Introduction

The Champlain Valley is situated in northwest Vermont between the Green Mountains to the east and Lake Champlain to the west (Figure 1). Doolan (1996) identified the region as part of the Champlain Valley Lowlands Province. The rocks in this region constitute a continental passive margin that deformed in response to an arc-continent collision. Geologically it is best known as the location of the Champlain Thrust Fault— a beautifully exposed low-angle thrust fault that strikes approximately north– south and adjacent to the lake shore. Sub-parallel to the

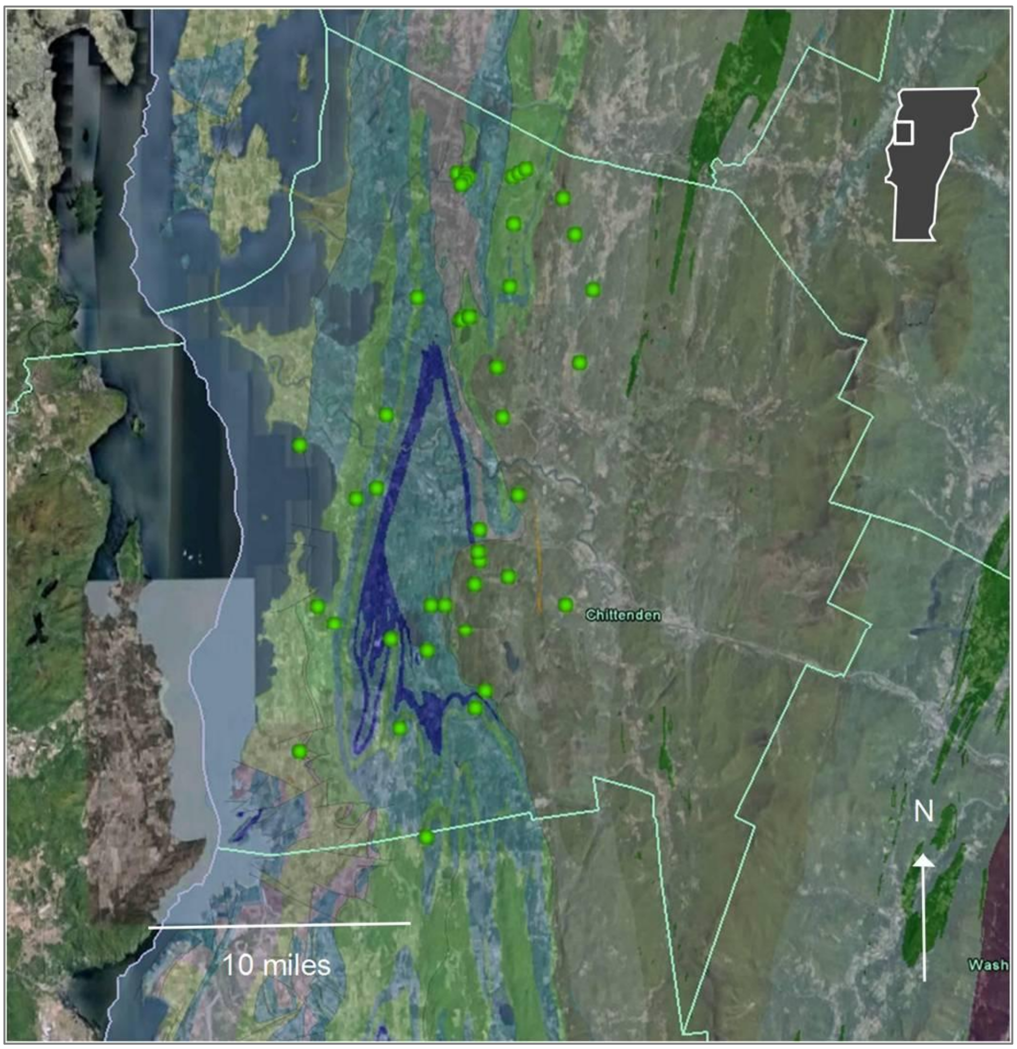


Figure 1 Google Earth image of field area overlain by state bedrock map and outcrop locations.

Champlain Thrust is the Hinesburg Thrust Fault. Its best exposure is located in Hinesburg, Vermont. The two faults define the major thrust sheets in the Champlain Valley.

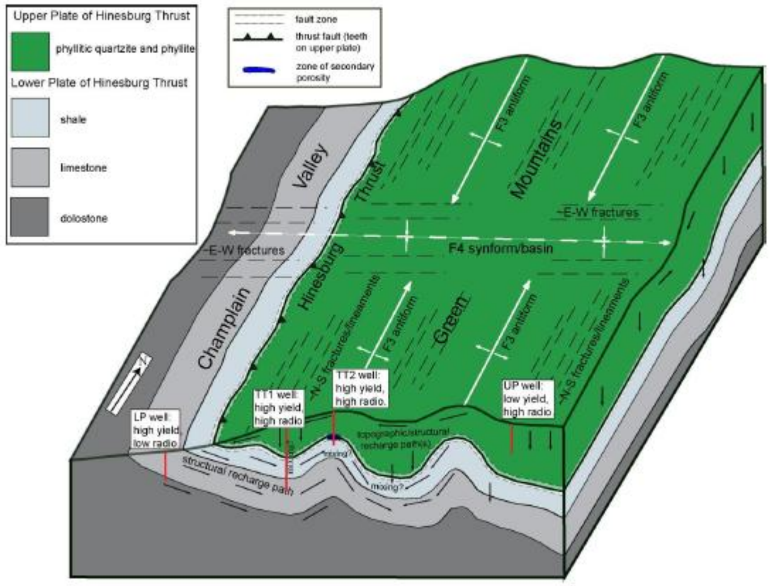


Figure 2 Conceptual model for hydrogeology (Kim et al., 2011)

A groundwater resource survey conducted by the Vermont Geological Survey (Kim, Gale, and Derman, 2007) concluded that high yields are generally associated with drilled domestic wells that penetrate the Hinesburg Thrust. This study, through drill core records of depth to the fault plane, confirmed the fault is folded at depth. Understanding this geometry is important because wells that penetrate the Hinesburg Thrust are associated with higher yields averaging ~50 gpm. Rock units below the thrust, particularly limestone units, contain structurally controlled groundwater recharge paths (Figure 2).

It is very common for thrust faults to have a planar geometry that tilts to one direction, but a folded plane adds a level of complexity in predicting groundwater resources. Earle et al. (2010) conducted a comparison study across the Champlain and Hinesburg thrust faults. He found early thrust-related structures within the area were folded by north– south trending tight folds and east–west trending open folds. Slope maps traced from LIDAR (Figure 3) and well log data also confirmed these field observations, and reveal a dome and basin topography.

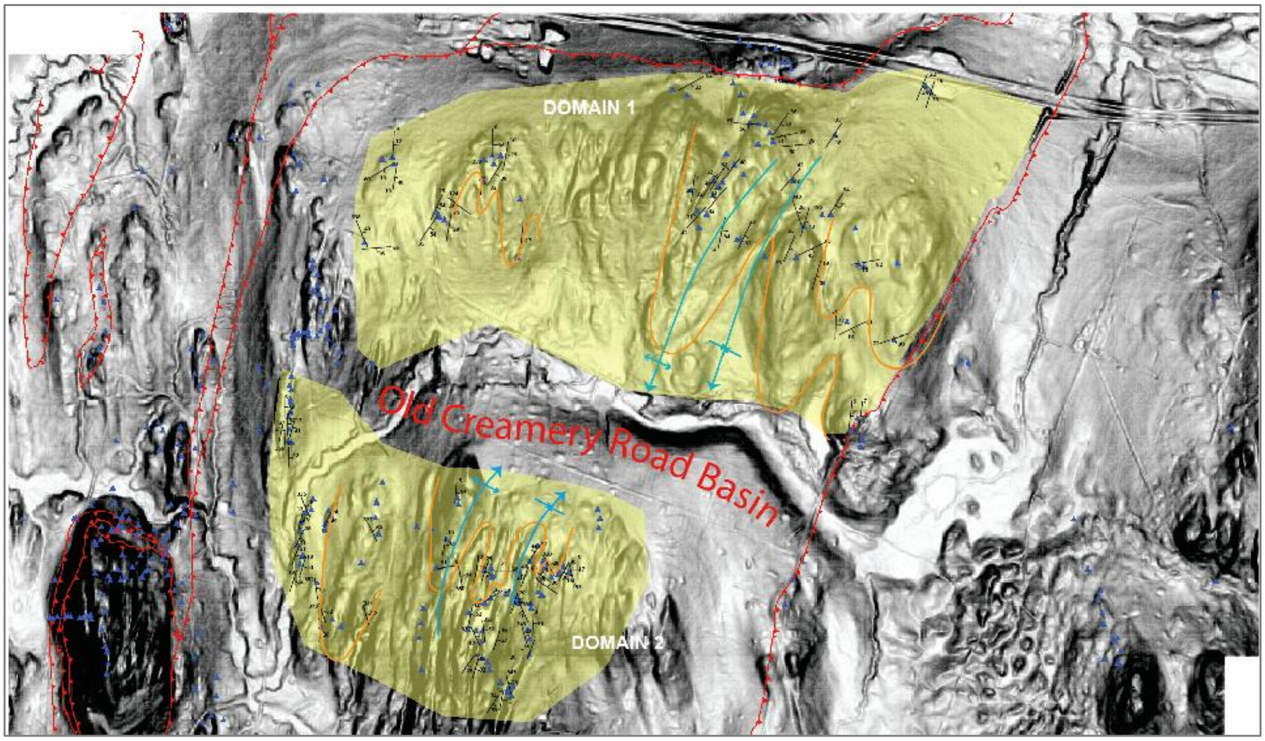


Figure 3 LIDAR imagery of a portion of Williston, VT. Thrust fault lines are in red (teeth on upper plate); N-S trending folds are blue. Yellow lines trace topographic features controlled by folding.

Geologically speaking, there is more that needs to be understood in the area. It has yet to be determined whether or not the orthogonal fold sets are restricted to the Williston area. As of now, the fold sets, which defines the domes and basins, is in proximity to a portion (or flap) of the Hinesburg Thrust that extends the extends the farthest west. The lithology that records these structures continues to the north and south and any change in geometry of fold sets could shed light on the influence of this flap on deformation. It is also unknown whether the geometry and distribution of the domes and basins exists and/or changes between thrust sheets. Initially my proposed hypothesis was that the east–west trending structures did not form contemporaneously with north–south trending structures. The hypothesis has changed to establish the role of lithology in controlling the extent and geometry of domes and basins in the Champlain Valley. This study tests that as well as provides the first order structural observations required to address the original hypothesis and broader questions such as the effect of structural geology on groundwater resources.

My research documents the locality and intensity of fabrics and relative ages, metamorphic conditions, and potential correlations with the Taconic Allochthon to the south and Stanbridge Nappe to the north, which are better understood. While my goals are currently environmentally driven, this dataset can provide a base for future tectonic-related research projects.

The study consists of field work and lab work. The field portion is data and sample collection; lab work is comprised of thin section preparation and analysis, stereographic projections, fault plane solutions, and possibly R_f/Φ diagrams. The major intention here is quantifying deformation fabrics and mechanisms, spatially describe deformation style and correlate well log data with mapped data to create a three dimensional representation of the subsurface.

Field Methods

Approximately 960 measurements were collected from 46 outcrops. Data for this project were collected during the 2010 and 2011 field seasons from Chittenden County, VT (Figure 1). County lines served to constrain field work and maximize data density. Specifically these boundaries were selected because of the presence of orthogonal features observed within it. Data was collected from outcrop spaced throughout the area with special attention paid to outcrop close to or within fault zones. LIDAR data partially covers Chittenden County and is a supplement to field data.

Field methods included identifying lithology, measuring the attitude of foliations, lineations, fault planes and associated structures, identifying kinematic indicators and collecting oriented samples for petrographic analysis. Field work also involved creating detailed sketches and taking scaled photos.

Data collected from field work is organized in a spreadsheet according to outcrop and location for future use. The data has been stereographically projected on a bedrock map to visually illustrate the extent of folding and cleavage rotation. The bedrock map is overlain with LIDAR imagery from Chittenden County, VT.

Laboratory methods

Stereographic projections

A stereograph projects a sphere onto a plane. Stereographic projections preserve the angular relationship between planes and lines within a sphere. The orientations of fabrics observed at the outcrop scale are plotted on stereographs (also referred to as stereonets) to illustrate spatial changes in orientation of a particular fabric as well as the relationship between fabrics in an area.

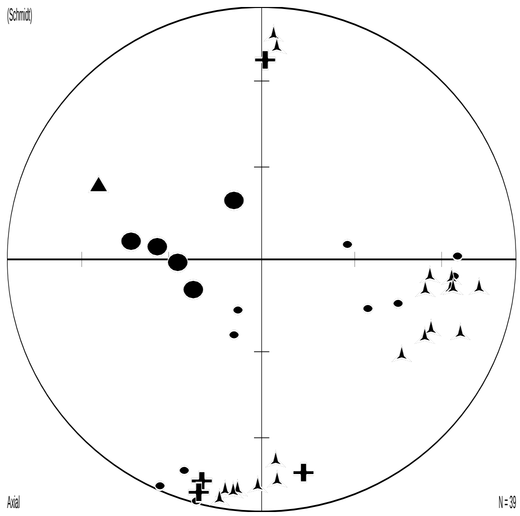


Figure 5a Outcrop 10WL09, quartzitic schist and quartz-sericite-chlorite phyllite, Williston, VT. Two sets of crenulation lineation (triangles) are orthogonal to each other. Crenulation lineations are the hinge lines of small folds. Cross-cutting relationship is ambiguous. The orientation of these lineation is in agreement with orthogonal fold sets observed in nearby outcrop.

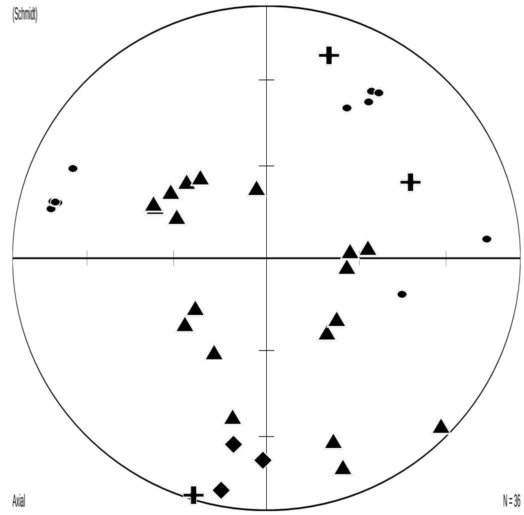


Figure 5b Outcrop 11WF02, quartz-albite-sericite- biotite- chlorite schistose greywacke, Westford, VT. NE–SW trending fold (crosses) doubly plunges indicating a subtle NW–SE trending fold. Evidence for two sets of folds exists outside of the Williston area, but the orientations differ.

This is where a fairly large collection of stereonets will go. I have included a couple for reference. The final version will have colored net symbols. Should these be captioned as individual figures? Perhaps there can be an appendix including them all?

Microstructural analysis

Thin section analysis will focus on microstructures and fabrics of the rocks from the field area. The purpose here is to reconstruct the structural and/or metamorphic history of the area (Passchier and Trouw, 2005). Rock chips were cut from oriented samples and sent out to become thin sections. The samples are cut in such a way that sense of shear may be determined and cross sectional views of foliation and cleavage definition are possible. Rock chips are cut from samples in pairs: one chip parallel to lineation and perpendicular to foliation; a second chip cut perpendicular to lineation and perpendicular to foliation. Samples that do not exhibit these features will be cut twice as well: one chip parallel to strike and perpendicular to dip direction; a second chip cut perpendicular to strike and parallel to dip direction.

Grain-size structures constrain the sequence of metamorphic and deformational events and are observed in thin sections from 13 oriented samples from the lower plate of the Champlain Thrust, lower plate and upper plate of the Hinesburg Thrust.

Strain analysis

R_f/Φ diagrams can be helpful in analyzing the stretched pebble information already collected. The R_f/Φ method (Ramsey, 1967) is used to measure the strain in deformed clasts (commonly pebbles). "Final shapes and orientations of ellipsoidal pebbles in the deformed rock are the product of the original shapes and orientation in the undeformed rock and the shape and orientation of the finite strain ellipsoid to which the undeformed rock was subjected" (Davis and Reynolds, 1996). These diagrams calculate the ellipticity of the strain ellipse. (Ellipticity is the ratio of the long axis of an ellipse to the short axis.) The intention is not so much to quantify strain, but observe how the stretched pebbles relate to strain ellipse intensity and orientation.

R_f/Φ will go here is an effort to qualify strain. Data has been collected to enter into computer software that constructs R_f/Φ diagrams, but not sure how relevant the results would be.

Initial Interpretations

Dome and basin structures have been confirmed in the upper plate of the Hinesburg Thrust specifically in the town of Williston. The location of these structures will serve as a reference point, as will the lithologies the structures have been recorded in. In Williston, the domes and basins are topographically expressed. (Figure 3)

Lithology strongly controls the fabrics recorded in the rock record. Thus far, folds, cleavage generations and stretched mineral lineations are observed in the fine-grained rocks of the Hinesburg Thrust's upper plate and Champlain Thrust's lower plate. The carbonate sequence that makes up much of the lower plate of the Hinesburg Thrust does not exhibit folding. Fine-grained argillaceous units are less competent than the carbonate units and, thus, more likely to exhibit the fabrics observed in Williston. In fact, bedding planes are the one dominant feature of the relatively undeformed carbonate rocks. The higher metamorphic grade in the upper plate of the Hinesburg Thrust (sericite-biotite) also indicates a pressure-temperature contrast between the upper and lower plate; which may explain the difference in structures observed.

In Williston, an E–W trending fold set is observed folding a N–S trending fold at the outcrop scale. This is also observed to the south as two sets of crenulation lineation with the same orientation. However, to the north both sets are not as clearly presented at the outcrop scale even though the lithology is the same. NE–SW trending folds are observed plunging to the north at one outcrop and plunging 180º at another outcrop to the south of it. This reversal of plunge direction is indication that the fold set has been deformed by an orthogonal fold set without actually observing the second fold set.

The sense of shear is consistent throughout the field area— top to the NW. The controlling factors on the presence of brittle versus ductile kinematic indicators will be further explained by thin section analysis. Nevertheless, the consistency in shear direction suggests an unchanging stress direction during a single or multiple deformation events. NNW–SSE compressional forces resulted in NNE–SSW stretching and fold trends. Therefore, fold trends parallel to sense of shear must be explained other than an isolated compressional deformation event.

Work Remaining

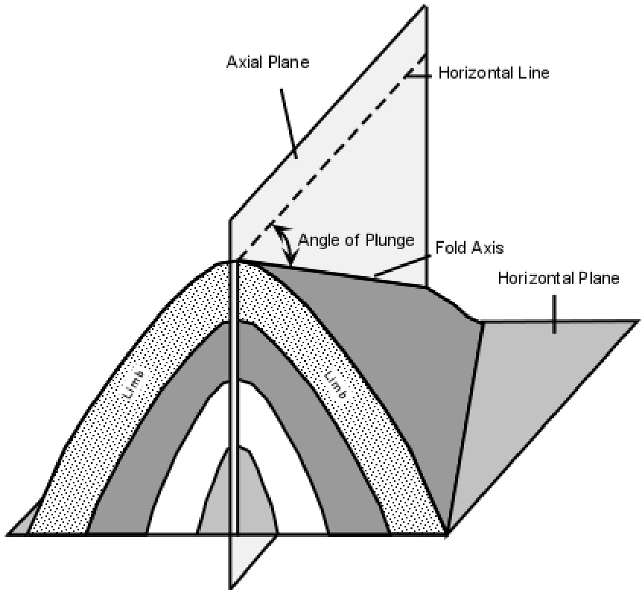
Thin section analysis needs to be conducted. A compiled list of microstructures must be made and correlated to lithologies and their pressure/temperature conditions. Field data and thin section analyses should be compared with previous studies, specifically Dorsey and Stanley (1983) and Strehle (1986) to check for consistency in data collection and avoid redundancy.

Map symbols will be plotted on existing geologic maps showing the extent of orthogonal folds and their geometry. A delineation of dome and basin geometry deforming the Hinesburg Thrust fault and aquifer will be constructed from that map and well log constraints..

I have access to a database of well logs maintained by the Vermont Geological Survey. I intent to extract well location, elevation and depth to the Hinesburg or Champlain Thrust so that I may contour the data and create a three dimensional model of the folded thrust at depth.

Detailed time line for completion of research

November 17-19, 2011	Contour well log data provided by Vermont Geological Survey
November 28, 2011	Present progress report
December 2011	Submit abstract to Geological Society of America Northeastern Meeting
December 2011- January 2012	Complete two chapters of thesis: Geologic Background/Literature Review and Methods
December 2011- February 2012	Continue microstructural analysis of thin sections.
	Determine cross-cutting relationship (or lack thereof) between orthogonal fold set
	Cross reference field data with that collected by Dorsey and Stanley (1983) and Strehle (1986)
January- April 2012	Write Results and Discussion Chapters of thesis as I work.
March 18-20, 2012	Present research of Geological Society of America Northeastern Meeting
April- May 2012	Complete writing thesis
May 2012	Defend thesis
	This is not a complete timeline. My advisor and I will beef it up a bit as we get closer to the deadline.



Example of a plunging fold. A doubly plunging fold has two directions of plunge 180º of each other. The resulting shape is akin to an elongate dome.