STRATIGRAPHY AND STRUCTURE AT THE SOUTHERN END OF LAKE CHAMPLAIN IN BENSON, VERMONT

A thesis presented to the Faculty
of the State University of New York
at Albany
in partial fulfillment of the requirements
for the degree
of Master of Science

College of Arts and Sciences
Department of Geological Sciences

Jennifer L. Granducci
1995

State University of New York at Albany

College of Arts and Sciences

Department of Geological Sciences

The thesis for the master's degree submitted by

JENNIFER L. GRANDUCCI

under the title

STRATIGRAPHY AND STRUCTURE AT THE SOUTHERN END OF LAKE CHAMPLAIN IN BENSON, VERMONT

has been read by the undersigned. It is hereby recommended
for acceptance by the Faculty with credit to the amount of
6 semester hours

(Signed) ______________________
William S. F. Kidd, Advisor

(Date) 11 May 95

(Signed) W. D. Means
Winthrop D. Means

(Date) 5/11/95

(Signed) ______________________
Gregory D. Harper

(Date) May 11, 1995

Recommendation accepted by the Dean of Graduate Studies
for the Academic Council

(Signed) ______________________

(Date) ______________________

STRATIGRAPHY AND STRUCTURE AT THE SOUTHERN END OF LAKE CHAMPLAIN IN BENSON, VERMONT

Abstract of
a thesis presented to the Faculty
of the State University of New York
at Albany
in partial fulfillment of the requirements
for the degree
of Master of Science

College of Arts and Sciences
Department of Geological Sciences

Jennifer L. Granducci
1995

ABSTRACT

Detailed mapping and structural investigations in an area bound to the west by the Grenvillian basement of the Adirondack Mountains and to the east by the allochthonous slates of the Taconic Mountains led to the distinction of a Western Undeformed Zone and an Eastern Deformed Zone. The former is composed of the gently east-dipping shelf sequence of upper Cambrian to lower Ordovician clastics and carbonates which unconformably overlie the Precambrian basement. The latter is characterized by lower to middle Ordovician carbonates, striking roughly north-south and dipping predominantly to the east, which are overlain by well-cleaved shales and slates. The stratigraphic sequence is thought to represent the tectonic stages of super-continent rifting (Bird & Dewey, 1970; Rankin, 1976), thermal subsidence of the passive margin and ocean transgression (McKenzie, 1978), and obduction of slope/rise shales and slates (Rowley & Delano, 1979; Rowley & Kidd, 1981).

The only published geologic maps which include the entire study area are the Vermont Centennial Map (Doll et al., 1961) and the Geologic Map of New York State (Fisher et al., 1970), both at a scale of 1: 250,000. While these maps and other previous studies (Rodgers, 1937; Cady, 1945; Zen, 1961; and Fisher, 1984) correctly identified the rocks in the area as faulted and deformed, the extent and nature of deformation was heretofore unrealized. In addition, some strata and structures were either not identified or were misinterpreted (i.e. Unit 1-def and the Root Pond Thrust).

In contrast, this thesis identifies four major east-dipping thrust faults in the Eastern Deformed Zone; from west to east they are the Temple Road, Shaw Mountain, Root Pond, and Forbes Hill Thrusts. Regional geology suggests east over west thrusting driven by convergent plate motion during the medial Ordovician Taconic Orogeny (Chapple, 1973; Rowley & Kidd, 1981). I propose that the thrust faults in the field area represent an imbricate duplex system formed by the foreland propagation of thrusts during Taconic Allochthon emplacement. Movement along normal faults is interpreted to be a response to the loading and ensuing flexural extension of the subducting slab. The sequential development of the structures in the field area, as well as the processes causing their formation, are discussed in detail in the final chapter.

Based on stratigraphic and structural evidence, regional structures are correlated with those in the field area. Furthermore, supported by evidence from Coney et al., (1972), I propose that the Temple Road, Shaw Mountain, and Root Pond Thrusts represent the southern extension of the Champlain Thrust System, the location of which was previously unknown this far south.

STRATIGRAPHY AND STRUCTURE AT THE SOUTHERN END OF LAKE CHAMPLAIN IN BENSON, VERMONT

A thesis presented to the Faculty
of the State University of New York
at Albany
in partial fulfillment of the requirements
for the degree
of Master of Science

College of Arts and Sciences
Department of Geological Sciences

Jennifer L. Granducci
1995

Acknowledgments

This thesis would never have been possible without the help and support of many. I would like to thank all the people who contributed to the completion of this project and who offered me guidance during my time at SUNY.

My advisor, Bill Kidd, introduced me to Vermont geology and spent hours discussing its complexities with me. Without his untiring help in the field and his encyclopedia-like knowledge of New England geology, much of Benson would still be a mystery to me. In addition, I am grateful for his many suggestions during the writing of this thesis.

To the other members of my committee, Greg Harper and Win Means, I express my gratitude for reading and commenting on my thesis. When I called Win from the summit of Mt. Washington 3 years ago, I could hardly imagine the day this project would be finished. I'm glad there was someone at SUNY who could relate to my love of the White Mountains.

I would have missed countless deadlines and been left without funding were it not for the help of Diane Paton. Her humor, advice, and answers to my numerous questions were invaluable during my time in the Department. Remember, Diane, the Red Sox will win the pennant someday.

Without my personal Macintosh consultant and friend, Kristen Landry, I would have had to type my thesis tho old-fashioned way.

The residents of my field area were most friendly and helpful in allowing me to roam about their land in search of outcrops. I especially want to thank Joey Corner who, after a chance meeting, let me camp on her beautiful property and became a long-term friend.

To my fellow grad students I offer my thanks and respect. I would especially like to express my appreciation to the women of SKIFWIG and to Max, Bruno, and Mike E., who provided the friendship and laughs I will always remember (and Max even survived days in the field with me!). And to Ben, one of the best teachers I know, I owe more than will fit on this page - I could not have done it without your help.

I owe several of my teaching skills to the undergrads I taught. Their challenging questions and unique insight taught me to look at geology in a variety of ways.

My husband, Bill, endured the trials and tribulations of my entire graduate career. Without his love, support, and patience, I couldn't have finished my work, and the Capital District would have been a very lonely place.

Finally, to my mother I give my love and deepest gratitude. Her encouragement, support, love, and advice were priceless gifts. Thank you for all the strength you gave me, as well as the never-ending desire to learn.

Table of Contents

PLATES in back pocket

List of Figures

1. Introduction

"Speak to the Earth, and it shall teach thee."

Job, 12:8

This quotation is taken from the King James version of the Bible, and I find it to be a particularly fitting way to begin a thesis in geology. As I interpret this statement, it means one must communicate with the earth in order to understand it, and this communication, I believe, can be accomplished by observation. The keys to success in geology are the careful collection and study of data, and it is the successful and respectable geologist whose hypotheses are supported by her data. A *true* scientist must resist the temptation to jump to conclusions or to consider only the portion of data which fits most comfortably with a hypothesis. She must instead rely on her observations.

What follows is my attempt to understand the segment of earth around Benson, Vermont. It is an *attempt* because I can neither claim to comprehend all the data I collected nor boast that I have offered the one and only correct interpretation of that data. This thesis is, however, my honest endeavor to be a true scientist.

1.1. Location of Field Area

This study investigates the structural and stratigraphic relations of rocks in the southern Champlain Valley in west-central Vermont where I mapped an area of approximately 50 square kilometers in detail. It is located around 73°20'W, 43°40'N in the town of Benson, Vermont and part of the adjacent town of West Haven, Vermont. The northern boundary coincides with the county line of Rutland, the eastern limit is marked roughly by Route 22A, and the southern border is on a parallel with the West Haven town center. The area is bounded to the west by the southernmost end of Lake Champlain. It includes portions of the Benson and Putnam USGS 7.5 minute quadrangles. ***(Figure 1.1.).***

Several locations outside the area described were visited to gain understanding of the local and regional geologic relationships. Various field trips with Dr. W. S. F. Kidd to sites in Whitehall, New York; Fort Ann, New York; and West Haven, Vermont were invaluable to my knowledge of Taconic geology. In addition, I explored numerous outcrops directly south and north of my field area in order to correlate structures within the Benson area.

The study area is topographically characterized by low, rolling hills, with elevations ranging from 80 feet at the edge of Lake Champlain, to 700 feet on Shaw Mountain. The hills, though mostly covered by woods and dense undergrowth, contain most of the outcrop. In addition, steep cliffs on some of the loftier hills allow the valuable opportunity to study outcrops of 25 to 50 meters in height. Cow pastures and farms occupy the lowlands. Glaciation during the last ice age is largely responsible for this landscape, as evidenced by glacial striations (trending approximately 010°) on several large outcrops, as well as various erratic boulders of Monkton Quartzite. Due to sands and clays deposited in periglacial Lake Champlain (Chadwick, 1935; DeSimone, 1983), outcrop is scarce below an elevation of 250 feet ***(figure 1.2.).***

1.2. Methods of Examination

I worked in the field area during the spring and fall of 1993 and 1994. I mapped on a scale of 1: 10,000, using enlargements of USGS 7.5 minute topographic quadrangles. As a result of glacial and post glacial cover, as well as Holocene sedimentation, the exposure in the area is less than 1%. The sedimentation level of periglacial Lake Champlain has left significant portions of the field area without outcrop. Over 800 outcrops were recorded, however, concentrated in elevations above 250 feet ***(Plate 1).***

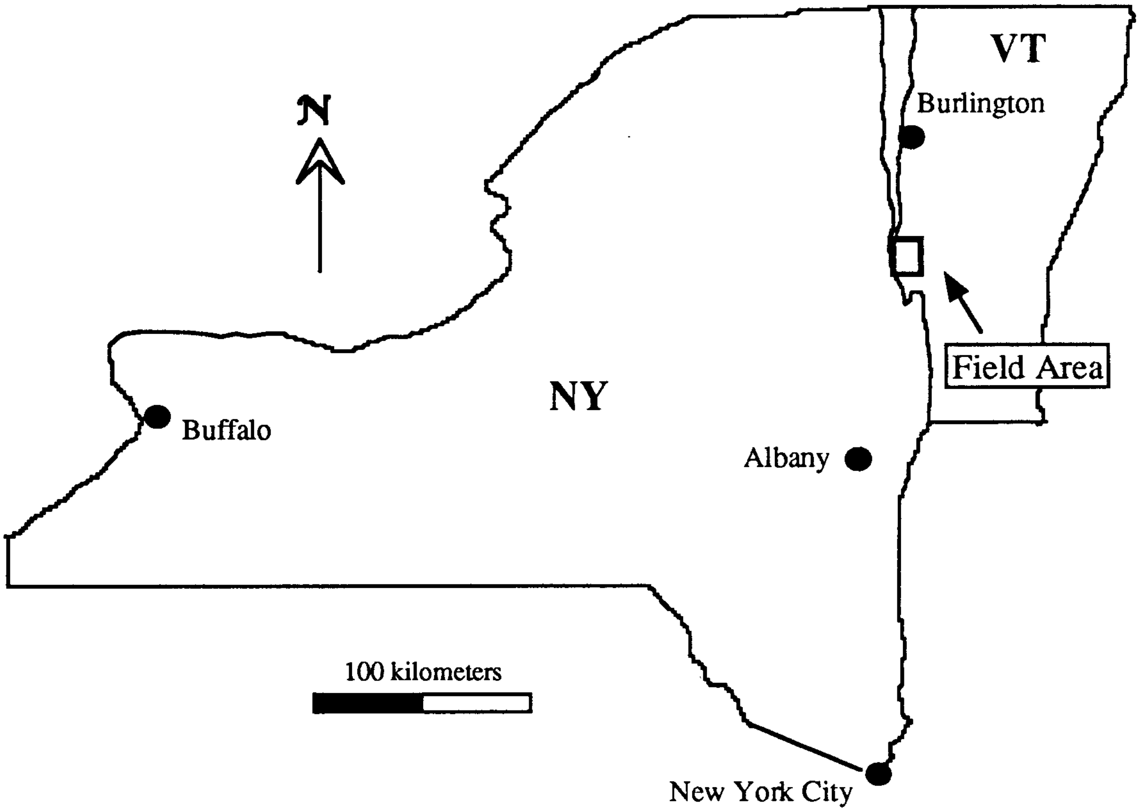


Figure 1.1. **Location of field area .**

Figure 1.2. Scenic picture of Benson, Vermont, showing typical landscape. Note scarce outcrop due to deposition of sands and clays by periglacial Lake Champlain.

In addition to my own field work, this study is also based on field work conducted by undergraduate geology majors during the SUNY Albany field camp in the summers of 1989, 1992, and 1993. I compiled data from their maps and correlated it with my own field data. This method had the advantage of allowing me to pinpoint discrepancies and questionable areas to visit while saving me some degree of legwork in the field. However, there were some disadvantages. My interpretations were often substantially different from those of the undergraduates, and I found several of their outcrop locations and rock type identifications to be incorrect. While this caused confusion and frustration, use of their maps nevertheless aided the completion of my study.

Structural analyses of the area have been conducted on different scales. At some of the better outcrops, structures and numerous fabric elements were measured and examined in detail. The outcrop pattern and interpretation of the cross-sections led to the development of the map-scale structure. In addition, I used the description of local and regional geology provided in the available literature.

Comparison of rocks found in the field with those described in relevant literature (Fisher, 1984; Cady, 1945) led to the correlation and dating of lithologic units ***(figure 1.3.)***.

1.3. Previous Work

Several geologists have studied the rock units in or near the Benson area. In 1937, J. Rodgers published the first (and only) study that includes my field area and describes it in any detail. He correctly identified the rocks of the area as deformed, and he created three sketch maps outlining the main geologic features ***(figure 1.4.)***. Unfortunately, he did not publish a detailed geologic map. In addition, Zen (1961) studied portions of the area and named the Forbes Hill Mélange.

STRATIGRAPHIC CORRELATION CHART

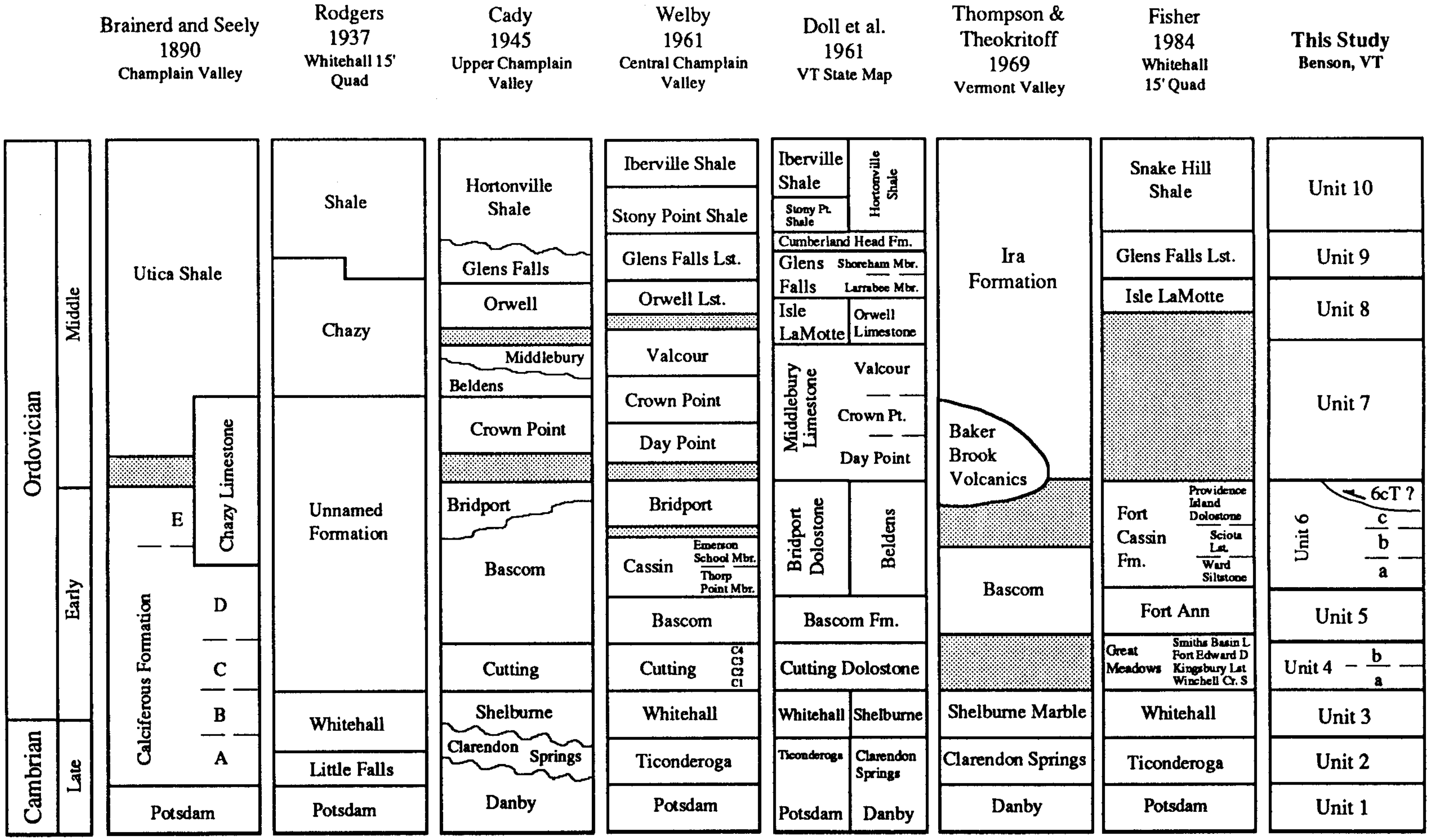


Figure 1.3. **Stratigraphic correlation chart for the shelf sequence in the southern and central Vermont area.**

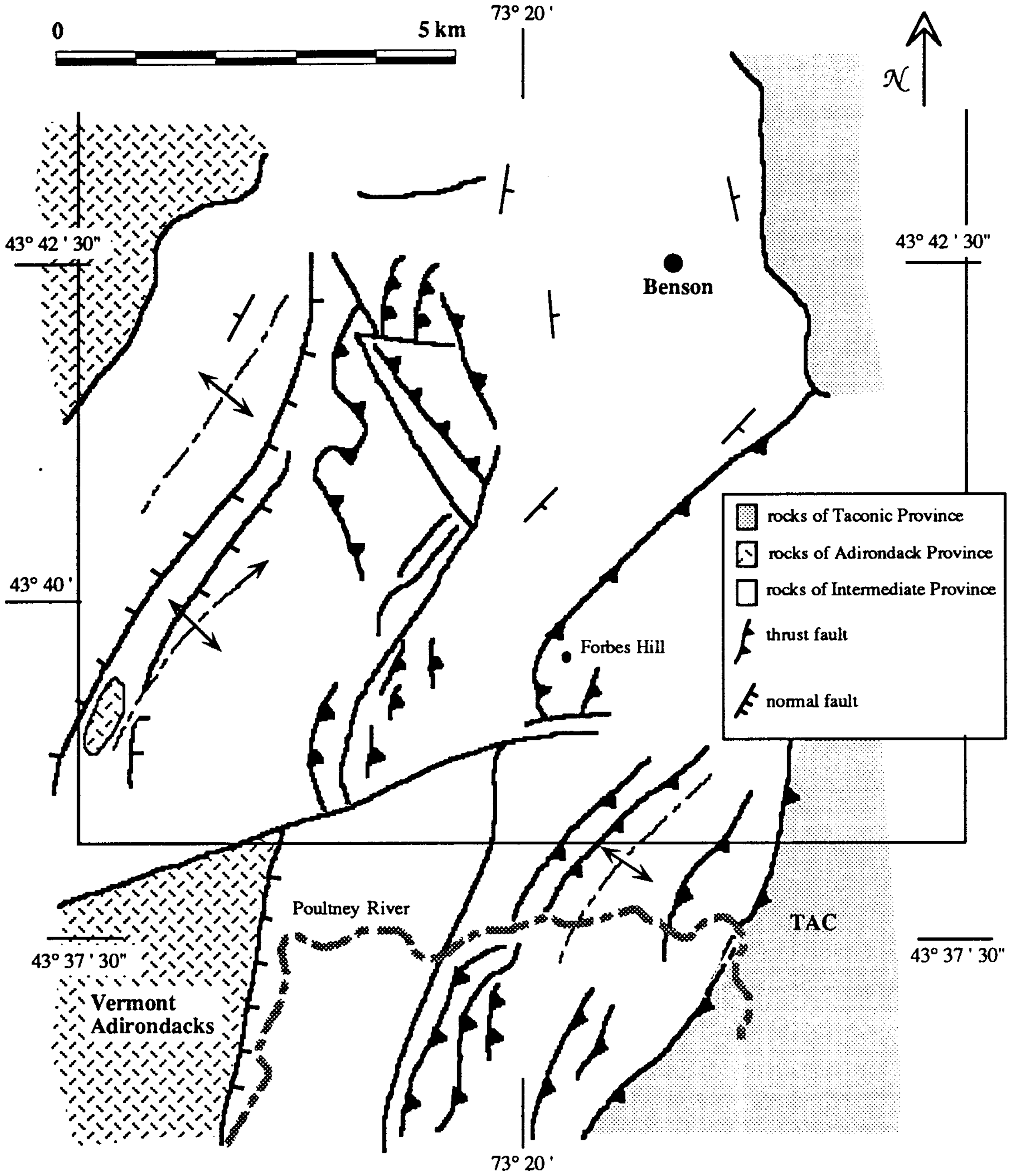


Figure 1.4. **Structural provinces, normal and thrust faults, in a portion of the Whitehall Quadrangle (redrawn from Rodgers, 1937, with no alterations). Portion of this study area shown in rectangle.**

The Centennial Map of Vermont (Doll et al., 1961) ***(figure 1.5.)***, and the Geologic Map of New York State (Fisher et al., 1970) are the only published geological maps which cover the entire study area, but they are both at a scale of 1: 250,000. In 1945, W. Cady published a map on a scale of 1: 62,500 which includes the northern portion of this study area. His investigation of West-Central Vermont reveals structures which can be correlated with ones observed in the field area.

The Geologic Map of Whitehall, NY (Fisher, 1985) shows lithologies and structures similar to those found in the Benson area. As a stratigrapher and paleontologist, however, Fisher concentrated on fossil data and neglected much of the structural geology. This has caused difficulty in the correlation of my map with his because it is the structural geology which has the most influence on the map pattern and its interpretation. In addition, fossils and sedimentary fabrics have been almost entirely obliterated due to deformation in the eastern portion of the area. The lateral variation of dolomitization causes problems in determination of stratigraphy in some locations as well.

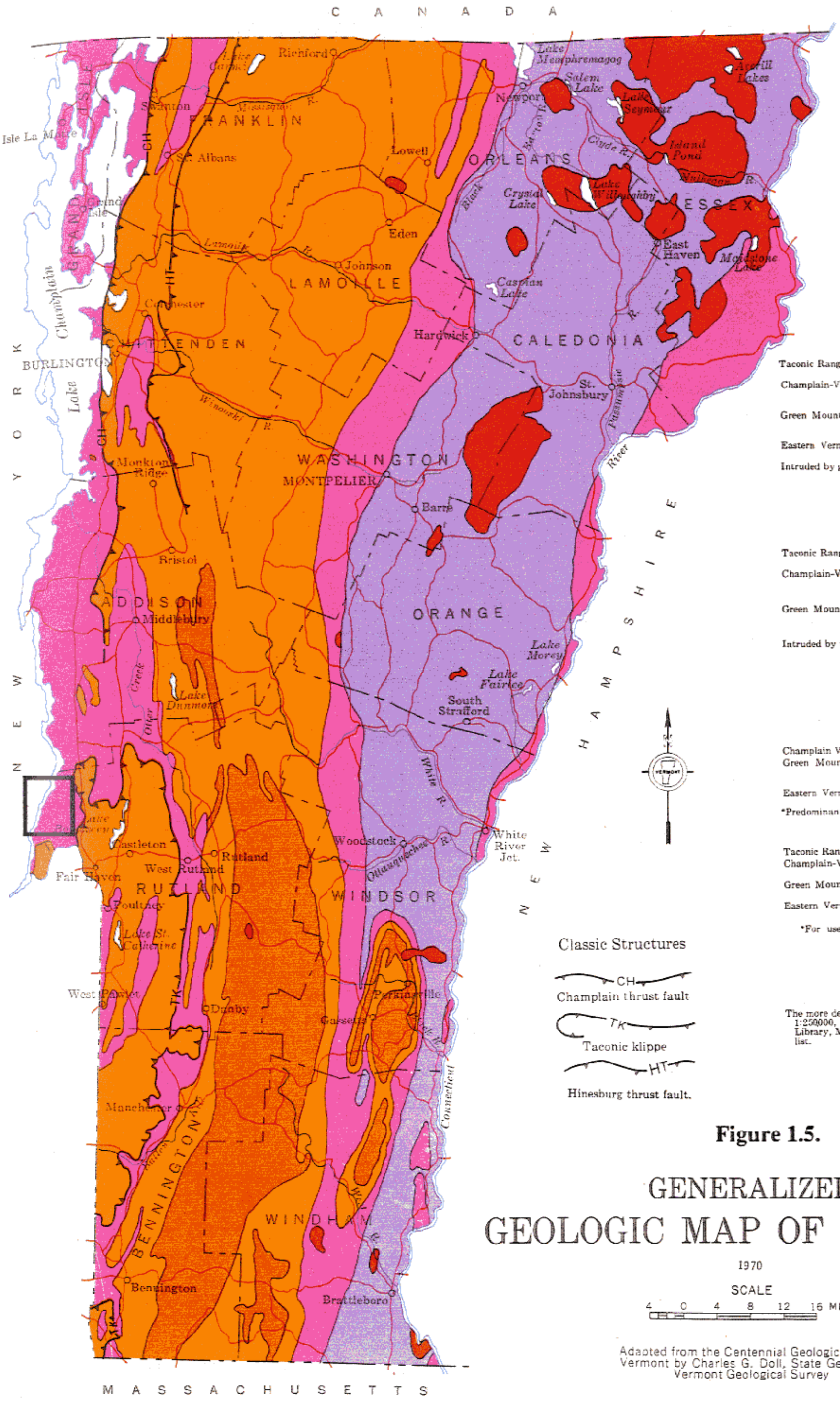
As mentioned previously, several SUNY undergraduates had drafted geologic maps of the Benson, Vermont region. This study uses data from maps created by Loren Weinheimer, John Waechter, Greg Young, Yoshiko Hosojima, Jim Duesel, Eryn Klosko, Bob O'Brien, and Ken Wolf.

1.4. Purpose of Study

By an in-depth investigation of this area, I intend to reveal more of the complex structure and lithology of this region than has been discovered previously. Producing the first detailed geologic map of this complicated area is one of the obvious beneficial outcomes. Additional purposes of this study are the following:

- To determine the structural effects of the emplacement of an allochthonous complex of continental rise and slope sediments (Taconic Allochthon) on top of a carbonate shelf sequence. Due to the proximity of the Taconic Allochthon to the autochthonous basement of the Adirondacks, this area has provided an excellent opportunity to view the effects of transport recorded in the structure of the rocks ***(figure 1.6.)***.

- To unravel the deformation history of the area.
- To trace the continuation of the Champlain Thrust, a major thrust fault known to the north and south of the field area.



EXPLANATION

■ Igneous Rocks*

Granite, syenite, basalt, dunite, peridotite, *serpentinite*.

■ Silurian-Devonian

Slate, *phyllite*, *limestone*, quartzite, conglomerate, greenstone, schist, *amphibolite*. Intruded by granite, and syenite.

■ Ordovician

Taconic Range—*Slate*, *graywacke*, quartzite, *limestone*, cc
erate, *marble*.

Champlain-Vermont valleys—*Shale*, dolomite, *limestone*,
ite, phyllite, slate, san
conglomerate, *marble*.

Green Mountains—*Phyllite*, *schist*, quartzite, *greenston*
graywacke, gneiss, conglomerate, a
olite.

Eastern Vermont—Phyllite, quartzite, greenstone, *schi*
iss, slate, *amphibolite*.

Intruded by granite, syenite, basalt, *ultrabasic rocks*.

■ Cambrian

Taconic Range—*Slate*, *graywacke*, quartzite, limestone, p
sandstone, *marble*, dolomite.

Champlain-Vermont valleys—*Quartzite*, *dolomite*, slate, p
sandstone, *shale*, lim
conglomerate, *marble*.

Green Mountains—*Schist*, *phyllite*, quartzite, graywac
glomerate, *greenstone*, dolomite
stone, *gneiss*, *amphibolite*.

Intruded by ultrabasic rocks, basalt.

■ Precambrian

Champlain Valley (small area)—*Gneiss*, quartzite, gran
Green Mountains—*Schist*, *gneiss*, metagraywacke, qu
calcite and dolomite marbles, an
lite.

Eastern Vermont—*Gneiss*, *schist*, quartzite, calcite, an
mite marble, amphibolite.

*Predominant and important rocks in *italics*.

Earth Materials*

Taconic Range—Slate, marble.

Champlain-Vermont valleys Limestone, marble, clay,
roadstone.

Green Mountains—Talc, asbestos, verd antique marbl
stone.

Eastern Vermont—Granite, talc, roadstone, copper (na
tive).

*For uses consult *The Mineral Industry of Verm*
U. S. Bureau of Mines, Prep
obtainable from Superinten
of Documents, U. S. Governm
Printing Office, Washington, D
20402

Also, use information avail
from the mineral industries,

The more detailed Centennial Geologic Map of Vermo
1:250000, available from State Librarian, Vermon
Library, Montpelier, Vermont 05602. Write for pub
list.

Figure 1.5.

GENERALIZED
GEOLOGIC MAP OF VERMONT

1970

SCALE

4 0 4 8 12 16 MILES

Adapted from the Centennial Geologic Map of
Vermont by Charles G. Doll, State Geologist.
Vermont Geological Survey

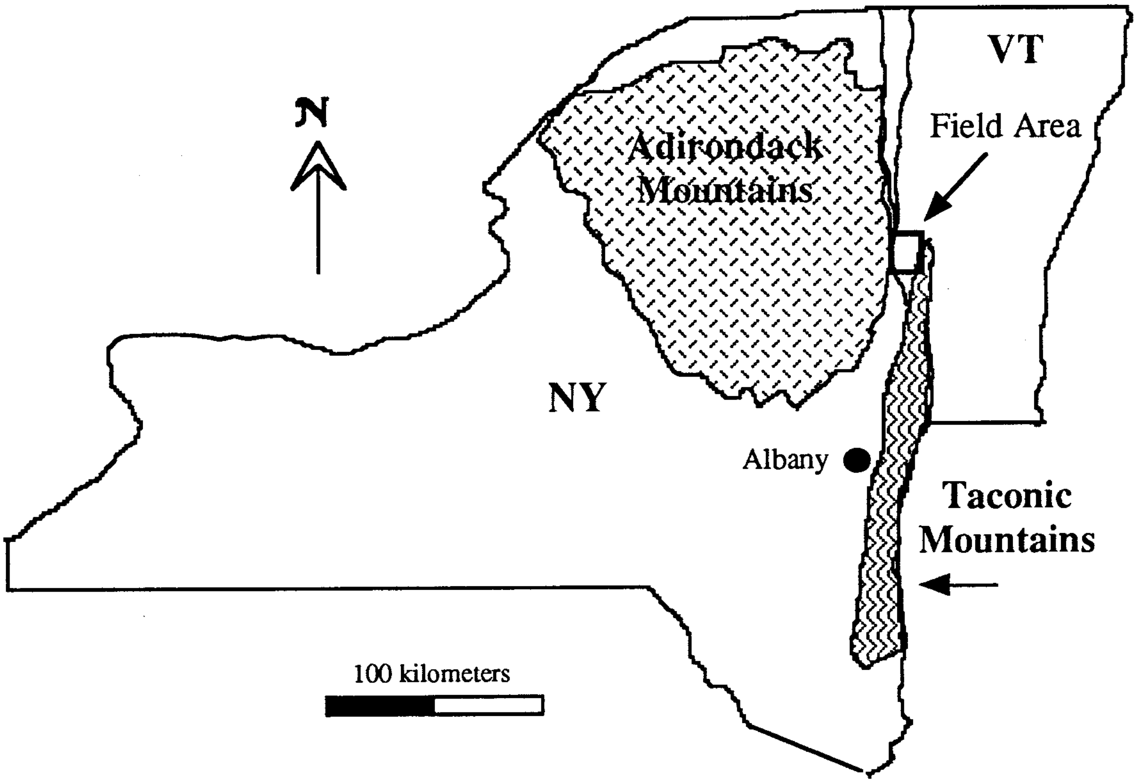


Figure 1.6. **The location of the field area between the Taconic Allochthon and the autochthonous basement of the Adirondacks (adapted from Fisher, 1984).**

2. Stratigraphy

2.1. Introduction

The rocks in the study area include portions of a Paleozoic carbonate shelf sequence and continental slope/rise shales. These rocks form an elongate north-south trending belt in the Champlain and Vermont Valleys in New England. This belt extends southward into the Hudson River Valley in New York and northward into the Province of Quebec, Canada.

Several geologists have studied the rocks in this belt, and they have supplied a more than adequate variety of names and descriptions for the stratigraphic sequence. Brainerd & Seely (1890) published the first stratigraphic nomenclature and descriptions that covered the general equivalents of rocks observed in my field area. Their study was based on investigations by Hall, Emmons, and others on sites around Lake Champlain and Fort Cassin (Welby, 1961). This work laid a foundation for further investigations by Rodgers (1937), who assigned new names and constrained the ages of rocks more accurately, and Cady (1945), who formed a more detailed stratigraphy in certain areas. One of the most valuable references for this area is a comprehensive study of the Paleozoic carbonate sequence in the Central Champlain Valley published by Welby in 1961. The formation names chosen for The Vermont Centennial Map (Doll et al., 1961) were largely based on Welby's work. Fisher (1984) conducted the most recent examination of rocks in this belt, concentrating on the area around Whitehall, New York. ***(Figure 1.3.).***

Due to lateral facies variations and dolomitization in some beds, I have had difficulty comparing carbonate rocks of similar age from different localities. In addition, approximately 70% of the stratigraphic column is composed of dolomitic rocks lacking determinable fossils. Although I used lithologic criteria and observable differences (when possible) to distinguish these formations, an individual unfamiliar with the area would have monumental problems locating herself in the stratigraphic column if she visited most of the outcrops in the carbonate sequence. For this reason, field outcrops were mapped descriptively, and lithologic units were identified later. Unit boundaries on the map are drawn to link outcrops of similar lithologies, and they are believed to represent possible gradational contacts rather than sharp ones.

The rocks in the western portion of the field area are relatively undeformed, and their lithologies are therefore easier to order. The rocks in the eastern zone, however, have been significantly displaced and deformed, possibly affecting the observable lithologies and making paleoenvironmental interpretations based on sedimentary structures difficult. The quality of outcrops of some rock types, such as the cross-bedded quartz-rich sandstone denoted as Unit 4a, is far superior to that of outcrops of other units. This quality variation is caused by differences in lithology, and it leads to the observations and interpretations for some rock types being more complete than for others. Units are described in their stratigraphic and structural order from lowest to highest, with any distinctive feature being described in detail.

I have chosen not to conform to the nomenclature used previously by geologists studying similar rocks. I found the lithologic constraints and rock descriptions in the literature to be often vague and confusing (such as that for the dolomite and limestone sequence of the Fort Ann Formation), occasionally misleading (such as the Winchell Creek Siltstone, which actually has the grain size of a sandstone), and sometimes inaccurate and not applicable to my field area due to lateral facies variations or a change in dolomitization of the rocks compared to those of the type locality. Instead, this study uses a simple, non-prejudicial, numerically-based nomenclature I developed, along with detailed descriptions of the rocks in the outcrops I observed. I found this approach preferable to the dangerous game of pigeon-holing the rocks in the Benson area into descriptions of rocks found in the type localities of certain formations. In order to facilitate the correlation of rocks in my field area with those in other localities, I have included the traditional lithologic names of formations which may correspond to ones I studied. These traditional names, however, were only used in this study to determine the possible age range of rocks I investigated and to credit the geologists who first studied them.

2.2. Unit 1 *Potsdam Formation*

Unit 1 can be stratigraphically correlated to the Potsdam Formation, first named by Emmons in 1838, and comprising rocks along the northernmost shore of Lake Champlain. In this study area the unit underlies the rocks in the western portion of my map. It is exposed, in its undeformed state, in the southwest corner, as well as along the shore of Lake Champlain where it forms cliffs. Although the lower boundary of Unit 1 is not seen in the field area, it is known to unconformably overlie the Grenvillian basement. The contact, observed approximately 8 kilometers to the west on Route 22, shows a transgressive conglomerate with clasts derived from the underlying metamorphic basement.

Around Benson, Unit 1 is composed of light gray to tan, medium to coarse grained sandstones and quartzites. In some places, such as the outcrop at Kline Hill, I found arkosic sandstone with calcareous matrix. In the bottom portion of the observed column, thin beds of quartzites protrude on weathered surfaces due to their high degree of resistance. They vary in color from gray to dark gray.

The column is dominated by medium to coarse grained sandstones with carbonate matrix, and colors vary from tan to gray on fresh surfaces, and light yellowish brown on weathered surfaces. A rusty brown color in some spots denotes the presence of iron hydroxide, suggesting that portions of the original matrix have been affected by solution processes.

White to gray quartzites in beds up to one meter thick compose the upper half of the observed column. Bedding is marked by occasional lamination, made visible by differential weathering possibly caused by compositional changes in the material at the deposition site.

The observed section is approximately 50 meters thick. Because neither the upper nor the lower contacts are visible, however, I have followed the example set by Steinhardt (1983) and placed the contact with the overlying Unit 2 at 15 meters above the top of the exposed section at Kline Hill. I have also assumed the basal contact to be well below the bottom of the observed section because the grain size there is significantly smaller than that seen at the contact with the basement outside the field area. A minimum thickness is then calculated to be approximately 100 meters, which is consistent with the values of 75 meters (Fisher, 1984), 160 meters (Cady, 1945), and 135 meters (Rodgers, 1937) reported by previous workers. Unit 1 probably varies laterally in thickness due to its unconformable deposition on the Precambrian gneiss of the Grenville basement, which most likely showed relief prior to being covered.

Due to fossils found outside the field area (Brainerd & Seely, 1890; Rodgers, 1937), the corresponding Potsdam Sandstone has been assigned an upper Cambrian age.

Unit 1-def., the metamorphosed (or deformed) counterpart to Unit 1, is a vitreous gray quartzite with beds typically about 20 centimeters thick ***(figure 2.1.)***. This unit is exposed in two transported lenses in the western deformed zone of my map, where it is indicative of the overthrusting of lower stratigraphic units. On the Vermont Centennial Map (Doll et al., 1961), this quartzite is referred to as the Root Pond Member of the Orwell Limestone. This assignment presumes it to conformably overlie the limestone, thus making it an Ordovician lithology. I believe this to be an erroneous interpretation by previous geologists. Unfortunately, no fossils have been found in this sub-unit.

Figure 2.1. Outcrop picture of quartzite unit 1-def exposed near Root Pond.

2.3. Unit 2 *Ticonderoga Formation*

Unit 2 conformably overlies Unit 1 and corresponds to the Ticonderoga Formation named by Rodgers (1955). In my field area I found only two examples of this lithology, discovered previously by Steinhardt (1983). These two outcrops, located in the southwest corner of the map area, show a fine grained, gray dolomitic sandstone that weathers to a yellowish color, with thin beds of quartz sandstone. The small amount of quartz in this portion of the unit makes it less resistant to weathering than Unit 1, and has led to the poor exposure of it in this zone.

Because neither the top nor the bottom contact of this unit are exposed in my area, I had to take the thickness of Unit 2 from the literature. The type section of the Ticonderoga Formation is approximately 20 kilometers northwest of my area in the village of Ticonderoga (Rodgers, 1955). The thickness at this locality is measured at 62 meters. In the Whitehall, New York quadrangle, Fisher has mapped the Ticonderoga with a thickness of 50 to 80 meters (1984). For my mapping purposes, I have chosen a thickness of 60 meters for Unit 2.

Although I found no fossils in the two outcrops I observed, Rodgers (1937) used fossils to determine the age of late Cambrian for the Ticonderoga. This is supported, as well, by Fisher (1984).

2.4. Unit 3 **Whitehall Formation**

Unit 3 is a coarse grained, clastic, gray to light gray, massive dolostone, with dark gray to light gray weathering colors. Lamination and calcite veins are visible in some outcrops, though bedding is poorly developed. The most obvious features are the fractures perpendicular to bedding. This description concurs with that of the Whitehall Formation

(Rodgers, 1937). Although Rodgers (1937) and Fisher (1984) distinguished several limestone members within this formation, I have not found evidence for these in my field area. This absence is possibly due to lateral variation of the unit or a change in degree of dolomitization of the rocks.

Rodgers reports a thickness of 295 feet (90 meters) for the Whitehall Formation. From the outcrop positions on my map, and constraints allowed by the easily identified underlying Unit 2 and overlying Unit 4, I have estimated the thickness of Unit 3 to be 60 to 70 meters. This difference in thickness values could be explained by possible thinning of the unit to the north from the type locality in Whitehall, New York. Steinhardt (1983) inferred a value of 30 meters for the Whitehall in the area directly south of mine, but according to my data, his value seems low.

Although I discovered no fossils in this unit in my field area, this formation has been determined to be latest Cambrian due to fossils found at other localities (Rodgers, 1937).

2.5. Unit 4 *Great Meadows Formation*

Unit 4 in the Benson area corresponds to the Great Meadows Formation named by Flower (1964), and used by Fisher and Rodgers (1969) and Fisher (1984) in reference to the rocks disconformably overlying the Whitehall Formation in northeastern New York. In addition, it correlates to the Cutting Formation described by Cady (1965) and the Calciferous C of Brainerd & Seely (1890), and it offers a good example of the confusion created by numerous names.

According to Fisher (1984), four map units within the Great Meadows Formation are distinguishable . Starting at the bottom, they are the Winchell Creek Siltstone, Kingsbury Limestone, Fort Edward Dolostone, and Smith's Basin Limestone. The two limestone members, however, are not seen in my field area, most likely due to lensing out along strike. The fact that Fisher cites thickness values of both limestone members to be zero to 12 meters is consistent with this idea. Therefore, I have divided Unit 4 into two subunits, 4a and 4b, which correspond to the Winchell Creek Siltstone and Fort Edward Dolostone, respectively.

2.5.1. Unit 4a *Winchell Creek Siltstone*

The Winchell Creek Siltstone lies disconformably above the Whitehall Formation (Fisher, 1984). In the field, however, this contact is not exposed between my Unit 3 and Unit 4a, and thus I have no definitive evidence for a disconformity existing here. Steinhardt (1983) interpreted the contact as gradational in the rocks he found around West Haven, Vermont. In my study area, Unit 4a is characterized by medium grained, quartz rich sandstone with colors varying from blue-gray to gray on fresh surfaces to buff on weathered surfaces. The beds range from 10 to 50 centimeters thick and are easily distinguished. The most obvious feature of this unit is the beautifully developed crossbedding, seen most readily on weathered surfaces due to relief formed by quartz grains ***(figure 2.2.)***. The crossbedded layers are interspersed with varying amounts of homogenous dolostone that is gray and "sugary" on fresh surfaces and weathers to light gray.

Due to the crossbedding, Unit 4a is the most easily recognized in the field, and it was often used as a guide horizon within the monotonous carbonates. Without it, I would have had great difficulty determining my position among all the massive dolostones in this portion of the stratigraphic column. Because neither the upper nor lower contact seems to be exposed in my area, I referred to the literature for the thickness of 25 meters (Steinhardt, 1983). This corresponds to my field estimates of 25 to 30 meters. Fisher (1984) cites the age as early Ordovician.

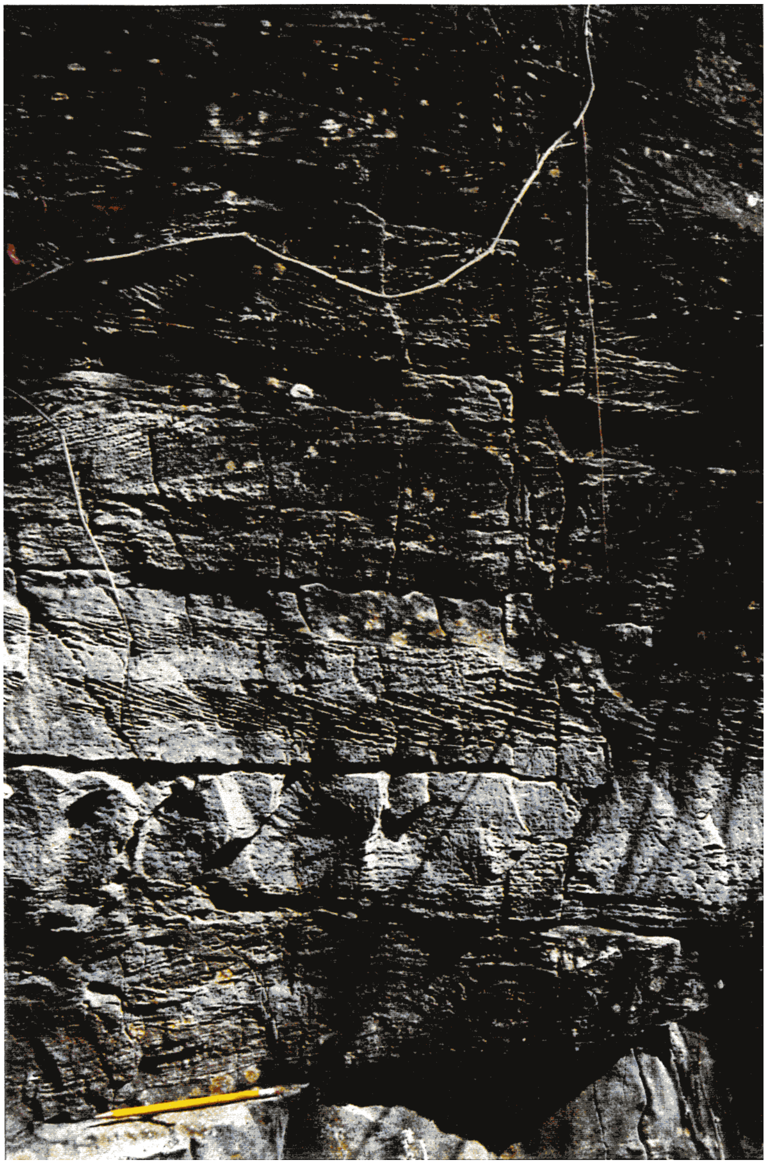


Figure 2.2. Outcrop picture of Unit 4a (Winchell Creek Siltstone). Note well developed crossbedding on weathered surface. Pencil for scale.

2.5.2. Unit 4b *Fort Edward Dolostone*

Unit 4a grades upward into Unit 4b, where the crossbedded strata give way to the massive dolostone which corresponds to the Fort Edward Dolostone of Fisher (1984). This unit is blue-gray, medium to coarse grained and weathers to yellowish gray. On fresh surfaces, it demonstrates the "sugary" texture of recrystallized dolomite. As bedding is not distinguishable in many places, subvertical joints are a prominent feature, as are the occasional chert nodules. Where seen, these silica-rich lenses are irregular shaped and dark gray to black ***(figure 2.3.)***.

Unit 4b is roughly 30 meters thick in the Benson area, making the total thickness of Unit 4 between 55 to 60 meters.

2.6. Unit 5 *Fort Ann Formation*

The carbonate Unit 5 corresponds to the Fort Ann Formation of Fisher (1984) and Flower (1964), the lower half of the Calciferous D of Brainerd & Seely (1890), the Bascom Formation on the Vermont State Centennial Map (Doll et al., 1961), and the lower half of Cady's (1945) Bascom Formation. Unit 5 contains more variety of grain size and composition than the underlying Unit 4, as well as the presence of two sets of joints. One parallel to bedding and the other perpendicular to bedding, these joints are often filled with quartz or calcite. The "fretwork" appearance created by these minerals on weathered surfaces is a helpful feature in distinguishing this carbonate formation from the one below.

Medium to coarse grained massive dolostones inhabit the lower portion of this formation, displaying colors of bluish gray on fresh surfaces that become yellowish gray when weathered. Locally, chert nodules similar to those in Unit 4b are found. Calcite crystals, up to 2 centimeters across, are frequently found in vugs in the rock.

Figure 2.3. Outcrop picture of Unit 4b (Fort Edward Dolostone). Note dark grey chert nodules and subvertical joints.

Figure 2.4. Outcrop picture of upper portion of Unit 5 (Fort Ann Formation). Note well bedded dolostones.

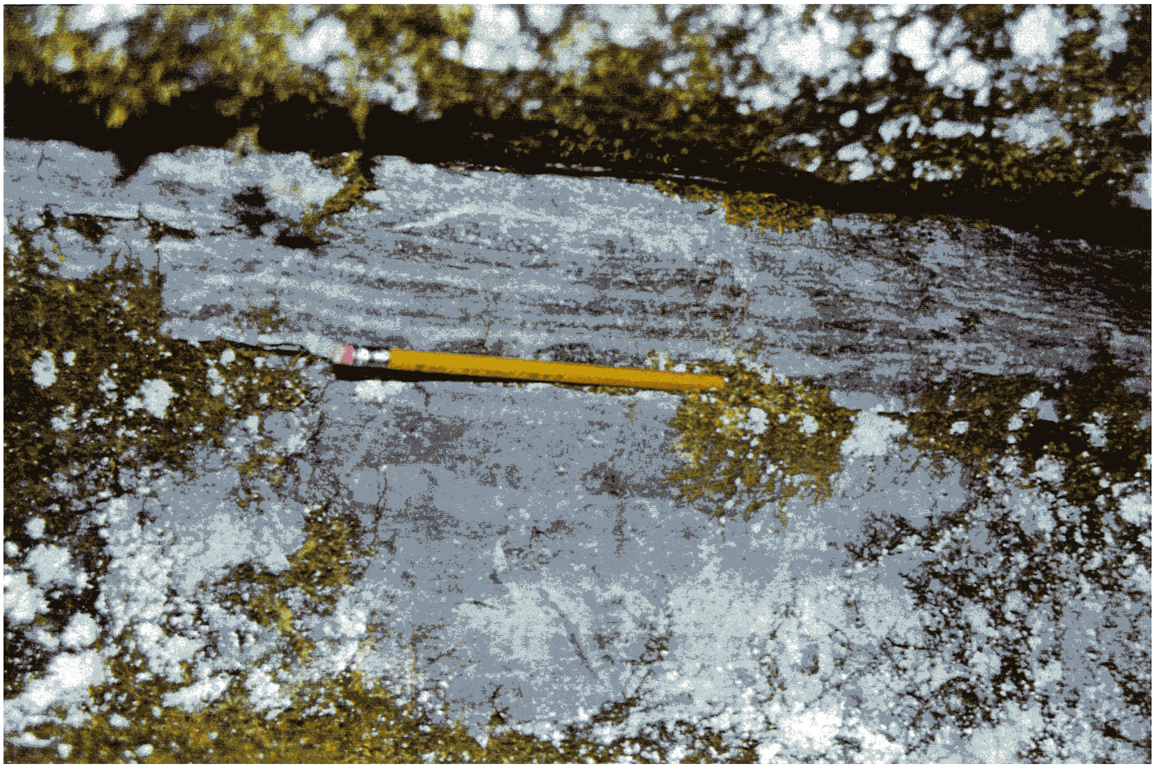


Figure 2.5. Outcrop picture of laminations in Unit 5, exposed 0.5 kilometers west of Shaw Mountain. These laminations have been interpreted as a build-up of algal mats in a supratidal environment.

Finer grained dolostones and limestones comprise the upper portion of Unit 5. These dolostones are much less massive and are well bedded, with some beds as thin as 5 centimeters ***(figure 2.4.)***. A fine, discontinuous lamination is exposed on fresh surfaces, with alternating layers of light gray and dark gray material as thin as 3 millimeters ***(figure 2.5.)***. This lamination is also found in the limestone portions of the unit which are composed of thick bedded, fine grained lime mudstones.

Field determinations show the thickness of Unit 5 to be 25 to 30 meters. My calculations agree with Fisher's thickness value of 15 to 35 meters (1984). From its stratigraphic position, Unit 5 appears to be early Ordovician in age.

2.7. Unit 6 *Fort Cassin Formation*

Unit 6 consists of a series of carbonate strata which correlate to the Fort Cassin Formation first named by Whitfield in 1890 and later used by Fisher in his study of the geology in Whitehall, New York (1984). From bottom to top, this formation includes the Ward Siltstone (Fisher, 1977), Sciota Limestone (Fisher 1977), and Providence Island Dolostone (Ulrich, 1938). In my field area these units are named 6a, 6b, and 6c, respectively.

2.7.1. Unit 6a *Ward Siltstone*

Unit 6a is a thin to medium bedded, laminated and occasionally crossbedded calcareous and dolomitic siltstone. Some sandstone is interspersed at the type locality, though none was seen in the outcrops of this lithology around Benson. This unit is gray on fresh surfaces and weathers to light gray or tan. The thickness offered by Fisher is zero to 12 meters, and my field estimate of 0 to 10 meters concurs. According to Fisher (1977), this unit disconformably overlies the Fort Ann Formation. This contact is not exposed in the study area, nor have I seen fossils in Units 5 or 6a, so I can neither support nor disprove this hypothesis.

2.7.2. Unit 6b *Sciota Limestone*

Unit 6b conformably overlies Unit 6a and is not only equivalent to Fisher's Sciota Limestone (1977), but also the Fort Cassin Formation of Welby (1961), the Beldens Member of the Vermont Centennial Map (Doll et al., 1961), and divisions D3 and D4 of the Calciferous Formation (Brainerd & Seely, 1890). Because it is the first unit, going stratigraphically upward, in which I have found fossils in the field area, I have used it as a guide horizon.

The fossils are this unit's most distinguishing feature, and they include examples of nautiloid cephalopods, gastropods, and brachiopods concentrated in thin, conglomerate layers comprising less than 10% of the total thickness of the unit. Fisher (1984) has examined the fossils of the Sciota Limestone in detail and has determined the age of this unit to be early to medial Ordovician. The fossils are best seen on the bedding plane of a few outcrops where the fragments are abundant and are often up to 10 millimeters across. Few of the fossils, however, are well preserved, and they appear to have been fragmented prior to deposition. The matrix of these fossiliferous interbeds is coarse grained, gray limestone.

In the outcrops lacking fossils, Unit 6b is a thin to thick bedded, light gray weathering, dark gray limestone. Grain size is small enough to call the rock a micrite. In two outcrops, a fine lamination is visible on fresh surfaces, showing distinct alternating layers of light gray and dark gray material. As with Unit 5, these laminations could be remnants of algal mats.

According to the outcrop constraints, the thickness of Unit 6b is 15 to 20 meters. Although neither the upper nor lower contact are exposed in the study area, this figure falls within Fisher's (1977) measurement range of 8 to 41 meters.

2.7.3. Unit 6c *Providence Island Dolostone*

Unit 6c in the Benson area can be correlated to the Providence Island Dolostone first named by Ulrich in 1938. On the Vermont Centennial Map (Doll et al., 1961), it is referred to as the Bridport Dolostone. Due to lack of fossils in this unit, the age of medial Ordovician must be inferred from its stratigraphic position.

In the undeformed, western portion of the map area, there is one outcrop of Unit 6c where it is interpreted to conformably overlie Unit 6b. This outcrop is small, however, and offers little opportunity to examine the lithology of this unit. Here the rock is a fine grained, light gray dolostone with buff weathering. Incipient joints have been eroded on the bedding plane to create a characteristic "egg carton" relief.

The majority of the rocks of this formation are exposed in the eastern deformed zone, where the effects of strain of the lithology are significant and lead me to designate this sub-member as **Unit 6cT**. The outcrops in this portion show a fine grained, thin to medium bedded, gray to dark gray dolostone that weathers yellowish brown. Joint sets that intersect at approximately 45° and are oriented perpendicular to bedding remain the most prominent feature, and they are assumed to be a result of transport. These joint sets give the rock a "scarified" appearance, and they were used as an identifying feature. No internal sedimentary structures are visible. ***(Figure 2.6.).***

Shaw Mountain, which at 700 feet is the highest elevation in the field area, is interpreted to be composed almost entirely of Unit 6c. Previous estimates of the thickness of this unit range from zero to 60 meters (Ulrich, 1938; Fisher, 1984), but thickness determinations in my field area are made difficult by the deformed nature of these rocks.

Figure 2.6. This outcrop of Unit 6cT (transported Providence Island Dolostone) is exposed on the eastern shore of Root Pond. Note the intersecting joint sets oriented perpendicular to bedding.

Based on the exposure at Shaw Mountain, I have adopted a thickness value of 80 to 100 meters for construction of my map and cross sections. However, this value may be an overestimate due to possible repetition of the unit during transport. In addition, I may have incorrectly identified this transported lithology as Unit 6c when it actually originated farther down in the stratigraphic column.

2.8. Unit 7 *Middlebury Limestone*

Unit 7 is equivalent to the Middlebury Limestone (Cady, 1945), and the Chazy Limestones found on the western side of the Champlain and Orwell Thrusts in the Northern Champlain Valley where they unconformably overlie the Providence Island Dolostone. The outcrops of this unit in the field area are within the deformed zone where tectonic activity has influenced the observed lithology. Due to the effects of transport, the field data may not yield a complete stratigraphic description for these rocks.

Unit 7 is a fine grained, dark gray, blue-gray weathering, clay-rich limestone. Due to the strained nature of these rocks, no fossils were detected and bedding was not discernible. The most prominent feature was the gently dipping cleavage, although the characteristic centimeter-thick calcite veins were observed in some outcrops ***(figure 2.7.)***. Steinhardt has estimated the thickness of the Middlebury Limestone to be 100 meters in the West Haven, Vermont area, and I choose to agree with this value because the contacts of this lithology in my area are all of a tectonic nature. The age of medial Ordovician, derived from fossil dating, was taken from the literature (Welby, 1961).

Figure 2.7. Outcrop picture of Unit 7 (Middlebury Limestone) depicting calcite veins and gently dipping cleavage.

Figure 2.8. This outcrop of Unit 8 (Isle La Motte Limestone) is exposed south of Money Hole Road. The distinct cleavage in this unit makes it difficult to distinguish from the underlying unit (see figure 2.7).

2.9. Unit 8 *Isle LaMotte Limestone*

The Orwell Limestone (Cady, 1945) and Isle LaMotte Limestone (Emmons, 1842; Fisher, 1984) are equivalent to Unit 8. Rocks of this lithology were recorded only in the deformed zone of the map area, and strain due to transport may have altered some features. As observed, it is a fine grained, dark gray, light gray weathering, massive limestone which conformably overlies Unit 7. A distinct cleavage has been developed in the rocks in my field area, making it extremely difficult to distinguish from the underlying Unit 7 and adding the possibility of incorrect identification ***(figure 2.8.)***.

The lower contact of this unit is tectonic, and therefore, an accurate stratigraphic thickness can not be determined. It appears to be at least 15 meters thick, and this estimate coincides with Fisher's (1985) value of 0 to 20 meters. Welby (1961) reports the age of the unit as late-medial Ordovician.

2.10. Unit 9 *Glens Falls Limestone*

Unit 9 is a thin bedded, medium grained, light gray weathering, dark gray limestone. Shaley interbeds up to 10 centimeters in thickness, as well as a shaley cleavage, are the most characteristic features used for field identification. Due to similarities in lithological description and stratigraphic location, I believe this unit corresponds to the Glens Falls Limestone (Ruedemann, 1912) described by Cady (1945). It overlies Unit 8 conformably.

Where this unit is observed in the study area, the apparent thickness is 10 meters. This is most likely an underestimate, however, because the upper contact is tectonic in nature. According to the literature, the true thickness value is from 21 to 35 meters.

Examination of fossils found outside the field area has led to the determination of late-medial Ordovician age (Fisher, 1984).

Unit 9-def., a fine grained, light gray weathering, dark gray to black shaley limestone, is interpreted as the deformed and highly transported counterpart to Unit 9. This lithology is found within the leading thrust slice in the deformed zone of the map area. The observed thickness of approximately 45 meters is probably not accurate due to the effects of thrusting and possible repetition of strata. This figure represents the structural, rather than the stratigraphic, thickness. The well-developed slaty cleavage is the dominant feature *(figure 2.9.)*.

2.11. Unit 10 *Hortonville Shale*

Unit 10 has been given a variety of labels in the past. In New York State, the Snake Hill Shale (Rickard and Fisher, 1973), Utica Shale, and Canajoharie Phyllite (Bain, 1959) refer to rocks of similar stratigraphic position and age. The coarser grained versions are called Austin Glen or Normanskill Graywacke. The name Ira Formation was introduced by Thompson (1959) and used by Zen (1964). The Vermont Centennial Map (Doll et al., 1961) adopted the name Hortonville Shale (Keith, 1932) to describe the formation which occupies the majority of my field area.

In much of the map area, this unit is a black phyllite or slate which weathers greenish to brown and overlies the autochthonous shelf carbonates. The dark color may be due to the high content of organic matter, and this color varies locally from black to gray

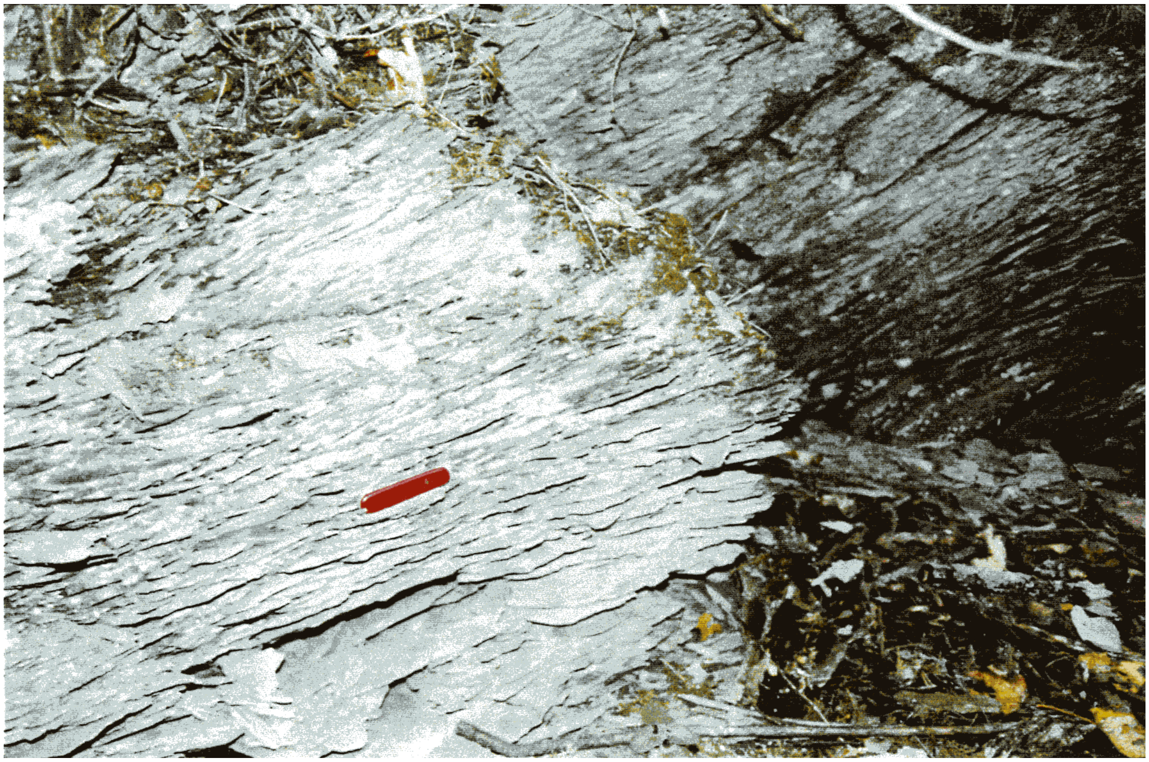


Figure 2.9. Outcrop picture of Unit 9-def. (deformed Glens Falls Limestone). This unit is exposed within the leading thrust slice in the field area. Note the well-developed slaty cleavage.

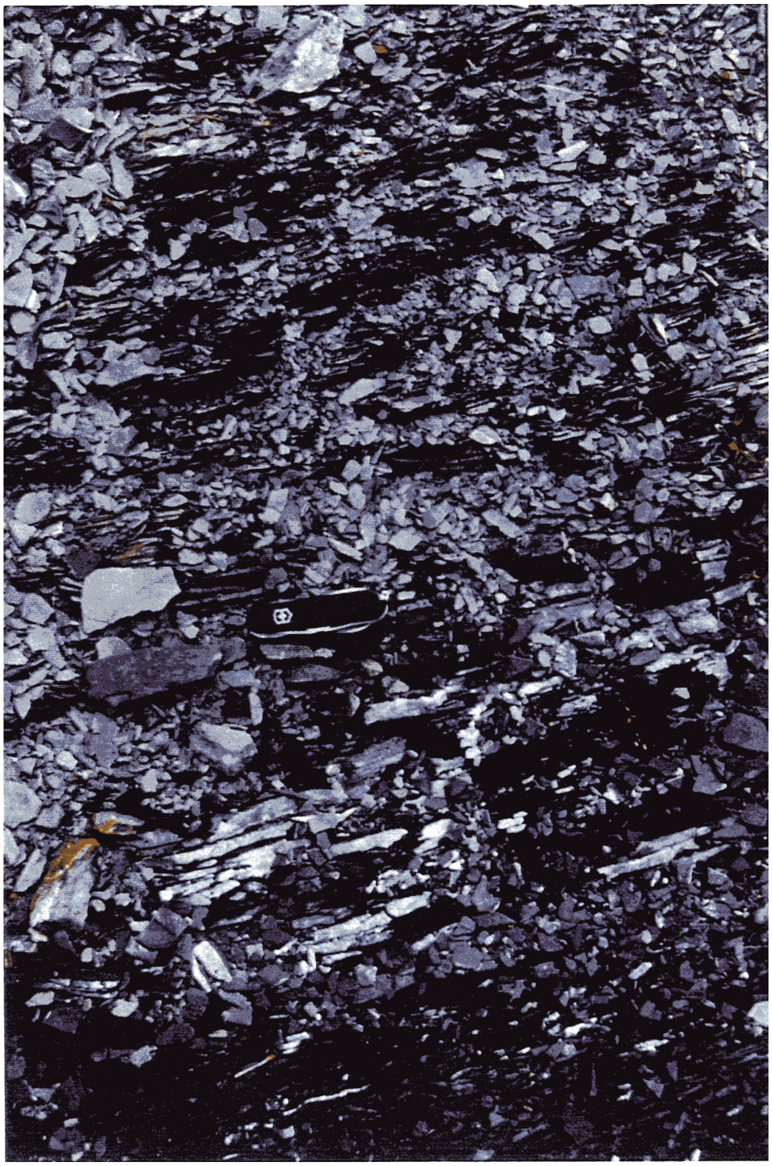


Figure 2.10. This outcrop picture, taken in the Root Pond Quarry, shows the varying color of Unit 10 (Hortonville Shale). The different colors may be due to changes in organic matter content.

Figure 2.11. Outcrop picture of well-developed cleavage and chevron folds in Unit 10, observed in the Root Pond Quarry. This internal deformation obviously makes these rocks unsuitable for roofing slates.

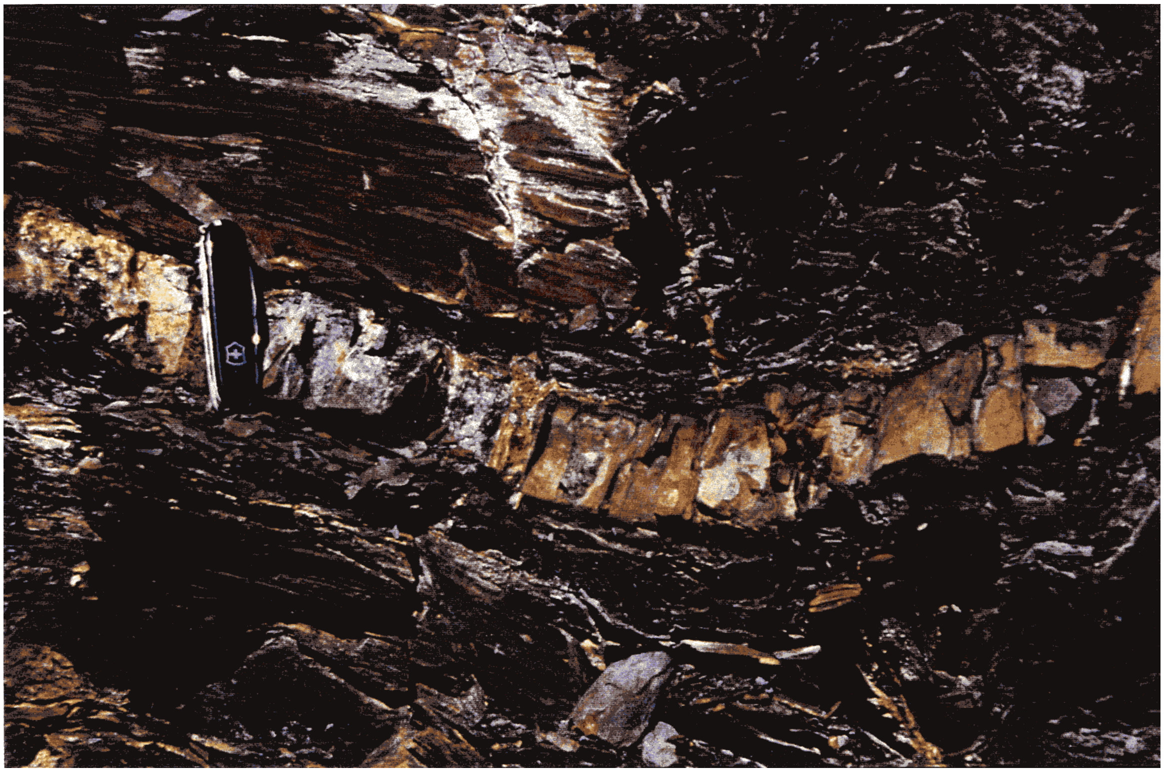


Figure 2.12. The calcareous portion of Unit 10, found in the zone closest to the underlying carbonates, may be a result of tectonic mixing below the basal thrust. This outcrop , exposed at the Lake Road Quarry, displays a 5 centimeter bed of limestone.

(figure 2.10.). On cleavage planes, occasional small pyrite crystals are visible, as well as a purple sheen caused by manganese oxides and hydroxides (Steinhardt, 1983).

The rocks display a well-developed slaty cleavage which is often irregular and changes orientation frequently, thus making the rocks unsuitable for roofing slates. The only economic value of this unit is as fill for roads and driveways. Internal deformation is extensive within the slates, and this is manifested in numerous small chevron folds and minor faults, visible in several quarries in the Benson and West Haven Area ***(figure 2.11.).***

The zone of Unit 10 closest to the underlying carbonates contains a small degree of calcareous component, just enough to cause a reaction with a standard dilute solution of hydrochloric acid. One outcrop even displays a 5 centimeter bed of limestone ***(figure 2.12.).*** It is in this zone that internal deformation is most intense, leading to the idea this unit was tectonically mixed with carbonates below the basal thrust (Steinhardt, 1983). Another possibility is that this leading edge portrays a gradational contact between the calcareous material deposited on the distal slope and the organic-rich mud syn-orogenically accumulated in the foreland basin.

Determining the age of this formation is virtually impossible due to the scarcity of fossils and their destruction during deformation. Thompson (1967) has assigned an age of medial Ordovician based on fossils found in limestones thought to be associated with the Hortonville in the Pawlet Quadrangle of Vermont. The location of Unit 10 above Unit 9 in this apparent stratigraphic sequence is not truly correct, as fossil evidense suggests this unit formed, in a deeper marine setting, concurrently with Units 6 through 9 (Thompson, 1967; Fisher, 1984). In addition, this lithology may include some material from the Taconic sequence which has been transported even farther than the rest of Unit 10. The distinction between Unit 10 and lithologies belonging to the Taconic Allochthon has been easily confused and misinterpreted by previous workers (Zen, 1964; Bierbrauer, 1990).

An accurate thickness measurement of Unit 10 is not feasible because the tectonic reworking of the strata has altered the sequence. In addition, due to structural relationships discussed further in Chapter 3, I believe the lower contact of this unit in the Benson area is tectonic, thus making a vertical thickness determination impossible to obtain. The structural vertical extent in the field is roughly 600 to 650 meters.

2.12. Unit 11 *Taconic Allochthon*

The allochthonous strata of the Taconic sequence are undifferentiated on my field map. They are exposed only in the far eastern section of the Benson area where they include shales, argillites, and slates emplaced on the underlying units. The characteristic green, green-gray, and green-purple color was used to distinguish these rocks from those of Unit 10. Their deposition spans the late Cambrian and early Ordovician (summary in Fisher, 1984), although which part of this interval is represented in the map area is unknown. Thickness determinations are impracticable owing to intense deformation and probable repetition.

2.13. Age and Depositional Environments of Lithologic Units

Due to the paucity of outcrop in the Benson area, I often had to refer to the literature to determine the depositional environment of each unit. Previous workers (Brainerd & Seely, 1890; Rodgers, 1937; Cady, 1945; Welby, 1961; Thompson & Theokritoff, 1969; and Fisher, 1977 and 1984) have documented the occurrence of fossils in several formations which can be correlated to the units found in my field area. From detailed study of these fossils, they proposed ages for each formation. In addition to analyzing fossils, they also examined sedimentary structures such as bedding, lamination, cross-bedding, and grain size, as well as chemical composition, in order to ascertain the depositional environment of each lithology. With increased knowledge of the tectonic history of the area (discussed further in Chapter 4), geologists can link depositional environment information to the phases of tectonic evolution. The following section is intended as a summary of depositional environments of each unit in the field area. For a more complete account, one should refer to the studies cited.

Deposited unconformably on the Grenvillian basement, the carbonates and clastics of **Units 1 through 3** have been assigned an age of late Cambrian (Brainerd & Seely, 1890; Rodgers, 1937). Due to fossils found outside the field area and sedimentary characteristics, the corresponding Potsdam Sandstone, Ticonderoga Formation, and Whitehall formation are inferred to be products of deposition in a shallow marine environment.

Evidence such as crossbedding in Unit 4a, lateral thickness variation of carbonates, and fossils found outside the field area (Fisher, 1984) suggests **Unit 4** was deposited in a shallow marine environment during the early Ordovician.

Laminations found in **Unit 5** have been interpreted by Mazullo and Friedman (1977) as a build-up of algal mats in a supratidal, hypersaline environment. They offer their discovery of desiccation cracks and curled polygonal clasts as supportive evidence for this theory. According to them, the dark gray laminae represent organic rich remainders of the algal filaments.

The depositional environment of **Unit 6** is certainly shallow marine, and intertidal for Unit 6b. In support of this hypothesis, I offer the following facts:

- The crossbedded strata within Unit 6a suggest possible wave action or preferential deposition of material due to currents.
- The algal mat laminations within Unit 6b imply that these rocks formed in an intertidal position on a shore.
- The fossils within Unit 6b were possibly fragmented by wave action and then deposited in layers by storm surges.

- Fossils identified by Fisher (1984) outside the field area are indicative of a shallow marine deposition environment.

Fossil examination by Welby (1961), suggests both **Unit 7 and Unit 8** were deposited in a subtidal marine environment during the middle Ordovician.

As inferred from the presence of shale layers, **Unit 9** represents a period of deepening water at the time of deposition, as well as the diachronous migration of its facies westward due to tectonic thrust loading of the former passive margin of North America (Rowley & Kidd, 1981). Abundant fossils found in this lithology outside my map area support the theory that it is a distal subtidal shelf deposit formed during the late-middle Ordovician.

Fossil evidence found in limestone layers possibly associated with **Unit 10** suggests this lithology formed concurrently with Units 6 through 9 (Thompson, 1967; Fisher, 1984). These mudrocks are likely the product of deposition in a deeper marine setting.

Graptolites and other fossils detected in the black Taconic slates outside the Benson area suggest the slope/rise deposition of **Unit 11** spans the late Cambrian and early Ordovician (Fisher, 1984) but may also include the medial Ordovician.

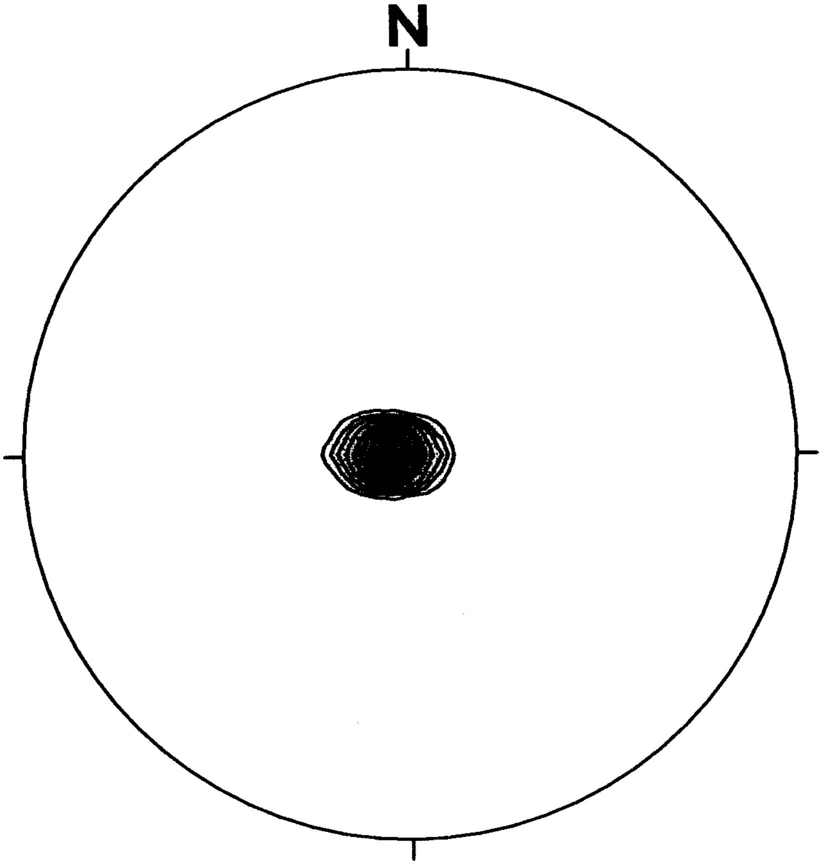
3. Structure

3.1. Introduction

This study was undertaken for the primary purpose of investigating structural features. Specifically, my aim is to clarify the nature and amount of deformation of rocks immediately underlying the Taconic Allochthon. As mentioned previously, the proximity of the Taconic Allochthon to the autochthonous basement of the Adirondacks makes this area especially promising for attaining my goals. In this exploration, I limited my study to macroscopic features.

My most simple observation led me to divide the field area into two domains — the Western Undeformed Zone and the Eastern Deformed Zone. The boundary between the two is defined by the major north-south striking normal fault shown on the map as the Lighthouse Fault ***(Plate 1)***. The rocks in the Western Undeformed Zone are mostly flat lying or, locally, dip less than 10°, and they appear not to have been transported, whereas the rocks in the Eastern Deformed Zone generally dip more than 10° and show the well-developed cleavage or fracture patterns typical of transported material. These zones, however, are used only as descriptive terms; they neither exclude the presence of deformation in the west nor rule out the local absence of deformation in the east. Stereonet plots of strike and dip data for the Western Undeformed Zone, the Eastern Deformed Zone, and the shale reveal the preferred orientation of the bedding and cleavage ***(figure 3.1. a, b, c)***.

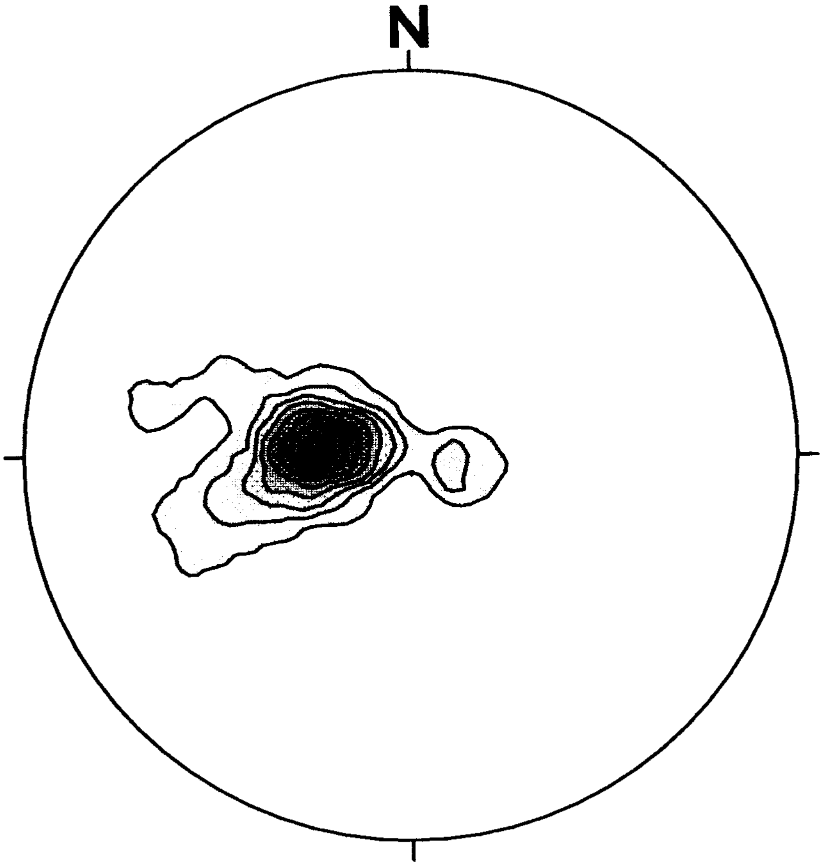
***Figure 3.1.* Stereonet plots of the zones in the field area. Data is expressed in contours of the poles.**



n = 41

(a) Bedding in the Western Undeformed Zone.

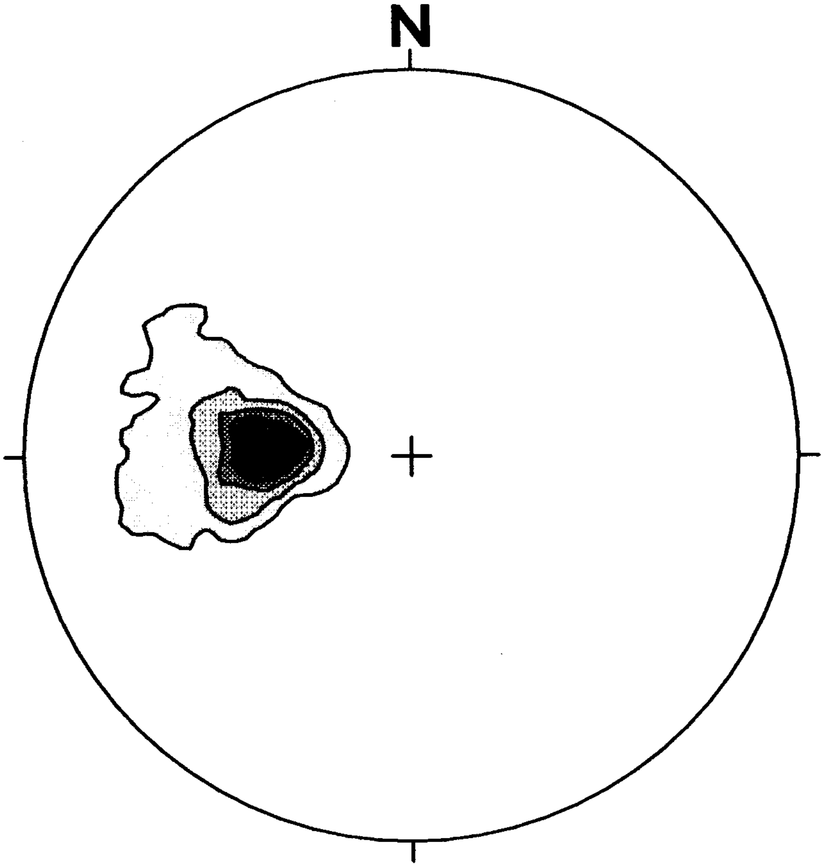
Figure 3.1. **Stereonet plots of the zones in the field area. Data is expressed in contours of the poles.**



n = 111

(b) Bedding in the Eastern Deformed Zone.

Figure 3.1. **Stereonet plots of the zones in the field area. Data is expressed in contours of the poles.**



n = 55

(c) Cleavage in the shales in the Eastern Deformed Zone.

3.2. Structures in Different Lithologies

General structural features vary remarkably from one lithology to another, and it is necessary to note these differences before continuing to analyze the rocks in detail. The contrast in outcrop structures between carbonates and shales is the most striking, but there is also a distinction between structures of limestones and dolostones. These differences express themselves in both primary and secondary structures.

Bedding is seldom prominent in the shales and slates, thus making cleavage the dominant planar structure in these lithologies. In addition, this cleavage orientation may vary widely over any given outcrop due to folding and internal deformation. Where bedding in shales is detected, it is only discerned where layers of coarser grain size exist. Differential weathering and color changes denote the compositional variation in these beds, but they are rarely traceable even over a single outcrop.

Bedding in the carbonates, however, is the dominant feature and usually can be traced easily. This primary structure is only overprinted by cleavage or fractures in highly strained zones close to faults or folds or in transported material. Other primary structures, such as cross bedding, algal laminations, fossil layers, and grains and cement, are often well preserved in the less deformed outcrops. In dolostones, joints and fractures tend to be prominent planar features, particularly in the poorly bedded or massive outcrops.

3.3. Faults

Faults are the most prominent structural feature in the field area, and their profound influence on the topography is rivaled only by the influence of glaciation. The significant effect of faults on the land was used as one tactic for identifying their location. In addition, the juxtaposition of some different lithologies and other unusual field relationships can be explained only by fault contacts. Both low-angle and high-angle faults are present in the Benson area, although there appears (not surprisingly) to be more fault influence in the Eastern Deformed Zone than in the Western Undeformed Zone. For the purposes of this investigation, the numerous faults within the transported slates of Unit 10 and the Taconic Allochthon are not discussed in detail.

3.3.1. Thrust Faults

In the field area, thrust faults are demonstrated only in the Eastern Deformed Zone where they are detected either by the contact of an older lithology over stratigraphically younger rocks or by the intensely cleaved or fractured nature of transported material on and near the fault.

The **Root Pond Thrust** is an example of the former kind of thrust. Just southeast of Root Pond, the late Cambrian, quartz-rich sediments of Unit 1 lie structurally above the early Ordovician dolostones of Unit 6 in a lens of quartzite dubbed Unit 1-def. Just south of Shaw Mountain, another lens of Unit 1-def is exposed above a thrusted lens of limestone. The thickness of this carbonate is 2 to 3 meters and is presumed to be a portion of Unit 7. However, due to the lithologic similarities of Units 7 through 9, this interpretation may be incorrect. Unfortunately, the fault itself is not exposed in these locations.

The **Forbes Hill Thrust**, found at the base of Forbes Hill, places the carbonates of Unit 6 over the shales of Unit 10. The difference in resistance to weathering of these lithologies has created a westward-facing ledge 45 meters high. The outcrop pattern in the Forbes Hill area constrains this fault as low-angle. In support of my conclusion that this contact is a thrust fault, I offer the following observations:

- Structure and stratigraphy are discontinuous at the contact; bedding in the carbonates is cross-cut (Steinhardt, 1983), cleavage in the underlying shales mimics that of the carbonates, and the carbonates are known to be older than the underlying shale.

- The shale/carbonate contact on the eastern side is not exposed and has not formed a ledge (Steinhardt, 1983).
- Cleavage traces of the overlying limestones and dolostones dip steeply (≈50° to 60°) to the east, and the cleavage strike changes from north-south to northeast-southwest, paralleling the contact between carbonates and shales. The consistent steep dip and swing of strike suggest the failure of these rocks in a regular way due to a directional stress field.
- This field area is adjacent to the Taconic Frontal Thrust, a major thrust along which there has been significant east over west movement during a period following the middle Ordovician deposition of limestones in the Benson area (Bosworth et al., 1985). The proximity to the Taconic Frontal Thrust leads me to suggest the possibility of east over west movement along thrust horizons in this area.
- As previously mentioned, the shales underlying the carbonates on the western side of Forbes Hill are known to be younger than the carbonates (Welby, 1961; Zen, 1967; Fisher, 1984). Emplacement of carbonates above these younger shales requires movement up section, which in turn involves thrusting (e.g. Hobbs, Means, and Williams, 1976).

The **Temple Road Thrust (TRT)** is seen where a slice of the shaley limestone of Unit 9-def has been placed over the carbonates of Units 4 through 6. Because limestones and dolostones weather similarly, faults within carbonates do not have the distinct effect on topography that faults between shales and carbonates do. The presence of a thrust has been interpreted based on the following factors:

- No primary sedimentary structures are visible in Unit 9-def, and it displays the well-developed cleavage of highly transported material ***(figure 3.2.)***. This

Figure 3.2. Outcrop picture of Unit 9-def depicting well-developed cleavage of this shaly limestone. This unit is exposed above the Temple Road Thrust, directly northwest of Shaw Mountain.

planar feature consistently dips steeply to the east at 60° to 80°, and the strike swings, going north through the field area, from northwest-southeast to northeast-southwest . I believe the former strike denotes the strike of the thrust. However, according to my interpretation, the thrust is truncated by later normal faulting (discussed in the following section), and this may have altered the orientation of Unit 9-def's cleavage.

- The underlying rocks of Units 4 through 6 have dip angles no greater than 20°, and the extrapolated bedding of these lithologies is cut by the fault.
- The east over west sense of movement of the Taconic Basal Thrust leads me to suggest the same kind of movement on this fault.

Because this fault places younger limestones above older carbonates (largely dolostones), it has been suggested that the contact might alternatively be a low-angle normal fault. Although this contact may represent a connection with pre-thrust normal faulting (discussed further in Chapter 4), I believe it is a thrust fault for the following reasons:

- Exposure along this fault to the north of the field area shows clear indicators of east-over-west sense of shear in folds in the carbonates underlying the Glens Falls Formation (Unit 9-def). This evidence led Coney et al. (1972) to conclude the contact with the shaley limestones is a thrust, which they dubbed the St. George's Thrust. I believe this structure can be directly correlated to the Temple Road Thrust.
- To the south of the field area, Steinhardt (1983) has noted the local absence of shaley limestone in the zone beneath the transported dolostones of Unit 6cT. This could be explained by possible ramping of the Temple Road Thrust over pre-existing structures in the underlying strata (discussed further in section 3.4.).

- In addition, evidence of strain in the strata beneath the Comstock Fault in the Whitehall area (Fisher, 1984) suggests the presense of other thrusts in this zone (Kidd, personal communication, 1995).

Unit 9-def is overlain by another carbonate thrust slice that may have affected the features in the underlying limestone during emplacement. The **Shaw Mountain Thrust (SMT)** has transported the dolostones of Unit 6cT to a position above the younger limestones of Unit 9-def. As evidence of this thrust I offer the following arguments:

- The dolostone outcrops above the contact with Unit 9-def show the exaggerated "scarified" fracture pattern often seen in transported sections of the Providence Island Dolostone (Unit 6cT) (Steinhardt, 1983).
- Unit 6cT is stratigraphically older than the limestones of Unit 9-def. In order to place Unit 6cT over Unit 9-def, thrusting is most likely necessary.
- The pronounced cleavage of Unit 9-def (mentioned previously) could be due, in part, to the emplacement of a thrust slice above the limestone.
- 2.5 kilometers north of the field area, the contact between transported dolostone and shaley limestone is seen along the shore of Lake Champlain in Benson Bay and at the base of Blue Ledge, where it crosscuts the cleavage of Unit 9-def and bedding of Unit 6cT. It has been mapped as a thrust fault by previous workers (John Waechter, Greg Young, Eryn Klosko, and Bob O'Brien) under the advice of W. S. F. Kidd (personal communication, 1995). I believe this is the northern extension of the Shaw Mountain Thrust.
- Outcrop identification on and south of Shaw Mountain has led to a map pattern that closely follows topography, suggesting a low angle fault.
- As stated above, the regional geology suggests east over west movement along low angle faults in this area.

The **Money Hole Thrust Faults** are partially responsible for the complicated and perplexing field relationships observed in the Money Hole Duplex. The duplex is composed of a zone of imbricate slices, as well as several carbonate and shale slices separated by thrust and normal faults. Three prominent faults have placed the older carbonates of Units 8 and 9 over the younger shales of Unit 10. Thrusting is required to achieve this lithic association. In addition, a lens of calcareous shale exposed in a quarry along Lake Road displays the intense folding and inconsistent cleavage orientation indicative of faulted material. Other features associated with the Money Hole Duplex are discussed in greater detail later in this chapter.

Faults within shales and slates were not studied in detail in the Benson area. Due to the lack of markers such as bedding and different lithologies, faults within Unit 10 are difficult to determine on map scale, although they are easily detected and numerous in individual outcrops. Here they are discerned by an interruption in cleavage or the juxtaposition of cleavages with different orientations, meaning the faults must be a structurally younger feature. Although their strike orientation varies widely, the faults consistently dip to the east. This is consistent with the thrusting seen in the carbonates. Because shales generally demonstrate a lower resistance to shear stress than carbonates, it is possible that shear in carbonates occurred on one or two planar surfaces while shear deformation in shales occurred in a wider zone. The small faults seen in outcrops, therefore, are perhaps indicative of larger shear zones within Unit 10.

The **Sunset Lake Thrust**, termed after the fault studied by Zen (1961) in the same location, is found in the northeast corner of my study area and extends northward and eastward outside the mapped region. It is revealed by the juxtaposition of highly transported green Taconic-like slates with the less allochthonous black slates of Unit 10. Cleavage orientation is not altered noticeably across this feature, implying thrusting predates the cleavage. The contact between the two units is not exposed, so fault location is designated only by the change in outcrop lithology.

The Sunset Lake Thrust is possibly equivalent to the Taconic Basal Thrust of Rowley (1980) and Rowley and Kidd (1981), rather than the cleavage truncating Frontal

Thrust which projects north-northeastward outside and east of this field area. However, I think it is more plausible that the Basal Thrust lies below the slates of Unit 10 seen in the map area. The following arguments support this idea:

- As mentioned previously, the cleavage orientation does not change across the contact between the black slates of Unit 10 and the green slates of the Taconics, indicating the Sunset Lake Thrust pre-dates cleavage development.
- The fact that this well-developed slaty cleavage of Unit 10 is virtually identical, in appearance and orientation, to that of Taconic lithologies exposed in and adjacent to the field area suggests a similar directional stress field acted upon all the non-calcareous slates found in the Benson region. This, in turn, implies the black and green slates moved as one "slice."
- Internal deformation is most intense in the calcareous zone of Unit 10 found closest to the underlying carbonates. This led Steinhardt (1983) to propose that this zone represents tectonic mixing between carbonates below and slates above the Basal Thrust.
- Rocks of lithologies equivalent to Unit 10 found in locations outside the field area do not display the well-developed slaty cleavage characteristic of Benson exposures (Welby, 1961; Fisher, 1984).

3.3.2. Normal Faults

Normal faults in the Benson area have been demonstrated in both the Western Undeformed Zone and the Eastern Deformed Zone. In both zones they play a strong role in influencing topography, and this influence has been a deciding factor in locating several faults. In addition to topographical effects, unusual stratigraphic relationships (such as younger rocks juxtaposed structurally adjacent to and above much older rocks) and unusual structural relationships (such as sudden changes in the strike and dip of lithologies) were used as diagnostic tools for determining the location of some normal faults. Unfortunately, I found only two instances where normal faults are exposed in the field area.

In the undeformed zone of the map area, I have proposed two cases of faults evidenced only by topography. The distinct linear nature of the two elongate hills in the central western portion of my field area is unmistakably the work of high angle faulting. The trace of these faults is clearly defined by the northeast-southwest striking troughs between the 30 to 60 meter high sides of the hills and the erosion pattern of the streams entering Lake Champlain. Dotted lines represent these faults on the map ***(Plate 1)***, however, because I have no other definitive evidence for their existence. It is possible these faults are the westward continuation of faults found, with similar orientations, in the Eastern Deformed Zone, although I have no proof of this.

The **Kline Hill Fault**, located in the southwest corner of the map area, strikes northwest-southeast and dips to the north. A stream follows its trace, but the strongest indication for this fault is a change in lithology. Unit 1 is exposed on Kline Hill striking north-south and dipping 10° to the east. One kilometer directly north, however, there is an outcrop of Unit 3. Displacement of roughly 70 to 90 meters along this normal fault is required to meet the constraints of this field relationship.

The two major southwest-northeast striking faults in the Eastern Deformed Zone were described in detail by Steinhardt (1983) in his study of the field area directly south of mine. The **Warren Hollow Fault** marks the southern terminus of my field area, and it is characterized by a deep valley extending over half the width of the field area.

One outcrop of Unit 6b adjacent to the fault shows the effects of faulting on the rocks ***(Plate 1, outcrop 1)***. Here the beds of Unit 6b have been fractured and folded and angular clasts of fault breccia can be seen cemented by sparry calcite (Steinhardt, 1983). In non-faulted zones in the field area, bedding of Unit 6b consistently strikes north-south and dips 15° to 20° to the east. In this outcrop, however, the beds strike northeast-southwest and dip 58° to the north. I believe a likely cause for this displacement of bed orientation is bending by a "fault-drag mechanism" during faulting (Steinhardt, 1983). Assuming the hanging wall is on the northern side, distributed shear near the fault would alter the original orientation of the beds appropriately. Outcrops of Units 4 and 6c adjacent to the fault also display altered bedding orientation consistent with this idea.

The stratigraphic contacts of lithologies adjacent to the Warren Hollow Fault demonstrate an apparent left-lateral offset. Because these contacts dip to the east, this offset also supports the assumption the hanging wall is on the northern side of the fault. Using outcrop data and simple geometry, Steinhardt (1983) has determined a vertical displacement of approximately 200 meters, and I agree with this estimate.

The **Coggman Creek Fault** also strikes northeast-southwest and is expressed as a valley crossing approximately half of the field area. The apparent left-lateral sense of offset is easily determined from the stratigraphic boundaries, although the amount of displacement cannot be established accurately because outcrop is scarce. Unit 4 is exposed on both sides of the fault in contact with itself, suggesting the vertical offset is less than the thickness (55 to 60 meters) of this unit. A collection of outcrops approximately 2 kilometers west of the West Haven Town Center shows the effects of fault movement ***(Plate 1, outcrop 2)***. Distal from faults, bedding of Unit 4 dips to the east or southeast, whereas in this location it dips to the northeast. This change in bedding orientation is probably due to processes similar to those affecting Units 4 and 6 along the Warren Hollow Fault, and it also implies that the hanging wall of the Coggman Creek Fault is on the northern side.

The **Burr Road Faults** are partially responsible for the unusual structural relationships found in the Burr Road Fault System, which is discussed further in section 3.4. Directly west of Shaw Mountain and adjacent to Burr Road, two parallel normal faults have been detected, striking roughly 025° and dipping southeast. The faults demonstrate a significant impact on topography; several northeast-southwest striking cliffs and ridges mark the trace of these faults on the land.

Perhaps the best evidence for the existence of the Burr Road faults is seen in the stratigraphy and structure of the outcrops ***(Plate 1, outcrop 3)***. Traversing from east to west across the Burr Road Fault System, I found the following sequence of outcrops exposed on successive ridges:

- Unit 6b striking north-south and dipping approximately 20° to the east.
- Unit 5 striking roughly 034° and dipping 12° to the northwest.
- Unit 6b in the same orientation as the previous unit.
- Unit 5 striking roughly 026° and dipping 11° to the northwest.
- Unit 6b in the same orientation as the previous unit.

In order to achieve the above field relationships, faulting is necessary. A fault between the first two units viewed here, with the down-thrown side on the east, would account for the immediate change in the orientations of the units. Another normal fault between the third and fourth outcrop mentioned above, with the hanging wall again on the east side, would result in the repetition of the stratigraphic sequence and the juxtaposition of an older unit over a younger one. Vertical displacement along the Burr Road Faults is about 30 meters apiece.

The **Stony Point Fault**, named for the school located directly south of it and the jut of land on the lake shore directly north of it, strikes roughly northwest-southeast and has contributed to the erosion pattern of a stream entering Lake Champlain. The apparent sinistral sense of offset is clearly determined by the shift of the Shaw Mountain Thrust across the fault boundary. Because this thrust already has been determined to dip to the east, I have concluded that the hanging wall is on the northern side. An accurate value for vertical displacement is nearly impossible to attain due to the complicated structural relationships and poor outcrop in this portion of the field area. My rough estimate of total vertical movement on the fault is approximately 100 meters.

The **Benson Landing Fault**, labeled for the boat landing approximately one kilometer northwest of it, strikes 050° and runs through a narrow valley with steep cliffs on both sides. This fault marks the contact of Unit 9-def with the underlying dolostones of Units 4b and 5, implying that Units 6 through 8 have been "skipped". This stratigraphic configuration could be accomplished either by low- or high-angle faulting. According to outcrop constraints, the northern contact dips too steeply (>60°) to the southeast to be considered a thrust fault. Assuming normal faulting, the hanging wall must be on the southeast side in order to juxtapose Unit 9-def and Unit 4b. The well-developed cleavage of Unit 9-def is aligned parallel to this fault, suggesting post-thrust normal faulting altered cleavage orientation. Vertical displacement is troublesome to determine owing to the disturbance of stratigraphy by the surrounding faults.

Titled after the road running perpendicular to them, the **Money Hole Faults** are responsible for the confusing structural relationships of the rocks in the Money Hole Duplex, which is discussed further in section 3.3. The duplex is bounded on each side by major normal faults which are discussed later in this chapter. The Money Hole faults, striking roughly north-south, lie parallel to each other in a zone 0.5 kilometers wide and approximately 4.25 kilometers long. Their trace on the topography is noticeable but not pronounced. The strongest evidence for their presence is the lithologic changes observed in outcrops while traversing the duplex from west to east. The following are average cleavage orientations taken from several outcrops:

- Unit 7, striking 005° and dipping 24° east.
- Unit 10, striking 356° and dipping 24° east.
- Unit 8, striking 350° and dipping 29° east.
- Unit 10, striking 005° and dipping 55° east.
- Unit 9, striking 340° and dipping 35° east.

Using my established stratigraphic constraints and being guided by the changes in cleavage orientations, I have ascertained the location of one normal fault and three thrust faults. In order to explain the juxtaposition of the younger Unit 10 with the older carbonates of Units 7 and 8, normal faulting is required. As mentioned previously, thrust faulting is necessary to account for the placement of the older limestones of Units 8 and 9 above the younger shales of Unit 10. Due to the complex structure of this duplex and a lack of knowledge of the exact position of Unit 10 in the stratigraphic column, I can not determine an accurate value of vertical displacement along the Money Hole Faults.

The **Benson Fault** is a major feature responsible for placing the slates of Unit 10 above all other rocks in the field area except for the Taconic slates. It strikes roughly north-south, and its trace extends the entire length of my map area. South of Benson, it is offset by the Warren Hollow Fault (Steinhardt, 1983). The effect of this fault on topography is noticeable by the erosion pattern of streams and the shape of ridges, though it is not pronounced. A more definitive indication of the Benson Fault is the structural evidence. In places where outcrop control is good, Unit 10 can be found in close proximity to, and lying above, the older carbonates of Units 6 through 9. This requires down-droping of slates. Therefore, I have interpreted the hanging wall to be on the eastern side of the fault.

Verification of my conclusion came with the discovery of an important outcrop just east of Root Pond ***(Plate 1, outcrop 4)***. In a small stream bed, Dr. Kidd and I located the steeply dipping contact of Unit 10 with Unit 1-def. Although weathering and some soil cover made a precise measurement difficult, I found the contact striking about north-south and dipping 60° to 70° to the east. Cleavage of the overlying slate is parallel to this contact, but bedding of Unit 1-def is truncated by it ***(figure 3.3.)***.

Because an accurate stratigraphic position has not been determined for Unit 10, and because of disruption in the stratigraphic sequence of the underlying units, a vertical displacement value for the Benson Fault can not be ascertained with any certainty. I can safely say, however, that movement along this fault is one of the more recent tectonic occurrences in the field area; it truncates several other faults and is offset only by the Warren Hollow Fault.

According to my interpretation of field evidence, the Benson Fault splits into two faults directly northeast of Root Pond. Both faults continue to strike generally north-south,

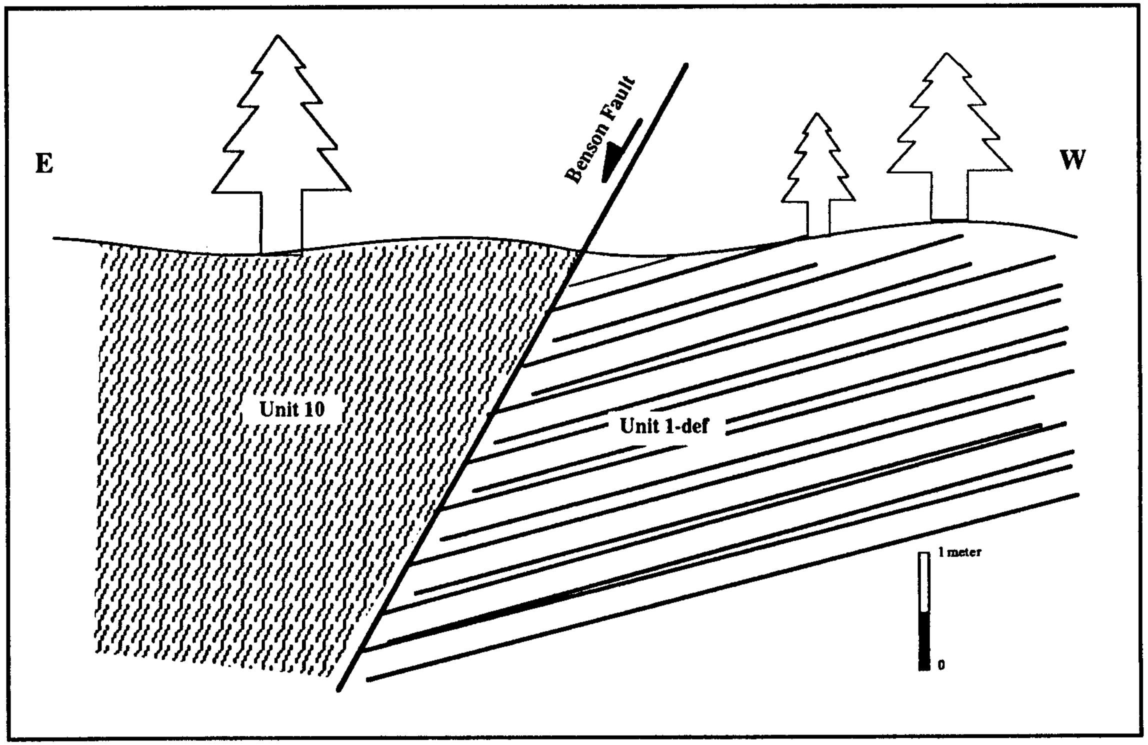


Figure 3.3. **Schematic diagram of stream bed exposure of Benson Fault. Note cleavage orientation of Unit 10 is parallel to the fault, while bedding of Unit 1-def is truncated.**

and they define the boundaries of the Money Hole Duplex. The western arm of the fault is clearly seen in an outcrop along Money Hole Road ***(Plate 1, outcrop 5)*** where Unit 7 is underlain by the transported dolostones of Unit 6cT. The two faults appear to converge again at the northern edge of the map area.

The **Lighthouse Fault**, named for the beacon on the edge of Lake Champlain, is the most prominent fault in my study area. I have used it to define the border between the Western Undeformed Zone and the Eastern Deformed Zone; virtually all units to the west of this fault dip less than 10°, and virtually all units to the east of it dip more than 10°. This evidence alone suggests the existence of a fault, but there are other supporting factors:

- The linear trace of this feature on topography strongly implies the presence of a high-angle fault.
- In several locations, the early Ordovician lithologies of Unit 3 in the west are found in close proximity to the older carbonates of Units 5 and 6 in the east, implying the hanging wall is on the eastern side.
- The angular clasts of fault breccia are found in an outcrop marking the fault contact ***(Plate 1, outcrop 6)***. The fault breccia in this location is among the strongest evidence I have for any of the faults in my area ***(figure 3.4.)***.

The Lighthouse Fault strikes roughly north-south and extends almost the entire length of the field area. In the northern section of the map, the fault continues into Lake Champlain. Because this fault truncates all other faults with which it comes in contact, I have assumed it represents the most recent tectonic activity in the Benson area. Estimates derived from outcrop data yield a vertical displacement value of about 150 meters for the Lighthouse Fault.

Figure 3.4. Angular clasts of fault breccia cited as evidence for the existence of the Lighthouse Fault.

3.3.3. Other Possibilities

Descriptions of faults mentioned above are only applicable to my preferred interpretation of field data. Of course, a variety of interpretations of the same data do exist. Therefore, I now discuss four other possibilities for the observed outcrop pattern in the critical northwest corner of the study area. In addition, I explain and support my reasoning for the fault arrangement I choose.

My **Favored Interpretation** is shown in the schematic diagram of ***figure 3.5.a***. The Lighthouse Fault strikes north-south with the hanging wall on the east side. The Benson Landing Fault strikes roughly 050° with the hanging wall on the southeast side, and it is truncated by the Lighthouse Fault to the west and truncates the Shaw Mountain Thrust to the east. The Shaw Mountain Thrust, striking generally north-south, is apparently sinistrally offset by the Stony Point Fault, which strikes northwest-southeast. The northern extension of the Shaw Mountain Thrust continues along the edge of Lake Champlain at an elevation of approximately 200 feet.

In support of my interpretation, I submit the following summary of evidence:

- All strata to the west of the Lighthouse Fault are either flat lying or dip less than 10°, while virtually all strata to the east of the fault dip more than 10°.
- The Benson Landing Fault is constrained by outcrop in the Benson Landing Brook valley to be a high-angle fault parallel to the cleavage orientation of the overlying unit.
- Directly north of the chert-rich outcrops of Unit 5 are outcrops of the scarified dolostone of Unit 6cT. To satisfy these exposure parameters, there must be a fault, located about where I have drawn the Stony Point Fault, with its hanging wall on the northern side.
- In Benson Bay, two kilometers north of my field area, the northward continuation of the Shaw Mountain Thrust, termed the Orwell Thrust by Welby

(1961), is found along the shore of Lake Champlain at an elevation of approximately 200 feet. The location of this fault immediately north of the Stony Point Fault corresponds to the elevation seen in Benson Bay.

- The apparent left-lateral offset of the Shaw Mountain Thrust across the Stony Point Fault is consistent with the hanging wall information mentioned earlier.

The **Overridden Block Interpretation** is shown in ***figure 3.5.b***. This version is similar to the previous one with the sole exception of the nature of the Benson Landing Fault. The overridden block theory portrays this fault as a thrust dipping to the southeast, representing the northern continuation of the Temple Road Thrust, which is responsible for placing Unit 9-def over the much older carbonates several kilometers to the south. Although this idea is potentially feasible, the Benson Landing Brook and nearby outcrops constrain the contact to dip steeply. Considering this field data, I do not favor this interpretation.

The **Continuous Thrust Interpretation** was suggested by W.S.F. Kidd prior to my field work (personal communication, 1995) and was used by previous workers (Waechter, O'Brien, both unpublished). This rendition eliminates both the Benson Landing Fault and the Stony Point Fault, and it has the Shaw Mountain Thrust continuing northward uninterrupted *(**figure 3.5.c**)*. The location of the Lighthouse Fault is the same as in the preceding interpretations. In this case, however, the Shaw Mountain Thrust changes elevation down to the west from approximately 300 feet above sea level adjacent to the Benson Landing Brook to about 200 feet above sea level going north towards Benson Bay. I do not favor this idea because:

- Flat lying strata on and south of Stony Point Road are unexplained in this model. Elsewhere in the area, flat strata are only found west of and structurally under the westernmost thrust (namely, the Temple Road Thrust). According to this version, however, flat strata lie above the Shaw Mountain Thrust. Therefore, this occurrence is anomalous in the areal context.

- The dolostone exposed near Stony Point School ***(Plate 1, outcrop 7)*** is not pervasively fractured, and it shows well-preserved burrows and good bedding. Based on my observations elsewhere in the field area, I believe if this lithology was transported by a thrust, preservation of these features and the absence of fracturing within the rock would be unlikely.
- In the same outcrop referred to above, chert nodules are observed on the bedding plane. These nodules are very similar to those found in outcrops of Unit 5 described in the literature and viewed elsewhere in the Benson area. The continuous thrust theory, however, requires this to be an outcrop of Unit 6cT, yet Units 6c and 6cT have never been noted to contain chert nodules or prominent burrows.
- The gentle west dip expected in the western portion where the thrust declines in elevation toward Benson Bay and in the hanging wall rocks is not seen.
- An outcrop of dolostone is located 250 meters east of the northern end of the Lighthouse Fault. According to the constraints of the Continuous Thrust Interpretation, the shaley limestones of Unit 9-def should appear in this area. Thus, additional faults are required to explain the presence of dolostone.
- With outcrops of dolostone and shaley limestone, the thrust is constrained at an elevation of 400 feet on the southeast side of the Benson Landing Brook valley. If there is a thrust at 300 feet or less on the immediate west side of the valley, this interpretation requires the additional presence of a west-down normal fault, within the shaley limestones, striking parallel with the valley.

The third possibility *(figure 3.5.d.)* involves eliminating the northern part of the Lighthouse Fault, and converting the Benson Landing Fault to the northern trace of the Lighthouse Fault, now curving to the northeast, and is therefore dubbed the **Curving Fault Interpretation**. This structural rendering has the Stony Point Fault truncating the Lighthouse Fault and causing the apparent sinistral shift of the Shaw Mountain Thrust.

The obvious problem with this idea is that this creates a stratigraphic dilemma. Outcrop data indicates that Unit 5 is exposed from 300 to 400 feet in elevation near Stony Point School *(Plate 1, outcrop 7; figure 3.5.a)*. In order for this to be true, these rocks must be vertically displaced down 100 to 150 meters compared with the area southwest of Lighthouse Point. Movement this great could be accomplished only by a fault to the west of these outcrops with the hanging wall on the east side, which is what is incorporated in the interpretations shown in *figures 3.5.a* and *3.5.b*.

The fourth possibility is the **Declining Thrust Interpretation**, shown in *figure 3.5.e.* Fault configuration in this version is similar to the arrangement in my preferred interpretation with the exception of the locations of the Stony Point Fault and the northern portion of the Shaw Mountain Thrust. The former has the same orientation and hanging wall, but it has been moved approximately 0.75 kilometers to the north. The latter has been drawn contouring the west side of the prominent hill north of Stony Point School and continuing down elevation north to its observed location in Benson Bay.

This explanation is the most plausible of all the alternative possibilities for fault relationships in the northwest portion of the field area. The changing elevation of the thrust inherent in this interpretation might explain the gentle westward dips of carbonate strata seen in outcrops 1.2 kilometers north of Stony Point School. In addition, numerous outcrops of bedded, gently dipping, or flat lying dolostone have been found on the hill 0.5 kilometers east of Stony Point by various workers. The Declining Thrust Interpretation assigns these dolostones to the non-thrusted zone, which is consistent with findings elsewhere in the field area. However, there are arguments against this idea:

- No outcrop of the shaley limestone of Unit 9-def is seen near Stony Point School or at the base of the hill to the north. Elsewhere in the field area, Unit 9-def is found well exposed at the base of the Shaw Mountain Thrust.
- Placing the Shaw Mountain Thrust to the west of the Stony Point School hill requires that the observed outcrop of Unit 6a be transported. However, this unit has never been noted as part of the Shaw Mountain thrust sheet, in this field area or elsewhere. In addition, the outcrop lacks the cleavage and fracture patterns seen in all other transported dolostones.

Similar to the Declining Thrust Interpretation is the idea of a **Tear-fault or Lateral Ramp Interpretation**, in which the Stony Point Fault is actually a ramp dipping to the north-east. This would produce the apparent sinistral offset of the Shaw Mountain Thrust and suggest north-west directed movement along it. The truncation of footwall rocks inherent in this interpretation, however, is not evidenced further to the north of the field area (Coney et al. (1972). Some properties of a lateral ramp could be duplicated by the upward propagation of a pre-existing normal fault in the footwall rocks. In view of this, I believe it is more likely that the Stony Point Fault is a normal fault.

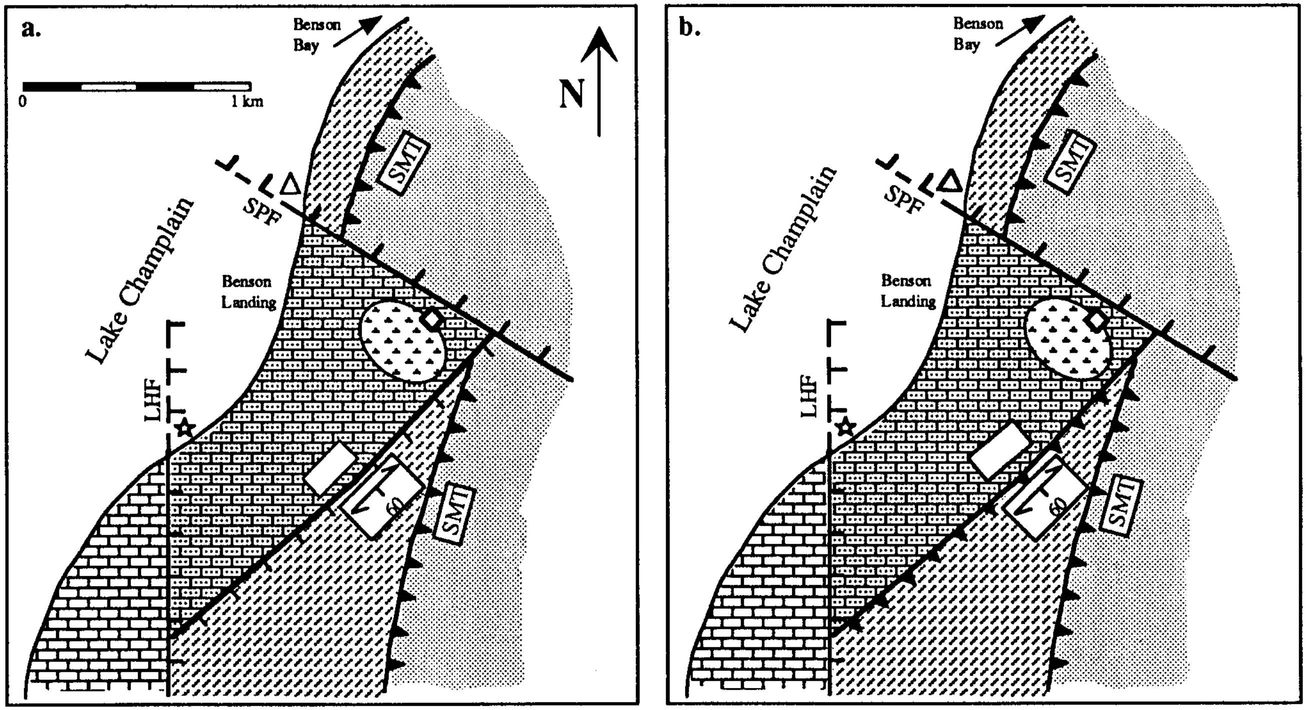


Figure 3.5. **Possibilities for fault interpretation. Preferred Interpretation (a); Overridden Block (b); Continuous Thrust (c); Curved Fault (d); and Declining Thrust (e).**

LHF - Light House Fault
SPF - Stony Point Fault
BLF - Benson Landing Fault
TRT - Temple Road Thrust
SMT - Shaw Mountain Thrust

☆ lighthouse
△ Stony Point
◇ school

▨ Unit 6cT - transported dolostone
▨ Unit 9-def - shaley limestone
▨ outcrops with chert and burrows
▨ Units 4 and 5
▨ Units 3 and 4 - dipping <10°

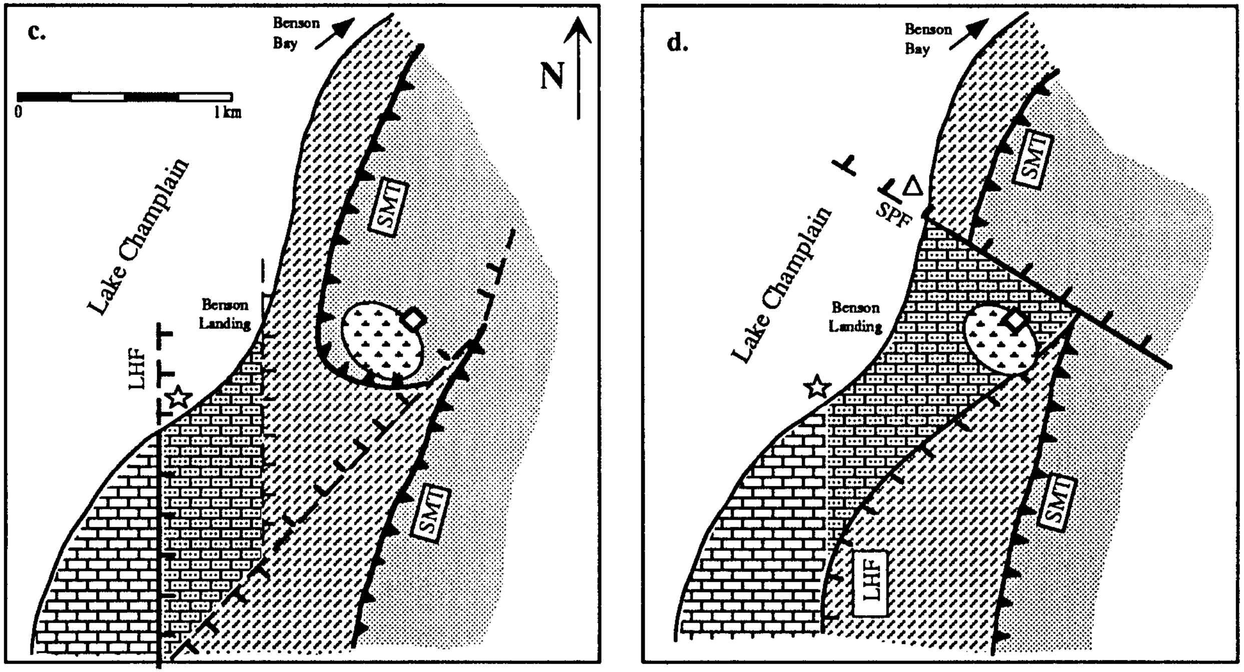


Figure 3.5. **Possibilities for fault interpretation. Preferred Interpretation (a); Overridden Block (b); Continuous Thrust (c); Curved Fault (d); and Declining Thrust (e).**

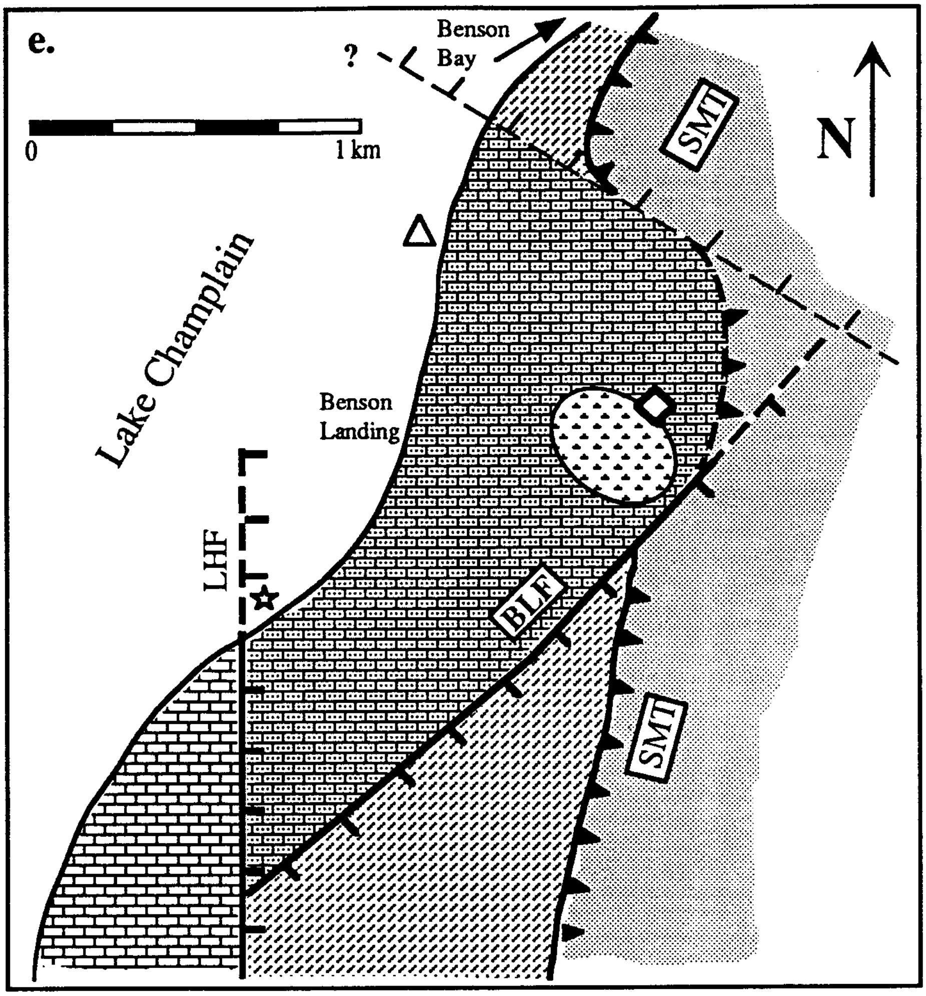


Figure 3.5. **Possibilities for fault interpretation. Preferred Interpretation (a); Overridden Block (b); Continuous Thrust (c); Curved Fault (d); and Declining Thrust (e).**

LHF - Light House Fault
SPF - Stony Point Fault
BLF - Benson Landing Fault
TRT - Temple Road Thrust
SMT - Shaw Mountain Thrust

☆ lighthouse
△ Stony Point
◇ school

▒ Unit 6cT - transported dolostone
▨ Unit 9-def - shaley limestone
⁘ outcrops with chert and burrows
▦ Units 4 and 5
▤ Units 3 and 4 - dipping <10°

3.4. Structural Synthesis

The aim of this section is to summarize the structural components mentioned previously, as well as to establish time and space relationships between them. The geometry of the major structural elements and the structural history of the features in the area are discussed.

The Money Hole Duplex and Burr Road Fault System represent the most complicated and confusing portions of the field area. The relatively simple faulting history sufficient for justifying the structural features observed in the Western Undeformed Zone and much of the Eastern Deformed Zone does not explain the complex relationships found in these two systems. They are discussed here; the nature and timing of the Temple Road Thrust Sheet, the Shaw Mountain Thrust Sheet, and the Forbes Hill Thrust Sheet are also considered in this section.

3.4.1. Money Hole Duplex

The developmental sequence of a thrust belt may promote the sequential development of duplex faults, and these subsidiary faults link the glide horizons of the floor and roof thrusts (Boyer and Elliot, 1982) and imbricate the included shelf sequence. Field data suggests that a duplex underlies Unit 10 and Unit 11. However, faults in the shelf sequence are difficult to recognize, as in many places they juxtapose limestone with limestone.

Identification of the faults within carbonates along Money Hole Road, with the exception of one that is exposed, are based on unusual stratigraphic contacts (detailed in section 3.3.) and on topography. Although the latter does not provide conclusive evidence, the linear traces of troughs and the consistent orientation of most ridges are likely indicators of faults. The stratigraphic contacts denote slices of carbonates and shale which strike roughly north-south with cleavage dipping moderately to the east. The ridges and troughs within Unit 8, however, strike northwest-southeast, and one ridge includes a unit of dolostone which strongly suggests imbrication of strata within this zone. This imbricate belt is relatively small; it is traceable for only 2 kilometers and does not reappear north or south of the field area.

The existence of a propagating shelf duplex under the ascending accretionary wedge of deep water sediments is often geometrically necessary to explain many thrust-and-fold belts (Boyer and Elliot, 1982). In the Benson area, I believe the Taconic Allochthon has overridden the carbonate platform, forming a hinterland-dipping duplex composed of the carbonate sequence and the overlying deep water sediments of Unit 10. This duplex is exposed along Money Hole Road, demonstrated by the occurrence of slices of Units 10, 8, 10, and 9, in that order. Due to lack of knowledge about the exact stratigraphic position of Unit 10 and the transported nature of the carbonates, accurate values for displacement along the faults within the duplex are impossible to obtain. Nevertheless, I have assumed displacement to be comparatively small because the three carbonate units are similar in age and are found conformably overlying one another outside this field area (Fisher, 1984).

The presence of an imbricate shelf sequence implies the existence of a floor thrust and a roof thrust bounding the duplex system. There are several possible locations for the duplex floor thrust. This detachment surface may lie underground, unexposed in the field area due to a combination of original depth and displacement by the down dropping of the major normal faults in the region. Alternatively, the lower décollement surface may be exposed further west as either the Shaw Mountain Thrust or the Temple Road Thrust. Both of these options, though, require a larger duplex than is observed, and they fail to explain why the duplex is not observed in the region north of Benson.

The most reasonable idea for the duplex floor thrust location, I believe, is along the contact between the western-most slice of Unit 10 and overlying Unit 8. Referring back to section 3.3.2., this contact is the first thrust fault observed on a west to east traverse of the

Money Hole Duplex. I suggest this slice of shale represents either the horizon upon which the duplex was transported, or (less plausibly) is a result of down dropping Unit 10 during later normal faulting.

Three conceivable locations exist for the duplex roof thrust. The first idea is that the roof thrust is simply above or below the present day erosion surface and truncated by a normal fault and is therefore unidentifiable. The second possibility is that the roof thrust for the imbricate system is the Taconic Frontal Thrust. This major detachment surface along which the Taconic slates were emplaced is discussed in section 3.3.1. and is believed to lie beneath the eastern portion of Unit 10 exposed in the field area.

I choose to discount both these possibilities because they require a more sizable duplex system than is observed along Money Hole Road. Although the Basal Thrust represents a duplex roof thrust in the Central Vermont Valley (Herrmann, 1992), the shelf duplex viewed there is substantially larger than the one I found in Benson. I propose, instead, that the roof thrust of this duplex is the last thrust in a west to east traverse of the limestones forming the Money Hole Duplex and its immediate surroundings. According to this interpretation, the duplex roof thrust accounts for the juxtaposition of Unit 9 over Unit 10. A schematic representation of the duplex structures is shown in ***figure 3.6.***

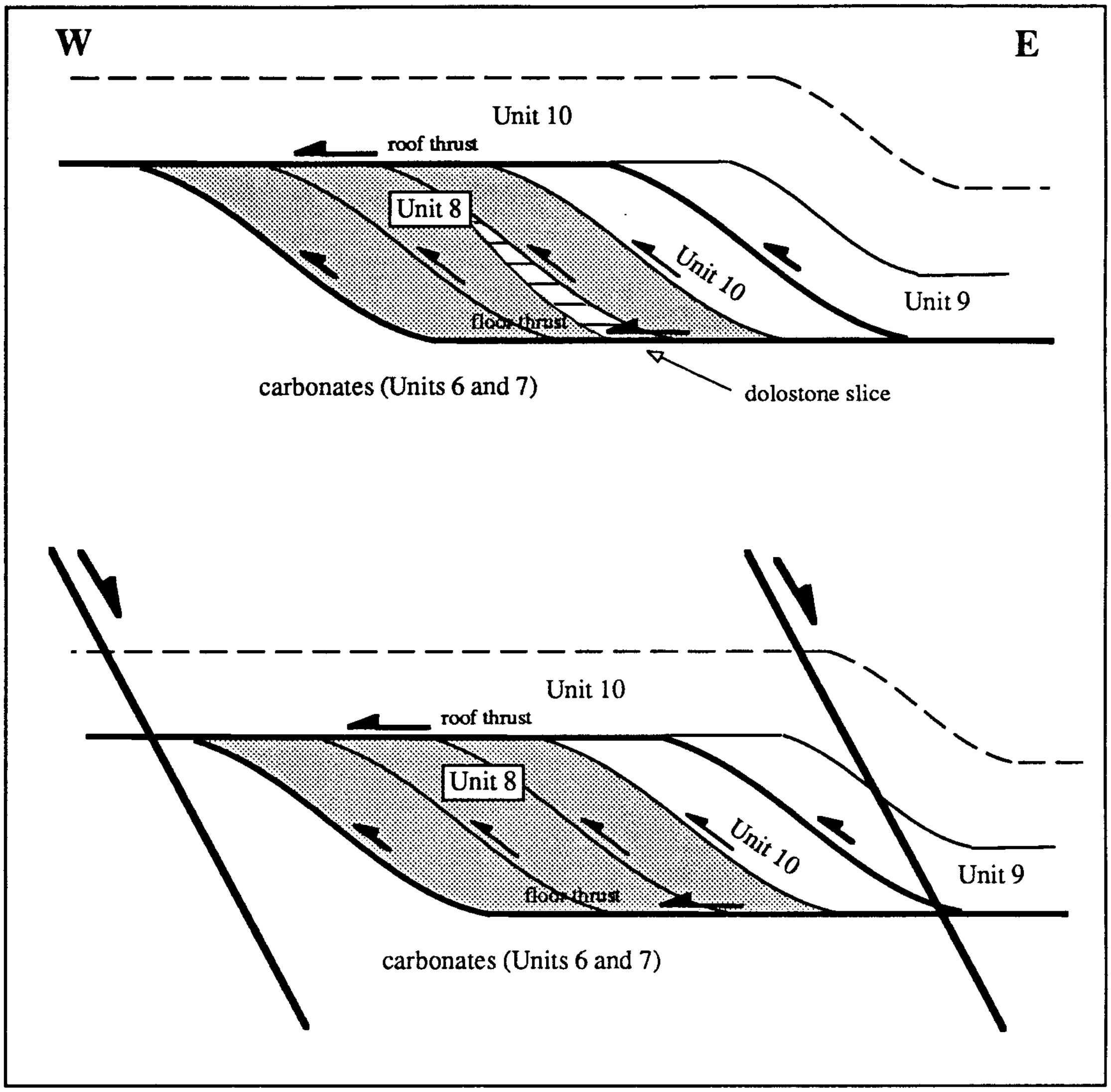


Figure 3.6. **Schematic diagram of Money Hole Duplex. Note floor thrust below Unit 8 and roof thrust below Unit 9. In this rendidtion, late normal faulting is responsible for the appearance of Unit 10 to the west of Unit 8.**

3.4.2. Burr Road Fault System

The Burr Road Fault System, named for the byway along which it is exposed, is located 0.25 kilometers west of Shaw Mountain. This area of the carbonate shelf sequence is composed of slices of Units 5 and 6a found in a zone roughly 0.5 kilometers wide and 1.5 kilometers long. It is bordered to the west by the Lighthouse Fault and to the east by the Temple Road Thrust. The stratigraphic and structural sequence of these slices is detailed in section 3.3.2.

The repetitive nature of the carbonate slices implies imbrication in a duplex system, or normal faulting, or both. Topographical evidence strongly suggests the presence of normal faults in this region, and a major thrust fault (Temple Road Thrust) overlies these repeated strata. According to my outcrop interpretation, the Temple Road Thrust appears to truncate the normal faults. This interpretation is supported by the topography of this region. Exposure is scarce directly east of the fault system, however, and I am unable to closely constrain the thrust in this critical area. There are several feasible explanations for the features observed in this confusing zone, and following are possible explanations of the structures seen.

The **Flexure Folding Interpretation** serves to explain the gentle west dip of the strata closest to the Lighthouse fault. In this scheme, the dip and the hanging wall of the Lighthouse Fault are to the west, and a fault drag and reverse drag mechanism causes the beds to dip west adjacent to the fault *(figure 3.7.)*. Field evidence, however, does not support this idea. The west dip of purported hanging wall rocks closest to the fault is not observed, and, more importantly, displacement considerations derived from stratigraphy clearly constrain the Lighthouse Fault as an east dipping normal fault. Even if the orientation of and the movement along Lighthouse Fault had changed during successive

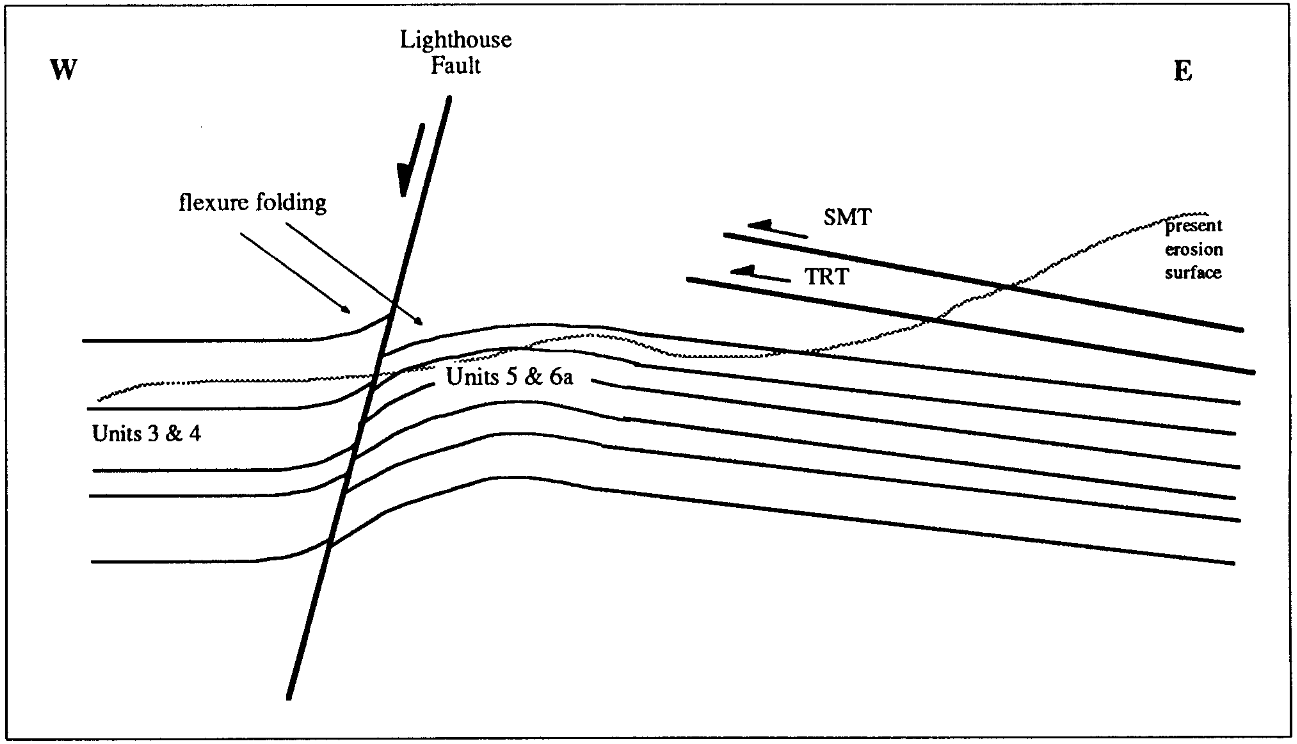


Figure 3.7. **Schematic diagram of Fault Flexure Interpretation. In this version, the gentle west dip of Units 5 & 6a are explained, though the repetition of carbonate strata are not.**
SMT - Shaw Mountain Thrust TRT - Temple Road Thrust

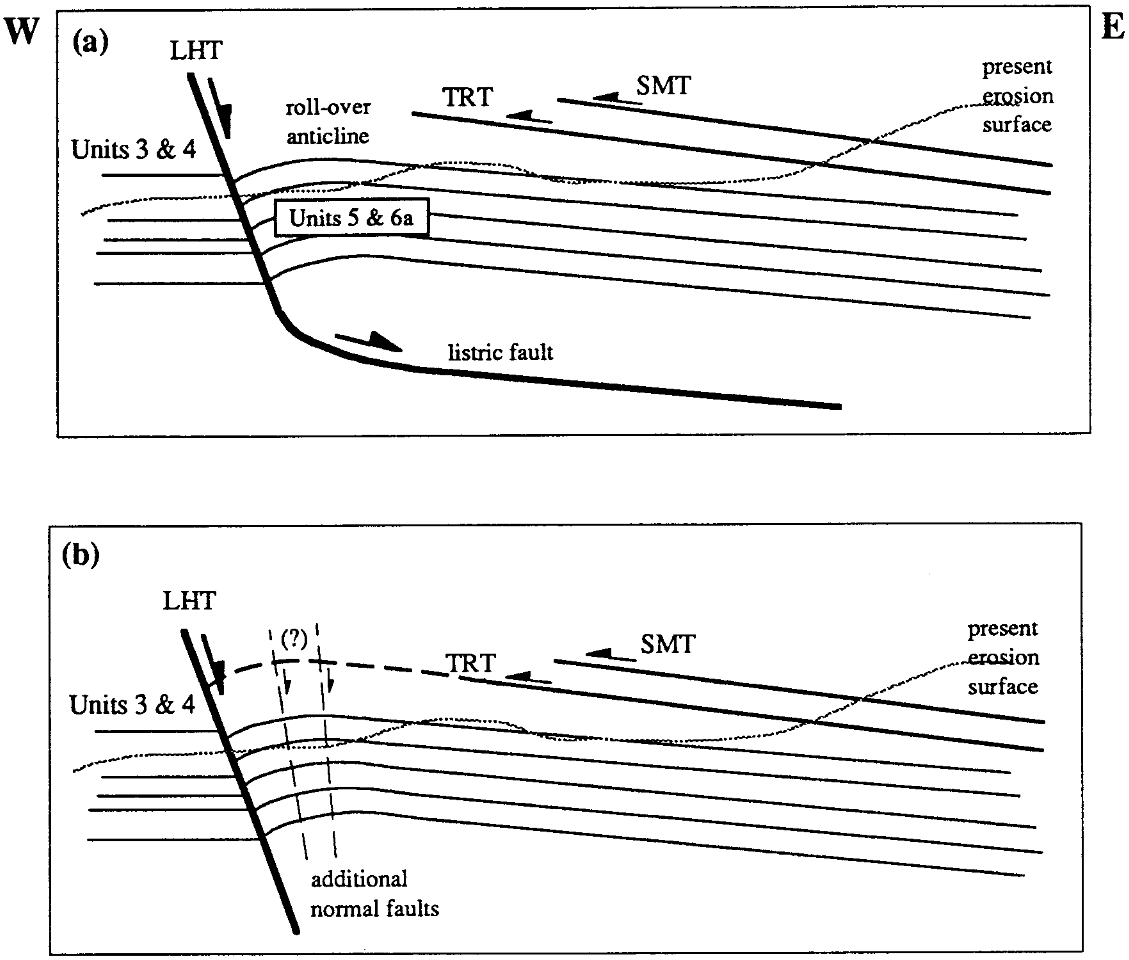


***Figure 3.8.* Schematic diagrams of Roll-over Anticline Interpretation. (a) This version involoves gentle folding in the hanging wall of a listric fault to explain the gentle west dip of Units 5 & 6a. (b) In order to account for stratigraphic repetition, addional normal faults are included. Note, however, that these normal faults are post-thrusting.**
TRT - Temple Road Thrust SMT - Shaw Mountain Thrust

tectonic events, I would still expect to see evidence of original hanging wall flexure in the strata to the west of the fault, which there is not.

The **Roll-over Anticline Interpretation** suggests gentle folding in the hanging wall of an east dipping listric normal fault to explain the gentle west dip of Units 5 and 6a closest to the fault. This approach requires the Lighthouse Fault to become listric beneath the carbonate strata, and accommodation to movement along the curved fault surface causes bending of the beds proximal to the fault ***(figure 3.8.a.)***. This interpretation fails to produce the repetition of the carbonates seen clearly in the field, and thus must be modified with the addition of subsidiary normal faults to achieve an accurate representation ***(figure 3.8.b.)***. The Temple Road Thrust is cut by the Lighthouse Fault, implying the subsidiary faults should also postdate thrusting. Unfortunately, due to the paucity of outcrop and consequent lack of fault constraints in the critical area adjacent to the Burr Road Fault System, the exact relationship between the subsidiary normal faults and the Temple Road Thrust can not be ascertained.

I suggest this interpretation is the most likely of those offered, as it sufficiently explains the available field data. However, a more complex modification of the Roll-over Anticline Interpretation allows for the truncation of the subsidiary normal faults by the Temple Road Thrust. I propose the following sequence of events:

- The Lighthouse Fault, including roll-over anticline and subsidiary normal faults, forms prior to thrusting in a manner similar to that suggested by Bradley & Kidd (1991).
- The limestones of Unit 9-def are emplaced on the underlying carbonates via the Temple Road Thrust, truncating the normal faults.
- Later reactivation of the Lighthouse Fault cuts the Temple Road Thrust.

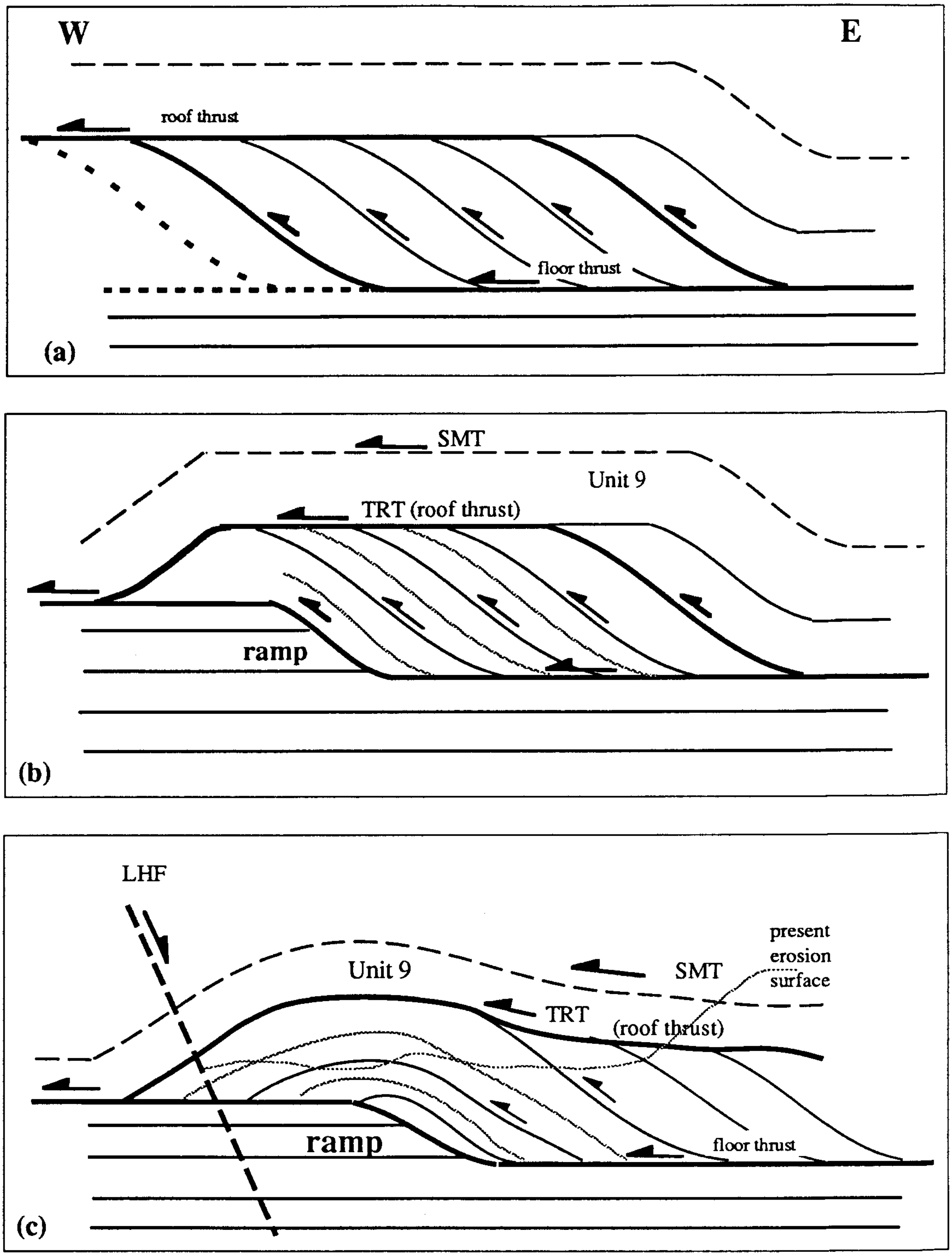


Figure 3.9. **Schematic diagrams of the Ramp Thrust Interpretation.**
(a) Geometry of duplex structure incorporating slices of carbonate Units 5 &6a. Note propagation of next active ramp thrust, shown with bold dashed line.
(b) Floor thrust ramping up on pre-existing normal fault scarp in basement or through carbonates.
(c) A ramp forces the hinterland-dipping duplex to form an anticlinal stack. Late normal faulting along the Lghthouse Fault (LHF) would produce structures seen in field area.

The **Ramp Thrust Interpretation** incorporates aspects from duplex thrusting as well as normal faulting to account for the stratigraphic repetition and west dip observed along Burr Road. It utilizes ideas suggested by Mitra (1988) and Herrmann (1992) in their studies of other fold-and-thrust belts. The concept involves the development of an imbricate carbonate sequence bounded by a roof thrust and floor thrust. The lower décollement surface then gains elevation by ramping up through competent strata. The ramp forces the hinterland-dipping duplex to form an antiformal stack. Normal faulting of this assemblage may be caused by extension along the crest of the fold, or may be associated with later faulting events responsible for the Lighthouse Fault. ***(Figure 3.9.).***

The lower detachment surface in this interpretation could lie within the younger carbonate units where it may ramp up through the more competent strata. In this case, I would expect the thrust either to be exposed west of the mapped area or to terminate below the present erosion surface. As mentioned previously, the Temple Road Thrust is a probable candidate for the roof thrust. This thrust is responsible for emplacing the shaley limestones of Unit 9 over the much younger carbonates revealed along Burr Road.

The Ramp Thrust Interpretation convincingly explains the fault relationships and repetitive sequence of carbonates at this location. In addition, duplex systems are often found associated with thrust belts, including the Taconic Thrust System. However, the dolostones and limestones of Burr Road do not show evidence of the strain associated with transport in a duplex. Sedimentary features such as bedding and laminations, as well as well-preserved fossils, are seen clearly in the outcrops of Units 5 and 6a. The rocks lack the distinct cleavage detected in the other duplex strata (Money Hole Duplex) in the field area. The Roll-over Anticline Interpretation, then, is the most plausible explanation.

3.4.3. Temple Road Thrust Sheet

The Temple Road Thrust Sheet lies directly above the carbonates of Units 5 and 6a and below the transported dolostones of Unit 6cT. It is composed of the strongly cleaved shaley limestones of Unit 9-def. The basal thrust of the sheet is not exposed in the field area, but it is closely constrained in most places by outcrop. Its dip is assumed to parallel that of the underlying Unit 6a (approximately 20° to the east) because this fossiliferous limestone is known to act as a dĕcollement horizon for thrusts outside the mapped area (Steinhardt, 1983; W.S.F. Kidd, personal communication, 1995). In addition, thrust faults tend to follow bedding surfaces in weaker units and climb up section in more competent beds (Ramsay et al., 1983; Boyer & Elliot, 1982). The stratigraphically lower dolostones are stronger than Unit 6a, suggesting a bedding parallel thrust would develop in the comparatively weaker unit (Steinhardt, 1983).

In the portion of the field area discussed in section 3.3.3., the Temple Road Thrust Sheet is offset by successive normal faulting on the Benson Landing Fault and the Stony Point Fault. The resulting apparent sinistral shift of the sheet to the north places the floor thrust in present day Lake Champlain, making it impossible to trace directly north of the study region. The cleaved strata of Unit 9-def, though, are clearly exposed along the shore of the lake for several kilometers north of Benson. I believe the floor thrust reappears approximately 30 kilometers north near the town of Middlebury. There the St. George's Thrust places Glens Falls Limestone (Unit 9) over shales. The thrusted slice of Glens Falls is in turn overlain by a thrust sheet of Bridport Dolostone (Unit 6cT) transported on the Orwell Thrust (Coney et al., 1972). The obvious similarities between structures recorded around Orwell and those observed in Benson cause me to conclude that the St. George's Thrust and the Orwell Thrust are the northern extensions of the Temple Road Thrust and the Shaw Mountain Thrust, respectively.

The roof thrust of this sheet is the Shaw Mountain Thrust, which places the dolostones of Unit 6cT over Unit 9-def. This upper décollement surface is observed to the north and south of the mapped area. Directly to the south in West Haven, however, Unit 9-def is not detected below the West Haven Thrust (Steinhardt, 1983), posing a geometrical problem. The shaley limestone may be hidden in a zone lacking outcrop. Alternatively, the absence of Unit 9-def below the thrust may be resolved by a thickness change due to transport over pre-existing structures. Seismic profiling in central Vermont has indicated a synsubsidence horst and graben morphology below the Taconic Allochthon (Walsh, 1981). Ramping of the floor thrust on these pre-existing structures may effectively reduce the thickness of the transported limestone or truncate it altogether.

3.4.4. Shaw Mountain Thrust Sheet

The Shaw Mountain Thrust Sheet, named for the most prominent topographic feature in the field area, is situated directly above the Temple Road Thrust Sheet. It is composed entirely of Unit 6cT. This transported dolostone is easily recognized by its characteristic fracture pattern (detailed in chapter 2), and is frequently associated with thrust sheets outside the field area (Steinhardt, 1983).

The basal thrust of the sheet (the Shaw Mountain Thrust) is not exposed in the field area, but it is closely constrained in several places by outcrop data. As mentioned previously, this thrust is the roof thrust of the underlying sheet. The shaley limestone of Unit 9-def offers an ideal décollement horizon for movement along the Shaw Mountain Thrust, and the emplacement of the dolostone sheet may have contributed further to the development of the pronounced cleavage in the underlying strata. The orientation of the thrust is believed to parallel that of the Temple Road Thrust, striking roughly north-south and dipping approximately 20° to the east. The upper detachment surface of the Shaw Mountain Thrust Sheet is not exposed in the field area and is suggested from map data to be truncated by the Benson Fault. As a result of this late normal faulting, the dolostones are structurally overlain by Unit 10.

Similar to the Temple Road Thrust Sheet, the Shaw Mountain Thrust Sheet is apparently sinistrally offset in the northern part of my study area by sequential displacement along the Benson Landing Fault and the Stony Point Fault. The thrust sheet is traceable for several kilometers north of the Benson area. To the south, the thrust sheet is offset by both the Coggman Creek Fault and the Warren Hollow Fault, and is well constrained by outcrop data in the West Haven area (Steinhardt, 1983). As discussed in the preceding section, the shaley limestones of Unit 9-def are not exposed below the extension of the Shaw Mountain Thrust in the southern area mapped by Steinhardt (1983).

3.4.5. Forbes Hill Thrust Sheet

The Forbes Hill Thrust Sheet, named for the topographic high incorporated in it, lies structurally above Unit 10 in the southeastern portion of the field area. The basal thrust places the carbonates of Units 6cT, 7 and 8 over shales, and it is well defined by topography due to the difference in resistance of the lithologies. To the south, the basal thrust cuts up section through the dolostone and into the limestones (Steinhardt, 1983). Approximately 20 meters of shale is exposed between the limestones on Forbes Hill, suggesting the presence of smaller thrusts within the sheet. Zen (1967) places Taconic slates directly to the east of Forbes Hill, implying the Taconic Frontal Thrust is the roof thrust of the sheet. Because the outcrops are indistinguishable from those of Unit 10, however, Zen's interpretation has not been followed on my map.

The structural thickness of the carbonate portion of the Forbes Hill Thrust Sheet decreases north and south away from its center at the crest of Forbes Hill. This change in the form of the sheet implies that it may terminate laterally within a few kilometers. This lens-like geometry, in addition to the evidence of internal thrusting, leads me to conclude this thrust sheet may contain a duplex structure.

3.4.6. Timing of Thrusting

Each of the three thrust sheets recognized in the field area is structurally overlain by its eastern neighbor. In the classic opinion on fold and thrust belt geometry (Dahlstrom, 1970; Boyer & Elliot, 1980), this hindward dipping imbricate stack arrangement is interpreted as a foreland developing sequence. The sequence evolves as slices join the hanging wall at the leading edge of a thrust, and thus the thrust grows as it advances. Thrusts in the most foreland position are younger than the thrusts behind. Traversing from east to west across the Benson area, then, the successive thrusts become progressively younger.

In each imbricate sheet, a deformational sequence presumably developed during the propagation of its basal thrust. Forward movement of the most hinterland sheet could create folding and cleavage in the underlying strata due to shortening and shearing. As the thrust rejoins the roof thrust, the enclosed duplex moves cohesively. Deformation may continue as the assemblage traverses more ramps. A new thrust will begin to advance ahead of the last formed duplex, accompanied by deformation until the fault joins the roof thrust again. ***(Figure 3.10.)***

In each thrust sheet, the order of deformational events was probably similar, though the onset of each sequence was not simultaneous. In the Benson area, the Taconic Thrust Sheet (or Sunset Lake Slice) was the original, followed by the Forbes Hill Thrust Sheet, the Shaw Mountain Thrust Sheet, and the Temple Road Thrust Sheet, in that order. According to this idea, while the Forbes Hill Sheet was active, the future Shaw Mountain Thrust was propagating, coupled with deformation in the overlying units. Ultimately, when growth of new floor thrusts ceased in the study area, the Temple Road Thrust was

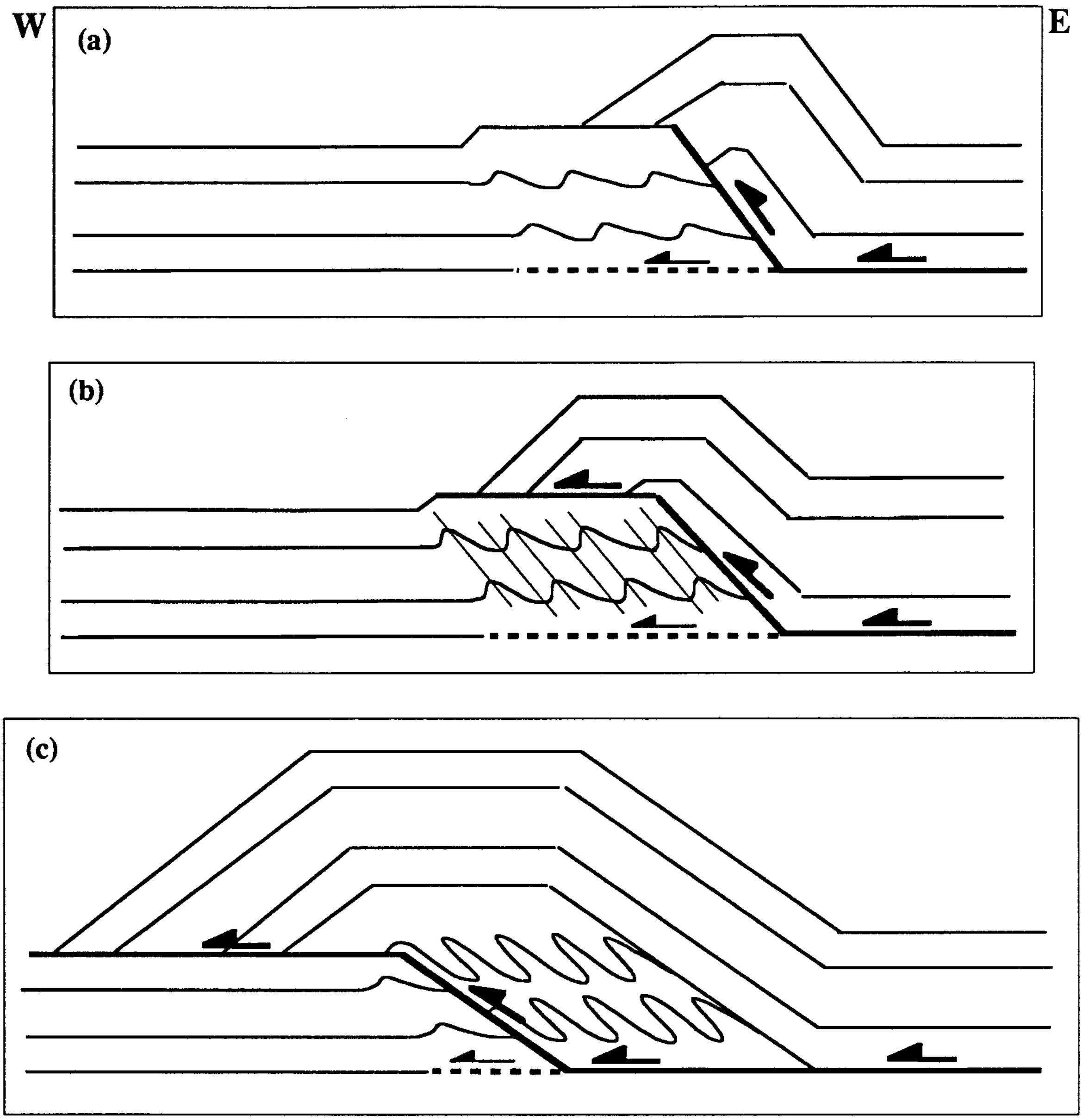


Figure 3.10. **Model explaining possible deformational sequence of thrust sheets in the field area.**
(a) Ramping of thrust causing shortening in underlying strata. Propagation of new thrust.
(b) Development of cleavage and continued thrust propagation.
(c) Basal thrust joins upper thrust and duplex is transported cohesively with the overlying thrust sheet.
(Modified from Steinhardt, 1983)

the foreland-most detachment surface and the Sunset Lake Thrust was the hinterland-most. Therefore, Unit 6b represents the lower décollement horizon, while Unit 10 is the upper horizon.

This foreland propagating thrust model is generally supported by my field observations, although it does not appear to be valid within the Forbes Hill Thrust Sheet. In one location, a sliver of Unit 10 is exposed with limestone on either side of it, separating it from the main body of slate ***(outcrop 8)***. This structural relationship requires the overlying thrust of this sliver to be younger than the Forbes Hill basal thrust ***(figure 3.11.)***. In other words, the thrust sequence at this location is hinterland younging, and the younger thrust may even crosscut the Forbes Hill basal thrust.

Rowley (1983) demonstrated hindward younging thrust faults within the Giddings Brook Slice of the Taconic Allochthon. His research revealed the basal thrust of the Taconic Allochthon is folded and crosscut by several faults, including the Frontal Thrust. As the Giddings Brook Slice directly overlies the carbonates of Units 7 through 9 outside my field area, evidence for a similar sequence in Benson may support his theory of a two step fault history. The single occurrence of late faulting noted at Forbes Hill, however, is insufficient to decide if Taconic lithologies are included in the thrust sheets in my map area.

From field observations and outcrop data, I conclude the thrust sheets recognized in the field area developed progressively toward the foreland. They were emplaced sequentially ahead of and beneath the advancing Taconic Thrust Sheet and were transported concurrently with the Taconic Allochthon.

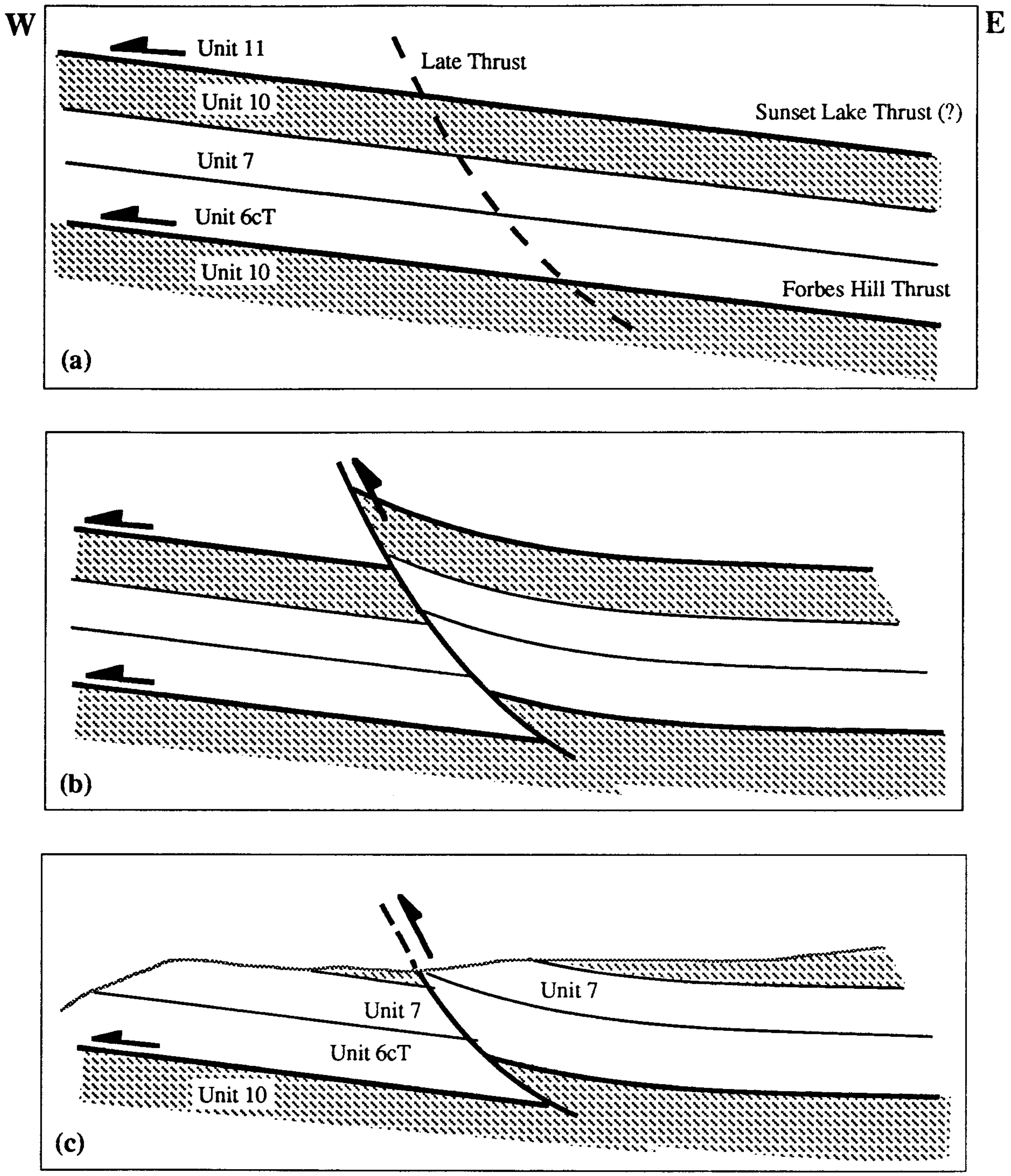


Figure 3.11. **Schematic diagram of late thrusting explaining the appearance of a slice of Unit 10 in the Forbes Hill Thrust Sheet.**
(after Steinhardt, 1983)

3.4.7. Late Normal Faulting

Normal faults in the Benson area can be grouped into two categories based on their orientation; there are west-down faults which generally strike northeast-southwest, and there are east-down faults which strike roughly north-south. Although there may be a component of strike-slip displacement, as seen along the Warren Hollow Fault near Forbes Hill (Steinhardt, 1983), stratigraphic constraints require the majority of movement to be dip-slip. The major normal faults in the study area crosscut or truncate all other deformational features, requiring them to postdate all other geologic structures. The fact that most of them are expressed distinctly in the topography may also suggest some relatively young movement along their surfaces. Normal faults of similar orientation are found outside the field area, and the mechanisms driving movement are thought to be the same for each orientation of normal faults.

Movement along east-side-down normal faults at the eastern margin of the Adirondacks, such as the McGregor Fault which strikes north-south through Saratoga Springs, was believed to be caused by reactivation of Precambrian rift structures (Young & Putman, 1979; Williams, Bosworth, and Putman, 1983). Bradley & Kidd (1991), however, propose normal faulting was the result of flexural extension of the crust due to its subduction beneath the overriding accretionary wedge during the Ordovician Taconic Orogeny. This conclusion was also reached by Cisne et al. (1982), who studied the paleobathymetry of mid-Ordovician limestones and shales through fossil assemblage analysis in the Mohawk Valley. They uncovered evidence for syn-depositional block faulting likely caused by flexural extension of the continental shelf and underlying lithosphere by loading of the advancing island arc during the Taconic Orogeny (discussed further in chapter 4).

North-east striking west-down normal faults with similar orientations to those observed in my map area are also seen in the Central Mohawk Valley (Fisher, 1980) and the Whitehall, New York area (Fisher, 1984). Although Fisher cites reactivation along old fracture lines in the basement as responsible for the normal fault pattern, I find the reasoning of Bradley & Kidd (1991) to be more plausible and have thus concluded the normal faults near Benson were the result of medial Ordovician flexural extension.

Although the above ideas account for the presence of normal faults in the field area during the Ordovician, it is still necessary to explain the movement along them after the carbonate thrust sheets were emplaced. The most recent displacement of these faults may be caused by reactivation of the Ordovician structures due to the doming of the Adirondacks (Barnett & Isachsen, 1980; Isachsen, 1975; Burke, 1976), although there is no conclusive evidence to support this idea.

4. Tectonic Interpretation

4.1. Introduction

Recent work by several geologists has led to the alteration of many original concepts about the nature of the geologic history of Vermont. Motivated by plate tectonic interpretations, Chapple (1973) and later authors proposed that emplacement of the Taconic Allochthon was due to tectonic movements rather than gravity slide mechanisms. This lead to the proposal of the Taconic Frontal Thrust System, the faults of which were active during or after the final stage of emplacement of the accretionary wedge (Rowley et al., 1979; Rowley & Kidd, 1981). The northeastern margin of the Taconic Allochthon has also been crosscut by late faults (Bierbrauer, 1990). The "Middlebury Synclinorium" and other prior interpretations for west-central Vermont (Doll et al., 1961) do not explain the structures observed, which has prompted interpretations including complex series of fault-bounded lithotectonic assemblages rather than the previously accepted idea of a largely intact and folded stratigraphic sequence.

The results of this study support thrust-dominated interpretations for the structural evolution of Vermont geology. The following chapter is an attempt to apply modern structural and tectonic knowledge to explain the complex geology of the Benson area. The reconstruction of the tectonic history is based on information presented in previous chapters.

4.2. Geologic History

The evolution of the stratigraphy and structure of the field area began with the early Cambrian or possibly latest Precambrian rifting of the Proto-Atlantic Ocean (Bird &

Dewey, 1970; Rankin, 1976), which in this region was centered roughly along a north-south trending axis well to the east of the present day Green Mountains. Extension in the continental crust initiated development of normal faults in the Grenvillian basement. The field area was perhaps cut by north-south striking, east-side-down normal faults, although its location extremely distal to the initial spreading center (Rowley, 1983) may have resulted in no late Precambrian / earliest Cambrian faulting at all in the area investigated (Bradley & Kidd, 1991).

Downflexing of the passive continental margin due to thermal subsidence following rifting (McKenzie, 1978) led to the deposition of a continental margin sedimentary prism, the basal part of which contains local conglomerates and coarse sandstones. Although Unit 1 represents the waning rifting stage and deposition of continentally-derived material, it is not the oldest known sediment of this sequence. To the east, the sandstones and carbonates of the Cheshire Quartzite and Winooski Dolomite (Thompson & Theokritoff, 1969; Doll et al., 1961) are the first widespread sedimentary sheets reflecting the initial stages of subsidence. The absence of these sediments below Unit 1 is consistent with the location of the field area far to the west of the rift axis (Rowley, 1983).

The continued opening of the Iapetus Ocean and ensuing thermally-driven crustal subsidence were coupled with deposition of the carbonate platform. The limestones and dolostones overlying Unit 1 characterize shallow marine shelf carbonates which succeed the basal sands. Modern examples of passive continental margins show a seaward-thickening wedge of sedimentary cover (Watts & Steckler, 1979) caused by increasing subsidence towards the continental margin.

The long-term transgressive nature of the passive margin sedimentary sequence is demonstrated in the stratigraphic sequence of the field area; the older cross-bedded, laminated, and fossiliferous shallow marine and intertidal carbonates of Units 3 through 6 yield to younger lithologies, with an increasing shaley component, deposited on the distal slope. The slates of Unit 10 are believed to have been deposited deeper still (Zen, 1967; Cisne et al., 1982), although their exact stratigraphic age range remains unclear.

This deepening sequence reflects the transgression of the sea onto the subsided continental margin as well as the initiation of tectonic destruction of the passive margin during the medial Ordovician Taconic Orogeny (Rowley & Kidd, 1981). The convergent plate motion associated with this major tectonic event was responsible for large scale thrusting as well as new or additional normal faulting due to the flexure and extension of the subducting slab. The encroaching Ammonoosuc island arc and associated accretionary prism were obducted onto the shelf (Rowley & Delano, 1979; Rowley & Kidd, 1981), and the Taconic Allochthon, composed of continental rise sediments, was thrust continentward with parts of the underlying shelf carbonates (Bird & Dewey, 1970). Rocks of the Taconic Allochthon and several underlying carbonate thrust sheets currently occupy the eastern portion of my study area.

Estimates of displacement of the outer shelf carbonate sequence and the Taconic Allochthon on the Champlain Thrust give values of about 80 to 94 kilometers (Rowley, 1982). The Allochthon was transported across the shelf during the Taconic Orogeny, requiring at least 100 kilometers of movement relative to the shelf sequence during the medial Ordovician and probably more in the off-shelf region (Bradley, 1989). This transport was previously proposed to have been caused by gravity sliding (Bird & Dewey, 1970; Zen, 1972; Rodgers, 1970). The proposal by Chapple (1973), elaborated by Rowley & Kidd (1981), that emplacement was a tectonic process driven by continued convergence of the Ammonoosuc Island Arc and the continental shelf offers a better explanation of the structures viewed in the field area.

During the Devonian Acadian Orogeny, there may have been reactivation of the thrusts upon which the Taconic Allochthon and carbonates were transported. Based on petrographic evidence of prograde chlorite found in recrystallized fractures above but not below, the thrust, Stanley & Sarkisian (1972) suggest the Champlain Thrust developed during the Taconic Orogeny, the rocks were metamorphosed, and then the thrust was reactivated during the Acadian Orogeny. Orientation of slickensides along thrusts in the same study, and elsewhere in the larger Champlain Thrust belt, however, trend 120° ±10° in faults of inferred Ordovician age, vs. 090° ±10° in Devonian lithologies between Albany and Kingston in the Hudson Valley (Stanley & Sarkisian 1972; Plesch, 1994; W.S.F.Kidd, personal communication, 1995). In the medial Ordovician flysch of the Hudson Valley, Bosworth & Vollmer (1981) have found that Taconic fold and thrust belt structures, and specifically a melange zone, are truncated by unconformably overlying Devonian beds, implying movement of the overlying thrusts and deformation of the underlying strata occurred only during the Taconic Orogeny. The belt of deformed flysch they studied can be traced into the West Haven area directly south of Benson (Steinhardt, 1983), disputing the previous suggestion for Acadian movement of originally Taconic thrusts. Unfortunately, there are no lithologies of post-Taconic and pre-Acadian age exposed in my field area that could offer completely unambiguous resolution of this problem.

4.3. Schematic Tectonic Evolution of Structures in the Field Area

Figure 4.1., figure 4.2., figure 4.3., figure 4.4.

STAGE I

Carbonate Platform Development — Following late Precambrian / early Cambrian rifting and normal faulting of Grenville age basement (Bird & Dewey, 1970; Rankin, 1976), thermal subsidence allows for the deposition of continentally derived material. Rift sediments such as conglomerates and quartz sandstones in unconformable contact with the Precambrian basement reflect the waning rifting stage. Continued downflexing of the passive continental margin creates room for the growth of a carbonate platform (McKenzie, 1978). This seaward-thickening wedge is composed of limestones and dolostones as well as interbedded shales and siltstones. These continental shelf sediments record the transgression of the sea onto the subsiding margin during the Ordovician.

STAGE II

Passive Margin Destruction and Onset of Normal Faulting — Tectonic destruction of the passive margin is initiated during the medial Ordovician Taconic Orogeny (Rowley & Kidd, 1981). The westward moving Ammonoosuc Island Arc forms an accretionary wedge of deep water sediments from the continental rise / slope. Convergent plate motion is responsible for the thrusting of these transported sediments over the underlying carbonates as well as the progressive subduction-related drowning of the passive margin (Rowley & Kidd, 1981). The flexural extension of the subducting slab causes normal faulting in the shelf sequence and perhaps underlying basement.

STAGE III

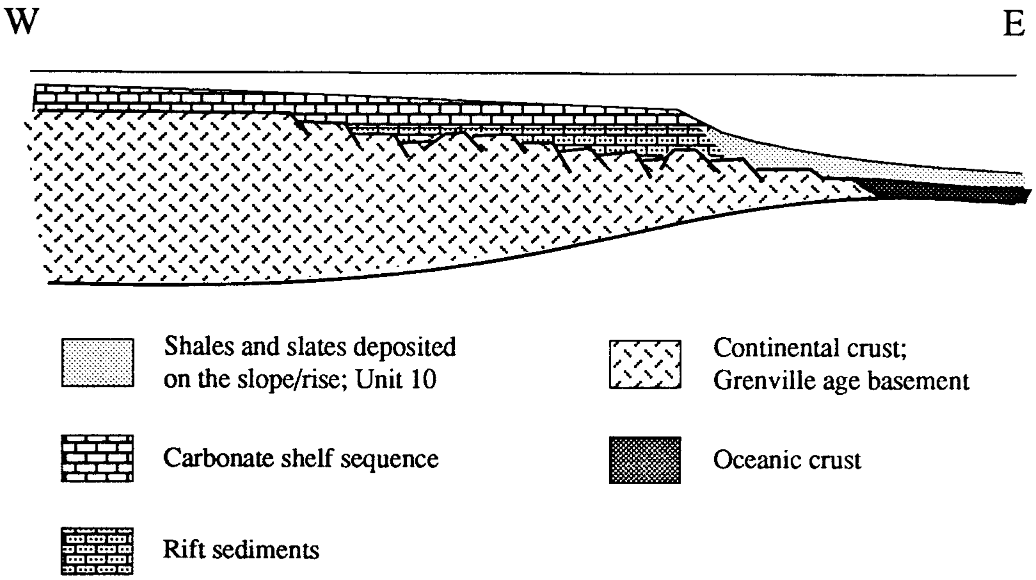
Duplex Development — Progressive westward movement of the Taconic Allochthon along the floor thrust of the accretionary prism results in the foreland propagation of additional thrusts which incorporate slices of shale, carbonates, and quartzite from the underlying strata. Cohesive movement of the shelf duplex follows, as well as additional normal faulting caused by continued loading and flexural extension of the subducting slab.

SCHEMATIC TECTONIC EVOLUTION OF THE STRUCTURES IN THE FIELD AREA

STAGE I:	thermal subsidence following rifting carbonate platform deposition syn-depositional slope/rise shales	***figure 4.1.***
STAGE II:	onset of thrusting flexural extension block faulting of carbonates	***figure 4.2.***
STAGE III:	foreland propagation of thrusts incorporation and transport of duplex continued normal faulting	***figure 4.3.***
STAGE IV:	late normal faulting and erosion	***figure 4.4.***

note: the following figures represent "snap shots" during the tectonic history of the Benson area, rather than pauses in the deformation sequence.

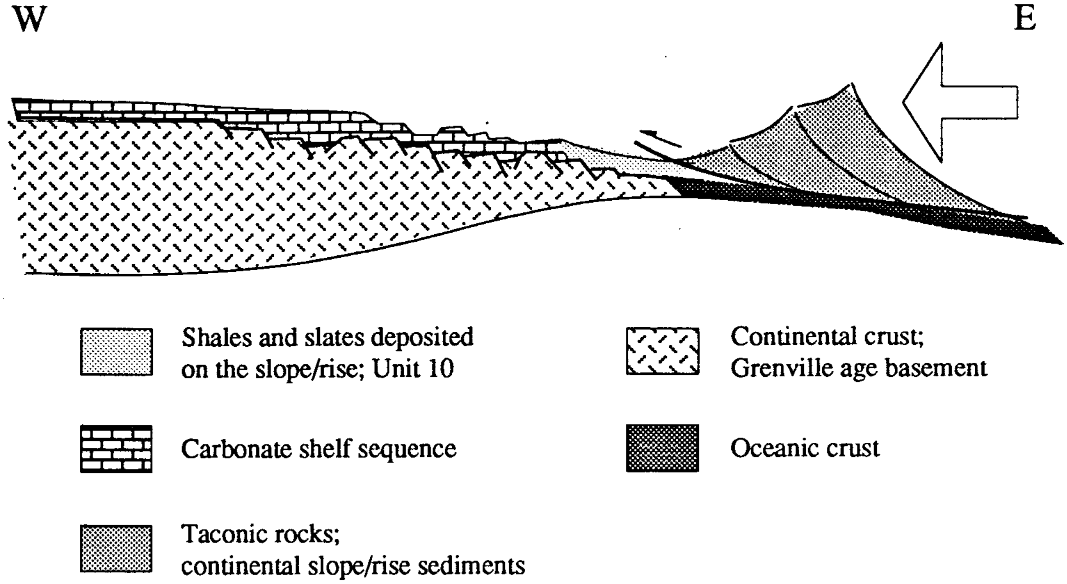
Passive continental margin of eastern North America in early / middle Ordovician



STAGE I

figure 4.1.

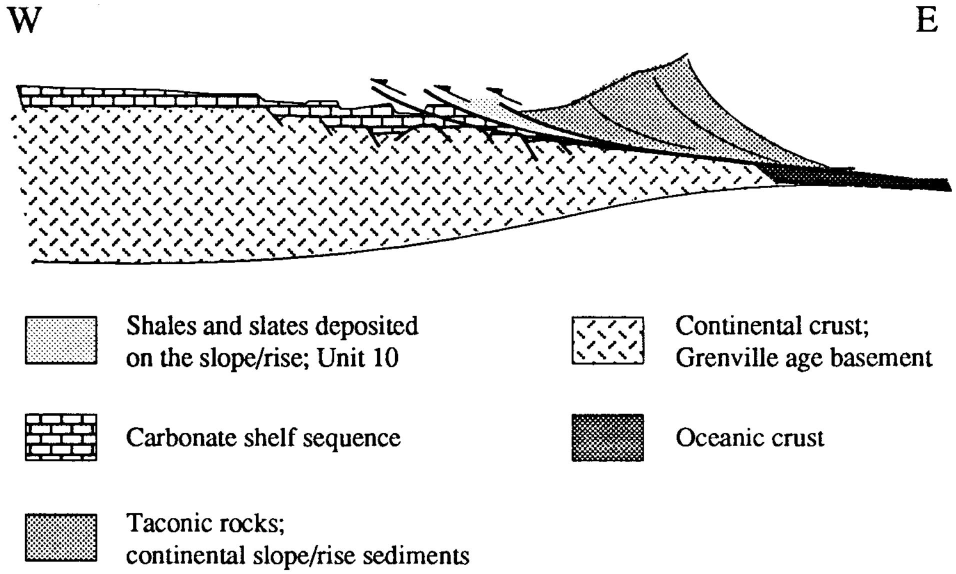
Medial Ordovician onset of thrusting and emplacement of Taconic Allochthon. Block faulting due to flexural extension of the subducting slab.



STAGE II

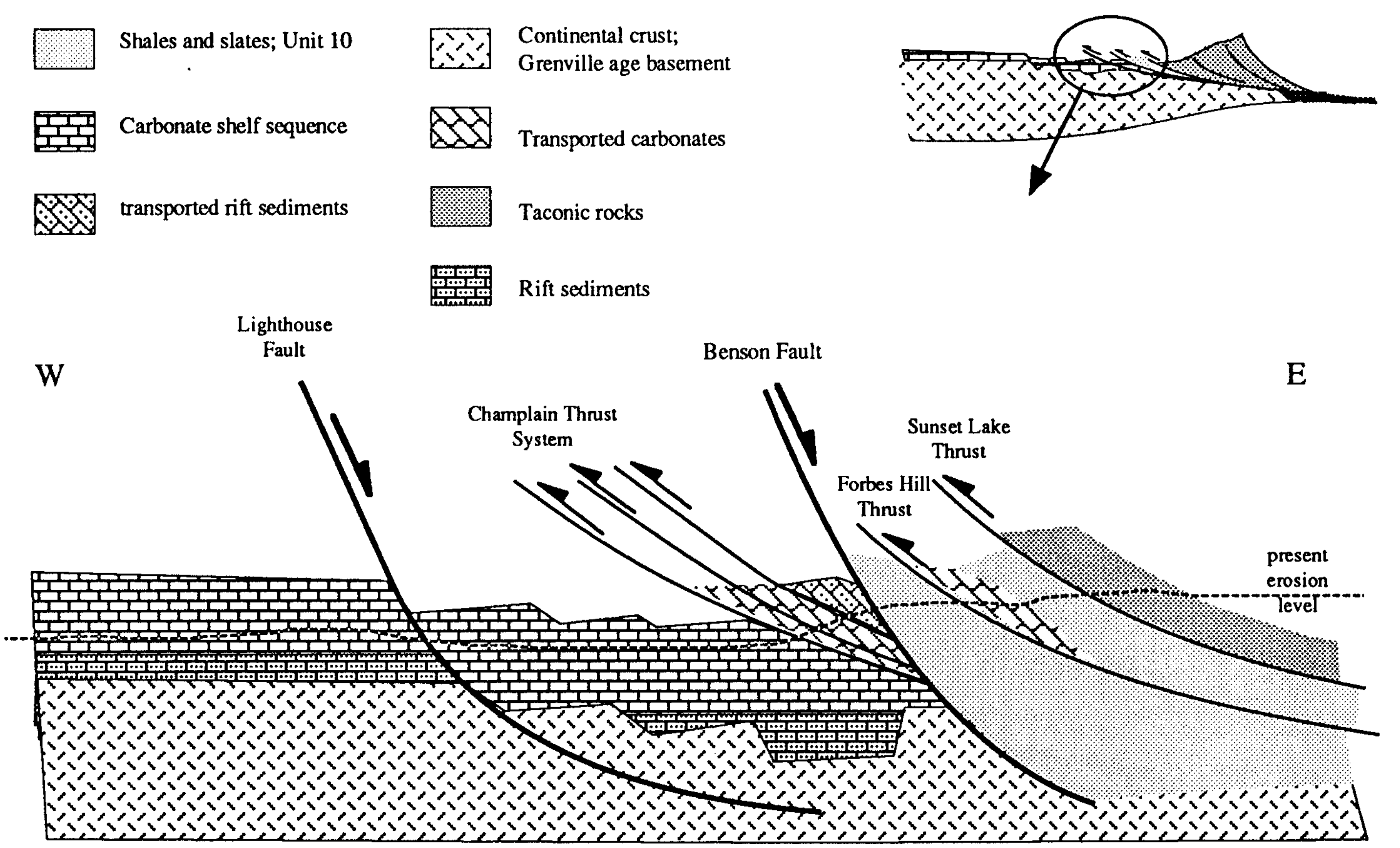
figure 4.2.

Development of shelf duplex and foreland-propagating thrust faults beneath the Taconic Allochthon, in addition to continued normal faulting on outer trench slope.



STAGE III

figure 4.3.



STAGE IV (final)

figure 4.4.

Late normal faulting and erosion leading to features currently observed in the Benson area

STAGE IV

Late Normal Faulting and Erosion — Following the emplacement of the Taconic Allochthon and shelf duplex, progressive normal faulting along the Lighthouse Fault juxtaposed deformed or transported rocks with relatively flat-lying strata. Late movement on the Benson thrust truncated the Root Pond Thrust and juxtaposed Unit 10 slates with the underlying carbonates and, locally, the quartzites of Unit 1-def. Erosion and glacial sedimentation led to the features currently observed in the Benson area.

4.4. Summary

By utilizing data from detailed outcrop mapping, this thesis serves to correlate several stratigraphic and structural features discovered in the Benson area with features found outside the field area, the most notable of which is the Champlain Thrust. Determining the location of the southern extension of this major fault has been a goal of numerous geologists. Coney et al. (1972), based on research to the north of the map area near the town of Middlebury, proposed the Champlain Thrust split southward into three separate faults, becoming the St. George's Thrust and the Orwell Thrust, in addition to continuing southward as the quartzite-transporting (Monkton, Danby, Potsdam Formations) Champlain Thrust. The Champlain Thrust then climbs rapidly upsection into the Danby Formation (Cady, 1945) before the trace of these faults is lost in the complex Shoreham Duplex area. In the previous chapter, I stated my belief and evidence that the Temple Road Thrust and the Shaw Mountain Thrust are the southern extensions of the St. George's Thrust and the Orwell Thrust, respectively. In addition, by referring to ***figure 1.3.***, one notes the quartzite of Unit 1-def is stratigraphically equivalent to the Danby Formation. Therefore, I now conclude that the Temple Road Thrust, the Shaw Mountain

Thrust, and the Root Pond Thrust represent the much sought-after southern continuation of the Champlain Thrust System.

The thrust system and other normal faults can be traced farther to the south in the Whitehall, New York region mapped by Fisher (1984). In an area first mapped by Flower (1964), Fisher has interpreted a thrust, dubbed the Comstock Fault, which has transported rocks of the Ticonderoga Formation (Unit 2), and locally slices of the Potsdam Formation (Unit 1-def), over the limestones of the Sciota Formation (Unit 6b). Evidence of disturbance in the lithologies directly underlying the thrust suggests the presence of other thrusts in an imbricate zone of carbonates (Kidd, personal communication, 1995). Although Fisher has not interpreted it as such, I propose this zone marks the southern continuation of the Temple Road Thrust and the Shaw Mountain Thrust, with the Comstock Fault representing the extension of the Root Pond Thrust. The Champlain Thrust System, therefore, can be followed past Whitehall, 20 kilometers south of my field area.

Also in the Whitehall region, the Mettawee River Normal Fault places the Hortonville Shale (Unit 10) adjacent to much older carbonates and truncates the thrust fault transporting Cambrian quartzites (Fisher, 1984). The obvious similarities in structural relationships viewed along this fault and those detected along the Benson Fault lead me to conclude that the Mettawee River Fault is the southern continuation of the Benson Fault.

In addition to developing a regional structural synthesis, I have strived to link the deformational history of the field area with that of the western Vermont region. With less than one percent outcrop by area, I have attempted to determine the complex order of tectonic processes that affected these rocks. Although more field research is needed to increase the certainty of my ideas, I believe I have offered the most plausible interpretations of the features I found.

References

Aleinikoff, J.N., Zartmann, R.E., Lyons, J.B., 1979. U-Th-Pb geochronology of the Messabesic Gneiss and the granite near Milford, south central New Hampshire: New evidence for Avalonian basement and Taconic and Alleghenian disturbances in eastern New England: Contri. Min, Petrol., v. 71, p.1-11.

Bain, G. W., 1959. Geology of the marble deposits near Rutland: *in:* N.E.I.G.C. Guidebook, no. 51, p. 35-44.

Baldwin, B., 1982. Geology of Vermont: Earth Science, v. 35, n. 3, p. 10-14.

Baldwin, B., 1982. The Taconic Orogeny of Rodgers, seen from Vermont a decade later: Vermont Geol., v. 2, p. 20-24.

Baldwin, B. & Raiford, A. V., 1979. Taconic geology near Fair Haven, Vermont: Vermont Geology, 1988, v. 5, VT Geol. Soc., Guidebook 2.

Bates, R.L. & Jackson, J. A., eds., 1980. Glossary of Geology: American Geol. Inst., Falls Church, VA, 751 pp.

Barnett, S.G. & Isachsen, Y.W., 1980. The application of Lake Champlain water level studies to the investigation of Adirondack and Lake Champlain movements: Vermont Geology, v. 1, p. 5-11.

Bierbrauer, K., 1990. The geology of Taconic thrust sheets and surrounding carbonates of he west central Vermont marble belt, north of Rutland, Vermont: Master's Thesis, SUNY Albany, 105 pp.

Bird, J.M., 1969. Middle Ordovician gravity sliding, Taconic region: *in* Kay, M. (ed) North American Geology and Continental Drift, Am. Assoc. Petr. Geol., Mem. 12, p. 670-686.

Bird, J.M., & Dewey, J.F., 1975. Selected localities in the Taconics and their implications for the plate tectonic origin of the Taconic region: *in:* N.E.I.G.C. Guidebook, p. 87-121.

Bosworth, W. & Kidd, W.S.F., 1985. Thrusts, melanges, folded thrusts and duplexes in the Taconic foreland: *in:* N.E.I.G.C. Guidebook, p. 117-146.

Bosworth, W. & Rowley, D.B., 1984. Early subduction-related deformation features of the Taconic Allochthon: Analogy with structures observed in modern trench environments: Geol. Sos. Am. Bull., v. 95, p. 559-567.

Bosworth, W. & Volmer, F.W., 1981. Structures of the medial Ordovician flysch of eastern New York; deformation of synorogenic deposits in an overthrust environment: Jour. of Geol., v. 89, p. 551-568.

Bosworth, W., Rowley, D.B., Kidd, W.S.F., Steinhardt, C., 1985. The Taconic Frontal Thrust System: Geol. Soc. Am. Ab. & Prog., v. 17, no. 1, p. 6.

Boyer, S.E. & Elliott, D., 1982. Thrust systems: Amer. Assoc. of Petrol. Geol. Bull., v. 66. no, 9, p. 1196-1230.

Bradley, D.C., 1989. Taconic plate kinematics as revealed by foredeep stratigraphy, Appalachian Orogen: Tectonics, v. 8, no. 5, p. 1037-1049.

Bradley, D.C. & Kidd, W.S.F., 1991. Flexural extension of the upper continental crust in collision foredeeps: Geol. Soc. Am. Bull., v. 103. p.1416-1438.

Bradley, R.W.H. & Klusky, T.M., 1986. Geologic evidence for rate of plate convergence during the Taconic arc-continent collision: Jour. of Geol., v. 94, p. 667-681.

Brainerd & Seely, H.M., 1890. The Calciferous Formation in the Champlain Valley: Am. Mus. Nat. Hist. Bull., v. 3, p. 1-23.

Brown, L., Ando, C., Klemperer, S., Oliver, J., Kaufman, S., Czuchra, B., Walsh, T., Isachsen, I., 1983. Adirondack-Appalachian crustal structure: The COCORP Northeast Traverse: Geol. Soc. Am. Bull., v. 94, p. 1173-1184.

Burke, K.C.A., 1981. Two problems of intracontinental tectonics: Revelation of old mountain belts and subsidence of intracontinental basins: *in* Proc. of Int. Conf. on Intracontinental Earthquakes, Ohrid, Yugoslavia, 1979. J. Petrowski and C. Allen, eds., Skopie, 1981, p. 157-164.

Cady, W.M., 1945. Stratigraphy and structure of west-central Vermont: Bull. of the Geol. Soc. Am., v. 56, p. 515-588.

Chadwick, G.H., 1935. Chemung is portage: Geol. Soc. Am. Bull., v. 46, p. 343-355.

Chapple, W.M., 1973. Taconic Orogeny: Abortive subduction of the North American continental plate: Geol. Soc. Am. Ab. & Prog., v. 5, p. 573.

Chase, J.S. & Hunt, A.S., 1972. Sub-bottom profiling in central Lake Champlain: A reconnaissance study: Proc. 15th Conf. Great Lakes Res., p. 317-329.

Chilinger, G.V., Zenger, D.H., Bissel, H.J., Wolf, K.H., 1979. Dolomites and dolomitization *in* G Larsen, G.V. Chilinger, eds. Diagenisis in Sediments and Sedimentary Rocks, Elsevier, Amsterdam, p. 423-536.

Cisne, J.L., Karig, D.E., Rabe, B.D., Hay, B.J., 1982. Topography and tectonics of the Taconian outer trench slope as revealed through gradient analysis of fossil assemblages: Lethia (Oslo), v. 15, p. 229-246.

Colton, G.W.B., 1970. The Appalachian basin - its depositional sequences and their geological relationships *in* G.W. Fisher, F.J. Pettijohn, J.C. Reed, and K.N. Weaver (eds), Studies of Appalachian Geology, Central and Southern; Wiley Interscience, New York, P. 30-78.

***Coney, P.J., Powell, R.E., Tennyson, M.E., Baldwin, B.**, 1972. The Champlain thrust and* related features near Middlebury, Vermont: *in*: N.E.I.G.C. Fieldguide, 64th Ann. Mtng., p. 97-116.

Dale, T.N., 1902. Structural details in the Green Mountain region and in eastern New York: USGS Bull., no. 195, p. 1-22.

Dale, T.N., 1915. Calcite marble and dolomite of eastern Vermont: USGS Bull., no. 589, p. 1-67.

Davis, G.H., 1984. Structural geology fo rocks and regions: Wiley & sons, Inc., Canada, 492 pp.

Dellorusso, V. & Stanley, R.S., 1986. Bedrock geology of the northern part of the Lincoln Massif, central Vermont: VT Geol. Surv., Spec. Bull., no. 8, p. 1-56.

De Simone, D.J., 1983. A northern limit for glacial Lake Albany: Geol. Soc. Am. Abstr. and Prog, v. 15, p. 178.

Dewey, J.F., & Burke, K.C.A., 1974. Hot spots and continental breakup; implications for collisional orogeny: Geology, v. 2, p. 57-60.

Doll, C.G., Cady, W.M., Thompson, J.B.Jr., Billings, M.P., 1961. Centennial geologic map of Vermont: VT Geol. Surv., scale 1:250,000.

Drake, A.A. Jr., Sinha, A.K., Laird, J., Guy, R.E., 1989. The Taconic orogen: GSA, *in:* The geology of North America, The Appalachian-Quachita orogen in the US, v. F-2, ch. 3, p. 101-177.

Emmons, E., 1938. Natural history of New York: NY Geol. Survey, 2nd Ann. Report.

Emmons, E., 1842. Geology of New York, Pt. II - Comprising the survey of the second geological district: White and Visscher, Albany, 437 pp.

Escher, A. & Watterson, J., 1974. Stretching fabrics, folds, and crustal shortenning: Tectonophysics, v. 22, p. 223-231.

Fairbridge, R.W., 1967. Syndiagenesis, anadiagenesis, epidiagenesis: Phases in lithogenesis *in* G. Larsen and G.V. Chilinger (eds.), Diagenesis in Sediments: Elsevier, Developments in Sedimentology, v. 25B, p. 18-113.

Fisher, D.W., 1968. Geology of the Plattsburg and Rouses Point, New York - Vermont quadrangles: Spec. Bull., v. 1, VT Geol. Surv.

Fisher, D.W., 1977. Correlation of the Hadrynian Cambrian and Ordovician rocks in New York State: NY State Mus. Map and Chart Series no. 25, 75 pp.

Fisher, D.W., 1980. Bedrock geology of the central Mohawk Valley, New York: NY State Mus. Map and Chart Series no. 33, 46 pp.

Fisher, D.W., 1984. Bedrock geology of the Glens Falls - Whitehall region, New York: NY State Mus. Map and Chart Series no. 35.

Fisher, D.W., Isachsen, Y.W. & Rickard, L.V., 1970-1971. Geologic map of New York State, 1:250,000, 4 sheets and legend: NY State Mus. Map and Chart Series no. 15.

Flower, R.H., 1964. The foreland sequence of the Fort Ann region, New York: NM Bull. Mines and Min. Res., Mem. 12, p. 153-161.

Fowler, P., 1950. Stratigraphy and structure of the Castleton area, Vermont: VT Geol. Surv. Bull., no. 2, p. 83.

Freidman, G.M. & Sanders, J.E., 1967. Origin and occurrence of dolostones *in* G.V. Chilingar, H.J. Bissel, and R.W. Fairbridge (eds.): Carbonate rocks: Origin, occurrence, and classification, Elsevier, Amsterdam, p. 267-348.

Freidman, G.M. & Sanders, J.E., 1976. Principles of Sedimentology: Wiley: NY, 792 pp.

Geiser, P., 1982. Stratigraphic relationships and detrital composition of medial Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic Orogeny: A discussion: J. Geol., v. 90, p. 227-229.

Gordon, C.E., 1919-1920. Studies in the geology of western Vermont: Rept. of the VT State Geologist, no. 12, p. 114-279.

Hall, J., 1847. Description of the organic remains of the lower division of the New York system: Paleo. of NY, v. 1, 338 pp.

Hawkes, H.E.Jr., 1941. Roots of the Taconic Fault in west central Vermont: GSA Bull., v. 52, p. 649-666.

Herrmann, R., 1992. The geology of the Vermont Valley and the western flank of the Green Mountains between Dorset Mountain and Wallingford, Vermont: Master's thesis, SUNY Albany, 101 pp.

Hewitt, P.C., 1985. A trip to the Taconic problem and back and the nature of the eastern Taconic contact: NY State Geol. Assoc., Field Trip Guidebook, p. 29-46.

Hobbs, B.E., Means, W.D., & Williams, P.F., 1976. An outline of structural geology: NY, Wiley, 571 pp.

Hubbert, M.K., & Rubey, W.W., 1959. Role of fluid pressure in mechanics of overthrust faulting, Part I: GSA Bull., v. 70, p. 115-166.

Isachsen, Y.W., 1975. Possible evidence for contemporary doming of the Adirondack Mountains, New York, and suggested implications for regional tectonics and seismicity: Tectonophysics, v. 29, p. 169-181.

Karabinos, P., 1988. Heat transfer and fault geometry in the Taconian thrust belt, western New England: GSA Spec Paper, no. 222, p. 35-45.

Karabinos, P., & Thompson, J.B.Jr., 1984. Thrust faulting in the northern Green Mountain Massif, central Vermont: GSA Ab. & Prog., v. 16, p. 27.

Keith, A., 1932. Stratigraphy and structure of northwestern Vermont: part I: Jour. of the Washington Acad. of Sciences, v. 22, no. 13, p. 357-379.

Keith, A., 1932. Stratigraphy and structure of northwestern Vermont: part II: Jour. of the Washington Acad. of Sciences, v. 22, no. 14, p. 393-406.

Keith, A., 1933. Outline of the stratigraphy and structure of northwestern Vermont: Inter. Geol. Congress, 16th Eastern NY and western New England, Guidebook 1, p. 48-61.

Mazzullo, S.J. & Friedman, G.M., 1977. Competitive algal colonization of peritidal flats in a schizohaline environment in the lower Ordovician of New York: J. Sed. Petr., v. 40, p. 25-32.

McClay, K.R., 1992. Thrust Tectonics: Chapman & Hall, 325 pp.

McKenzie, D., 1978. Some remarks on the development of sedimentary basins: Earth Plan. Sci. Letters, v. 40, p. 25-32.

Mehertens, C.J., Parker, R., Butler, R., 1987. The cambrian platform in northwestern Vermont, *in:* N.E.I.G.C. Guidebook, v. 2, p. 254-270.

Mitra, S., 1988. Three-dimensional geometry and kinematic evolution of the Pine Mountain thrust system, southern Appalachians: GSA Bull., v. 100, p. 72-95.

Naylor, R.S., 1976. Isotropic dating and New England stratigraphy: *in* Contributions to stratigraphy of New England: GSA Mem. v. 148, p. 419-425.

Plesch, A., 1994. Structure and tectonic significance of deformed medial Ordovician flysch and melange between Albany and Saratoga Lake and in the Central Hudson Valley, New York: SUNY Albany Master's thesis, 265 pp.

Rankin, D.W., 1976. Appalachian salients and recesses; later pre-Cambrian break-up and the openning of the Iapetus Ocean: Jour. Geophys. Res., v. 81, p. 5605-19.

Ratcliff, N.M., 1979. Field guide to the Chatham and Greylock slices of the Taconic Allochthon in western Massachusetts and their relationship to the Hoosac-Rowe sequence: *in:* N.E.I.G.C. Guidebook, 71st Ann. Mtng., p. 388-425.

Ratcliff, N.M., 1988. Along-strike variations in tectonics of the Taconian orogen: GSA Ab. & Prog. v. 20, no. 1, p. 64.

Ratcliff, N.M., Bird, J.M., Bahrami, B., 1975. Structural and stratigraphic chronology of the Taconide and Acadian polydeformational belt of the central Taconics of New York State and Massachusetts: *in* N.E.I.G.C. Guidebook, p. 55-86.

Ratte, C.A., & Ogden, D.G., 1989. Marble, granite, and slate industries of Vermont: Am. Geophys. Union, 28th Intern. Geol. Congress, Field Trip Guidebook T362.

Riva, J., 1974. A revision of some Ordovician graptolites of eastern North America: Paleo. v. 17, p. 580-590.

Rodgers, J., 1937. Stratigraphy and structure in the upper Champlain Valley: GSA Bull., v. 48, p. 1573-1588.

Rodgers, J., 1970. The tectonics of the Appalachians: NY, Wiley, 271 pp.

Rodgers, J., 1971. The Taconic Orogeny: GSA Bull., v. 82, p. 1141-1178.

Rodgers, J., 1982. Stratigraphic relationships and detrital composition of medial Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic Orogeny: a discussion: J. Geol., v. 90, p. 219-22.

Rodgers, J., & Fisher, D.W., 1969. Paleozoic rocks in Washington County, New York, west of the Taconic klippe: *in* N.E.I.G.C. Fieldguide, p. 6-1 to 6-12.

Rowley, D.B., 1980. Complex structure and stratigraphy of lower slices of the Taconic Allochthon near Middle Granville, New York: Master's Thesis, SUNY Albany, 258 pp.

Rowley, D.B., 1980. Timor-Australian collision: Analog for Taconic Allochton emplacement: GSA Ab. & Prog., v. 12, p. 79.

Rowley, D.B., 1982. Structural and stratigraphic implications of folded normal faults in orogenic belts: examples from Vermont: GSA Ab. & Prog., v. 14, p. 604.

Rowley, D.B., 1982. New methods for estimating displacement of thrusts affecting Atlantic-type shelf sequences, with an application to the Champlain Thrust, Vermont: Tectonics, v. 1, p. 369-388.

Rowley, D.B., 1983. Operation of the Wilson Cycle in western New England during the early Paleozoic, with emphasis on the stratigraphy, structure, and emplacement of the Taconic Allochthon: PhD thesis, SUNY Albany, v. 1+2.

Rowley, D.B. & Delano, L.L., 1979. Structural variations in the northern part of the Taconic Allochthon: GSA Ab. & Prog., v. 11, p. 51.

Rowley, D.B. & Kidd, W.S.F., 1981. Stratigraphic relationships and detrital composition of the medial Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic Orogeny: Jour. Geol., v. 89, p. 199-218.

Rowley, D.B., Kidd, W.S.F., Delano, L.L., 1979. Detailed stratigraphic and structural features of the Giddings Brook Slice of the Taconic Allochthon in the Granville area: *in:* N.E.I.G.C. Guidebook, p. 186-242.

Ruedemann, R., 1909. Types of inliers observed in New York: NY State Mus. Bull., no. 133, p. 164-193.

Stanley, R. & Sarkisian, A., 1972. Analysis and chronology of structures along the Champlain Thrust: *in:* N.E.I.G.C. Guidebook Trip B5, p. 117-149.

Stanley, R. & Ratcliff, N.M., 1985. Tectonic synthesis of the Taconic Orogeny in western New England: GSA Bull., v. 96, p. 1227-1250.

Steinhardt, C.K., 1983. Structure and Stratigraphy of West Haven, Vermont: Master's thesis, SUNY Albany, 167 pp.

Theokritoff, G. & Thompson, J.B., 1969. Stratigraphy of the Champlain Valley sequence in Rutland County, Vermont, and the Taconic sequence in northern Washington County, New York: *in:* N.E.I.G.C. Guidebook, p. 7-1 to 7-26.

Thompson, J.B., 1967. Bedrock geology of the Pawlet Quadrangle, Vermont: Part II, eastern portion: VT Geol. Surv. Bull., v. 30, p. 65-98.

Vollmer, F.W., 1981. Structural studies of the Ordovician flysch and mélange in Albany County, New York: Master's thesis, SUNY Albany, 151 pp.

Walcott, C.D., 1891. The fauna of the lower Cambrian or Olenellus Zone: USGS, 10th Ann. Rep., p. 515-629.

Walsh, T., 1981. Deep crustal structures of central Vermont: Inferred fron the COCORP seismic survey: The Green Mountain Geologist, Abs., v. 7, no. 4, p. 12.

Watts, A.B. & Steckler, M.S., 1979. Subsidence and eustacy at the continental margin of eastern North America: Am. Geophys. Union, v. 3, p. 218-234.

Washington, P.A., 1981. Structural analysis of an area near Middlebury, Vermont: Master's thesis, SUNY Albany, New York, 77 pp.

Washington, P.A., 1992. Stratigraphic relations in the central Champlain Valley: Recurring estuarine deposits and a retreating shellf margin: Field Trip 1, Field Conference of Taconic Geologists, p. 1-47.

Washington, P.A., 1992, Structural transitions: Southern Champlain Thrust to northern Taconics, central Champlain Valley: Field Trip 2, Field Conference of Taconic Geologists, p. 48-80.

Welby, C.W., 1961. Bedrock geology of the Central Champlain Valley of Vermont: VT Geol. Surv. Bull., v. 14, 290 pp.

Welby, C.W., 1965. A new Ordovician species of Lichenaria from Vermont: Jour. of Paleo., v. 39, p. 288-9.

Williams, H.X., Bosworth, W., Putman, G.W., 1983. Evidence for complex strain history of the McGregor fault, eastern Adirondacks: A possible reactivated late pre-Cambrian rift structure: GSA abs. & Prog., v. 15, no. 3, p. 124.

Wilson, J.T., 1966. Did the Atlantic close and then re-open?: Nature, v. 211, p. 676-81.

Young, J.R., & Putman, G.W., 1983. Evidence for complex strain history of the McGreggor Fault, eastern Adirondacks: A possible reactivated late pre-Cambrian rift structure: GSA Abst. & Prog., v. 15, no. 3, p. 124.

Zen, E-An, 1959. Stratigraphy and structure at the north end of the Taconic Range and adjacent areas: *in:* N.E.I.G.C. Guidebook, p. 1-17.

Zen, E-An, 1961. Stratigraphy and structure at the north end of the Taconic Range in west-central Vermont: GSA Bull., v. 72, p. 293-338.

Zen, E-An, 1967. Time and space relationships of the Taconic Allochthon and Autochthon: GSA Spec. Pap., no. 97, p. 107.

Zen, E-An, 1972. Some revisions in the interpretation of the Taconic Allochthon in west-central Vermont: GSA Bull., v. 83, p. 2573-2588.