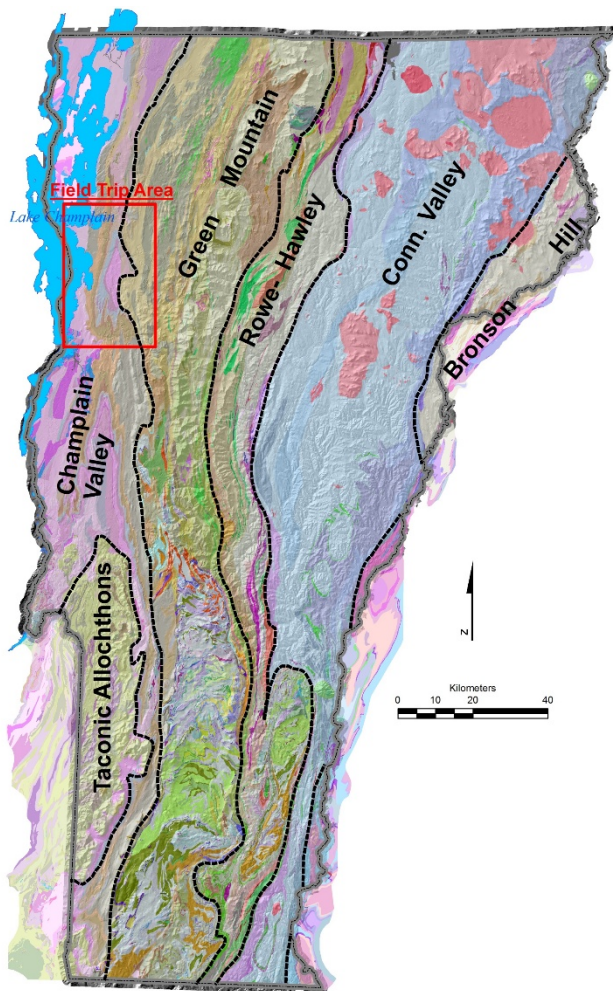


Figure 1. Tectonic belts in Vermont. Modified from Ratcliffe et al. (2011).

FIELD AREA GEOLOGY

The field area for this trip encompasses the western part of the Green Mountain Belt and the Champlain Valley Belt (Figure 1). These belts represent the foreland and western hinterland of the Taconian Orogen of west-central Vermont respectively (e.g., Stanley and Wright, 1997). This region can be divided into three lithotectonic slices which are, from west to east and from structurally lowest to highest: A) the Parautochthon, B) the Hanging Wall of the Champlain Thrust, and C) the Hanging Wall of the Hinesburg Thrust (Figure 2). The Champlain Thrust forms the tectonic boundary between A and B, whereas the Hinesburg Thrust separates B and C. The Parautochthon is primarily comprised of shales of the Stony Point Formation (note that the Iberville Formation shale is “lumped” with those the Stony Point Formation), representing Taconian flysch, but also contains normal fault- bounded carbonates of the informally-named Charlotte “Block”. These lithotectonic divisions are shown on the map in Figure 2 and can be interpreted from the tectonostratigraphic cross section in Figure 3. It is worth noting that the next lithotectonic unit to the west is the autochthon of eastern New York State, where Mesoproterozoic metamorphic rocks of the Adirondacks are unconformably overlain by

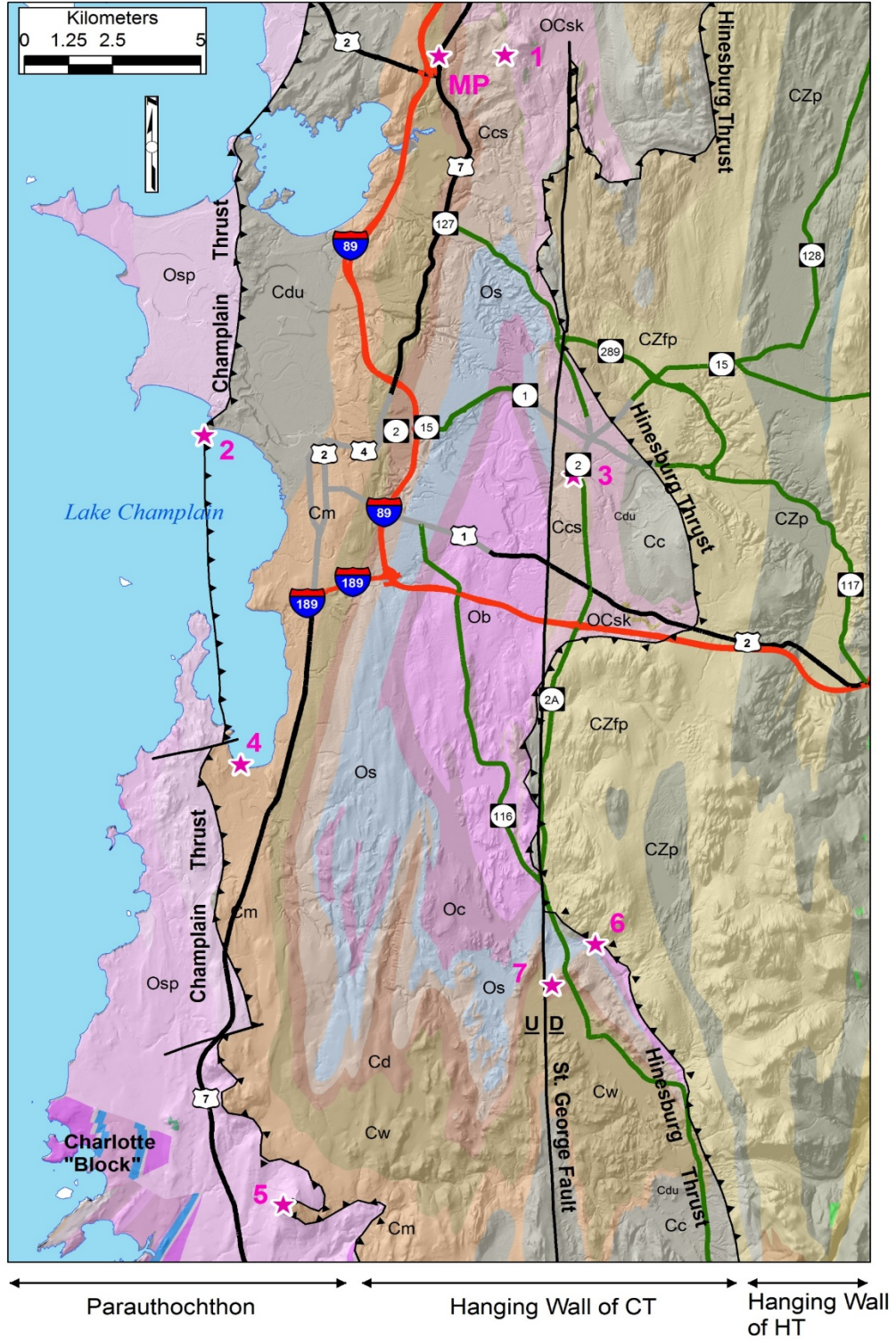


Figure 2A. Bedrock geologic map of the field area showing stop locations. MP = meeting place. Modified from Ratcliffe et al. (2011).

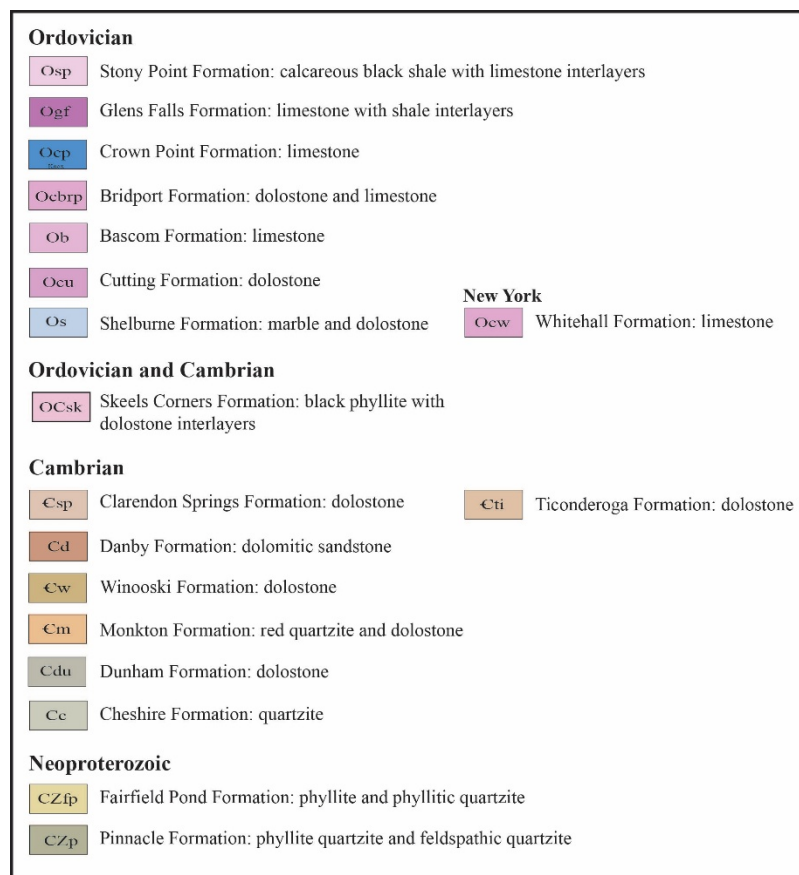


Figure 2B. Lithologic units for the map in Figure 2A.

Lower-Middle Ordovician sedimentary rocks of the Beekmantown Group (Isachsen and Fisher, 1970). There is a major unnamed Ordovician thrust fault in Lake Champlain that separates the Parautochthon from the Autochthon. To the north, Fisher (1968) called this the Cumberland Head Thrust. Although these slices were originally juxtaposed during the Ordovician Taconian Orogeny, subsequent deformation occurred during the Acadian (Devonian) and possibly later orogenies (e.g., Stanley and Sarkisian, 1972; Stanley, 1987).

Stratigraphy of the Lithotectonic Slices

The stratigraphy of the field area has been described in detail by Cady (1945), Doll et al. (1961), Welby (1961), Dorsey et al. (1983), Gilespeie (1983), Stanley (1980;1987), Stanley and Sarkisian (1972), Stanley and Ratcliffe (1985), Stanley et al. (1987), Stanley and Wright (1997), Mehrrens (1987; 1997), Landing et al. (2002), Thompson et al. (2003), Landing (2007), Kim et al. (2007; 2011, 2014b), and Gale et al. (2009). The legend in Figure 2B summarizes the lithologies for the map in Figure 2A. More detailed lithologic information is available for each individual stop in the road log. The reader is also encouraged to consult the above references for further information.

Figure 3 shows the tectonostratigraphy of each of the lithotectonic slices in the field area from west (left) to east (right). It is immediately apparent from west to east that each slice cuts into

successively older rocks and, consequently, deeper structural levels. Below are descriptions of the tectonic affinity and lithologies in each slice:

A) Parautochthon

- 1) Stony Point Formation- Late Ordovician black shales with thin carbonate interlayers that were strongly deformed by the overriding Champlain Thrust. These rocks were interpreted as flysch by Stanley and Ratcliffe (1985) and Rowley (1982).
- 2) Charlotte "Block"- Late Cambrian – Late Ordovician carbonate sedimentary rocks deposited on the Laurentian continental margin. These rocks were offset by normal faulting, probably during Late Ordovician or later time. The basal dolostone formations in this sequence were assigned using New York State nomenclature to the Ticonderoga/ Whitehall/ Cutting formations by Welby (1961).

B) Hanging Wall of the Champlain Thrust- Early Cambrian – Middle Ordovician carbonate and subordinate clastic sedimentary rocks that were deposited on the Laurentian continental margin. Slivers of Ordovician formations are found between this slice and the Parautochthon.

C) Hanging Wall of the Hinesburg Thrust- Late Proterozoic rift clastic metasedimentary and metaigneous rocks associated with the initial opening of the Iapetus Ocean, including the Pinnacle (CZp) and Fairfield Pond (CZfp) formations. These rocks are overlain by Iapetan drift- stage clastic rocks (argillaceous quartzite and quartzite) of the Cheshire formation (e.g., Stanley, 1980; Stanley and Ratcliffe, 1985). There are smaller lithotectonic packages of rocks that are caught between C and B, represented by the foot wall anticline in Figure 3.

STRUCTURAL GEOLOGY

Thrusts

In the field area, the Champlain Thrust juxtaposes the basal dolomitic member of the Middle Cambrian Monkton Quartzite with the Late Ordovician Stony Point Shale. North of the field area, the Champlain Thrust cuts down section ~2000' into the Lower Cambrian Dunham Dolostone (at Lone Rock Point in Burlington) (Stanley, 1987). Between Burlington and the Quebec border, this thrust generally follows the base of the Dunham Dolostone and then becomes the Rosenberg Thrust in southern Quebec (e.g., Sejourne and Malo, 2007). South of the field area, the Champlain Thrust can be mapped continuously at the base of the Monkton Quartzite to south of Snake Mountain near Middlebury, Vermont (e.g., Stanley and Sarkisian, 1972, Stanley, 1987). South of Snake Mountain, motion on the Champlain Thrust was probably taken up on structurally lower faults such as the Orwell Thrust (M. Gale, personal communication, 2011). Stanley (1987) suggested that total displacement on the Champlain Thrust is 55-100 km. (34-62 miles).

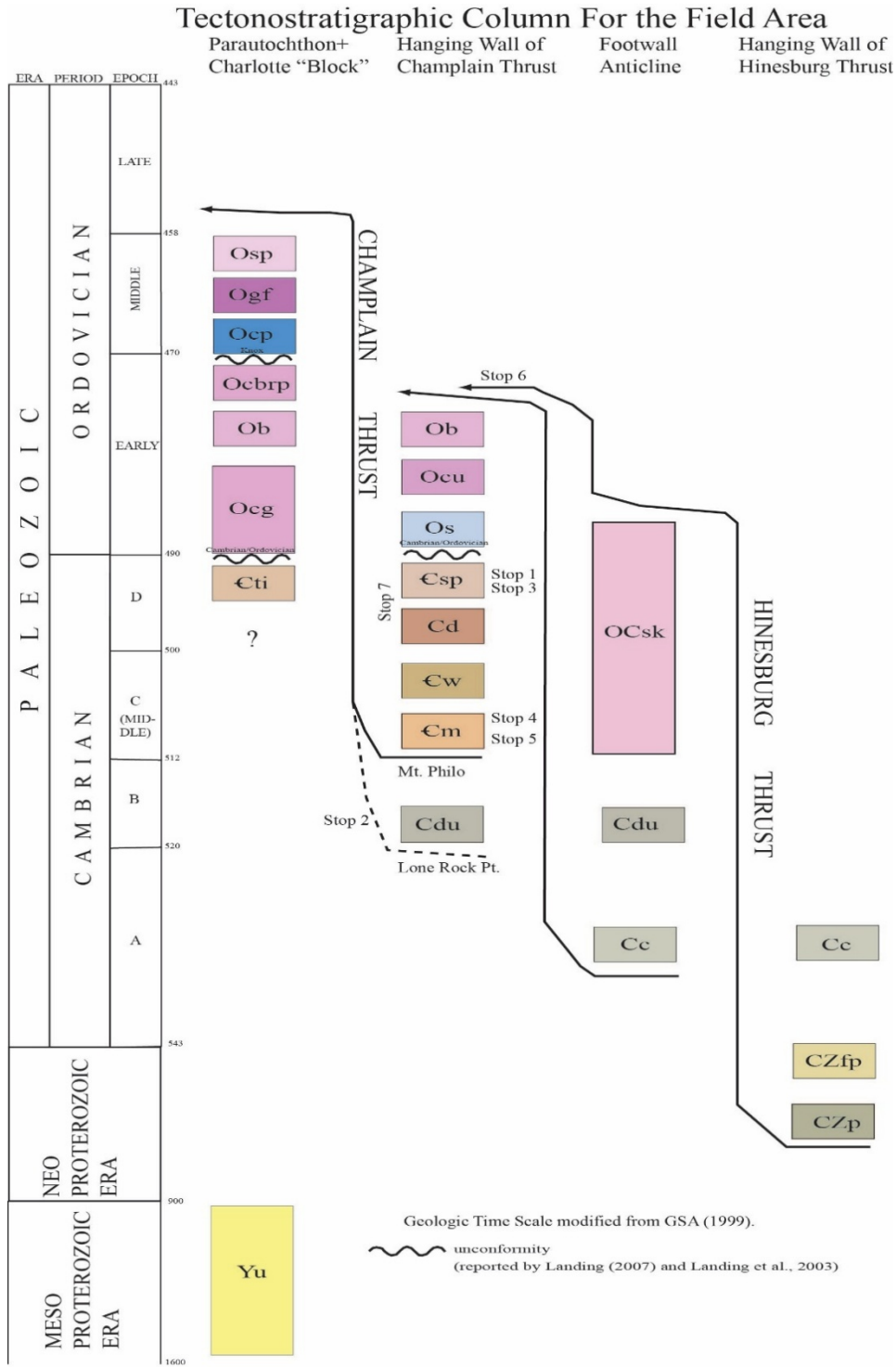


Figure 3. Tectonostratigraphic diagram of each of the lithotectonic slices in the field area from west (left) to east (right). Yu is in New York State.

In the field area, Late Proterozoic- Early Cambrian rift clastic to early drift stage metamorphic rocks of the Hanging Wall of the Hinesburg Thrust were driven westward over weakly metamorphosed sedimentary rocks of the Hanging Wall of the Champlain Thrust along the Ordovician Hinesburg Thrust. Dorsey et al. (1983) proposed that this thrust nucleated in an overturned fold/ nappe that ultimately sheared out along its axial surface. North and south of the field area, the Hinesburg Thrust appears to die out in large fold structures (Ratcliffe et al., 2011). For the southern extension of the Hinesburg Thrust, P. Thompson (personal communication, 2011) suggested that it may actually root in Precambrian basement in the northernmost basement massif. Kim et al. (2013, 2014c), based on mapping in the Bristol and South Mountain quadrangles, extended the Hinesburg Thrust southward into the Ripton Anticline, which is cored by Mesoproterozoic basement. Stanley and Wright (1997) suggested a total displacement of ~6.4 km. (4 miles) on the Hinesburg Thrust.

If the Hinesburg and Champlain thrusts represent a typical foreland-propagating (westward in this case) scenario (e.g. Boyer and Elliot, 1984?), then the Hinesburg Thrust should predate the Champlain Thrust. However, because map-scale fold structures (Hinesburg Synclinorium) in the Hanging Wall of the Champlain Thrust were truncated by the Hinesburg Thrust, it is possible that the first motion on the Champlain Thrust predated that on the Hinesburg Thrust (e.g., Doll et al., 1961; Gale et al., 2010). Alternatively, it is plausible that a second episode of motion on the Hinesburg Thrust truncated part of the Hinesburg Synclinorium. Another scenario proposed by Stanley and Sarkisian (1972) and P. Thompson (personal communication, 2011) suggested that the Champlain Thrust moved a second time after formation of the Hinesburg Thrust, partly on the basis of its metamorphic history (described below). The detailed structural history of the Hinesburg Thrust has been discussed by Gillespie (1975), Dorsey et al. (1983), Strehle and Stanley (1986), and is further described in Stop 6 of the Road Log. Descriptions of the deformational history of the Champlain Thrust can be found in Stanley and Sarkisian (1972), Stanley (1987) and in West et al. (2011).

Regional Trends

From the edge of Lake Champlain eastward across the Champlain and Hinesburg thrusts, several regional trends are evident. Nearest the lake, mostly brittle deformation is prevalent and includes blind normal faults (Figure 4a). Farther east, in the hanging wall of the Hinesburg Thrust, mostly ductile deformation, including superposed folds sets, transposed cleavages, and ductile shear bands (Figure 4f) are dominant. The outcrops on this trip exhibit an interesting interplay between ductile and brittle styles of deformation. This interplay has generated a spectacular variety of mesoscopic (outcrop scale) structures. These include many different types of sense of shear indicators that provide a wealth of information on the slip history of two thrusts, as well as the several phases of deformation that predate and postdate thrust faulting.

In addition to changes in the overall style of deformation, the variety of structures preserved along the transect collectively record a first-order increase in finite strain toward the east, with local maxima occurring within a few hundred meters of both the Champlain and Hinesburg thrusts. In the foot wall of the Champlain Thrust/ Parautochthon, F_1 folds of bedding planes (S_0) tighten as their axial planes rotate from steep and moderately east-dipping to shallowly east-dipping (Figures 4b, 4c). The styles and mechanisms of these folds also change from localized fault-bend folds several kilometers below the thrust (Figure 4b), to penetrative fold trains that formed by a combination of interlayer slip and ductile flow near the thrust (Figure 4c). The appearance of two cleavages reflects this increase in finite strain. These include an early

penetrative slaty cleavage (S_1) that formed during F_1 folding and a second localized pressure solution cleavage (S_2) that marks the presence of intraformational thrusts (Figure 4b). A similar increase in strain occurs near the Hinesburg Thrust. In the east-central part of the field area, a faulted anticline lies structurally below the Hinesburg Thrust. Here, isoclinal intrafolial folds of bedding (S_0), stretched pebbles and disarticulated compositional layers reflect a generally high magnitude of finite strain. Where the Hinesburg Thrust is exposed at Mechanicsville, even higher strains are recorded in mylonitic rock of the Cambrian Cheshire Formation.

Another interesting regional trend is the influence of rock type on the style and partitioning of deformation within the section. In general, deformation associated with the emplacement of the two major thrust sheets is expressed differently in competent units than it is in the weaker shales. For example, variations in the thickness and abundance of competent limestone layers have produced distinctive fold styles. In the shales, ductile flow during contraction resulted in recumbent isoclinal folds that became rootless at high strains. In contrast, thick competent limestone layers deformed mostly by interlayer slip, resulting in large inclined folds, preserve numerous *en echelon* vein sets. A similar pattern exists at the regional scale where most of the deformation that accompanied the formation of the Champlain Thrust is partitioned into the weak Stony Point Shales in the footwall. In this latter locality, the deformation is widely distributed. In contrast, deformation in the thick, competent quartzite layers of the Monkton Formation in the hanging wall tends to be more localized and mostly involves interlayer slip (Figure 4d).

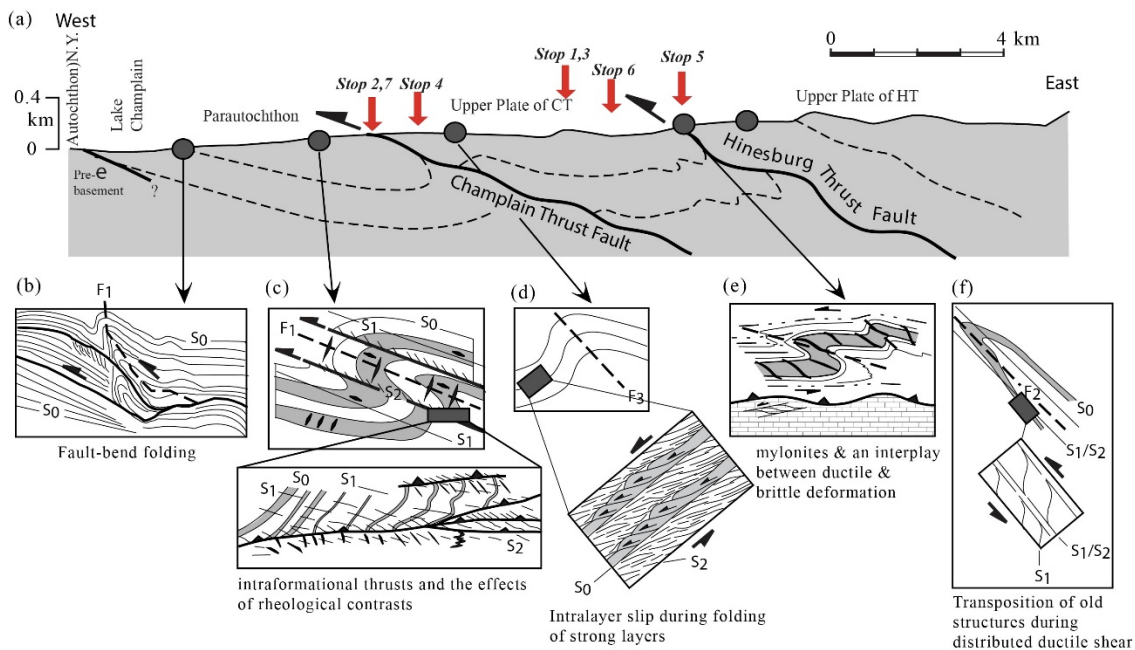


Figure 4. Simplified diagram showing the regional structural trends from west to east.

This influence of lithology and rheological contrasts on structural style also has resulted in many different types of kinematic indicators throughout the section. At Stop 6, competent metapsammite layers located above the Hinesburg Thrust (Figure 4e) preserve asymmetric vein sets and folds that record a top-to-the-northwest sense of shear. In the weaker pelitic layers it is recorded mostly by shear band cleavages. Although these structures generally show similar

top-to-the-west and –northwest senses of motion, the wide variety of types reflect different starting materials. These and many other examples illustrate one of the basic principles of interpreting the great variety of structures observed along this transect: differences in the strength and rheology of the rock units as they deformed can explain much of the great variety of structures observed in the Champlain Valley and in the lithotectonic slices to the east.

Since brittle structures, with the exception of normal faults, are not portrayed on Figure 4, we will give a brief summary of the characteristics of the dominant fracture sets. Fractures that have strikes orthogonal to the dominant planar fabrics (E-W to NE-SW) and steep dips are common throughout the field area. Since Cretaceous dikes intruded along many of these fractures, we know that these fractures are at least Cretaceous in age. Some fracture sets have north-south strikes with moderate-steep dips and can sometimes be associated with fracture cleavages associated with late generation folding (Figure 4C). NW-SE trending steep fractures are also common, but are of uncertain origin. In the field area, detailed fracture data have been acquired in the towns of Williston (Kim et al., 2007), Charlotte (Gale et al., 2009), Bristol (Kim et al., 2013; 2014), and Hinesburg (Thompson et al., 2004); Kim et al., 2014; 2015)

METAMORPHISM

Stanley and Wright (1997) summarized that the Taconian foreland rocks of the Parautochthon and Hanging Wall of the Champlain Thrust are “essentially unmetamorphosed” (p. B1-1) with temperatures of ~200°C and pressures corresponding to depths of ~2.5 km. Stanley and Sarkisian (1972) and Stanley (1974) reported prograde chlorite in fractures in the Monkton Formation in the Upper Plate of the Champlain Thrust, and used this occurrence to suggest that this thrust underwent multiple episodes of motion.

On the basis of field and petrographic observations presented by Strehle and Stanley (1986), Stanley et al. (1987), and this volume (Stop 6), the metamorphic rocks from the westernmost Taconian hinterland (Hanging Wall of the Hinesburg Thrust), reached biotite grade. In the field area, there is a pronounced metamorphic contrast between the rocks above and below the Hinesburg Thrust.

GEOCHRONOLOGY

There are few igneous crystallization or metamorphic ages from the field area. Cretaceous lamprophyre dikes have been reported throughout the field area by (McHone (1978), McHone and McHone (1999), and Ratcliffe et al. (2011) that intruded fractures and foliations. The dikes are likely correlative with the Barber Hill stock in the Town of Charlotte, which has been dated at 111 +/- 2 Ma (K/Ar biotite age; Armstrong and Stump, 1971). A whole rock Rb-Sr isochron age of 125 +/- 5 Ma on seven trachyte dikes from the Burlington area was reported by McHone and Corneille (1980), and probably provides an upper limit on the age of these dikes.

Rosenberg et al. (2011) used the K/Ar method to obtain cooling ages of illites from the fault zone of the Champlain Thrust at Lone Rock Point in Burlington. The ages obtained range from Carboniferous (~325 Ma) to Late Jurassic (~153 Ma). These authors speculated that post-Taconian illite growth may reflect fluid flow associated with the Alleghenian Orogeny and the Jurassic-Cretaceous unroofing of the Adirondacks and New England (e.g., Roden-Tice, 2000; Roden-Tice et al., 2009).

The ages of first motion on the Champlain and Hinesburg thrusts in the field area are weakly constrained by the youngest stratigraphic ages of rocks located below these faults. In the case of the Hinesburg Thrust, the age is Middle Ordovician (Bascom Formation, Ob) whereas for the Champlain Thrust it is Late Ordovician (Stony Point Shale).

PREVIEW OF APPLIED GEOLOGIC ISSUES

- Stop 1: Elevated naturally-occurring radioactivity levels in groundwater from Clarendon Springs Formation dolostones.
- Stop 2: Ductile and brittle structural history of the Champlain Thrust. Effect of structures and lithologies on groundwater flow and chemistry, respectively. High well yields in the hanging wall and lower well yields in the foot wall. Elevated fluoride in some foot wall wells.
- Stop 3: A newly-described strike-slip fault zone in the Clarendon Springs Formation and how it fits into the regional brittle structural history of the Champlain Valley Belt.
- Stop 4: Using a well-described wrench fault (and fracture site) as context for the regional brittle structural history of the Champlain Valley Belt.
- Stop 5: Overview of the Champlain Valley Belt.
- Stop 6: Elevated naturally-occurring radioactivity levels in groundwater from wells completed in the hanging wall (Pinnacle, Fairfield Pond, and Cheshire formations) or drilled through the Hinesburg Thrust. High well yields in the foot wall and low yields in the hanging wall.
- Stop 7: Integration of bedrock mapping with geophysical logging to understand the hydrogeology of a fractured bedrock well field in the Town of Hinesburg.

FIELD GUIDE AND ROAD LOG

Meeting Point: **Colchester Park and Ride Lot**- On the east side of Route 7, 0.3 miles north of the intersection of the intersection of Route 7 and Route 2 off Exit 17 (Champlain Islands-Chimney Point) on Interstate 89 in Colchester (at the VTRANS Maintenance Facility).

Meeting Point Coordinates: 44° 35.710' N, 73° 09.977' W

Meeting Time: 8:30 AM

Cumulative (miles)	Point to Point	Route Description
0.0	0.0	From parking lot, turn left onto Rt. 7 South
0.3	0.3	Continue on Rt. 7 through intersection of Rt. 2
1.3	1.3	Turn left onto Coon Hill Road
1.9	1.9	Turn right onto Galvin Hill Road
2.5	2.5	Turn left onto Tuckaway Pond Lane private drive and continue about 0.25 miles to destination.

Stop 1: Elevated Radioactivity in Groundwater from the Clarendon Springs Formation, Milton, Vermont

Location Coordinates: 44° 35.735' N, 73° 08.561' W

Introduction

Elevated radionuclide levels were reported in groundwater from ~30% of bedrock wells tested in the Clarendon Springs Formation in the towns of Colcheser Quadrangle.

Lithology

Massive gray dolostone of the Late Cambrian Clarendon Springs Formation.

Structure

The Muddy Brook Thrust (MBT), which is described below, is located in the valley to the east. In this area, the dominant fracture set strikes NE, dips steeply, and is associated with cross faults that offset the MBT and lithologies on both sides (Kim and Thompson, 2001).

Tectonic/Stratigraphic Context

This site is at the north end of the Hinesburg Synclinorium. The shallowly east- dipping MBT carried black phyllites with thin dolostone interlayers over the Clarendon Springs Formation dolostones during the Taconian Orogeny. The MBT is west of and probably synchronous with the Hinesburg Thrust (Kim and Thompson, 2001).

Hydrogeology and Groundwater Geochemistry

Groundwater produced from the Clarendon Springs Formation in Milton and Colchester is known to contain elevated uranium, radium, and alpha radiation. Radioactivity is high enough

that the average alpha radiation from 131 domestic bedrock wells tested in a 12 km² area is 32 picocuries per liter (pCi/L), and 22 % of these wells produce concentrations of alpha radiation above the EPA's maximum contaminant level (MCL) of 15 pCi/L; furthermore, the three most contaminated wells, which occur within a kilometer of each other, average 841 pCi/L. Dark grey to black phosphorites (with 7 to 37 % P₂O₅) occur throughout the region that contains elevated radionuclides in well water; in outcrop, these phosphorites occur in two main forms: (1) subangular, pebble-sized clasts in a dolostone matrix, sometimes with imbricated clasts that suggest deposition from a current, and (2) wispy beds of dark grey phosphorite (possibly "hardground"). Breccias are more common than wispy sedimentary layers, and both indicate that the concentrated phosphate is syndepositional in origin. McDonald (2012) cited a model involving upwelling sea water and reducing biochemical conditions as factors responsible for deposition of phosphorite with elevated U.

Rock samples collected from outcrops located upgradient of the most highly contaminated wells exhibited the following: (1) the phosphorites contain 80 to 430 mg/kg uranium while the dolostone matrix contains less than 10 mg/kg U; (2) the phosphorite mineral — as determined by powder XRD — is fluoroapatite, and trace amounts of autunite also occur in some phosphorites; (3) a gamma ray survey of a 160 m deep bedrock well documents the interbedding of U-rich phosphorite beds and dolostone beds throughout the Ccs in Milton-Colchester, perhaps alternating cyclically. U-rich phosphorites produce a gamma ray signal of 500 to 3400 cps whereas U-poor carbonates have a signal < 50 cps gamma radiation; and (4) SEM-EDS element maps (Bachman, 2015) show that phosphorite clasts and layers lacking significant post-depositional deformation contain the highest levels of uranium. SEM-EDS also indicates that U occurs in two broadly-defined mineralogical forms: (1) diffusely distributed U in cryptocrystalline fluoroapatite, and (2) perhaps more importantly, concentrated U in microcrystalline minerals (e.g. autunite, coffinite, brannerite) scattered throughout the phosphorite. This may suggest that uranium was initially substituted for Ca in fluoroapatite — during crystallization on the seafloor (consistent with literature reports)—, but then was incorporated into anhydrous secondary minerals when (at least some of the) fluoroapatite dissolved. This could have occurred any time from very early diagenesis to dolomitization. Weathering of pyrite may trigger U release by locally lowering pH — evidence for this is the occurrence of autunite [Ca(UO₂)₂(PO₄)₂·nH₂O] in rusty Fe hydroxide matrix at the boundary of weathered pyrite and adjacent, unweathered fluorapatite.

Cumulative (miles)	Point to Point	Route Description
2.5	0.0	Turn right onto Galvin Hill Road.
3.1	0.6	Turn left onto Coon Hill Road
3.8	0.7	Turn left onto Rt. 7 South
7.2	3.4	Turn right onto Rt. 127 (Blakely Road)
9.5	7.0	You will pass Colchester Middle School on your right.
9.9	7.4	You will see Mallets Bay on the right.
10.9	8.4	Turn left onto Prim Road (extension of Rt. 127)
12.1	9.6	Continue straight through intersection of Marce Road
13.1	10.6	At the fork in the road, bare left to the stoplight.
15.0	12.5	Take Rt. 127 to exit for North Avenue Beaches on the right.
15.4	12.9	Follow ramp to the T, and turn left onto North Avenue.
15.8	13.3	Turn right onto Institute Road at Burlington High School
16.0	15.5	Turn right into Rock Point into Rock Point Episcopal Center
16.2	15.7	Park in lot on the right.

Stop 2: Champlain Thrust at Lone Rock Point

Location Coordinates: 44° 29.441' N, 73° 14.931' W

Introduction

This stop description was modified from West et al. (2011). The Champlain thrust fault at Lone Rock Point is arguably the iconic geologic feature in Vermont and perhaps the finest thrust fault exposure in eastern North America. The “older-on-top-of-younger” relationship exposed here is a fundamental indicator of thrust faulting. Hitchcock et al. (1861) was the first to recognize that the contact relationships exposed at Lone Rock Point are the result of major regional faulting.

Lithology

Early Cambrian massive dolostone of the Dunham Formation structurally overlies Late Ordovician Iberville Formation black shales (Figure 5).

Structure

An interesting feature at Lone Rock Point is the interplay between **brittle deformation and ductile flow** mechanisms. Brittle deformation involves the breaking of material along discrete surfaces, which can be fractures, veins or, if they accommodate slip, faults. These two styles are not completely independent of one another, and commonly occur together to accommodate shortening. The material type and the conditions under which deformation occurs typically dictates the types of deformation processes. As such, the type of parent lithology (what type of rock was present prior to deformation) is a critical influence on style of deformation. At Lone Rock Point two significantly different rock types are juxtaposed with the strong Dunham dolostone thrust above the weak Iberville shale (Fig. 5A). Deformation is not restricted to slip along the fault plane, and can be divided into two domains as described by Stanley (1987). These are composed of an inner fault-zone including the fault surface at the base of the Dunham dolostone and a proximal region consisting of broken limestone and highly contorted shale. The outer fault-zone occurs in the Iberville Shale and consists of a high concentration of veins,

subordinate faults, and tightly folded compositional layering. By recognizing various features within both the Iberville Shale and the Dunham dolostone we can establish various mechanisms of deformation and compare the way these two units accommodate shortening. For this reason, the exposure of the Champlain Thrust fault at Lone Rock point is an excellent location to teach fault-zone processes and the influence of material properties on deformation.

The following sections briefly describe key features that document deformation styles and the motion history of Lone Rock Point.

Structural Slickenlines. The basal surface of the Dunham Formation is the slip surface on which a significant amount of displacement has occurred. This surface contains corrugations referred to as fault mullions with wavelengths on the order of half a meter. These features, as depicted in Figure 8 can form with crest lines parallel to the motion of the fault and, therefore, can help constrain motion direction. In addition to fault mullions, striations can occur from the scraping and gouging of the fault surface by resistant objects. These also help constrain the motion of the Champlain Thrust fault (Figure 5B).

Original Bedding. Despite the highly deformed nature of the Iberville Formation, compositional layering is visible as resistant quartz rich layers. These layers are frequently folded and faulted into small isolated pods surrounded by soft clay rich rock. Although dolostones of the Dunham Formation are massively bedded, depositional surfaces are intact and relatively undisturbed (Figure 5A).

Veins and Mineral Slickenlines. Veins form from the deposition of material from solutions that fill voids in rocks. The calcite veins at Lone Rock Point display complex geometries, including folding, faulting, and shearing. The shear veins, in particular, can be good indicators of the motion history of deformation and frequently form lineated surfaces known as mineral slickenlines. The formation of mineral slickenlines generally involves the infilling of void space with material created by offsets on the fault surface (Figure 5C).

Cleavage. Cleavage planes are formed from the preferential alignment of mineral grains due to flattening, which is accommodated by dissolution and the removal of soluble material. Cleavage is common in shales of the Iberville Formation, and are generally oriented at low angles to the fault surface. However, as the distance increases away from the fault, the orientation of cleavage planes tends to steepen. This rotation of cleavage planes can be used to infer the sense of motion on the thrust surface.

Fractures. Unlike the intensely deformed Iberville Formation, massive dolostones of the Dunham Formation are relatively intact and show little evidence of internal deformation (i.e., no visible cleavage). However, fractures (breaking of the rock along discrete planes without differential motion), are common in this more competent unit. New fracture data will be presented for the hanging wall.

Subordinate Faults. Many small scale faults can be observed within the footwall rocks of the Iberville Formation that offset folds, cleavage, and veins. These faults do not continue into structurally overlying dolostones of the Dunham Formation. These small scale faults in the Iberville tend to rotate into the direction of the fault motion with proximity to the fault (Stanley, 1987). Because the Champlain thrust fault at Lone Rock Point contains numerous features that help constrain the transport direction along the fault plane, an exercise can be constructed to identify as many of the features that contain motion information (i.e. fault

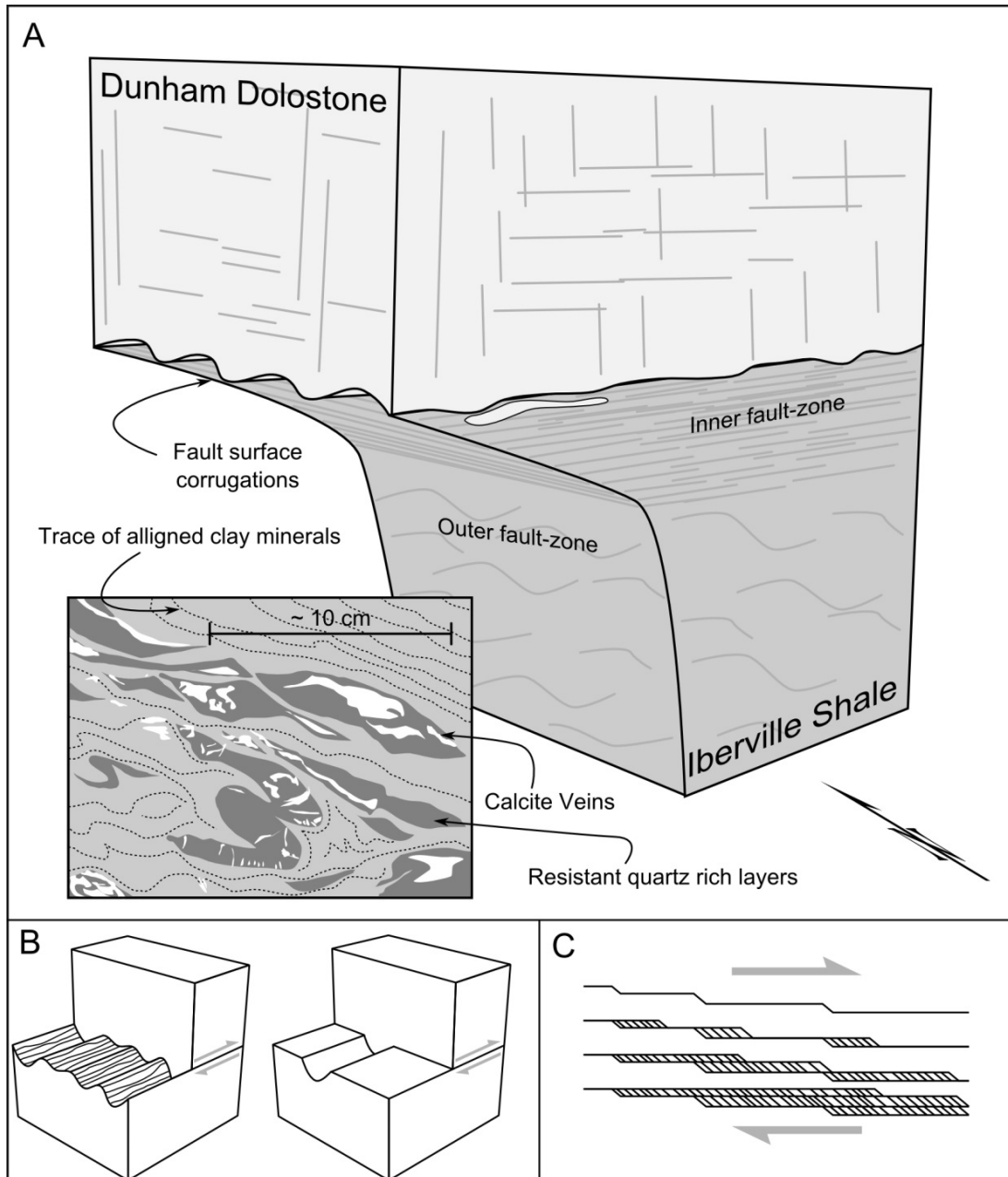


Figure 5. Sketches showing the general geometry of features observed at the Champlain Thrust fault at Lone Rock Point. (A) Block diagram of the Champlain Thrust fault with the resistant Dunham Formation (massive dolostones) above the weak Iberville Formation (calcareous shales). The fault-zone is divided into two domains consisting of the inner fault-zone and the outer fault-zone. The inset sketch depicts the relationships between folded and faulted quartz-rich layers (dark gray), clay rich shale material (light gray), alignment trajectories of clay minerals (dashed lines), and the geometries of calcite veins (white). (B) Block diagrams of two mechanisms of structural slickenline formation (modified from Means, 1987). The left diagram shows the formation of fault corrugations while the right diagram illustrates gouging caused by resistant material within the upper plate. (C) Formation of mineral slickenlines by the infilling of voids caused by steps within the fault surface.

mullions, gouges, and mineral slickenlines). These features generally indicate displacement and tectonic transport in a west-north-west direction. Teaching considerations include the following questions: How does the geometry of folded compositional layering change with proximity to the fault? How does the orientation of the dominant cleavage change with proximity to the fault surface? Is displacement constrained to slip along the fault surface only? What is the general temporal progression of deformational style using cross-cutting relations? What fundamental influence does the type of bedrock have on deformation style? These questions address the fundamental aspects of thrust faulting and the inherent relationship between initial lithology and deformation mechanisms.

New Work on Foot Wall Structures

The following has been modified from Strathearn et al. (2015). Although the Champlain Thrust has been studied previously at Lone Rock Point, the multiple generations of ductile and brittle structure in shales of the footwall have never been systematically defined. We present the following relative chronology of structures:

- 1) Formation of bedding planes (S_0), characterized by thin layers of carbonate within black shale.
- 2) Formation of rootless isoclinal folds (F_1) of brittle carbonate layers and the development of an spaced pressure solution cleavage (S_1) that parallels the axial planes of the folds.
- 3) The S_1 cleavage is deformed into asymmetric S-C shear bands that merge into parallelism with, and are cut by intraformational thrusts. The thrusts form oblate, eye-shaped structures that are stacked on top of one another forming thrust duplexes. A second cleavage (S_2) defines a part of the S-C fabric and is intensified in thrust zones. Calcite slickenlines on fault surfaces plunge to the SE and NW and slip directions fan up to 40 degrees with respect to one another in different thrust horses
- 4) Formation of sets of upright, north (F_3) and east-striking (F_4) folds of S_2 warping the CT.
- 5) Formation of conjugate sets of normal faults that record top-down-to-the-north and -south kinematics.
- 6) Formation of the steeply-dipping fracture sets (N-S and E-W striking) that cut across competent lithologies.

Hydrogeology and Groundwater Geochemistry

In a case study examined on this field trip (Hinesburg Thrust; Kim et al., 2014a), the hanging wall is sometimes responsible for producing groundwater with elevated radionuclides. In the case of the Champlain Thrust, the culprit is the footwall. Of 35 tests for fluoride (note: F can cause bone disease), 37 % (13/35) exceeded the Vermont recommended F level in public water systems (0.7 mg/L). [Relative to the EPA MCL of 4 mg/L, however, only 3/35 wells were above the F threshold]. Sodium is elevated in ~ 45 % of footwall wells (13/29) relative to EPA's 20 mg/L Drinking Water Equivalency Level (guidance level), and the average Na concentration in footwall wells (82 mg/L) is four times greater than the DWEL. Both issues are related to the behavior of illite in this black shale-influenced bedrock aquifer system. Regarding fluoride, diagenetic illites typically contain 0.2 to 0.5 % F in isomorphous substitution for OH (Thomas et al., 1977), so dissolution of illite or exchange of Cl^- or OH^- for F^- are potential F sources in groundwater.

Dissolution of apatite (4 % F) could also be a source, although it is far less abundant and likely less reactive than illite. Other potential F minerals (e.g. fluorite, titanite) are not likely F sources in this system. Regarding elevated Na, we observe a weak but positive correlation of Na and Ca in solution, an occurrence that likely relates to Na-Ca ion exchange. When Ca is released to solution upon weathering of calcite (nearly ubiquitous in these Ordovician black shales), the higher-charge, less-hydrated Ca^{+2} cation is more strongly attracted to cation exchange sites (e.g. on illite) than is Na^{+1} , and the exchange reaction releases Na^{+1} into solution. This also is cited as the cause of high Na in black slate-influenced wells of the Taconics of southwestern Vermont (Ryan et al., 2013). Another element worth noting in footwall wells of the Champlain thrust is arsenic, which exceeds 10 ppm in 3 % of wells tested for As and exceeds 5 ppm in 10 % of wells (3/29); by comparison, in Taconic slates, 22 % of bedrock wells (52/236) exceed 10 ppb and 24 % exceed 5 ppb. Deeper anoxia in the Taconic seaway relative to open-shelf Iberville and Stony Point shale depositional environments is likely the cause of greater amounts of pyrite and arsenic in Taconic black slates.

Cumulative (miles)	Point to point	Route Description
16.2	0.0	Turn left out of the parking lot, then follow Episcopal Center driveway.
16.4	0.2	Turn left onto Institute Road
16.6	0.4	Turn Right on North Avenue heading south. (BHS sports field should be on your right)
17.1	1.5	Turn left onto Sherman Street.
17.2	1.6	Turn right onto Park Street (127 South)
17.5	1.9	Continue straight through the intersection with College Street
17.8	2.2	Turn left onto Maple Street
17.9	2.3	Continue straight through the intersection with Pine Street
18.0	2.4	Turn right onto St. Paul Street.
18.8	3.2	Continue onto Route 7 South.
19.9	4.3	Take the ramp to the right for I-189 East.
21.4	5.8	Take the ramp to the right for I-89 South (Montpelier).
24.6	9.0	Take the ramp to the right for exit 12 (Williston and Essex).
26.8	9.2	Turn left at the light onto Route 2A.
27.1	9.5	Use the middle lane.
27.6	10.0	Continue through the intersection with Route 2
28.6	11.0	Continue straight through the intersection with Industrial Road on your left and Mtn View Road on your right.
29.7	12.1	Turn left into Overlook Park parking lot before the bridge.

Stop 3: Strike Slip Fault Zone in the Winooski River Gorge, Williston/Essex, Vermont

Location Coordinates: 44 ° 28.817' N, 73 ° 07.020' W

Introduction

The Winooski River flows through a bedrock gorge downstream of a hydroelectric dam at the Essex/Williston border. During bedrock mapping in the Town of Williston (Kim et al., 2007), it was observed that most of the bedrock channels were northeast-striking fracture intensification domains (FIDs). Further investigation revealed a more complicated scenario.

Lithology

Massive gray dolostone of the Late Cambrian Clarendon Springs Formation.

Structure

Preliminary mapping and analysis of the brittle structures in the Winooski River Gorge reveals that the river channels are northeast-striking and steeply-dipping fracture intensification domains (FIDs) that are also strike-slip fault zones. Throughout the river gorge, these faults are intersected by steeply-dipping, north-northeast striking Riedel shear zones. Riedel shears usually form at a 10-20 degree angle to the main strike slip fault, in clockwise and counterclockwise directions, respectively, to right lateral and left lateral displacements (e.g. Twiss and Moores, 2006). The Riedel shears in this gorge are consistent with left lateral displacement on the main strike-slip faults.

Tectonic/Stratigraphic Context

This body of Clarendon Springs Formation is bounded to the east by the Ordovician Muddy Brook Thrust Fault and to the west by the presumed Mesozoic down-to-the-east St. George normal fault.



Figure 6. Northeast striking, steeply-dipping strike-slip fault zone in the Winooski River gorge.

Hydrogeology and Groundwater Geochemistry

Bedrock geochemical analysis indicates some interesting differences in Ccs composition here compared to the phosphorite-bearing localities in Milton-Colchester and Highgate (McDonald, 2012). P_2O_5 here in the Winooski gorge is $< 0.5\%$ whereas P_2O_5 ranges from to 7.4 to 36.9 % in phosphorite-rich dolostone and phosphorite layers or clasts. Uranium is also low in the Ccs in

the Winooski River gorge (1.3 to 8.3 ppm) relative to Milton-Colchester (where it reaches 432 ppm). No phosphorite clasts or layers are observed in the Winooski River gorge, explaining the low amounts of P and U at this locality. Geochemically-notable are two samples of black wispy clasts coated with Fe hydroxide that contain 120 and 283 ppm As (for comparison, As < 16 ppm at Milton-Colchester outcrops). These black wispy clasts occur in a dolomitic breccia, and yet while this facies appears similar in outcrop to some of the phosphorite occurrences at Milton-Colchester, the black wispy clasts in Winooski gorge contain < 0.5 % P₂O₅ and < 10 ppm U. In terms of major elements, the Winooski gorge Ccs black clasts are dominantly Si, Mg and Ca; otherwise, only elevated iron (5.7 and 10.1 % Fe₂O₃, respectively) and arsenic (120 and 283 ppm, respectively) are anomalous relative to other dolomitic Ccs rocks. One possible interpretation: if the black color is from mature organic matter, these wispy black clasts may represent an organic-rich shallow marine or subaerial layer that was incorporated into a cave breccia. The As-bearing Fe hydroxide is likely remnants of weathered disseminated pyrite.

The municipalities in the vicinity of Winooski gorge are part of the Champlain Water District and their drinking water is supplied from Lake Champlain. We know of no chemical data for bedrock wells in this area, so it is unknown how the composition of this belt of Clarendon Springs Formation may affect groundwater.

Cumulative miles	Point to point	Route Description
29.7	0.0	Turn Right out of parking lot onto Route 2A.
30.7	1.0	Continue straight through the intersection.
32.3	2.6	Take right turn onto ramp for I-89 North
32.5	2.8	Merge onto I-89 North
35.8	6.1	Take exit 13 (Shelburne and Burlington) for I-189
36.1	6.4	Continue onto I-189 West.
37.5	7.8	At the fork in the road, stay to the left.
37.5	7.8	At the stoplight, turn left onto Route 7 South.
40.4	10.7	Make a right turn onto Bay Road
41.4	11.7	Turn right into parking lot for the Shelburne Bay boat access.

Stop 4: Wrench Faults and Fractures at the Shelburne Boat Access, Shelburne, Vermont

Location Coordinates: 44 ° 24.035', 73 ° 14.083'

Introduction

This site was used by Rolfe Stanley of the University of Vermont as a teaching outcrop for his structural geology classes for decades and is currently used by Keith Klepeis. Stanley (1974) wrote a Geological Society of America Bulletin article that details the structural history of this site.

Lithology

Early Cambrian ferruginous quartzite of the Monkton Formation. Stanley (1974) reported that the quartzite at this site is composed of 93% quartz, 5% hematite, 1% microcline, and traces of zircon, plagioclase, detrital staurolite, and dolomite.

Structure

As outlined by Stanley (1974), there are three major structural features at this site, which are:

1) High – Angle Wrench Faults:

A) Generation 1 Northeast to west striking, moderately-steeply dipping faults (Figure 7).

B) Generation 2 North-northeast to north-northwest striking, steeply dipping faults that offset generation 1 faults (Figure 7).

2) En Echelon Fractures: Dextral and sinistral *en echelon* fracture arrays that are filled with quartz. The trend of the *en echelon* arrays corresponds to the strike of a particular fault. These arrays are only associated with the first generation of high angle faults (see fracture arrays on Figure 7).

3) Fractures: The four major fractures sets (contoured maxima) at this field site are: A) East-west striking, steeply north-dipping, B) North-south striking, steeply west-dipping, C) Northwest striking, steeply southwest-dipping, and D) Northeast striking, steeply northwest dipping. Set A is associated with the first generation wrench faults whereas sets B, C, and D overprint set A and are associated with the second generation wrench fault generation.

Tectonic/Stratigraphic Context

Stanley (1974) proposed that the east-west striking and steeply dipping wrench faults were related to the Shelburne Bay cross-fault, which offsets the Champlain Thrust. Both sets of wrench faults were presumed to be related to the Devonian Acadian Orogeny. Kim et al. (2011; 2014) described dome and basin fold patterns in the Champlain Valley Belt that were the result of the superposition of fold sets with steeply dipping ~north-south and ~east-west striking axial surfaces. Could the two sets of wrench faults and their associated fractures be related to these folding events?

Hydrogeology and Groundwater Geochemistry

We are using this study as a detailed context for fracture analysis throughout the Champlain Valley Belt. These brittle structures may influence groundwater flow in the bedrock aquifer.

Cumulative miles	Point to Point	Route Description
41.4	0.0	Turn left onto Bay Road.
42.4	1.0	Turn right onto Route 7 South (Shelburne Road).
49.2	7.8	Continue straight through the intersection with Ferry Road.
51.6	10.2	Turn left onto State Park Road.
52.2	10.8	Continue straight through the intersection into Mt Philo State Park.

Stop 5: Mount Philo State Park in Charlotte, Vermont

Location Coordinates: 44° 16.804' N, 73° 13.082' W

Introduction

This stop description, which was modified from Kim et al. (2011), is designed to give an overview of the four major tectonic zones in the Lake Champlain area of west-central Vermont and eastern New York, which are, from west to east, and from structurally lowest to highest: 1) Autochthon, 2) Parautochthon, 3) Hanging Wall of the Champlain Thrust, and 4) Hanging Wall of the Hinesburg Thrust. A major thrust fault separates the Autochthon from the Parautochthon on the west side of Lake Champlain.

Lithology

At the top of Mt. Philo, you are standing on the upper member of the Monkton Formation, which is a ferruginous quartzite. The lower dolomitic sandstone member of the Monkton Formation is exposed near the Champlain Thrust below.

The autochthonous rocks on the west side of Lake Champlain include Mesoproterozoic metamorphic rocks of the Adirondacks (see Yu in Figure 3) that are unconformably overlain by sedimentary rocks of the Beekmantown Group (Isachsen and Fisher, 1970). The Autochthon is structurally overlain by: 1) Late Cambrian- Middle Ordovician weakly-metamorphosed sedimentary rocks of the Parautochthon, 2) weakly- metamorphosed sedimentary rocks of the Hanging Wall of the Champlain Thrust; and 3) low grade (chlorite-sericite to biotite) rift clastic metasedimentary rocks of the Hanging Wall of the Hinesburg Thrust.

Structure

At this lookout, the Champlain Thrust is ~160' vertical feet (50 m.) below your feet, where the dolomitic lower member of the Monkton Quartzite is in tectonic contact with the Middle Ordovician Stony Point Shale. From Mt. Philo, one can see the geomorphic expression of this thrust to the south as the slope breaks (steep = Monkton and gentler = Stony Point) on Buck and Snake mountains, and to the north on Pease Mountain.

Tectonic/Stratigraphic Context

At the Lone Rock Point exposure of the Champlain Thrust in Burlington (e.g Stanley, 1987)(Stop 2), this thrust juxtaposes the Lower Cambrian Dunham Dolostone with the Iberville Shale; this suggests the presence of an along-strike ramp that climbs ~2000' (610 m.) up section between Burlington and Mt. Philo. The stratigraphic throw of the Champlain Thrust is ~9000' (2743 m.) at Lone Rock Point and ~6000' (1830 m.) at Mt. Philo (Stanley, 1987). Total displacement along the Champlain Thrust ranges from 34-62 miles (55-100 km.) (Stanley, 1987; Rowley, 1982).

Apatite fission track work by Roden-Tice (2000) indicates that the exhumation of the Adirondacks was complete by the Cretaceous. This uplift may have reactivated faults between the Champlain Valley and Adirondacks.

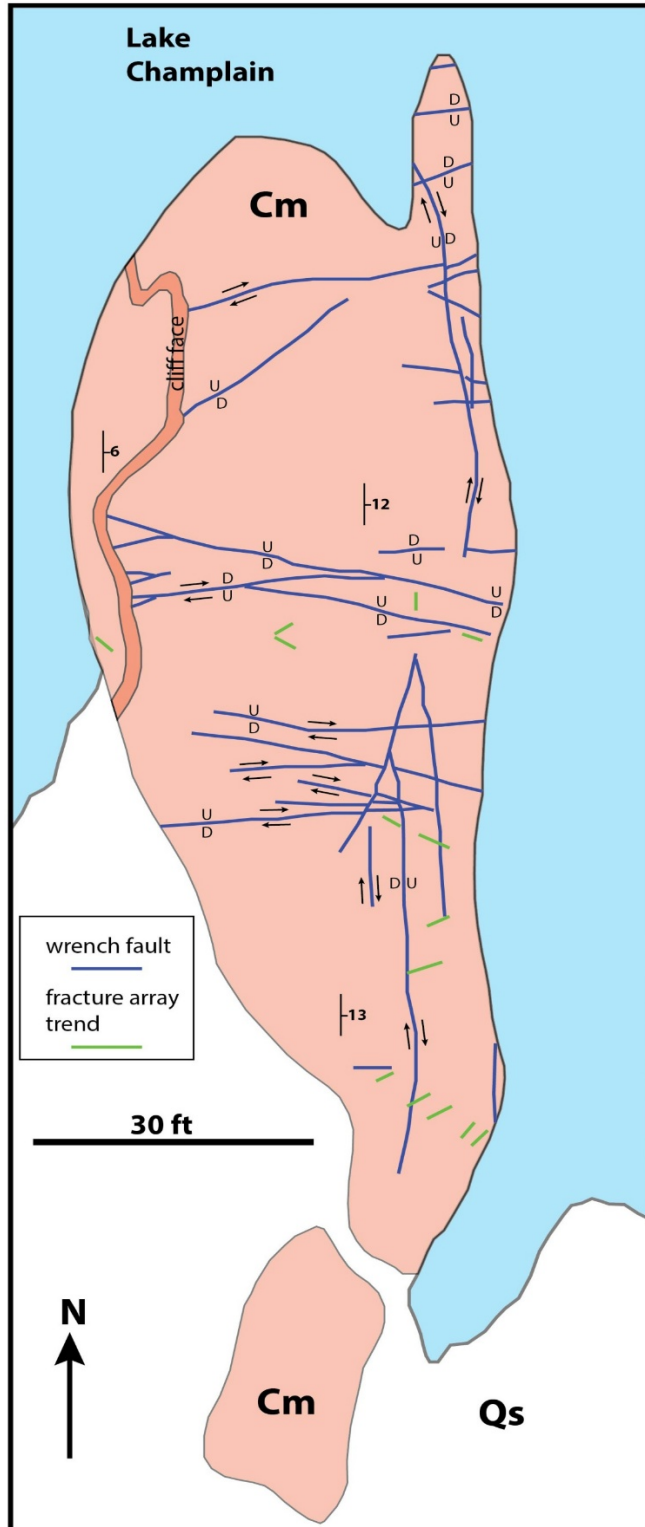


Figure 7. Brittle structure map of the Shelburne boat access. Modified from Stanley (1974). Cm = Monkton Formation quartzite and Qs = Quaternary surficial material.

Hydrogeology and Groundwater Geochemistry

Based on domestic well logs, average yields from the Monkton Formation in the Town of Charlotte are very favorable (Springston et al., 2010). Although we do not know of any bedrock groundwater wells that penetrate through the Monkton Formation into the underlying shales, Charles Welby (pers. Comm., 2009) said that numerous wells do. Such wells are often characterized by unpleasant amounts of hydrogen sulfide (rotten egg smell) gas. A Middlebury College student will be investigating the groundwater chemistry of the hanging and foot wall aquifers of the Champlain Thrust during 2015-2016.

Cumulative miles	Point to Point	Route Description
52.2	0.0	Turn right onto Mt Philo Road
54.7	2.5	Turn right onto Charlotte Road
56.4	4.2	Continue straight through the intersection with Spear Street Extension.
60.6	8.4	Turn left onto Route 116 N
60.8	8.6	Turn right onto Mechanicsville Road
61.7	9.5	Continue straight through intersection with Richmond Road.
62.3	10.1	Turn left onto Place Road East (a small gravel/dirt road)
62.4	10.2	Turn right onto an un-named road
62.5	10.3	Park on the right

Stop 6: Hinesburg Thrust at Mechanicsville, Vermont

Location Coordinates: 44° 21.126', 73 ° 06.472'

Introduction

Elevated radionuclide levels have been reported in groundwater from numerous bedrock wells completed in the Hanging Wall of the Hinesburg Thrust and drilled through this thrust (Kim et al., 2014a). This stop description was modified from Kim et al. (2011).

Lithology

The Hinesburg Thrust at Mechanicsville places overturned light green and gray metapsammitic schists and quartzites of the Early Cambrian Cheshire Quartzite (argillaceous member) on top of a slice of deformed dolomites, limestone and marble of the Ordovician Bascom Formation (Thompson et. al., 2004). The hanging wall rocks display a lower greenschist facies metamorphic mineral assemblage that includes chlorite, quartz, sericite, and biotite. The footwall is dominated by a chloritic and graphitic carbonate mineral assemblage, indicating that the Hinesburg Thrust is marked by an abrupt change in metamorphic grade as well as a change in lithology.

Structure

The thrust fault itself is defined by a narrow zone (<10 cm thick) of cataclastic dolomite at the top of the Bascom Formation (Figure 8). The dolomites below the fault are highly fractured and

sheared. Ductile shear bands (C' type) deform a penetrative phyllitic cleavage (S_1) up to at least a meter beneath the fault. The shear bands are variable in orientation, but most dip gently to the northeast (298 31 NE). Quartz rods define a mineral stretching lineation on C' shear planes. This lineation plunges gently to the east and southeast (093 02). The asymmetry of the shear bands yields a consistent top-to-the-northwest sense of displacement on the Hinesburg Thrust.

Above the Hinesburg Thrust at Stop 6 the metapsammite schists and quartzite layers of the Cheshire Fm are mylonitic (Strehle, 1985; Strehle and Stanley, 1986). The oldest structures preserved include a compositional layering (S_0) defined by alternating bands of micaceous and quartz-rich laminae and >3 cm thick quartzite beds (Figure 8). This layering, which most likely represents sheared, stretched, and recrystallized bedding planes, is deformed into a series of tight-isoclinal, reclined-recumbent folds (F_1). A fine grained mylonitic foliation (S_1) defined by the alignment of graphite, mica, and recrystallized quartz parallels the axial planes of the F_1 folds (Figure 8). On S_1 surfaces, a penetrative mica and quartz mineral lineation (L_1) plunges gently to the east and southeast. Locally, and especially within thin quartzite bands, the L_1 - S_1 fabric is deformed by a series of shear bands (C' type) similar to those in the foot wall rocks (339 13 NE). Both sets yield a similar top-to-the-northwest sense of shear parallel to the L_1 mineral lineation (106 12). The S_1 foliation also parallels the surface of the Hinesburg Thrust and is interpreted here to reflect early ductile thrusting at depth prior to the final emplacement of the Cheshire Fm onto the Bascom Fm along the semibrittle Hinesburg thrust fault.

The structural features observed in the mylonitic rocks above the Hinesburg Thrust display an elegant interplay between ductile deformation, in the form of folds and cleavages, and brittle deformation, in the form of veins. Throughout the outcrop the mylonitic S_1 foliation locally is cross cut by a set of quartz veins (V_1) that are tightly folded within the F_1 folds, indicating that they formed during folding, probably as a result of pressure solution and fluid transfer processes. Cross cutting both the S_1 cleavage and the V_1 veins is a second set of asymmetric quartz tension gashes (V_2) that localized within thick (>30 cm) quartzite layers (Figures 8, 9a). The tips of the asymmetric veins penetrate into the mylonitic schist surrounding the quartzite layers. A close inspection of the V_2 veins (both on the outcrop and in thin section) indicates that they are sheared and protomylonitic (look for the milky white, recrystallized appearance and the presence of quartz ribbons). These characteristics contrast with a younger set of quartz tension gashes (V_3) that cross cut the V_2 set in the same quartzite layers (Figure 8). The V_3 vein set is only weakly deformed, less recrystallized than the V_2 veins, and are mostly symmetric to slightly asymmetric. A black, quartz-poor pressure solution selvage surrounds the veined quartzite layers (Figure 9a) strongly suggesting that the vein material was locally derived and that dissolution and fluid migration depleted these zones of silica during progressive deformation. These relationships indicate that crystalplastic deformation alternated with brittle deformation as the superposed sets of tension gashes formed.

Both the V_3 and V_2 vein sets, as well as the F_1 folds, S_1 cleavage, and quartzite layers, are all deformed into a series of northwest-vergent asymmetric folds (F_2) of variable tightness (Figure 18). The fanning of the V_2 vein sets around fold hinges is a good indicator that they are folded (Figure 19c, 19d). The tightest folds are recumbent and tend to occur nearest the Hinesburg Thrust close to the base of the mylonitic section. Farther above the thrust, the F_2 folds tend to be more open and upright to gently inclined. This increase in fold tightness and orientation suggests that the folds record an increase in finite strain downward toward the Hinesburg Thrust.

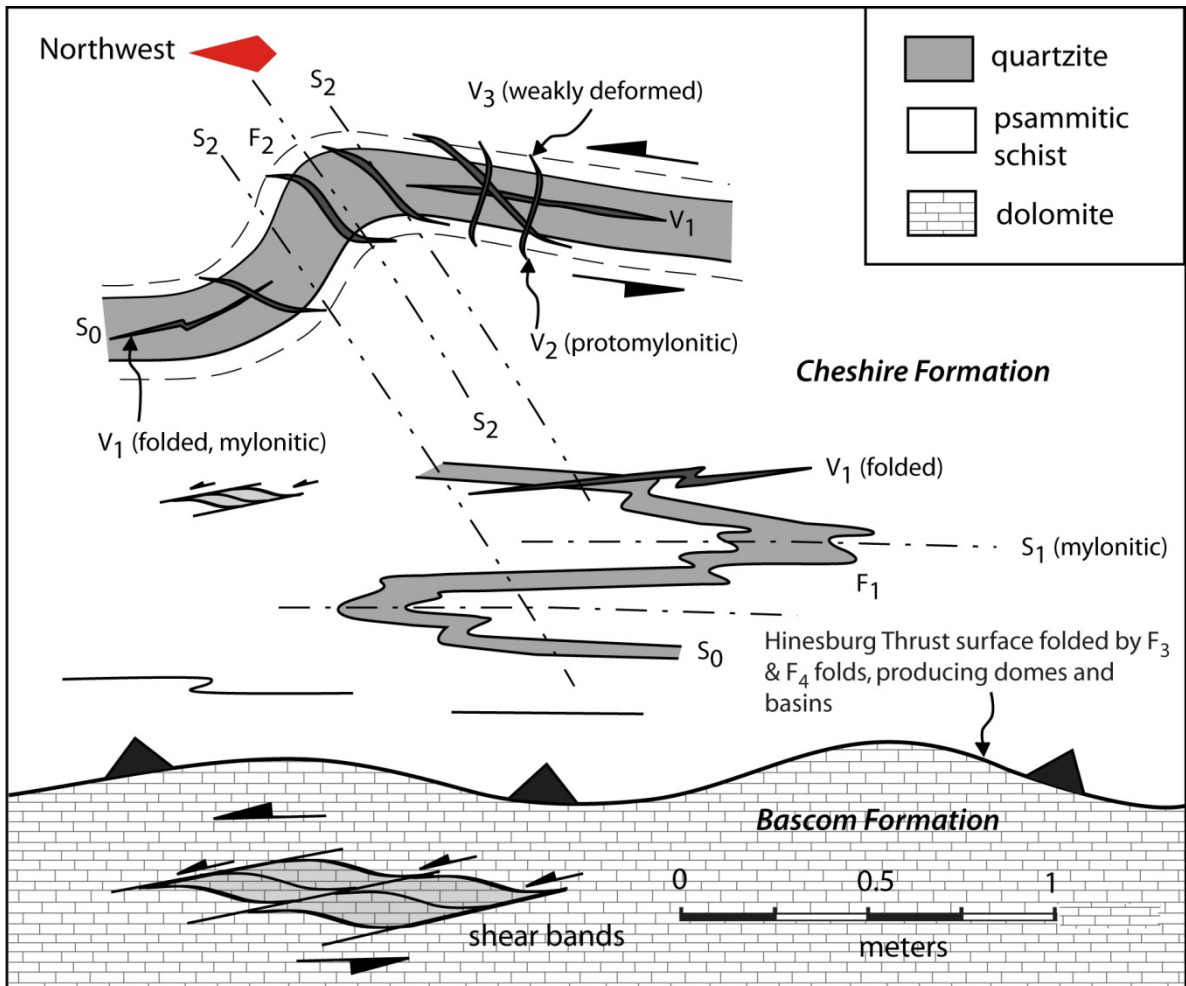


Figure 8. Sketch of structural relationships above and below the Hinesburg Thrust on vertical cliffs at Mechanicsville (Stop 5). Cliff face is oriented parallel to an L_1 quartz-mica mineral lineation.

A spaced crenulation cleavage (S_2) parallels the axial planes of the F_2 folds and also displays variable dips (Figures 8, 9d). In addition to recording a strain gradient, the variability in axial plane and cleavage orientation with increasing fold tightness provides kinematic information. The rotation of fold axial planes and S_2 to the northwest as fold tightness (and finite strain) increases, yields a top-to-the-northwest sense of shear identical to that indicated by the shear bands (Figure 9d). This relationship indicates that the F_2 folds reflect progressive deformation during the same ductile thrusting event that produced the S_1 mylonites and F_1 folds.

The following model, which is based on sketches of features at Mechanicsville, explains the evolution of the veins and the F_2 fold structures. See if you can find features on the outcrop that record each of these stages:

Stage 1 (Figure 9a).

En echelon arrays of quartz veins (V_2) open perpendicular to the direction of maximum stretch (X) of the instantaneous strain ellipse (ISE) in quartzite layers.

Stage 2 (Figure 9b)

After the V_2 veins finish forming, noncoaxial shear zones localized by the rheological contrast between the shale and the quartzite causes the parts of the vein tips that extend into shale to deform and rotate to the left. This process causes the veins to become asymmetric. A new set of veins (V_3) open

perpendicular to X-direction of instantaneous strain ellipse (ISE). A comparison of instantaneous and finite strain ellipses and the asymmetry of the two vein sets yield a top-to-the-NW sense of shear, identical to that recorded by shear bands in the mylonitic matrix. Note that this process differs than that which forms sigmoidal veins in brittle shear zones where the veins continues to open during shearing (Figure 10). In this latter model, a comparison of instantaneous and finite strain ellipses yields a top-to-the-SE (normal) sense of shear. This is because, in this latter case, the tips of V_2 veins are younger than their centers and so the former record instantaneous strains (ISE, Figure 10) and the latter record finite strains (FSE, Figure 10). We ruled out this model because, given the top-to-the-NW sense of shear at Mechanicsville, it would produce V_2 and V_3 vein asymmetries opposite to those observed (Figure 19). In the Mechanicsville model, the vein is required to form quickly and finish opening before ductile shear begins, yielding an asymmetry similar to that of a shear band.

Stage 3 (Figure 9c)

As the rotation of the veins during noncoaxial shear continues, the F_2 folds begin to form along with an axial planar crenulation cleavage (S_2). The F_2 axial planes and S_2 cleavage initially form at 45° to the quartzite layers and then rotate to the northwest toward the shear plane (defined by S_1). The V_3 vein sets also begin to rotate toward the northwest as noncoaxial shear continues.

Stage 4 (Figure 9d)

As noncoaxial shear continues the F_2 folds continue to rotate and tighten, recording a progressive increase in finite strain during ductile thrusting. The S_2 crenulation cleavage rotates to the northwest along with the folds. The V_2 veins exhibit a characteristic fanning geometry around fold hinges, indicating that they also rotated during folding. The F_1 and S_1 structures are transposed parallel to S_2 . The rotation of F_2 axial planes to the left with increasing fold tightness yields a top-to-the-northwest sense of shear, which is the same as that indicated by the asymmetric veins and shear bands.

The Hinesburg Thrust surface, and all other structures above and below it, are corrugated by two orthogonal sets of gentle, upright folds, forming a dome and basin pattern with a wavelength on the order of a few meters (Figure 10). This fold geometry mimics a kilometer scale dome and basin interference pattern formed by north-plunging (F_3) and east and west plunging (F_4) folds across the field trip area. These orthogonal fold sets are among the youngest ductile structures preserved at Stop 6. On the thrust surface itself two orthogonal crenulation lineations (L_3 , L_4) mark the presence of the corrugation folds (Figure 11). A regional correlation of similar structures across the field area indicates that the orthogonal fold sets everywhere postdate thrust sheet emplacement and imbrication on the Champlain, Hinesburg and Iroquois thrusts. Earle et al. (2010) suggested that the two folds sets formed together as a result of a constrictional style of deformation during the Acadian orogeny, possibly reflecting the reactivation of inherited basement faults or lateral thrust ramps. However, it is also possible that the fold sets formed in sequence as separate events.

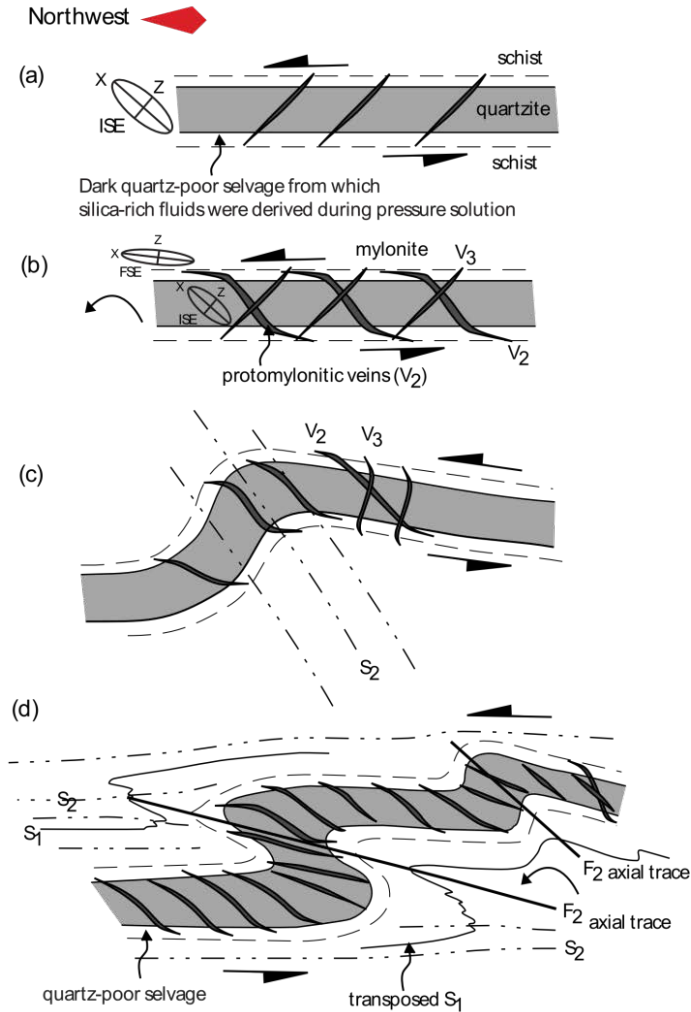


Figure 9. Cartoon showing the preferred model of progressive formation of F₂ fold and veins structures in the mylonitic hanging wall of the Hinesburg Thrust at Mechanicsville. This model requires the veins to finish opening prior to the onset of noncoaxial shear.

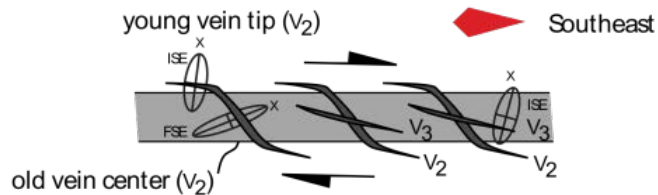


Figure 10. Cartoon showing an alternative model of progressive formation of vein sets during simple shear. This model requires the veins to continue to open during shearing. This model does not predict the correct orientation of V₃ veins or the top-to-the-NW sense of shear observed in the outcrop.

Hydrogeology and Groundwater Geochemistry

Elevated levels of alpha radiation (> 15 pCi/L as gross alpha) were observed in 38 % (12/31) of bedrock wells drilled into the hanging wall, including wells that penetrated the thrust into carbonates below; for comparison, no wells [0/21] in the carbonate-dominated footwall west of the thrust front exceeded 15 pCi/L (the EPA MCL). The source of the elevated radioactivity was evaluated by testing groundwater from hanging wall and footwall bedrock wells and by analyzing compositions of bedrock from local outcrops. The chemical composition of groundwater in hanging wall and footwall aquifers is mainly controlled by whole-rock geochemistry. Hanging wall groundwater is enriched in alpha radiation, K, Cl, Ba, Sr and U, whereas footwall groundwater is enriched in Ca, Mg, and HCO₃. These signatures reflect the distinct compositions of phyllite-dominated bedrock in the hanging wall compared to Ca-Mg-CO₃-rich limestones and dolostones of the footwall. Elevated alpha radiation and U in wells that produce from footwall carbonates below the thrust recorded compositions that are intermediate to hanging wall and footwall end-members, indicating that alpha and U are transported in groundwater downward through the thrust via fractures into the footwall below (Kim et al., 2014a).

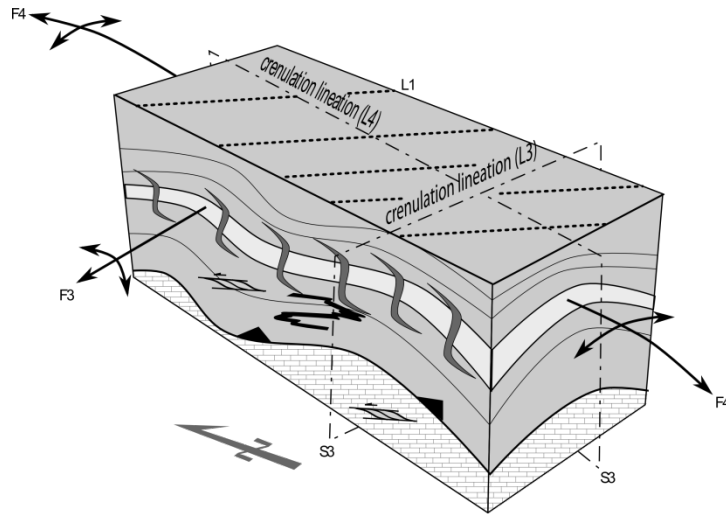


Figure 11. Block diagram showing the relative geometry of orthogonal fold sets that deform the Hinesburg Thrust surface and the mylonites at Mechanicsville, producing a dome and basin pattern. The two fold sets (F₃ and F₄) are associated with two steeply dipping orthogonal cleavages.

Cumulative miles	Point to Point	Route Description
62.5	0.0	Leave on un-named road, left onto Place Road East
62.7	0.2	Turn right onto Mechanicsville Road
63.2	0.7	Turn right onto CVU Road
63.8	1.3	Continue straight through intersection with Route 116 onto Shelburne Falls Road
64.3	1.8	Turn right into Geprags Community Park

Stop 7: Multiple Structural Generations and Hydrogeology at Geprags Park, Hinesburg, Vermont

Location Coordinates: 44 ° 20.448' N, 73 ° 07.389' W

Introduction

The Town of Hinesburg drilled three bedrock wells in Geprags Park in 1996. Although these wells were completed as future public water supplies, surface water contamination in one of these wells precluded them from ever being used. The Vermont Geological Survey and SUNY at Plattsburgh conducted comprehensive geophysical logging of these wells during 2012-2014 using temperature, conductivity, gamma, caliper, and acoustic televiwer tools. During 2014, Hinesburg drilled two new wells at a nearby site, which is also located on Shelburne Falls Road, but closer to the intersection with Route 116. These wells were drilled to increase water production for the town. One of these new wells (#48477) was logged with the previously mentioned tools. One well in Geprags Park (#7797) and another on the Wainer property were logged using a heat pulse flowmeter. Structures and lithologies were also mapped in the field to compare with those in the wells.

Lithology

In order of decreasing age, Early Ordovician Shelburne Formation (marble and dolostone), Late Cambrian Clarendon Springs Formation (dolostone) and Danby Formation (dolomitic sandstone), and Middle Cambrian Winooski Formation (dolostone).

Structure

All lithologies are folded by the north-plunging Hinesburg Synclinorium, which is thought to have formed during the Ordovician Taconian Orogeny. In the western half of Geprags Park, this synclinorium is truncated by the north striking and steeply east-dipping St. George Fault, a down to the east normal fault of presumed Cretaceous age (Figure 2). The dominant fracture set in this area is axial planar to parasitic folds in the Hinesburg Synclinorium (Figure 12). Isolated east-west trending fracture zones also occur (Figure 13). The integrated geophysical logs for Geprags Park well #7797 showed that this well was completed through the St. George Fault.

Tectonic/Stratigraphic Context

This site sits in a similar tectonic context to Stop 3, in the hanging wall of the Champlain Thrust just east of the St. George Fault.

Hydrogeology and Groundwater Geochemistry

Using temperature, conductivity, caliper, and acoustic televiwer logs for the four wells, we were able to delineate water producing zones. A summary cross section for Geprags Park only was drawn by Kim et al. (2014b) In addition, the attitude of structures intersecting each well were calculated from the acoustic televiwer logs. Using structural data from bedding and fractures acquired in the field as a template, we were able to accurately categorize the borehole structures. Finally, we were able to determine which structures were producing groundwater in each well (Kim et al, (2015). All of our data has been presented to the Consulting Hydrogeologist for the Town of Hinesburg.

Cumulative miles	Point to Point	Route Description
64.3	0.0	Turn left onto Shelburne Falls Road
64.8	0.5	Turn left onto Route 116
66.8	2.5	Bear right onto Route 2A
71.7	7.4	Left onto I-89 North
71.9	7.6	Merge onto I-89 North
85.6	21.3	Take exit 17 (Lake Champlain Islands and Milton)
85.8	21.5	Turn left onto Route 2 East
85.9	21.6	Turn left onto Route 7 North
86.3	21.9	Turn right into Colchester Park and Ride
		END OF ROAD LOG

Origin of Dominant Fracture Set

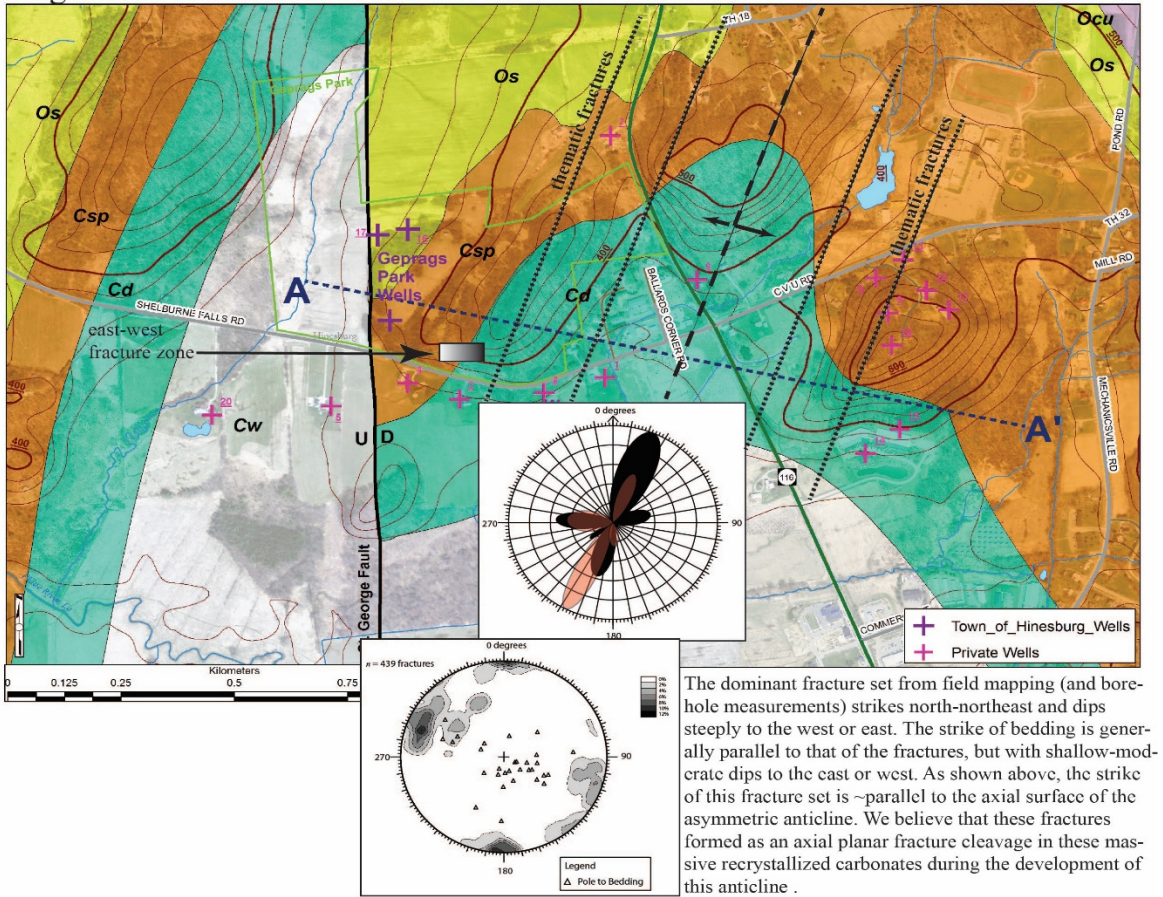
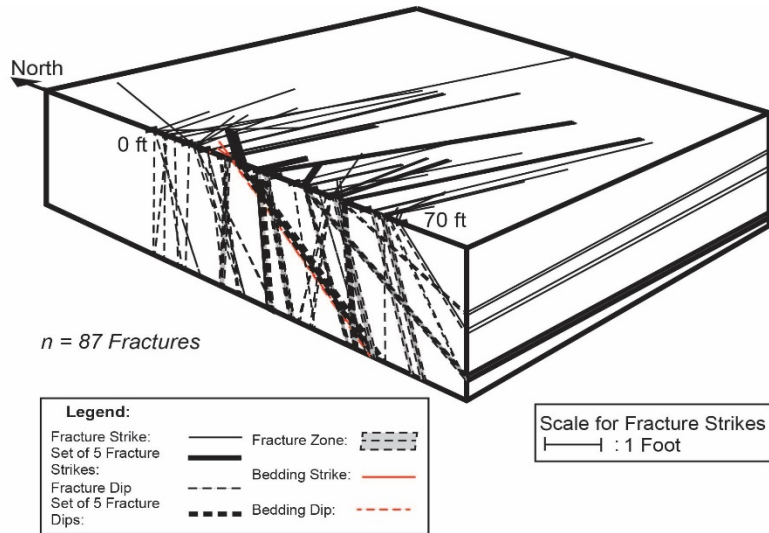


Figure 12. Rose diagram and equal area net for all structural data acquired in the field (black = fractures and red = bedding) (Salvini et al., 1999) overlaid on bedrock geologic map (modified from Kim et al. (2015). Map base modified from Ratcliffe et al. (2011). Note that the dominant fracture peak is axial planar to the fold in the Hinesburg Synclinorium.

Figure 13. 3-D configuration of fractures at an outcrop in Geprags Park where east-west trending fractures are dominant (Chirigos, pers. comm., 2015)



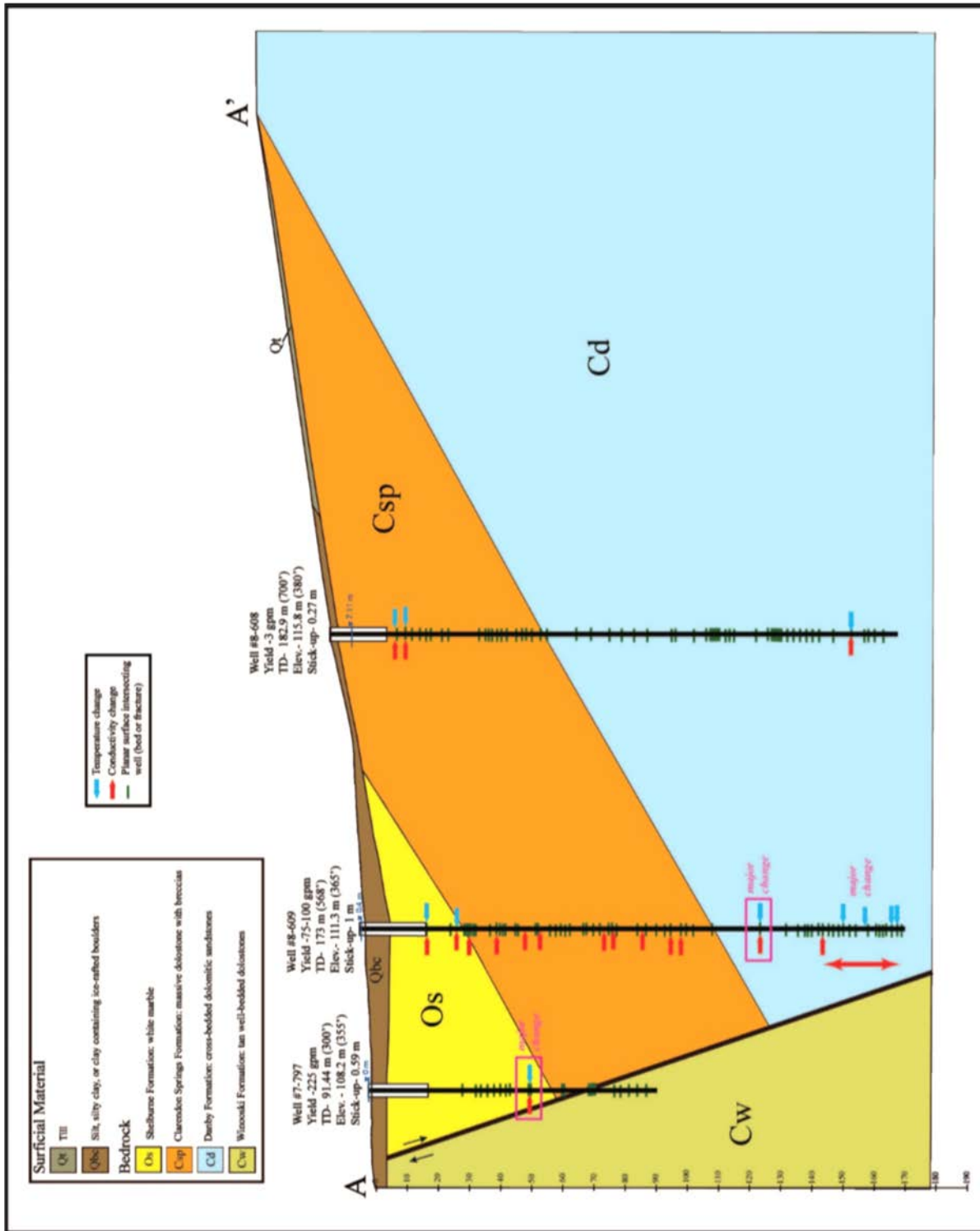


Figure 14. Summary cross section for the well logs in Geprags Park. West =left and right = east. Modified from Kim et al., (2014b).

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