THE GEOLOGY OF THE VERMONT VALLEY AND THE WESTERN FLANK OF THE GREEN MOUNTAINS BETWEEN DORSET MOUNTAIN AND WALLINGFORD, 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 Science and Mathematics
Department of Geological Sciences

,Rolf Herrmann
1992

State University of New York at Albany
College of Science and Mathematics
Department of Geological Sciences

The thesis for the master's degree submitted by
ROLF HERRMANN
under the title

THE GEOLOGY OF THE VERMONT VALLEY AND THE WESTERN FLANK OF THE GREEN MOUNTAINS BETWEEN DORSET MOUNTAIN AND WALLINGFORD, 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.

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(Date) ______________________

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ABSTRACT

The carbonate sequence of the Vermont Valley has been generally believed to lie on the east limb of a major unfaulted syncline ("Middlebury Synclinorium"), and the exposed Precambrian basement and overlying cover rocks of the Green Mountain massif on the west limb of the adjacent major unfaulted anticline ("Green Mountain Anticlinorium"). Except for the Basal Thrust of the Taconic Allochthon, all faults shown on previous maps die out north of Dorset Mountain.

In contrast, detailed mapping for this thesis in the Vermont Valley and the western flank of the Green Mountain massif has revealed several major north/south trending thrust faults, which can be traced through the field area, and document the progressive evolution of the Vermont Valley as a complicated thrust-and-fold belt in four different stages.

A tectonically derived, highly-strained rock unit, previously mapped as the Baker Brook "volcanics", which separates Ordovician black phyllites of the Hortonville Formation from the shelf carbonates to the east, shows a pervasive transposed and differentiated layering. The fault zone fabrics in these rocks display an anastomosing mylonitic foliation, locally containing coarser fragments derived from intermediate-silicic plutonic rocks, presumed to originate from the Grenville basement. Asymmetrical feldspar porphyroclasts and recrystallized quartz grain shape fabrics give a clear and consistent east-over-west sense of shear. Adjacent Ordovician marbles are mylonites too, with a steeply plunging stretching lineation. This contact between the Middle Ordovician black phyllites and the Cambrian to Early Ordovician shelf units has previously been interpreted as an angular unconformity ("Tinmouth unconformity"). In contrast, I suggest there is a major thrust fault here, which has transported the carbonates in the east over the black phyllites of the Hortonville Formation in the west, named the Baker Brook Thrust (T_1).

The carbonate sequence is interpreted as a duplex thrust system (T_2), that was progressively developed and is necessary to explain the complex structural relationships of the Vermont Valley carbonate shelf units. While overriding a footwall ramp, or alternatively by footwall plucking, underlying basement slices were detached and brought up by the Pine Hill Thrust. The Pine Hill Thrust, which extends through the field area, is believed to be entirely a T_2- imbricate thrust of the shelf duplex. Detailed correlation of units of the Vermont marble belt suggest a single, however internally imbricated, large marble slice, attached to the sole of the moving Basal Taconic Thrust and emplaced with the Taconic Allochthon to the west. The overthrust, named the Dorset Mountain Thrust (T_{2r}), truncates all earlier structures north of the Dorset Mountain massif and follows the Basal Taconic Thrust throughout the Vermont Valley.

Further progressive shortening during the last stage of deformation culminated in foreland directed thrust faults (T_3), and folding of the shelf duplex; these are presumed to belong to the Taconic Frontal Thrust System. This stage is probably responsible for cross-cutting relationships along the complexly folded western flank of the Green Mountains (Green Mountain Thrust), and reactivation of some earlier T_2-thrust faults.

The regional interpretation strongly suggests that the entire Vermont Valley, the eastern part of the Taconic Allochthon to the west, and probably the Green Mountain massif to the east, are underlain by a complicated deformed shelf duplex, which has been cut by major north/south trending, eastward dipping late thrust faults.

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This thesis would not have been possible without the help and support of many. I want to thank all the people who contributed somehow to the completion of this project and supported me in many ways over the last two years.

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I wish to express my thanks to the residents of my field area, for allowing me to carry out field work on their property (sorry, I did not find any gold !). I want to especially thank Sally and Jack Frost for their hospitality and the possibility to let me camp on their property, possibly the nicest campsite in the Vermont Valley.

I benefitted greatly from the help and cooperation in the field of Duncan Ogden, Nick Ratcliffe and Tom Armstrong.

I would not have survived the past two years without my fellow graduate students and friends, suffering along with me. Thanks go to Christoph, Pan, Andreas, Laura, Rob, Wolf, Young-do, Andrea, Markos, Haig, Michael and the ones I forgot, who all made my stay enjoyable and fun; I hope to see you all some time at my place in Germany (☎ 01149-2562-4163). Ben has been a good friend and there are many things we did together, I will never forget ! Jake, please take a bath, will you ! Kay introduced me to the Vermont geology (remember our endless plate tectonic scenarios in the SUNY cafeteria ?), the Albany night life and taught me how to make thin sections. I wish you all good luck with your work, or whatever you do !

Without the support, patience and love of Susi, I would not have finished my work, and the good time in Albany I had; Susi, I will try to do the same for you !

The encouragement and support of my parents made all this possible, I am very fortunate to have parents like you ! Finally I want to thank my sister, who also contributed to those horrible high telephone bills each month and much more.

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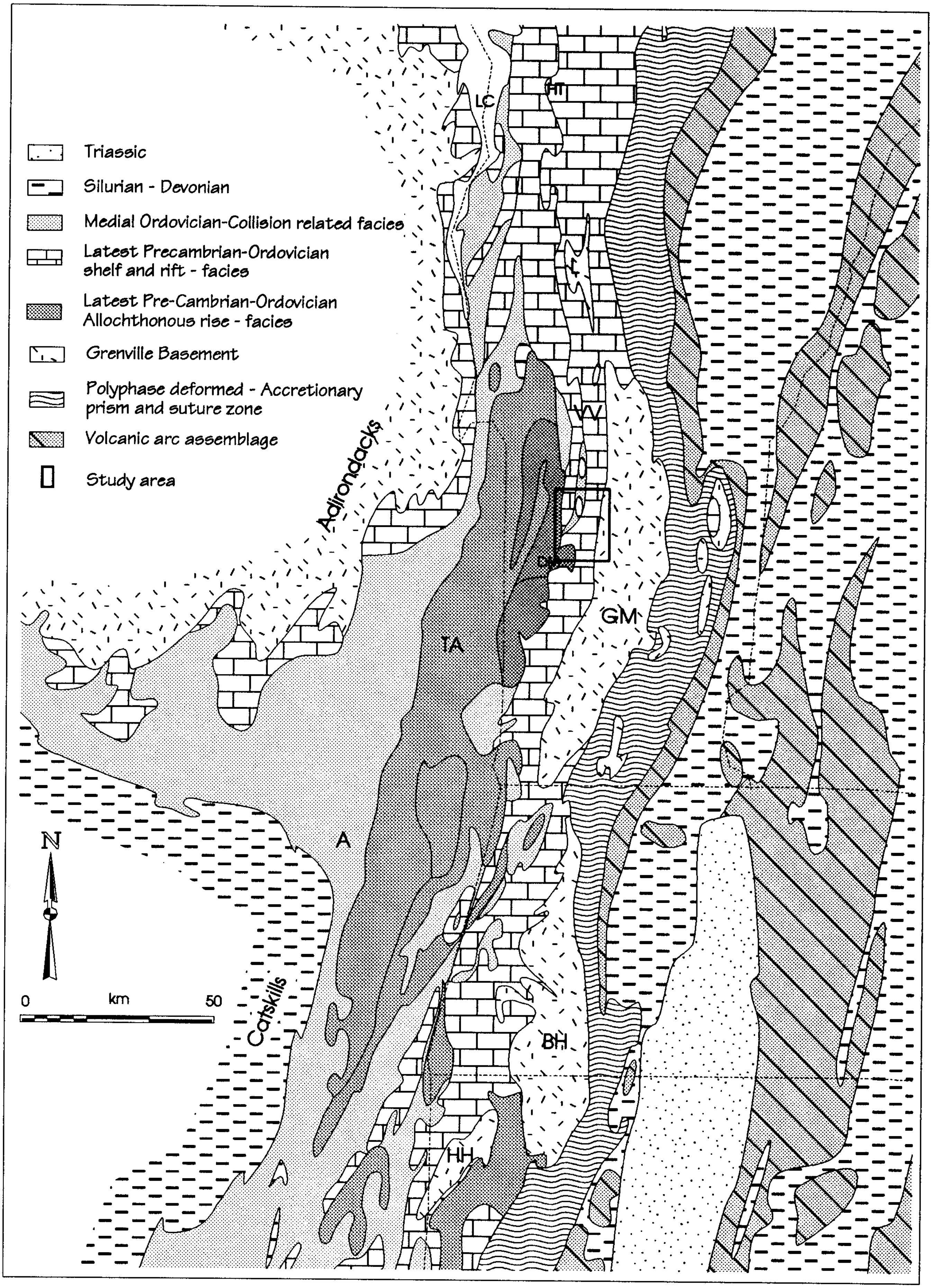
1. Introduction

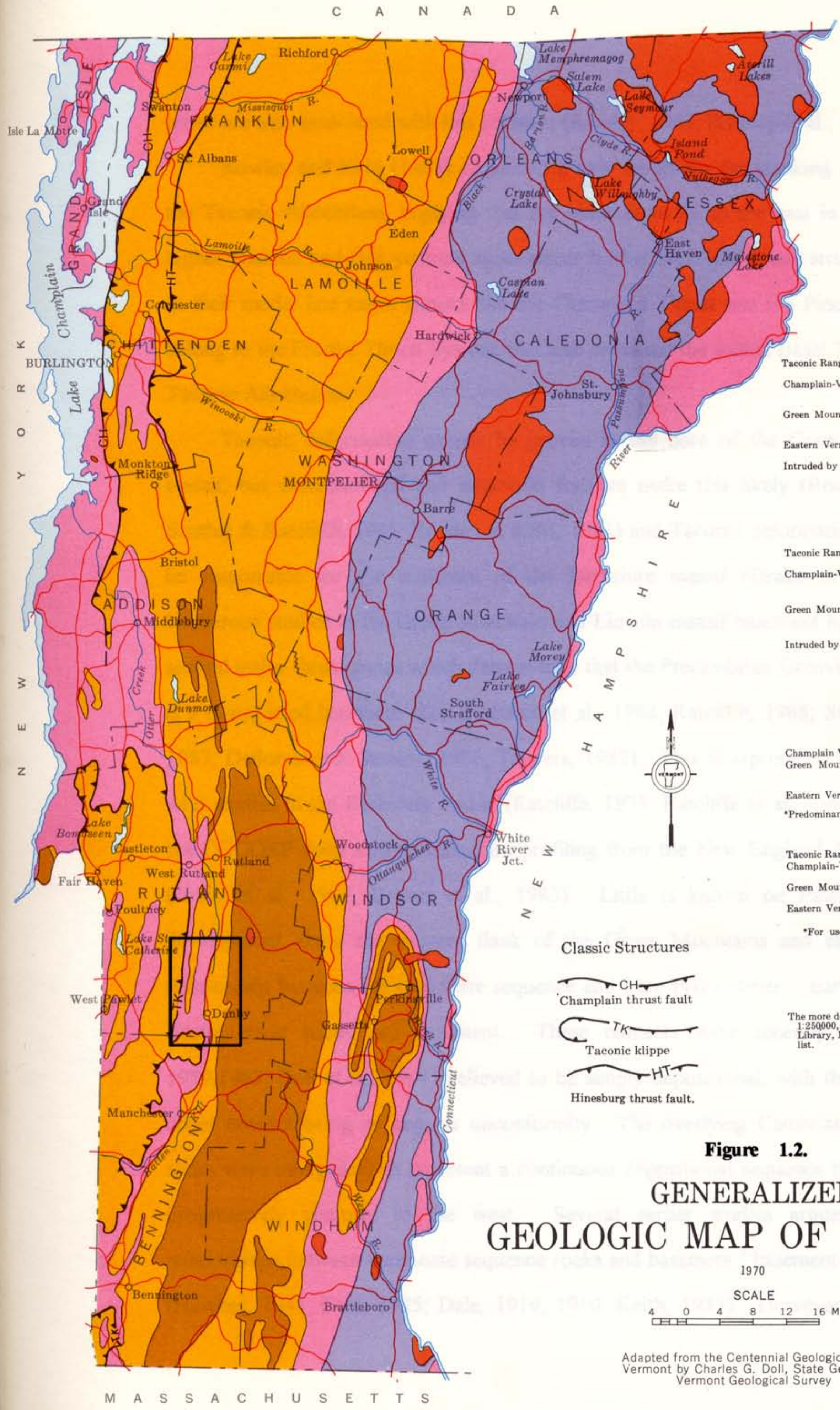
> *"... on account of the extremely complicated structure of the rocks, no man living (and one might add, or those who are to come) would ever see a perfect map of the Taconic region. "*
>
> *Elkanah Billings, 1872*

The Appalachians are a deeply eroded Paleozoic mountain chain exposed from Alabama to Maine which has undergone several different orogenic events - in particular the Taconic, Acadian, Alleghanian events. This thesis is primarily concerned with stratigraphy and tectonics of the Taconic orogen in the central Vermont area. The Paleozoic "Proto-Atlantic" (Iapetus Ocean) opened about 600 million years ago and sediments and some volcanic materials accumulated on the continental margin and the adjacent ocean floor. In the Early Ordovician the ocean began closing, eventually resulting in the collision of the North-American passive continental margin with a volcanic arc (Ammonoosuc volcanic arc) (Chapple, 1973; Rowley & Delano, 1979) and/or micro continent (Rowley, 1983) in the Late Ordovician, named the Taconic Orogeny. A major thrust and fold belt developed with large nappes containing North American continental rise and slope sediments and locally ophiolites, which were thrust westward onto the Early Paleozoic carbonate shelf (*Figure 1.1.* and *Figure1.2.*). Imbrication, deformation and metamorphism of continental basement and

Figure 1.1. ⟶

Generalized geologic map of western New England and eastern New York (redrawn from Rowley, 1983). A-Albany, TA-Taconic Allochthon, GM-Green Mountains, BH-Berkshire massif, L-Lincoln massif, VV-Vermont Valley, DM-Dorset Mountain, HT-Hinesburg Thrust, HH-Housatonic Highlands, LC-Lake Champlain.


Triassic
Silurian - Devonian
Medial Ordovician-Collision related facies
Latest Precambrian-Ordovician shelf and rift - facies
Latest Pre-Cambrian-Ordovician Allochthonous rise - facies
Grenville Basement
Polyphase deformed - Accretionary prism and suture zone
Volcanic arc assemblage
Study area
LC
HT
VV
GM
D
TA
A
BH
HH
Adirondacks
Catskills
N
0
km
50



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*, conglomerate, *marble*.

Champlain-Vermont valleys—*Shale*, dolomite, *limestone*, quartzite, phyllite, slate, sandstone, conglomerate, *marble*.

Green Mountains—*Phyllite, schist*, quartzite, *greenstone*, slate, graywacke, *gneiss*, conglomerate, amphibolite.

Eastern Vermont—Phyllite, quartzite, greenstone, *schist*, gneiss, slate, *amphibolite*.

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

🟧

Cambrian

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

Champlain-Vermont valleys—*Quartzite, dolomite*, slate, phyllite, sandstone, *shale*, limestone, conglomerate, *marble*.

Green Mountains—*Schist, phyllite*, quartzite, graywacke, conglomerate, *greenstone*, dolomite, limestone, *gneiss, amphibolite*.

Intruded by ultrabasic rocks, basalt.

🟫

Precambrian

Champlain Valley (small area)—*Gneiss*, quartzite, granulite.

Green Mountains—*Schist, gneiss*, metagraywacke, quartzite, calcite and dolomite marbles, amphibolite.

Eastern Vermont—*Gneiss, schist*, quartzite, calcite, and dolomite marble, amphibolite.

*Predominant and important rocks in *italics*.

Earth Materials*

Taconic Range—Slate, marble.

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

Green Mountains—Talc, asbestos, verd antique marble, roadstone.

Eastern Vermont—Granite, talc, roadstone, copper (now inactive).

*For uses consult *The Mineral Industry of Vermont*, U. S. Bureau of Mines, Preprint, obtainable from Superintendent of Documents, U. S. Government Printing Office, Washington, D .C. 20402

Also, use information available from the mineral industries,

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

Figure 1.2.

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 cover are also associated with this collision (Rowley, 1983; Rowley et al., 1979).

Rowley and Kidd (1981) suggested a new model for the stacking geometry of the Taconic Allochthon, implying that the older slices lie to the east in a structural higher position and that younger slices occur further west in a lower structural level. In their model late major thrusts like the Champlain Thrust and the Pine Hill Thrust belong to the Frontal Thrust System, that also cross-cut the folded Basal Thrust of the Taconic Allochthon.

Taconic deformation cannot be proven in the core of the Green Mountains massif, but deformational and structural features make this likely (Rodgers, 1971, Stanley & Ratcliffe, 1985; Rowley & Kidd, 1981) and Taconic deformation is held to be responsible for the structure of the Berkshire massif (Drake et al., 1989). Numerous studies in the Green Mountain and Lincoln massif basement have revealed several major thrust zones which demonstrate that the Precambrian Grenville basement is a transported basement slice (Ratcliffe et al., 1988; Ratcliffe, 1988; Stanley et al., 1987; Dellorusso & Stanley, 1986; Tauvers, 1982). This interpretation is consistent with studies in the Berkshire massif (Ratcliffe, 1975; Ratcliffe et al., 1988) and with the COCORP deep seismic reflection profiling from the New England Appalachians (Ando et al., 1984; Brown et al., 1983). Little is known on Paleozoic thrust development along the western flank of the Green Mountains and especially the relationship between the carbonate sequence and Late Precambrian - Early Cambrian clastic cover rocks and basement. These contacts were recently (Thompson, 1959,1967; Doll et al., 1961) believed to be simply depositional, with the basement-cover contact being an angular unconformity. The overlying Cambrian-Ordovician rocks were interpreted to represent a continuous depositional sequence that becomes progressively younger to the west. Several earlier studies argued for fault relationships between carbonate sequence rocks and basement / basement-cover rocks (Hawkes, 1941; Bain, 1925; Dale, 1919, 1910; Keith, 1933). However, Doll et al.

(1961) using Thompson (1959) showed purely stratigraphic relationships for the Precambrian basement, located in an anticlinal structure, relative to the Ordovician marbles of the carbonate sequence.

The Vermont Valley and the western side of the Green Mountains are bounded to the east and west, respectively, by major fault systems that are most likely temporally correlative with one and another (Herrmann & Kidd, 1992). However, structural relationships are rather complex within this zone. Recent results of studies within the Appalachian belt of the Taconic Orogeny have led to interpretations of the geologic history that contrast sharply with interpretations that evolved prior to the influence of plate tectonic theory. This study tries to explain the depositional history and structural evolution in west-central Vermont and attempts to correlate this with relationships observed in related areas both along and across strike.

1.1. Location of the Field Area

This study investigates the structural and stratigraphic relations in the central Vermont Valley in west-central Vermont. The field area chosen is located between Danby and Wallingford and is bounded to the west by the Taconic Allochthon, and to the east by the massif of the Green Mountains, shown in *Figure 1.1.* and *Figure 1.3.*. The Vermont Valley consists, north of Dorset Mountain, of two valleys separated by a ridge; the main Valley along Route 7 and the Tinmouth Valley to the west.

The area mapped is approximately 10 by 30 kilometers in size and is bounded by the longitudes 72°05', 72°55' and the latitudes 43°20', 43°25'. It includes portions of the Pawlet (Shumaker, 1967; Thompson, 1967) and the Wallingford (never mapped) 15 minute quadrangles (scale 1:62,500).

Detailed outcrop mapping (*Figure 1.4.*) at a scale of 1:24,000 was carried out on 7 ½ minute topographic quadrangle sheets. The south-western part is covered by

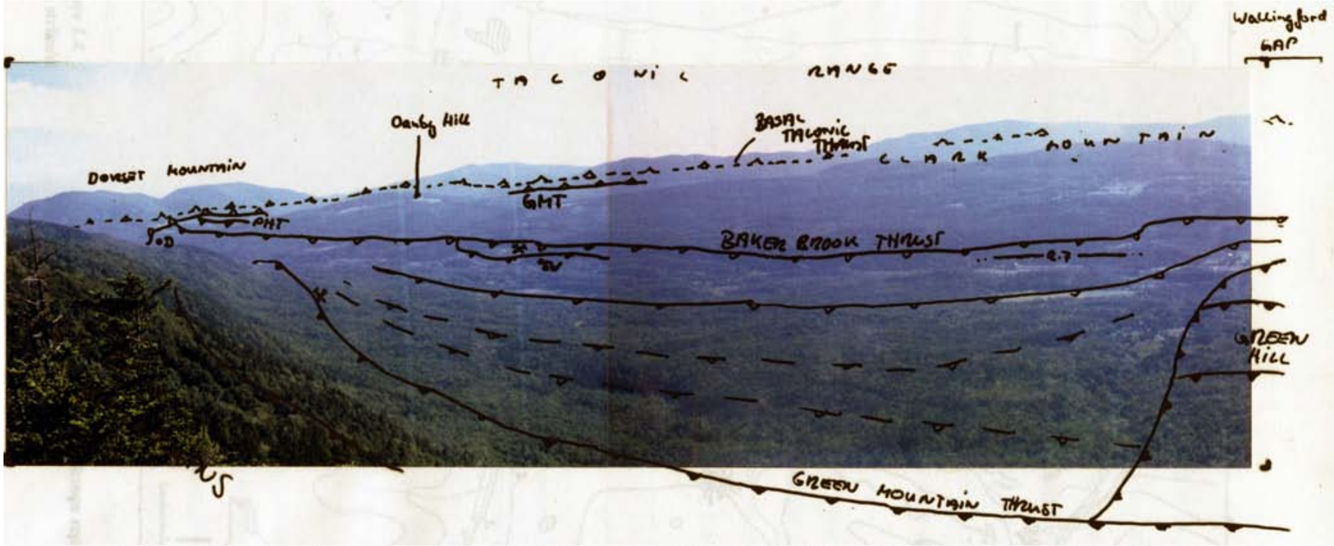


Figure 1.3. **View of the field area, looking south-southwest. Left side of the picture shows the steep flank of the Green Mountain massif.**

The Vermont Valley and the Tinmouth Valley are separated by a ridge along a fault (Pine Hill Thrust) which brings up basement slices.

The background shows the peaks of the mountains of the Taconic Allochthon, with Dorset Mountains truncating the Valley.
The base of Dorset Mountain contains the large reservoir of highly valuable marble deposits.

[Note: page reformatted from original; picture above, with lift-up overlay; below, without overlay

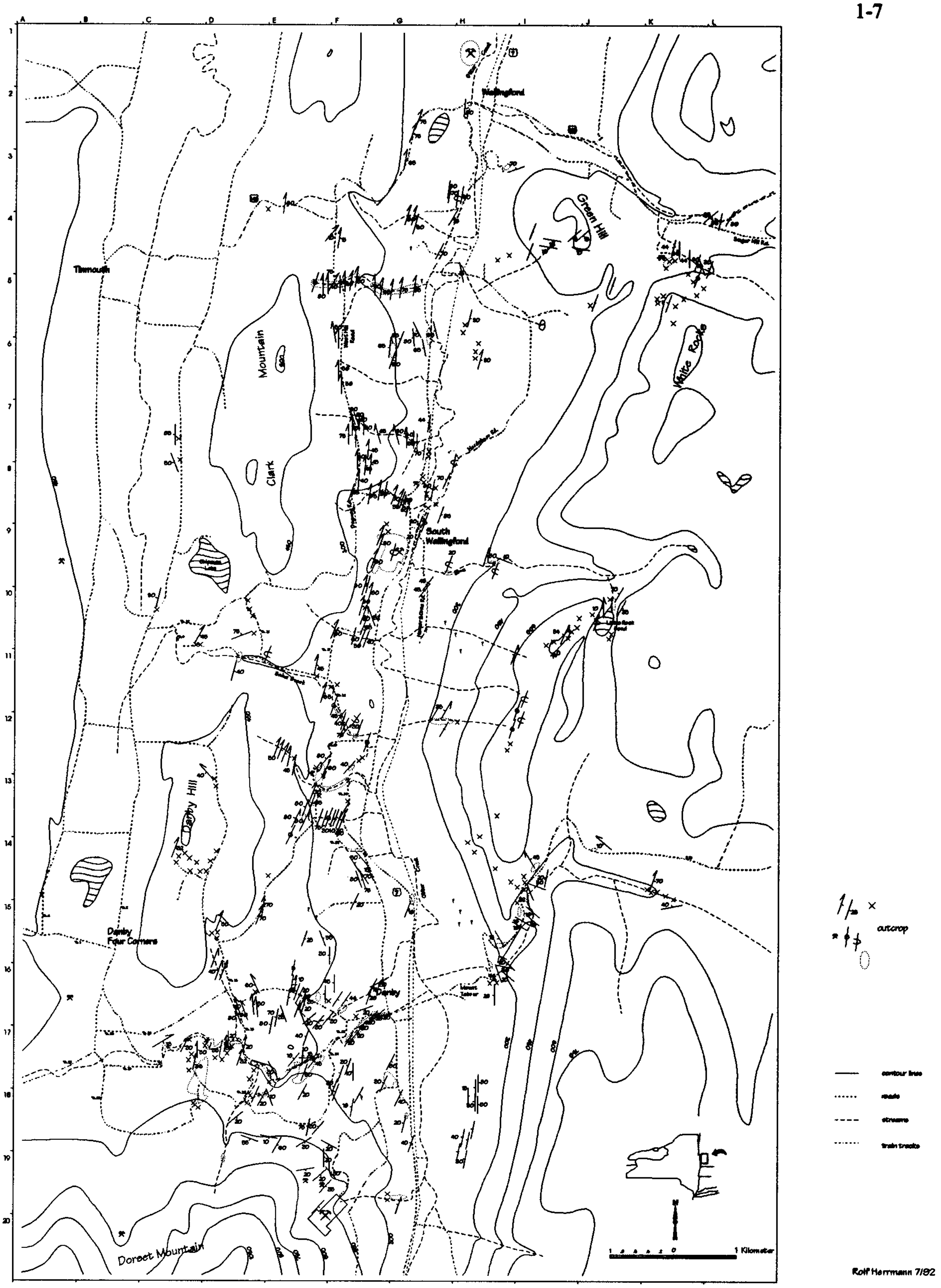


Figure 1.4. **Topographic base map shows the distribution of outcrops represented by a strike/dip symbol, X, or dotted line.**

USGS Dorset Quadrangle, north-western part by USGS Middletown Springs Quadrangle, the north-eastern part by USGS Wallingford Quadrangle and the south-eastern part by USGS Danby Quadrangle. Unfortunately, contours and elevations of the recent published maps for the Danby and Wallingford quadrangles are shown in meters, whereas Middletown Springs and Dorset are in feet; this causes problems for constructing a single base map. A set of aerial photographs (1:5000) was used to improve station locations in the field area and to attempt to trace faults, particularly in the western flank of the Green Mountains.

Detailed field work was done during a two month field camp in June and July of 1991. Additional work was undertaken during weekends of the following fall and in spring and summer of 1992; also reconnaissance field work in the adjacent quadrangles was done during weekends of fall 1990, spring 1991 and spring 1992.

1.2. Purpose of Study

A detailed study of the area chosen was intended to reveal more of the complex structure and lithology of the region. On the most recent previous maps the carbonate sequence in the Vermont Valley and the western flank of the Green Mountains is shown as an unfaulted structure with no major continuous faults parallel to the Taconic Frontal Thrust and the Champlain Thrust; the only major thrust shown is the Pine Hill Thrust.

The initial reasons to investigate this field area arose from questions about the Vermont State Map (Doll et al., 1961) based on the N.E.I.G.C. field trip guide (Thompson, 1959) and the Pawlet quadrangle map (Thompson, 1967) (*Figure 1.5.*):

- The origin of the Baker Brook "volcanic" unit, unconformably overlying the eroded (?) units of the shelf sequence, between the carbonates and the black phyllites of the Ira Formation.

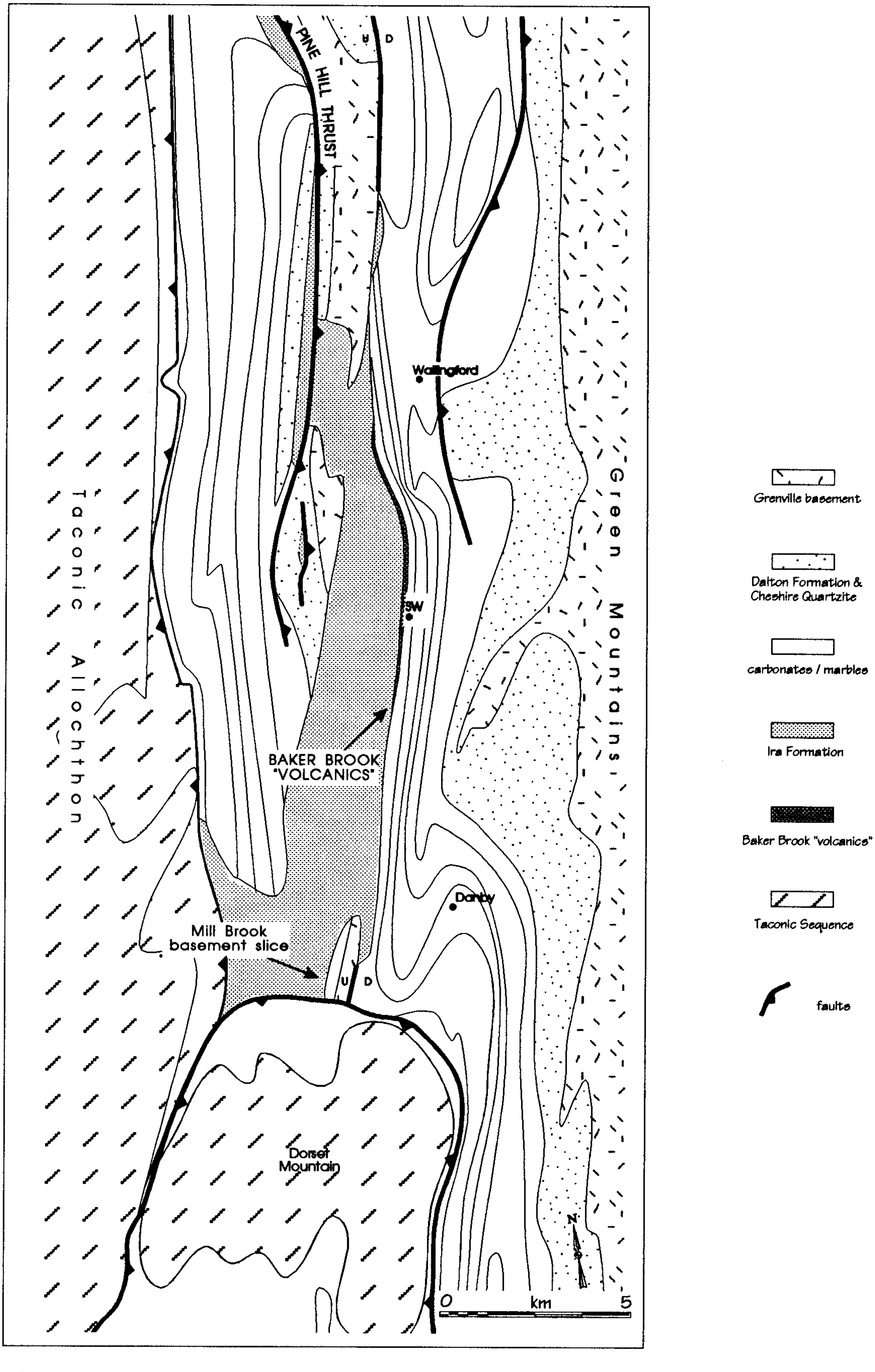


***Figure 1.5.* Geologic map of Thompson (1959, 1967) showing no continuous faults within the carbonate sequence and the Green Mountain massif; very simple structural and stratigraphic relationships and stratigraphic continuity; conformable contact relationships between basement and Ordovician black phyllites (Ira FM), Ordovician carbonates and a "volcanic" unit unconformably overlying the carbonate unit.**

- The origin of the Mill Brook basement slice and its relationships to other basement slices north along the Pine Hill Thrust.

  a) continuation of the Pine Hill Thrust through the field area ?

  b) relationship of the basement slice and overlying marbles of Dorset Mountain.

- Structural relationships within the carbonate sequence, especially the simple folded structures shown on previous maps.

The priority set to approach the field area was changed while mapping, after the previously proposed intact stratigraphic sequence for the western flank of the Green Mountains was not found and rock units appear to be lithologically different from what has been formerly defined (especially no basement in some areas) !

Results from the field area are later used to propose a modified structural view for the carbonate sequence of the Vermont Valley and the western flank of the Green Mountains.

1.3. Previous Work

The structural relationships of the geology of Vermont is mainly expressed on the Centennial Geologic Map of Vermont (Doll et al., 1961), which is based on a "basic mapping program" of the Vermont Geological Survey between 1947-61, carried out by several workers (*Figure 1.6.*). A large scale map of the geology of east-central New York, southern Vermont and southern New Hampshire has been published in a field guide of Billings, Thompson and Rodgers (1952). Especially in southern Vermont, detailed mapping was incomplete and reconnaissance mapping work added. Quadrangle mapping was carried out on a 1:62,500 scale that results in the loss of accuracy and detail necessary to solve the complex and complicated structural relationships in this mountain belt.

Because of their lithologically different rock units, the structural problems in the

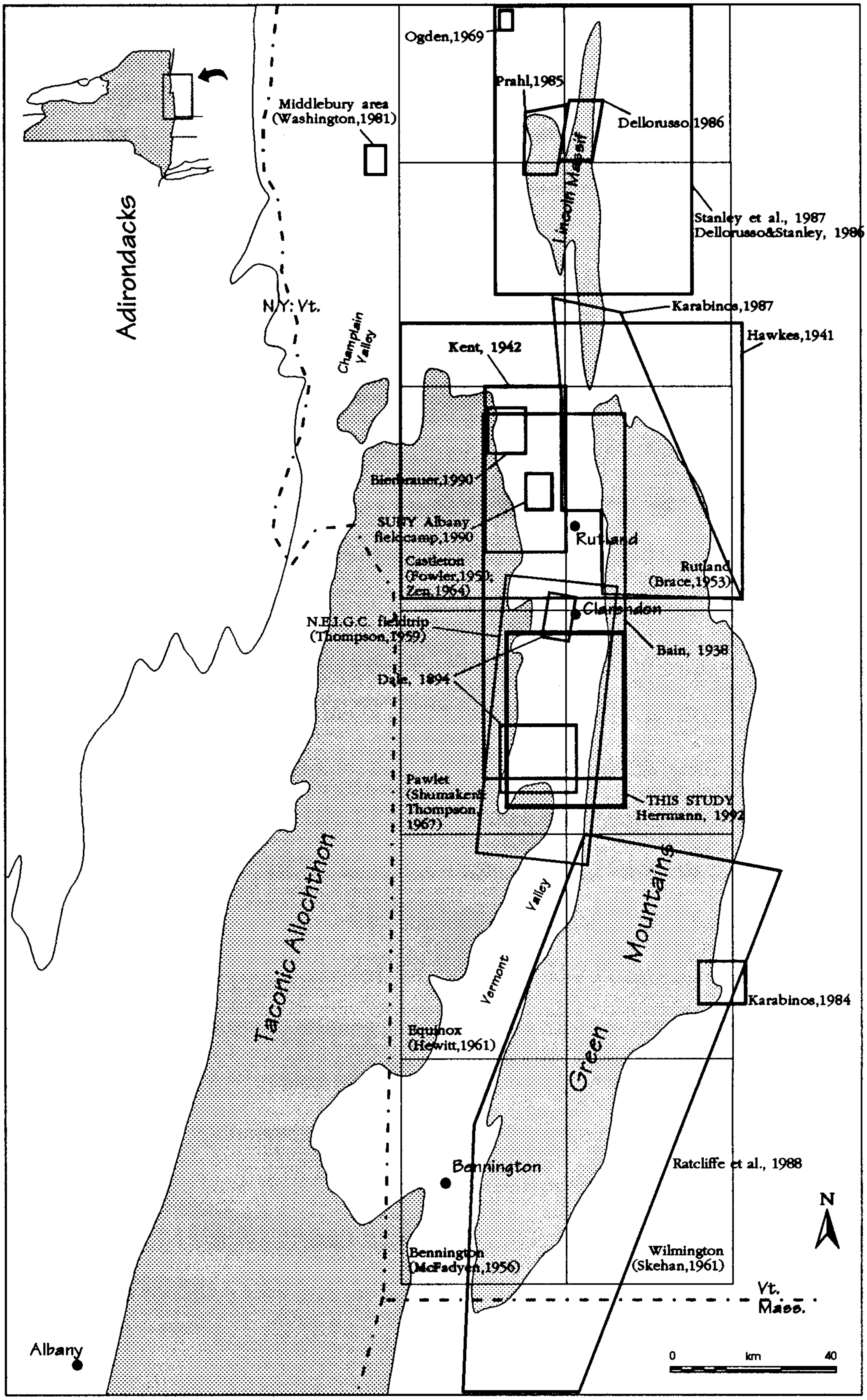


Figure 1.6. **Location of the field area (heavy bounded rectangle). Map shows also the location of previous projects relevant for the interpretation of Vermont Valley and the Green Mountains. Grid of thin rectangles shows the location of USGS quadrangles of the area.**

Vermont Valley are traditionally separated into an eastern portion, the rocks of the Green Mountain massif and a western portion, the carbonate sequence in the Vermont Valley and the Middlebury lowland.

The lack of recent structural mapping projects in the Vermont Valley leaves the problem that, for single detailed projects, a large scale interpretation for the regional geology is impossible due to correlation problems with adjacent areas. The most recent mapping projects by Bierbrauer (1990) at the north end of the Taconic Allochthon, Karabinos (1984, 1987, 1988) along the western flank of the northern Green Mountain massif, and Ratcliffe et al. (1988) in the southern Green Mountains, have revealed major structural differences and attempts to explain a "new" geologic interpretation of the Vermont Valley and the Green Mountains.

Bierbrauer (1990) suggests major north / south trending, eastward dipping late thrust faults for the entire length of the eastern Taconic margin and the Vermont Valley and complicated relationships between Taconic rocks and Ordovician (?) black phyllites (Hortonville Formation) in a melange zone between carbonate slivers, separated by major faults. These major late out-of-sequence imbrications within the carbonate belt have been demonstrated for the Taconic Allochthon by Rowley and Kidd (1981) which explains the existing stacking order that was controversly discussed for several years by many Taconic geologists (Zen, 1961; Stanley & Ratcliffe, 1985). A continuation of the imbricated structure to the east is necessary and likely, especially since several workers have demonstrated that formations mapped east of the Green Mountains consist of a series of fault slices. However this structure has not yet been proven for the Vermont Valley and the Green Mountains (Baldwin, 1982; Dellorusso & Stanley, 1986).

Karabinos (1988) proposed a major thrust for the western boundary of the Green Mountain massif, north of Clarendon, which carried Grenville basement and eastern cover rocks over the western shelf sequence. For the western boundary south of Clarendon he suggests an unfaulted structural relationship and an intact stratigraphic sequence. He further suggests that the Green Mountain massif is composed of two different tectonic units. A detailed geologic outcrop map of the western Green Mountain massif is however not available and Ratcliffe (pers.comm., 1992) argues strongly against the interpretation of Karabinos.

Ratcliffe et al. (1988) and Ratcliffe (1988) shows the existence of several faults zones with extensive ductile deformation within the core of the Green Mountain massif. He points out the difference in tectonic style between the Green Mountain massif and the Berkshire massif and suggests a north-east extension of the major faults in the southern part and no (or very few) through-going thrust faults in the central part of the Green Mountain massif.

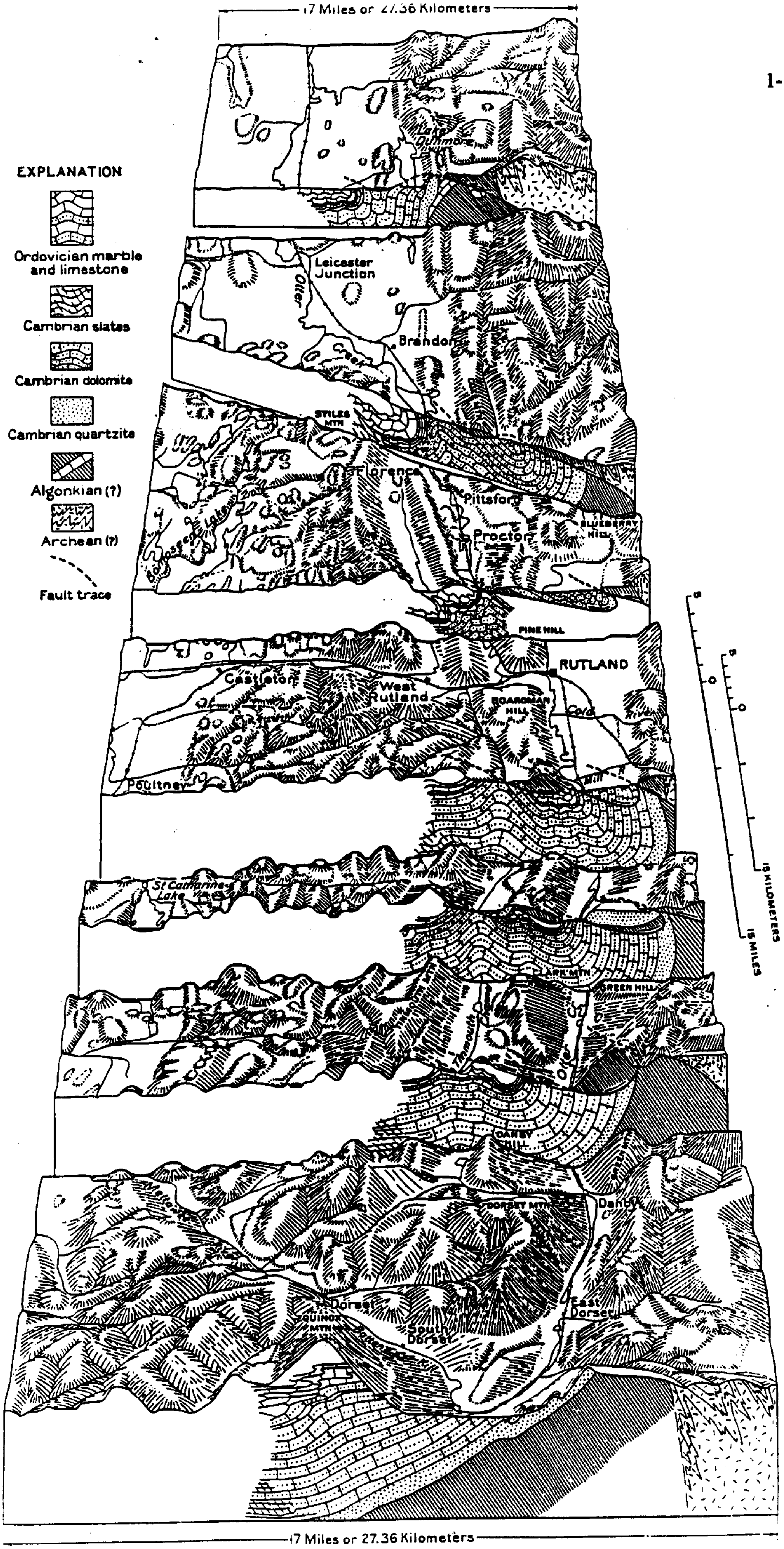
However, a major thrust fault along the western flank of the Green Mountains is a suggestion made by several workers, but ignored by the preparation of the Vermont State Map (1961) and all other workers since that. The fact that structural reports, maps and interpretations of many workers in the Vermont Valley and the Green Mountains have been disregarded in later reports, resulted in a slow and backward development of the structural interpretation.

A very revealing report including detailed geologic maps was done by Dale (1894) concerning the ridge between the Tinmouth and Vermont Valleys along the "Pine Hill Thrust" and the contact relationships along the north side of Dorset Mountain. The first large scale detailed map in the Vermont Valley was completed in the Proctor / Rutland area by Kent (1942). He basically verified the structure and stratigraphy of Bain (1938), but included fault relationships for the Green Mountain / shelf sequence contact following Hawkes (1941).

Kent's interpretation, especially for this contact, is in strong contrast with the results of Thompson (1959, 1967) who worked in the Vermont Valley between Clarendon and Dorset. For the south-eastern part of the Pawlet quadrangle including the Taconic phyllites of Dorset Mountain Thompson (1967) published a detailed geologic map. The eastern half of the Vermont Valley including the shelf sequence / Green Mountain basement relationships is covered only by a large scale sketch map (Thompson, 1959) not appropriate to demonstrate convincing evidence for stratigraphic and structural relationships. He interpreted the Vermont Valley as a mainly unfaulted structure with a purely intact stratigraphy from the Precambrian basement to the Ordovician phyllites of the Ira (Hortonville) Formation. Major evidence for this stratigraphic relationship is the Baker Brook "volcanic" unit, which Thompson (1967) interpreted as unconformably overlying the carbonates.

T. N. Dale (1894, 1902, 1910, 1912, 1913-14 (2x), 1915) and especially Bain (1925-26, 1931, 1933, 1934, 1938, 1959) (*Figure 1.7.*) among others, published several reports and detailed geologic maps and interpretations, unfortunately not appreciated or referenced by all later workers. Although plate tectonic theories were not known at that time, their large scale geologic interpretation is more plausible than later workers (see block diagram cross sections from Bain, 1925-26, 1933, 1938). Important is the precise stratigraphic nomenclature for the Ordovician marbles of Bain (1938), which is the key to understanding of the overall structural relationships within the carbonate belt. Their reports and maps also provide us with detailed observations of now abandoned quarries.

Discussions about the root zone of the Taconic Thrust east of the Taconic Allochthon were based mainly on lithological differences of the rock units. Several workers presented evidence for fault relationships along the western margin of the Green Mountains (Hawkes, 1941; Bain, 1925-26; Balk, 1952; N.C. Dale, 1917-18, 1919-20; T.N. Dale, 1902, 1910; Gordon, 1916; Whittle, 1894, 1894). Later maps proposed a pure stratigraphic sequence and completely unfaulted structures for the portion of the Green Mountains (Brace, 1953, 1958; Thompson, 1959, 1967, 1972; Hewitt, 1961, 1985; MacFadyen, 1956; Doll et al., 1961).



BLOCK DIAGRAMS OF THE MARBLE BELT FROM THE NEW HAVEN RIVER SOUTH TO EQUINOX MOUNTAIN,

Figure 1.7. **"Block diagram of central Vermont showing the extremely complex imbricate structure which has developed in the thrust of the Green Mountain front", Bain (1933). Two other versions have also been published by Bain (1938, 1925-26).**

Ogden (1969) examined the kaolin deposits in Monkton and proposed their hydrothermal origin within a zone of fracture. However the very curious existence of a chain of large kaolin and manganese deposits along the Green Mountain flank has never been investigated and put into structural relationships with structures found in the Green Mountains and the Valley sequence.

Previously published reports and maps of the Vermont Valley and the Green Mountain massif (see *Figure 1.6.*)

Billings, Thompson & Rodgers - Southern Vermont,	1952,	1:540,000
Doll et al. - Centennial Geologic Map of Vermont,	1961,	1:250,000
Thompson - Vermont Valley,	1959,	1:152,000
Bain - Vermont Marble Belt,	1938,	1: 76,000
Brace - Rutland Quad.,	1953,	1: 62,500
Fowler - Castleton Quad.,	1950,	1: 62,500
Hewitt - Equinox Quad.,	1961,	1: 62,500
McFadyen - Bennington Quad.,	1956,	1: 62,500
Skehan - Wilmington Quad.,	1961,	1: 62,500
Shumaker & Thompson - Pawlet Quad.,	1967,	1: 62,500
Zen - Castleton Quad.,	1964,	1: 48,000
Herrmann THIS STUDY - Vermont Valley,	**1992,**	**1: 24.000 (31,250)**
SUNY fieldcamp - Proctor area,	1990,	1: 12,000
Bierbrauer - Proctor/Florence,	1990,	1: 10,000
Washington, Middlebury area,	1981,	1: 6,200

2. *Lithology and Stratigraphy*

2.1. Introduction

The Vermont Valley is underlain by a sequence of Paleozoic carbonate rocks forming an elongate north-south trending belt. This sequence is overridden and covered on the west side of the Valley by the slates and phyllites of the Taconic Allochthon and on the east side by the Paleozoic metasedimentary schists and quartzites covering the Grenville basement of the Green Mountain massif. Locally slices of basement of the Green Mountain core are exposed within the carbonates of the Vermont Valley along a major thrust fault.

After early investigations by Emmons, Billings, Dana, Whittle and others, Dale (1894, 1902) published several papers on the Vermont Valley Geology. Bain (1931), Cady (1945) and Keith (1932) tried to establish a stratigraphic nomenclature and rock descriptions for the units in the Vermont Valley. Hawkes (1941), Gordon (1916) and Dale (1919) discussed the rocks of the western flank of the Green Mountains and attempted to establish a major fault there, the roots of the Taconic Thrust. The lack of a detailed geologic outcrop map east and south-east of Thompsons map (1967) make it difficult to understand the structures in the Vermont Valley shown on his map. The Vermont Centennial Map (Doll et al., 1961) finally summarizes all work done so far, but from a structural point of view it lacks many features expected in a major orogenic belt and produced by modern tectonic models.

Each outcrop has been mapped in a descriptive way and stratigraphic units have later been defined. The redefinition of the previously named "Baker Brook volcanics" from being a metamorphosed volcanic ash to a strongly foliated mylonitic high strain zone, termed by me *Baker Brook Greenschist*, changes the interpretation of the stratigraphy of the upper part of the carbonate sequence dramatically. The second major difference to previous maps is that the proposed extensive belt of continuous units of the Cheshire Quartzite / Mendon Formation overlying Grenville basement is not verified in the field area, strongly suggesting non-conformable, structurally controlled relationships along the western flank of the Green Mountains. A schematic overview of the stratigraphic positions of all lithic units in correlation with the schemes of other workers has been made in *Figure 2.1.* for the upper part of the shelf sequence. The lower part of the sequence and the suggested stratigraphic relationships for the western flank of the Green Mountains are shown in *Figure 2.2.*.

2.2. Black Phyllites of the Hortonville / Ira Formation (Oh) Middle Ordovician ?

The Hortonville Formation (Cady, 1945) is a dark gray to black phyllite which overlies the authochthonous shelf carbonates conformably to unconformably. This rock is lithologically equivalent to the Canajoharie phyllite of Bain (1959), the Ira Formation (Thompson, 1959; Zen, 1964; [Keith, 1932, introduced Ira slate]) and the Walloomsac slate / phyllite, and is related to syn-orogenic sedimentation, deposited in a foreland basin on the block-faulted and rapidly subsiding carbonate shelf of the North American craton. As introduced by Thompson (1959) and Zen (1961) the name Ira Formation is traditionally used in this area; the Whipple Marble Member associated with a gray dolomite breccia is said commonly to occur at the base of the Ira Formation (Zen, 1964). In contrast I believe that the "Whipple Marble" as described by Thompson (1967), is an upper member of the Vermont marble belt (Blue Marbles) as shown on the stratigraphic correlation chart (*Figure 2.1.*) and is brought up by thrust faults hidden in the black phyllites. Therefore I suggest using the name Hortonville Formation for the black phyllites of the Vermont Valley.

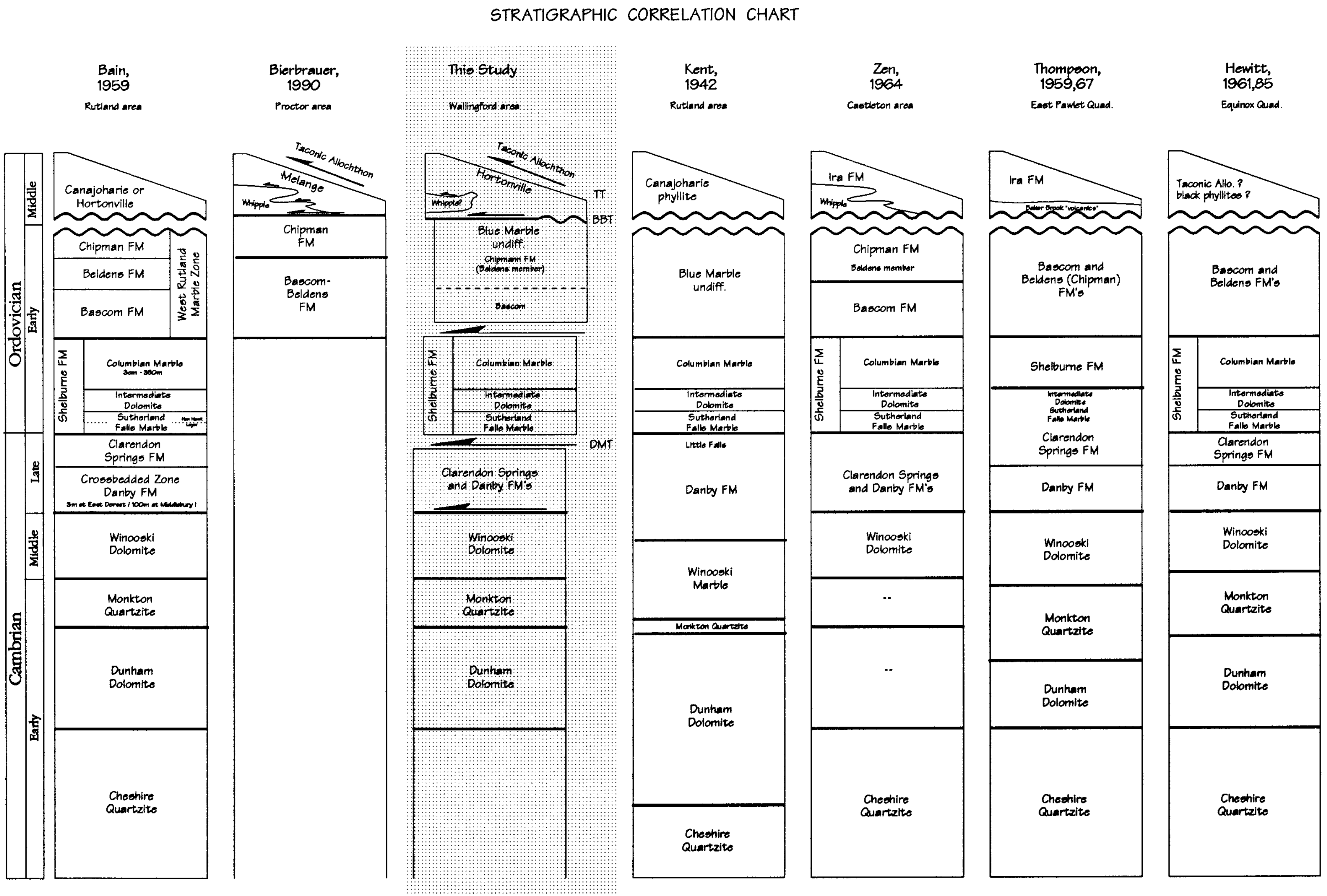


Figure 2.1. **Stratigraphic correlation chart for the upper part of the shelf sequence in the Vermont Valley. Note three major thrusts: the Dorset Mountain Thrust, DMT, separating the marbles from the dolomite sequence; the Baker Brook Thrust Zone, BBT, separating in parts the Hortonville from the marbles; the Taconic Thrust, TT, transporting the Taconic Allochthon.**

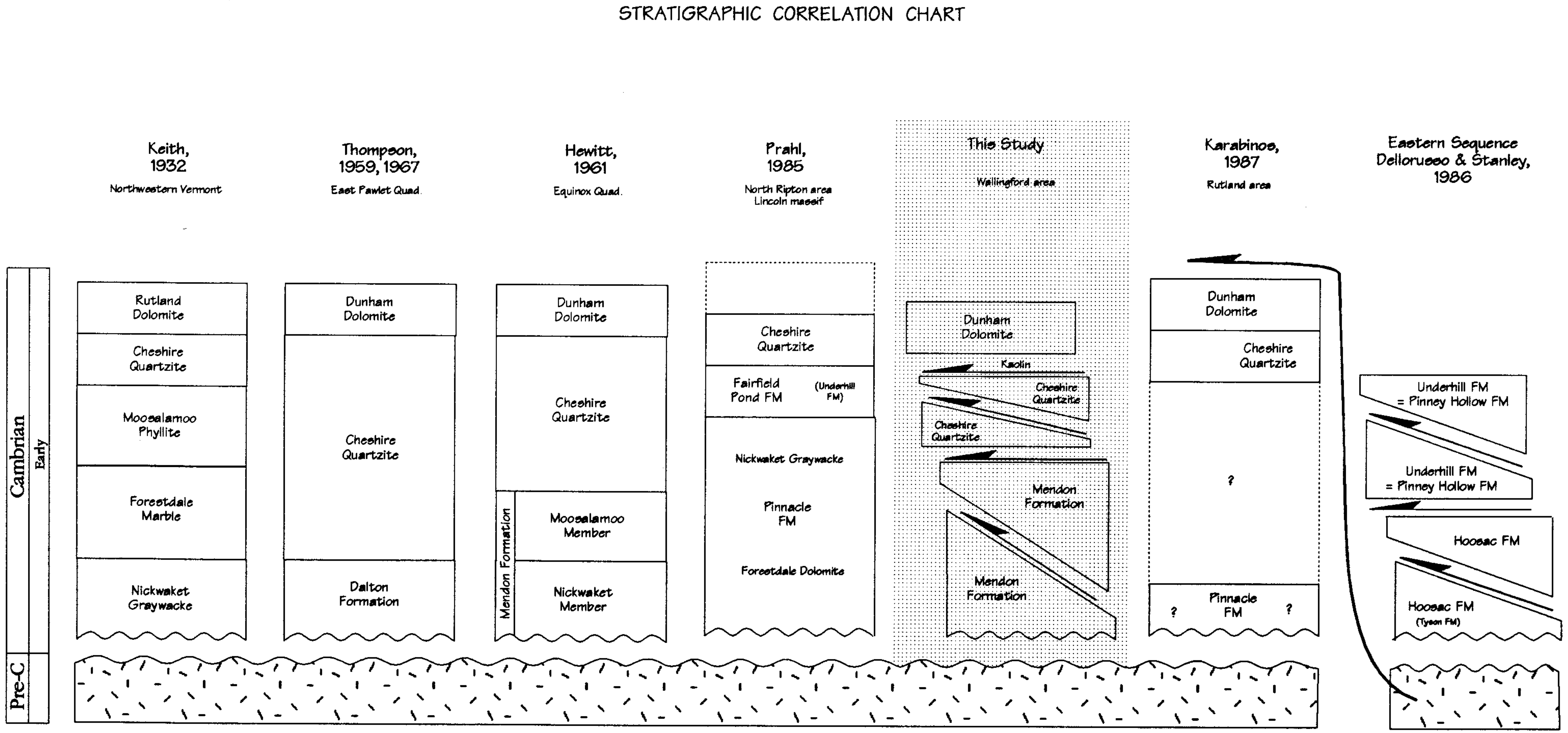


Figure 2.2. **Stratigraphic correlation chart for the lower part of the shelf sequence in the Vermont Valley. Note an imbricated thrust system for the lower part of the sequence, which has locally overridden units of the Vermont Valley Sequence. The Eastern Sequence is shown for comparison and to explain Karabinos interpretation of a major detachment, thrusting Eastern Sequence over Western Sequence rocks.**

Thompson (1967) reports minor variants including gray to gray-green phyllites, calcareous phyllites and phyllites with sandy laminae a few millimeters thick. These different types of phyllites within the sequence point to the major problem; determining if parts of this sequence are part Taconic Allochthon and have been tectonically incorporated in the phyllite terrain and must therefore be viewed as allochthonous. Bierbrauer (1990) demonstrated for the Proctor area that rocks mapped as authochthonous black phyllites of the Hortonville Formation represent allochthonous pelitic Taconic lithologies. He concluded that rocks of the undisturbed Hortonville Formation do not occur in his field area. His very careful and detailed work revealed two major late thrust faults hidden in the black phyllites, which are important for the structural interpretation and understanding of this area. The time stratigraphic position of the Hortonville Formation is believed to be Middle Ordovician (Thompson, 1967) based on fossils founds in limestones / marbles, thought to belong to the black phyllites. The detailed stratigraphic position is unclear since Bosworth & Vollmer (1980) demonstrated the paucity of fossils and their obliteration through deformation, their time transgressive occurrence; there is also the redefinition of black phyllites as belonging to the Taconic Sequence or a tectonic melange unit as demonstrated by Bierbrauer (1990).

In a few places, conspicuous pebbles of black coarse quartzite and white buff arenite pebbles occur in the black phyllites. The black rounded lens-shaped arenite pebbles were found only at one locality along the creek paralleling the road **Th.15**$_{[D16]}$[1]. The pebbles are about 10 cm in size and resemble in their color and grain size the dark coarse quartzite found at a large roadcut along road **Th.9**$_{[D10]}$. Steinhardt (1983) and Bierbrauer (1990) also report the occurrence of black quartzite pebbles and interpreted them as syn-depositional with the black phyllites which then were deformed together later. Bierbrauer (1990) suggested a Taconic source (Early Cambrian part of the sequence) for the blocks

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[1] outcrop location on geologic map (plate 1) given by D, 16 - coordinates.

of black and gray quartzite in the disrupted phyllite (Hortonville Formation) sequence (melange units), which are closely related to thrusting.

The best outcrop location to study the distinct lithological and structural features of this unit in the field area are along the steep cliffs of Dugway Road$_{[F8]}$ off Route 7. Here, the thrust contact of the Ordovician marbles with the highly deformed Greenschist and the very quartzose phyllites, and the transition back in the black phyllites, is exposed.

All workers have mapped this unit as exclusively autochthonous overlying the shelf carbonates unconformably after deep erosion (Thompson, 1959, 1967; Zen, 1961; Fowler, 1950). In fact this relationship ("Tinmouth unconformity") could easily be misinterpreted, and might alternatively be viewed as a tectonically derived contact, a normal fault contact (Rowley, 1982). Thompson (1959, 1967) suggested a high angle fault only for the basement / carbonates contact, but not for the basement or carbonate shelf / black phyllite contact.

Thompson (1967) also included beds of blue or blue-black limestone with minor beds of gray dolomite and black phyllite and a gray dolomite breccia in the Ira Formation. The dark gray dolomite breccia is characterized by light gray fragments re-healed in a lighter matrix. These rocks have also been mapped by Fowler (1950) and Zen (1961, 1964) as Whipple Marble. The origin of the dolomite breccia is unclear, but I suggest these rocks are highly sheared dolomites and marbles, resembling units of the Undifferentiated Blue Marble Sequence, brought up by faults hidden in the black phyllites; they could alternatively be part of the normal fault system along the eastern side of the basement slices. I also interpret micaceous and quartz-rich calcareous phyllites as adjacent to and produced by faults in the Ira Formation (Hortonville Formation).

The black phyllites grade eastward over about 50 meters into the mylonitic greenschist of the Baker Brook high strain zone, mainly by getting richer in quartz and carbonate content. The Hortonville Formation is not easily distinguishable from the Mendon Series in the overthrust slices on the western slopes of Clark Mountain (Bain, 1959; Thompson, 1967).

2.3. Units of the Baker Brook High Strain Zone (BB)

One focal point of this thesis is to define the origin of the so called Baker Brook "volcanics", a thin not very extensive unit, shown to be sandwiched between black phyllites of the Hortonville Formation and the Ordovician shelf carbonates on previous maps (Thompson, 1959, 1967) (*Figure 1.5*). In contrast, I suggest there is a major thrust fault here, and that this unit is a tectonically derived lithology, here named Baker Brook Greenschist. This very different view of this contact is quite important for the structural interpretation within the Vermont Valley. The proposed angular unconformity between black phyllites of the Hortonville Formation and shelf carbonates does not exist, at least east of the Pine Hill Thrust, and there is now evidence for faulting in the carbonate units. Further discussion of the structural relationships and regional tectonic interpretation is given in Chapter 3 and Chapter 4.

The Baker Brook Greenschist trends approximately north-south on the east side of the intermediate ridges, Danby Hill, Clark Mountain, Flat Rock and Boardman Hill, and paralleling the Pine Hill Thrust. The unit is traceable from a small creek along road **Th.32**$_{[D18]}$, where it is truncated a few hundred meters to the south by the Dorset Mountain Thrust, all the way north to the marble quarry in South Wallingford$_{[G9]}$ and crossing Dugway Road just north of South Wallingford$_{[G8]}$. The unit can be picked up in the Wallingford quarry$_{[H1]}$ next to Otter Creek north of the field area and at the steep cliffs along the road and Otter Creek just 1 km west of Clarendon. The best exposures are at the falls in Baker Brook and adjacent to the east side of the road **Th.16**$_{[F11]}$. The best outcrops to get the whole lithologic sequence of the high strain zone with the adjacent rock units are west up the hill along road **Th.20**$_{[E12/13]}$, from its junction with road **Th.21** to where it bends down to join road **Th.16**. Exposures at the north cliff in the South Wallingford marble quarry$_{[F9]}$ help to establish the relative position for all involved units and are the basis for the structural interpretation of the field area. The newly identified Baker Brook Greenschist is also exposed in this outcrop, separating the Ordovician Blue Marbles and the black phyllites of the Hortonville Formation.

This conspicuous rock unit has been identified by several workers but always grouped with the Cambrian units of the Mendon Series or Cheshire Quartzite. Zen (1964), Brace (1953) and Osberg (1959) report a green, chlorite schist on the north slope of Boardman Hill associated with a black, calcareous, silty schist, but did not find any need to distinguish those rocks from the Mendon Series. Thompson (1959) reported a "feldspathic schist and actinolitic greenstone believed to be metamorphosed volcanic tuffs" in Danby and Wallingford and included them in the Hortonville Formation. Thompson (1967) introduced a new name for this unit, the Baker Brook "volcanics". In contrast I suggest that the Baker Brook Greenschist is a mylonitic highly strained rock unit, separating the black phyllites of the Hortonville Formation from an overturned section of the Ordovician marbles and dolomites of the carbonate shelf sequence by a major thrust fault (Baker Brook Thrust). This structural relationship was later obscured in most places by later faults, slicing through this contact.

The Baker Brook Greenschist (BB) is an easily identifiable rock unit, conspicuous in its greenish color and pervasive transposed and differentiated layering, due to high strain; it usually forms small ridges due to its resistance to weathering (*Figure 2.3.* and *Figure 2.4.*). Locally, Grenville basement fragments, with sizes up to 80 centimeter, can be identified within the greenschist. It can in places be called a quartz mylonite containing a major amount of strongly recrystallized quartz grains and quartz veins in the matrix of this rock. The fabric displays locally lenses of quartz and K-feldspar, which form a planar mylonitic fabric with well-developed quartz ribbons. Both the large quartz grains and

Figure 2.3. **Outcrop picture of the Baker Brook Greenschist exposed at the north cliff in the South Wallingford marble quarry.**

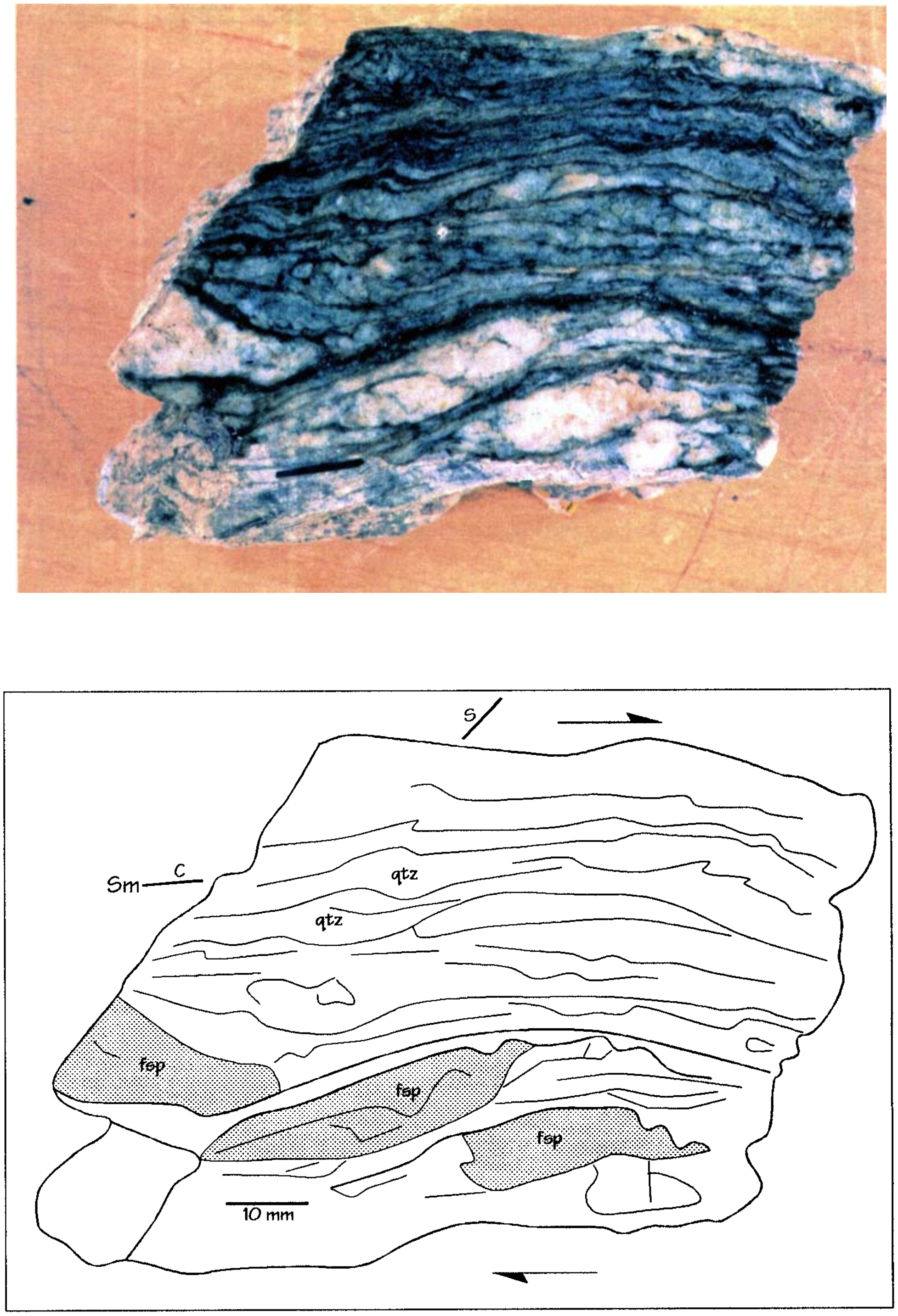


Figure 2.4. **Rock sample of Baker Brook Greenschist showing pervasive and transposed layering and an anastomosing mylonitic foliation with weak feldspar megacrysts (fsp) in a quartz-sericite-chlorite-carbonate matrix. Deformed quartz vein (qtz) parallel to Sm. Sm = mylonitic foliation.**
(Rock from location F12, Baker Brook Falls Th.16)

coarser fragments of feldspar clasts are surrounded by a fine-grained quartz-sericite-chlorite-carbonate matrix. Epidote is the predominant associated mineral. Within the anastomosing mylonitic foliation of this rock are locally coarser fragments derived from intermediate-silicic plutonic rocks, presumed to originate from the Grenville basement. Other more mafic basement lithologies could perhaps have also contributed to the unit. The size and content of the feldspar clasts varies from outcrop to outcrop. In some places they are almost unrecognizable, in others they reach sizes of more than 2 centimeters. The content of carbonate is often high and is presumably derived from the adjacent carbonates.

The adjacent marbles are mylonites too, exposing a prominent stretching lineation plunging steeply to the south. The east side of the greenschist high strain zone is marked by a very sharp contact. The west side, however, consists of a wide transition into the black phyllites of the Hortonville Formation. The contact relationship between the marbles and the greenschist is best exposed along the north-west face in the South Wallingford quarry. There it is possible to get rock samples showing the actual contact. The outcrop relationships of the best exposures suggest a thickness here of about 5 to 10 meters for the greenschist. The transition zone west of the contact has a thickness of about 50 meters or more.

The transition zone consists mainly of a very quartz-rich black phyllite. The highly strained character is more easily identifiable in the more quartz-rich rocks. Another rock type within the black phyllites, and usually only occurring close or next to the west side of the Baker Brook Thrust, is a dark black, slaty to massive graphite rich slate. This rock is clearly associated with the fault zone fabrics, exposed only in small patches or slivers.

2.4. The Ordovician Marbles

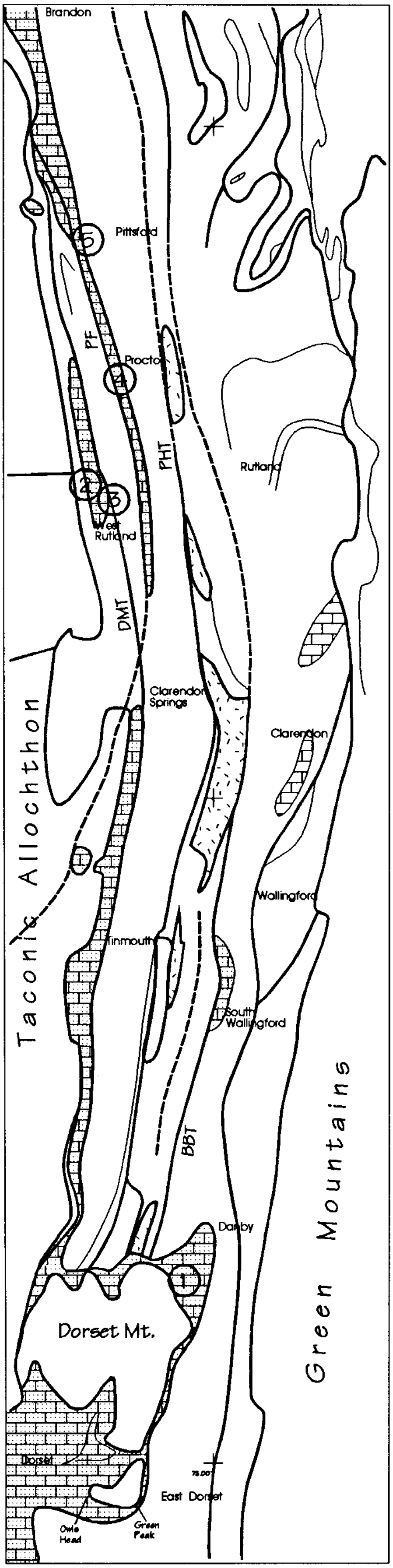
Generally the marble consists of alternating beds of calcite marble of various grades of texture and colors; white, gray (graphitic), greenish banded (muscovitic, actinolitic).

These beds are interbedded with bluish or grayish untwinned dolomite and with muscovite schist in small beds, in places graphitic and up to 10 m thick (Bain, 1912). The uppermost part of the marble is generally more or less graphitic and therefore of various shades of bluish gray. For the purpose of a large scale correlation, it is necessary to start with a marble sequence that is undifferentiated in its upper part (Undifferentiated Blue Marble), underlain by the Shelburne Formation. Because not all members of the Undifferentiated Blue Marble Sequence are exposed in my field area, I have based my correlation on Bain's (1959), the most reliable and extensive source for work done within this sequence (*Figure 2.5.*). Major differences in this sequence can only be demonstrated by a very careful, small scale mapping investigation (Bierbrauer, 1990). However it is not clear from each outcrop if tight folding "flowage" or slicing was the major tectonic process to produce the strong variations in thicknesses that are observed.

Important for the stratigraphy presented here and the tectonic model for the Vermont Valley is that bore-hole data from all marble quarries in the Vermont Valley, from Manchester to Middlebury, show clear correlations with each other (Ogden, pers.comm., 1992) (*Figure 2.6.*). The cores do not, however, necessarily support a fine scale distinction of every unit within the Blue Marbles.

2.4.1. Undifferentiated Blue Marbles (Ob) Early Ordovician

The Bascom Formation crops out only locally in the field area and is not well defined, in contrast to the thick, highly deformed Blue Marble sequence along the Taconic Allochthon south of Manchester. Because this Formation lies north of Dorset Mountain adjacent to the Ordovician (?) black phyllites of the Hortonville Formation, several different names and stratigraphically different interpretations obscure the obvious and mappable outcrop relationships within this unit. Therefore all dark gray or blue marbles and dolomites are included in the Bascom Formation and are shown on the map as an



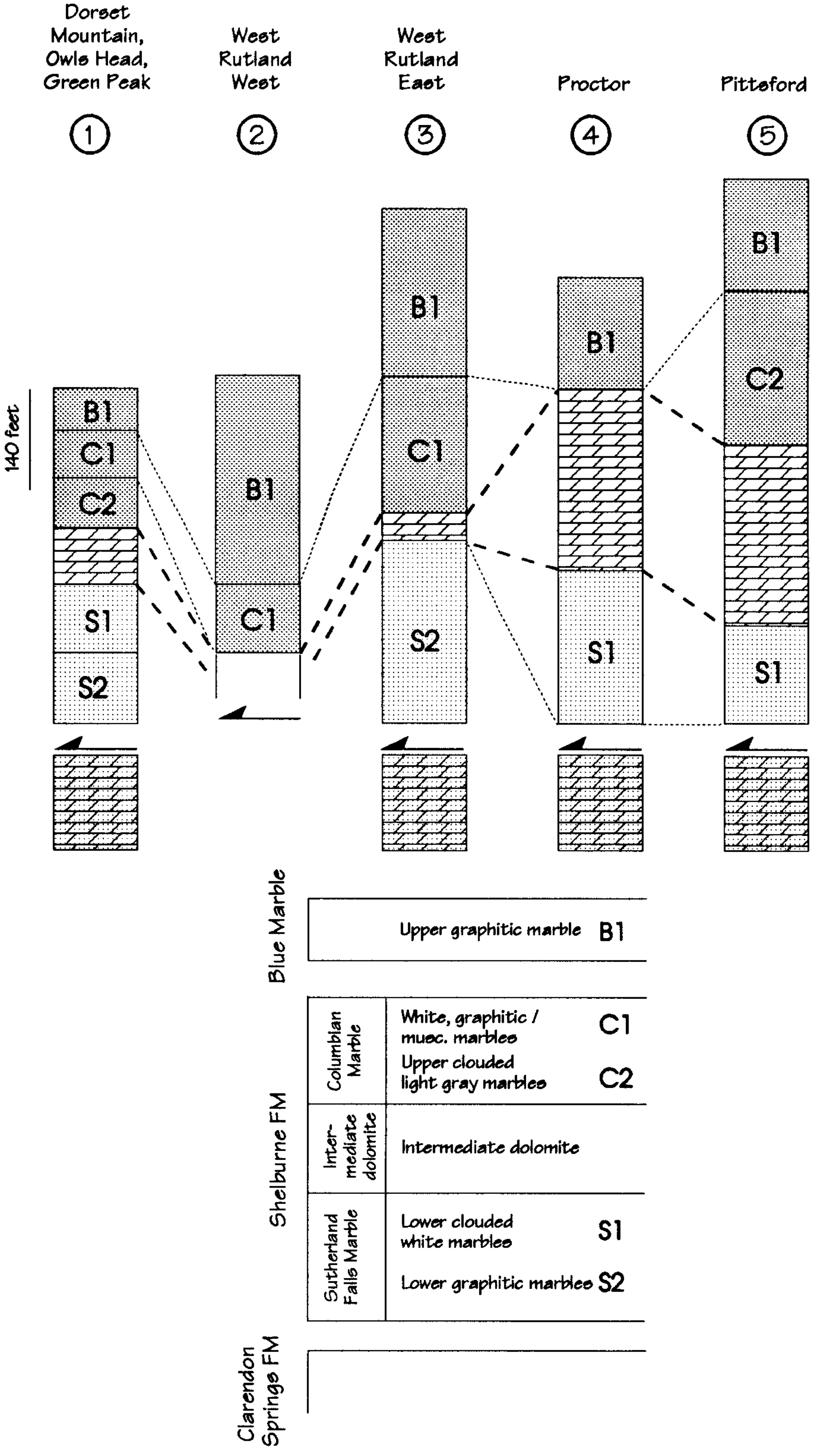


Figure 2.5. **Correlation of the major marble deposits in the Vermont Valley. The most striking feature in the chart is the disparity in thickness of the intermediate dolomite in the West Rutland section and the Proctor-Pittsford belt. Note the absence in the Proctor section of the Columbian Marbles, and the thinning out of the Columbian Marbles and a thick quartzose dolomite on Dorset Mountain.** (data from Bain, 1912, p.96)

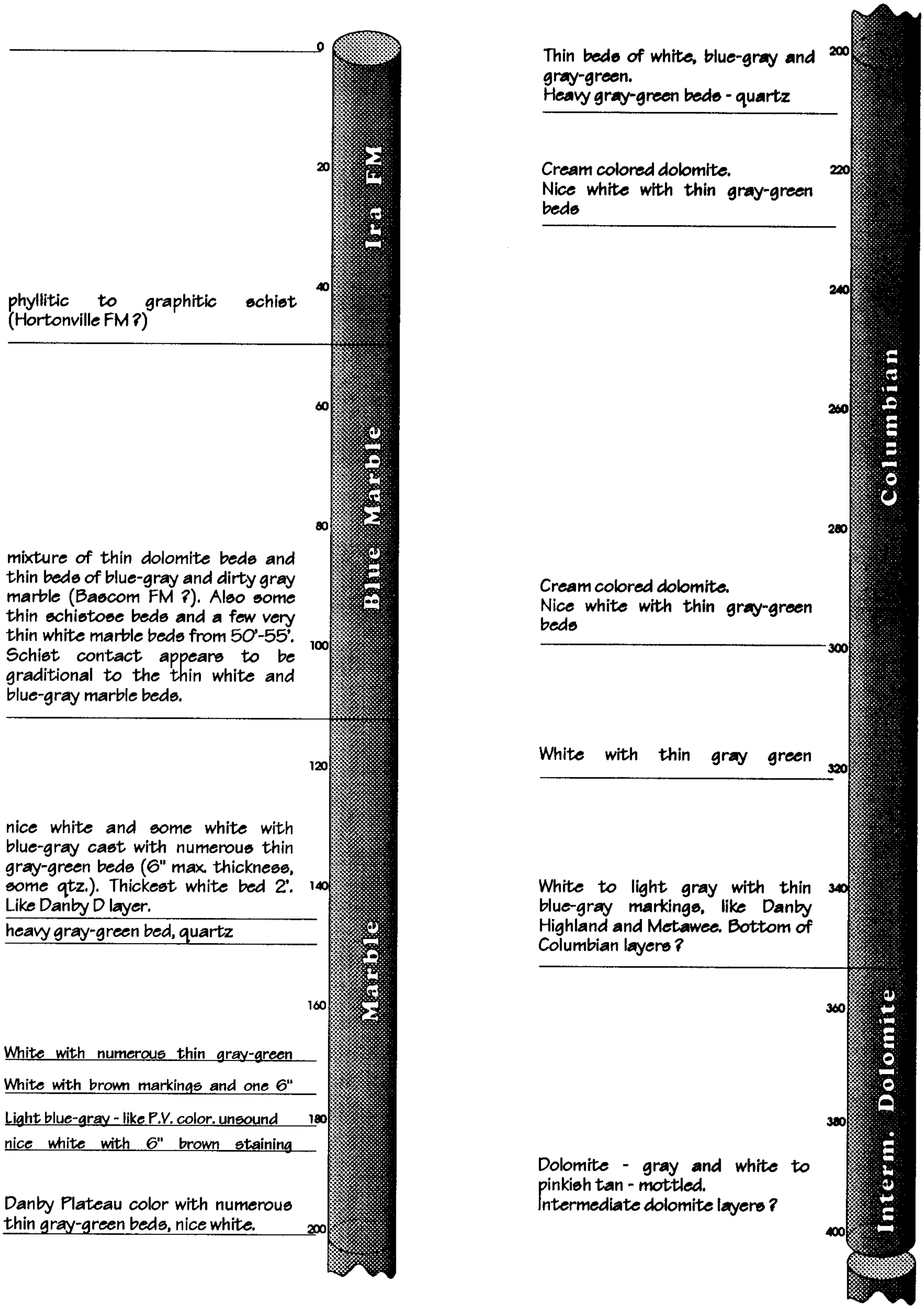


Figure 2.6. **Bore hole core (thickness in feet) from Dorset Mountain, Freedly Tunnel Quarry, clearly shows the proposed thicknesses of a thin (20 m) section of dolomitic Blue Marble and a very thickened section of white Columbian Marble (80 m). This example also demonstrates how exact, layer by layer, correlations can be made at different locations in the Vermont Marble belt. (Vermont Marble Company, 09-20-1962, D.G. Ogden)**

undifferentiated unit. Bain (1959) named this sequence the West Rutland Marble Zone and also describes it as an undifferentiated unit showing high deformation. A stratigraphic correlation is not possible so far; however its chaotic relationships to adjacent units suggest tectonically derived relationships. Bain (1938) reports a disconformity at the top of the Upper West Rutland Marble. The most careful distinction has been done by Bain (1938) showing seven distinguishable units within the Blue Marble sequence on his geologic map for the central part of the Vermont marble belt. The whole sequence is characterized by layers and boudins of gray- or orange-weathering dolomite within the blue-gray and white marbles. The sequence is divided into units separated by marker dolomite beds. The lower part of the sequence is characterized by dolomitic mottling and minor beds of gray- or orange weathering dolomite. Minor rock beds include thin beds of black phyllite. The sequence is only locally thick enough to make an adequately commercial deposit (Bain, 1959).

The following chart correlates differently used unit names of the Upper Blue Marble Sequence (also shown in *Figure 2.1.*):

THIS STUDY	**BAIN (1959)**	**? ?** **(equivalents inserted in Bain 1959))**
Blue Marble	True Blue Marble	Whipple in part ?
	Blue Marble and Dolomite	Burchards (Chipman FM)
Ob	Westland Marble	Beldens Marble (Chipman FM)
	Upper West Rutland Marble	Beldens Marble
	Main West Rutland Marble	Beldens Marble
	West Blue Marble	Bascom FM
	Blue Marble and Dolomite	Bascom FM

Marble or limestone and a gray dolomite breccia are shown on Thompson's map (1967, *Oil*) within the black phyllites, or cross-cutting the carbonate sequence as a basal bed belonging to the Ira Formation. These carbonate rocks have been mapped farther north as the Whipple Marble (Fowler, 1950; Zen, 1964). In contrast I interpret these rocks as highly deformed marble slivers of the Blue Marble Sequence brought up by hidden faults in the black phyllites. Ogden (1992, pers.comm.) also identifies these rocks as part of the upper Blue Marbles.

2.4.2. Shelburne Formation (Os) Lower Ordovician

Traditionally the white marble sequences were included within the Shelburne Formation (Bain, 1959; Cady, 1945; Hewitt, 1961). Thompson (1967, 1969) redefined the Clarendon Springs Dolomite and the Shelburne Formation, by moving the lower two members of the Shelburne Formation (Intermediate Dolomite and Sutherland Falls Marble) into the Clarendon Springs Formation. Following his interpretation the only member present in the Shelburne Formation is the Columbian Marble (*Figure 2.1.*). Thompson (1959) assumes that the Intermediate Dolomite is not a member of the marble sequence, which is in strong contrast with the traditional nomenclature.

Columbian Marble

The Columbian Marble consists of a white, massive, coarse marble with green silicate streaks. A dolomite bed ranging in thickness from 2 to 15 meters occurs at the top, marking the contact to the Blue Marbles. The lower part of the unit is dolomitic like the Sutherland Falls Marble. Dolomitic mottlings (dolomite chains) are present in the unit, but not so contorted and the markings usually have a linear pattern. No thick continuous dolomite beds are known within the lower part of the Columbian Marble. This marble has a well-developed shear fabric given it an extremely low porosity, a very high elasticity and low inter-granular pore width (Bain, 1938, 1959; Ratte & Ogden, 1989). The marble weathers white with dark lines along bedding planes perfectly exposed in the abandoned quarries.

This is the commercially most important marble and been worked in the Danby, Proctor and Middlebury quarries. Its total thickness is not identifiable because of extreme changes of thickness due to "flowage" that thins the marble to a few centimeters in places and in other places it increases to over 350 m. The largest underground marble quarry in the world (20 acres) is driven into the east side of Dorset Mountain near Danby. The productive layers are quarried in the Columbian Marble member of the Shelburne Formation, consistent in physical character throughout the quarry and identified by a "marketing" name. The Columbian Marble is extremely thickened in this part of the layer and reaches a thickness here of about 180 meters. On the picture (*Figure 2.7.*) the distinguishable layers within the Columbian Marble are worked along strike (here horizontally; note the steps at the walls); the brownish dolomite bed, which occurs at the roof of the quarry, marks the base of the Bascom Formation.

Intermediate Dolomite

The Intermediate Dolomite is the marker bed for the marbles and distinct in all locations. It consists of a thick bedded, massive, light gray weathering dolomite, typically about 65 m thick although quite variable. A silicified band occurs near the mid section at most places (Bain, 1938, 1959; Thompson, 1959; Ratte & Ogden, 1989). Thompson (1967) included all units up to and including this dolomite within the Clarendon Springs Formation. This is confusing because the distinction between marble and dolomite units can then not be made if the Sutherland Falls Marble is missing in between. Several marble quarries in the Dorset area have been shut down in the early 1990's because the Intermediate Dolomite was confused with the Danby Dolomite, without knowing that these beds of the Intermediate Dolomite are there only a few tens of centimeter (20-100 cm) thick, and underlain by valuable marble

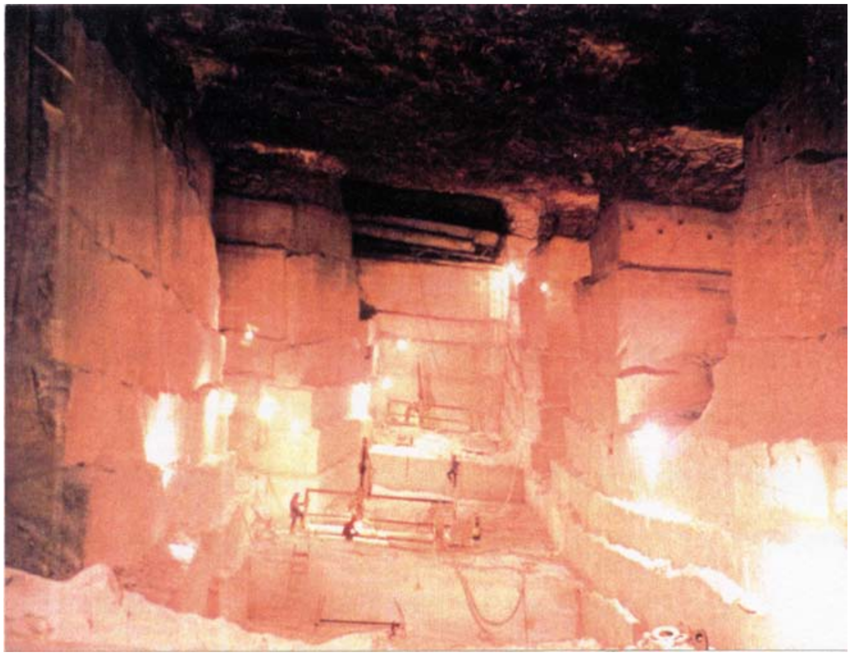


Figure 2.7. **Imperial Danby Quarry in Danby driven into the east flank of Dorset Mountain (photo from Vermont Marble Company, Proctor Vermont, 1983). The brownish dolomite at the top of the quarried section marks the base of the Bascom Formation; the high quality layers of the Columbian Marble, a member of the Shelburne Formation, can be distinguished by the steps at the quarry walls. The Columbian Marble is thickened here to a total of about 180 meters.**

Sutherland Falls Marble

The Sutherland Falls Marble is a very distinct massive, white to light gray marble with contorted dolomitic mottling across almost any surface. A single phyllite band occurs through the middle of the unit, named the Hen Hawk Layer (Bain, 1938, 1959; Thompson, 1959; Ratte & Ogden, 1989). The entire unit is thinned to cm locally and at other places thickens to more than 100 m.

2.5. The Dolomite Sequence

Having the idea of a conformable stratigraphy in mind, the distinction of the different formations of the carbonate sequence seems to be obvious. Proof of the contact relationships, however, is very difficult and leads me suggest a tectonically disrupted zone (duplex ?) containing several slices and slivers. The demonstration of conformable contact relationships is in most cases impossible or highly interpretative. Neglect of this fact by previous maps results in an interpretation of pure stratigraphic relationships of all formations.

As an example there is an outcrop in the Vermont Valley described very differently in two different field trip guides: A large, very beautiful outcrop on Route 7, 2 miles south of Wallingford is interpreted by Thompson (1959) as exposures of the quartzites and dolomites of the **Monkton Formation**, whereas Ratte & Ogden (1989) interpreted this exposure as **Dunham Dolomite** displaying clearly its cream colored dolomite beds. I believe that this outcrop is actually a great example of thrust-repeated beds (see outcrop picture *Figure 3.12.*), exposing at least two thrust slices (approximately 10 meters thick) of the Winooski and Monkton Formations.

Another example is a roadcut 0.2 miles south of East Dorset (at the Junction between Rt. 7 and Rt. 7A). Hewitt (1961) interpreted this exposure on his geologic quadrangle map

(Equinox Quadrangle) as belonging to the **Dunham Formation**. In his field trip guide (1985) he interpreted this outcrop as **Winooski Formation**, a remarkable stratigraphic jump !

All workers in the Vermont Valley report extreme variations in the thickness of all formations. Different in my interpretation is that I interpret these thickness variations to be tectonically controlled and not as all other workers to be simple thickness changes depositional controlled. Especially, the Danby Dolomite is reported to change its thickness from 350 m or more in the Rutland Quadrangle (Brace, 1953) to 3 m at East Dorset (Bain, 1959) and to less than 100 m reported by McFadyen (1956) for the Bennington area.

2.5.1. Danby / Clarendon-Springs Formation (Cdc) Late Cambrian

The Danby / Clarendon-Springs Formation is described here as single unit. Near its type section in Danby (Keith, 1932) this formation is reported to be characterized by a siliciclastic basal unit overlain by an upper carbonate unit termed the Wallingford Member (Clarendon Springs of Bain (1938, 1959)). To the north the Danby / Clarendon-Springs thins and becomes a mixed siliciclastic-carbonate unit (Mehrtens et al., 1987).

It is a gray weathering gray calcitic dolomite, in some place sugary due to a higher sand content, in well-defined beds about 25 cm thick. The lower part is characterized by cross-bedding and named by Bain (1938) the "crossbedded zone" (Bain, 1938, 1959; Thompson, 1959, 1967; Cady, 1945; Fowler, 1950; Brace, 1953). The massive medium-bedded appearance can be best seen in a canyon and the falls of Mill Brook in Danby (*Figure 2.8.*)$_{[F17]}$. Beds of pure vitreous quartzite up to 1.5 m to 2 m thick in the lower part of the section are described by Thompson (1959), but have not been identified in the field area. According to Bain (1959) the section thins to 3 m at East Dorset and is thicker near Middlebury. Most workers suggest a minimum thickness of 150 m for the Danby

Figure 2.8. **Picture of the type location for the Danby Formation in the stream bed of Mill Brook in Danby. It is a gray weathering, medium bedded dolomite. (looking west)**

area, requiring depositional thinning along about 9 km of strike to 3 m ! The peculiar situation of the dramatically narrowing valley in this area suggests thinning by faulting, which is a more plausible explanation, especially for passive margin shelf deposits.

2.5.2. Winooski Formation (Cw) **Lower Cambrian**

The Winooski Dolomite consists of a buff, white and gray weathering medium bedded dolomite. The beds are commonly about 10 cm thick separated by thin siliceous partings. The boundary between the Winooski and the underlying Monkton Quartzite is difficult to define and in most cases arbitrary (Thompson, 1967). Therefore Bain (1959) included the Winooski, Monkton and Dunham in one single unit called the Rutland Formation (or Pittsford Valley Dolomite).

2.5.3. Monkton Quartzite (Cm) **Early Cambrian**

The Monkton is the most conspicuous unit within the carbonate sequence and used as a marker horizon. Introduced by Keith (1923) at it type locality in the Champlain Valley the exposures in the Wallingford area show a gray-green massive quartzite, interbedded with dolomite and dolomitic sandstone, with a few thin beds of phyllite, lacking all the distinct characteristics as described by Keith. Cross-bedding is characteristic for the quartzite beds and the dolomite beds. Whereas the Monkton Quartzite is well identifiable at its type locality at Monkton due to its red color, beds of the Monkton can be easily confused with other sand-rich dolomitic beds farther south.

Cady (1945) and Fowler (1950) report that the Monkton dies out to the south in a series of dolomites, however rocks in the Bennington area described by MacFadyen (1956) resemble those in the same stratigraphic position and lithologic characteristics as farther north in the Vermont Valley, where the Monkton Quartzite (reddish color) is distinct and easily recognizable in the northern Champlain Valley, but is not distinct in the Vermont Valley; because in outcrop this unit is often not distinguishable from other quartzitic horizons in dolomites (e.g. in the Danby Formation) and therefore is unusable as a marker horizon in the Vermont Valley.

2.5.4. Dunham Formation (Cd) — Early Cambrian

The Dunham Dolomite represents the first carbonate deposit on the newly formed shelf (Mehrtens et al., 1987) overlying the siliciclastic sequence. Due to its poor resistance to erosion, outcrops are poor in this area. The formation is primarily composed of massive, gray weathering dolomite. Beds up to 3 m in thickness are not uncommon, in places showing conspicuous cross-bedding. It is marked by interbedded thin siliceous beds.

It is quite difficult to determine the exact stratigraphic position of the Dunham within the field area. It might to some extent have been overridden by the Green Mountain Thrusts in the Otter Creek Valley and by the Pine Hill Thrust in the Tinmouth Valley and be only exposed in slivers. A continuous sequence along strike could nowhere be demonstrated and the large thickness over 300 meters, suggested by previous workers, is not supported at any locality by a continuous stratigraphic section. No Dunham is exposed west of the Pine Hill Thrust adjacent to the black phyllite belt.

2.6. Cheshire Quartzite (Cc) — Lower Cambrian

The Cheshire Quartzite is an important unit because it represents the transition from the siliciclastic rift basin sediments to those of the newly developing platform (rift-drift transition) (Mehrtens et al., 1987). Most workers agree that the Cheshire Quartzite consists of three major units. The upper part consists of a massive, non-pebbly, white or blue-gray vitreous quartzite locally with cross-bedding. The intermediate part is a mottled brown and rusty looking tan-weathering gray massive quartzite. Most parts appear to be schistose feldspathic quartzites with abundant small beds of quartzose gray to black phyllites best described as a graphitic, quartz sericite schist. The lower part which is reported to consist of a dolomitic sandstone and conglomerate (Bain, 1938) does not exist in the field area. Good exposures of the vitreous gray massive quartzite are along road **F.10**$_{[I15 \text{ to } J14]}$, locally with black schistose lenses and especially at the cliffs of the White Rocks$_{[K5]}$ and around Green Hill$_{[H3,\ J4]}$; the rusty looking tan-weathering gray massive quartzite is best exposed along road **Th.16**$_{[E10]}$.

A complete section through the whole Cheshire Quartzite can not be demonstrated at any place (Thompson, 1967). The stratigraphic relationships within the sequence can not be demonstrated clearly. In fact the various unit differences and the drastic thickness changes in small distances along strike, suggest that this sequence has undergone tectonic processes which have resulted in the repetition of its units and possibly imbrication with lithologically similar quartzite units in the basement of Precambrian age. Ogden (1969) and Thompson (1967) confirm the occurrence of a highly faulted unit in many places, resulting in many displaced layers shattered into a friable condition.

2.7. Metasediments, Graywackes, Schists (Cmd) **Lower Cambrian ?**

This sequence is probably the most confusing and worst understood in the Vermont Valley along the western flank of the Green Mountains. There exists a wide variety of completely different descriptions of this rock unit and their stratigraphic position, explained by drastic facies changes and/or tectonically derived disruptions along strike (Ratcliffe, 1992, pers.comm.; Ratcliffe et al., 1988). Its continuity along strike has never been established, and is in question for at least north of Manchester by this report, Kent

(1942), Karabinos (1988) and Harding & Hartz (1987), suggesting considerable lateral variation in composition and thickness, probably due to tectonic processes.

The Mendon Formation is shown on the map of Doll et al. (1961) to unconformably overly, wrapping in a relatively thin band around, the Precambrian Grenville Basement of the Green Mountain core. This relationship has been demonstrated for the eastern flank of the Green Mountains to be not true, instead revealing major thrust faults there (Dellorusso & Stanley, 1986; Karabinos, 1984; Ratcliffe et al., 1988). The proposed stratigraphic sequence from Cheshire Quartzite, to the Mendon Series into the basement can not be demonstrated for the western flank of the Green Mountain either. No basement is exposed where previously mapped in the field area, except for the basement slices brought up by the Pine Hill Thrust.

The Mendon Formation introduced by Whittle (1894) is probably the stratigraphic equivalent of the Dalton Formation of western Massachusetts described by Emerson (1892). Whittle (1894) defined three members for the Mendon Series, but these have been used by different workers in confusingly different stratigraphic positions. The upper part is the Moosalamoo Phyllite consisting of a gray to black quartzose phyllite. The middle member is the Forestdale Dolomite showing considerable thickness differences from 0 to 60 meters (Whittle, 1894). Its a white and buff dolomite in beds up to 30 cm thick. The lower member is the Nickwaket Graywacke which is a schistose greywacke with minor beds of green chlorite-chloritoid phyllite. In contrast Karabinos (1988), Kent (1942) and Foyles (1932) prefer to correlate at least the conspicuous Forestdale Dolomite with dolomites of the Valley sequence, as slivers in a faulted area. The discussion about the stratigraphic position of members of the Mendon Formation suggests non-continuous units along strike; I also propose this for my field area, as a result of some (unknown) combination of tectonic slicing and tight folding.

The most common rock unit is a fine to medium grained psammitic phyllite that typically weathers rusty-brown. Blue quartz clasts represent derivation from a source area like the

Green Mountains basement. This unit can be found along the steep flank of the Green Mountains in repeated sequence with a dirty-brown weathering, flaggy, schistose quartzite. The underlying conglomerate, supposed to represent the basal unit of the Mendon Formation, is well exposed on Clark Mountain$_{[E6]}$, although the proposed unconformity itself has not been located in outcrop (*Figure 2.9.*). Coarse quartz and rare gneiss cobbles are characteristic of this unit. The clasts in the unit are typically well-rounded, in some place elongated, and up to 8 cm in size. The conglomerate unit of this outcrop is however distinct different from all other 'unconformity outcrops', because of its well-rounded non-elongated clasts. The conglomerates of Clark Mountain are identical to conglomerate units described for the Lower Mendon units by Dale (1910) in the Ripton area of the Lincoln massif. Karabinos (1987) however correlated this unit with similar rocks of the Tyson Formation, representing the basal unit of the Eastern Cover Sequence. Important to note here is that the only outcrop found containing basement and the basal conglomerate of the overlying cover rocks is in a coherent slice brought up by the Pine Hill Thrust. I also argue against the interpretation of Ratcliffe et al. (1988) that a 60 to 150 meter thick unit of pebbly quartz conglomerate is the basal Dalton unit, overlying unconformably the Grenville basement.

An obvious problem exists to correlate rocks of these units with similar rocks to the north in the Lincoln massif, because of the different use of terminology. Prahl (1985) and Doll et al. (1961) proposed a stratigraphic sequence from Precambrian basement, unconformably overlain by the Pinnacle Formation, which is overlain by the Fairfield Pond Formation and the Cheshire Quartzite. These units names are more or less equivalent to the Cheshire Quartzite and the Mendon Formation (Ratcliffe, 1992, pers.comm.).

All non-pebbly, massive, gray, vitreous quartzites were considered to belong to the Cheshire Quartzites in contrast to the rusty, dirty, flaggy quartzites that are considered to belong to the Mendon Formation; this interpretation is consistent with the distinctions

Figure 2.9. **Outcrop picture of abundant, coarse well-rounded quartzite cobbles of the basal conglomerate of the Mendon Formation, exposed in the Clark Mountain basement slice brought up by the Pine Hill Thrust. This is the only exposure of the basal conglomerate overlying Precambrian basement in the field area. However this conglomerate is unusual compared with occurrences in the Green Mountains.**

made by Ratcliffe et al. (1988) in the southern part of the Green Mountain massif and the Berkshire massif.

2.8. Grenville Basement (CB) **Precambrian**

Precambrian gneisses crop out only in the Mill Brook stream valley, named the Mill Brook Basement slice; other exposures are on top of Clark Mountain. No basement was found where previously shown (Thompson, 1959, 1967; Doll et al., 1961) in the westernmost margin of the Green Mountain massif. Whittle (1894) used the term Mount Holly Series for all rocks of the core of the Green Mountain massif. A detailed distinction of the Precambrian basement rocks is possible as demonstrated by several workers (Stanley et al., 1987). They distinguished five distinctive map units, mainly by subdivision of the augen gneisses.

The basement of the Mill Brook slice is made up of a massive to well-foliated brown, white-gray feldspathic orthogneiss that is significantly overprinted by later deformation and metamorphism. The gneiss grades to the west over about 30 meters into a highly foliated area, giving the rocks an almost schistose appearance.

Prahl (1985) reports a quartzite unit belonging to the Precambrian rocks. His description is quite similar to what is exposed along the western flank of the Green Mountains in my field area. A mistake might exist in confusing Precambrian quartzites with Cambrian quartzites of the Cheshire Formation; however this problem could not be confirmed.

THICKNESSES IN METERS	Ogden 1989	Osberg 1959	Zen 1964	Thompson 1959	Thompson 1967	Cady 1945	Bain, 1959	Kent, 1942	Keith, 1932	Hewitt, 1967	Brace, 1953
Blue Marble (Chipman, Bascom, Beldens)				50-80	?		?	?	?	131	?
Shelburne FM (Columbian)	180	80	165	65-80	80		165-200	165-200	?	65	?
Intermediate Dol.	65	65		50-65	65		65	100-200	?	50	?
Sutherland Falls	35	15-35		15-50	35		30 0-100	30	?	30	?
Clarendon Springs	65	25-35	100	65-80	65		50-65	400	30-65	100	65
Danby FM	-	165-230		15-50	50		3-100		200		330
Winooski Dol.	-	300-330	115	100-130	200		-	330	?	100	200
Monkton Qtz.	-	15-35	-	100	200	0-260	-	15-25	?	100	130-260
Dunham Dol.	-	300-330	-	300	300	330-660	-	650-1000	?	260-300	560
Cheshire Qtz.	-	300-460	330	330-525	330	300-330	-	100-260	260	260	330
Dalton / Mendon FM	-	0-65	-	15-100	80	260-330	-	?	-	165	
Pinnacle		7-230							-		-
Moosalamoo Phyllite		-							165		165-260
Forestdale Dolomite/Marble		0-100							65-200		0-50
Nickwaket Graywacke		-							?		8-260
Basement											

Figure 2.10. **Chart giving an overview of the estimated thicknesses for the units of the Vermont Valley and adjacent rocks. Note the enormous difference for some units !**

2.9. Dikes

Diabase dikes are known in many places in the region. Several dikes cut through the phyllite sequence, the adjacent marbles and, as seen in East Dorset along Route 7 and in several other outcrop locations in the field area, through the dolomites. These dikes belong to a regional fracture system trending NNE-SSW (Ogden, 1992, pers.comm.). The dikes are definitely late features as they are not affected by metamorphism or deformation. The dikes are thought to be camptonite dikes, showing in thin section hornblende, augite, plagioclase, magnetite and secondary minerals.

2.10. Summary and Discussion of the Stratigraphic Relations of the Units in the Field Area

In summary only the major definite stratigraphic units are used in order to not add more to the already existing confusion about the stratigraphic relationships for the rocks in the Vermont Valley and the Green Mountains. Most stratigraphic relationships are more easily explained if the structural relationships are known. Many of the units are so similar, or their lithologic character modified extensively by metamorphism and/or tectonic processes, that it is often impossible definitively to assign a particular outcrop to a specific unit. I chose to give a precise lithologic description for each outcrop, to leave room for changes in lithologic correlation in the light of later evidence. In order to cover a field area of the size of about 300 km^2 there is in some places not as much detail as could be obtained. I focused my detailed field work mainly on the fault relationships in the field area and the involved rock units. However I think that many of the difficulties in correlating units are the result of the disruption due to tectonic processes (thickening, fault slivers), which probably play a much greater role than previously thought.

The major differences to previous detailed maps of the field area, the Vermont Valley and the Green Mountain massif are:

- No purely stratigraphic sequence is demonstrable from the Precambrian basement, unconformably overlain by an argillaceous - siliciclastic sequence, then the carbonate shelf sequence, through the Ordovician marbles, and the black phyllites of the Hortonville Formation to the (tectonic) base of the Taconic Sequence of the Taconic Allochthon.
- The complete marble sequence (Blue Marble and Shelburne Formation) west of the Pine Hill Thrust in the field area, and on a more regional scale from Bennington to at least Brandon, probably extending to the northern end of the marble belt at Middlebury, is suggested to be a more or less coherent large carbonate sliver, attached to the sole of the moving basal Taconic Thrust and transported with the Taconic slices to the west. A correlation of units south of Dorset Mountain with units of the Proctor and Rutland marble belt is possible and supports this model. The marble belt is viewed as allochthonous with respect to the carbonate shelf sequence of the Vermont Valley. Following this interpretation the Taconic slices west of the Vermont Valley paralleling the marble belt must also be viewed as belonging to the same lithotectonic unit containing not only the marble slices of Dorset Mountain and south (Stanley & Ratcliffe, 1985), but also Taconic slices farther north. This is in strong contrast to previous interpretations. No major marble units are known east of the Pine Hill Thrust. Exposed marble layers in that area are limited to small areas and thought to be independent detached slivers.
- A mylonitic high strain zone, containing basement remnants has been discovered along the eastern margin of the phyllite terrain, separating the black phyllites and the carbonate sequence by a major thrust (Baker Brook Greenschist).
- The extensive continuous belt of Cheshire Quartzite and Mendon Formation along the western flank of the Green Mountain massif, as shown on previous maps, does not

appear to be correct. A continuous belt of Cheshire Quartzite does not exist. The complex lithologic structure encountered within the Mendon belt does not correspond with what has previously been defined.

- Besides the basement slices brought up by the Pine Hill Thrust, there is no Precambrian basement exposed in the field area along the present topographic steep of the western flank of the Green Mountains.

3. Structure

3.1. Introduction

The initial purpose of this study was mainly to investigate the structural and lithologic relations of the rock unit previously called "Baker Brook volcanics", and the possible continuation of the Pine Hill Thrust to the south including a basement slice west of Danby (Mill Brook basement slice), and the nature of a pure stratigraphic sequence across strike of the Vermont Valley shelf carbonates. Detailed mapping with careful correlation attempts gives a very different interpretation for the Vermont Valley and the Green Mountains than previously proposed.

Detailed mapping in and on the western margin of the western Taconic Allochthon (Rowley & Kidd, 1981) and along the eastern Green Mountain massif (Stanley et al., 1987; Ratcliffe et al., 1988) has revealed a "new" interpretation for the structural history of the Taconic Orogeny and the geology in these areas is relatively well understood. However, the developed structural interpretation has never been applied to or demonstrated for the Vermont Valley and the western flank of the Green Mountain massif (*Figure 3.1.*).

The structural history of the study area is complex and involves three important phases. Poor outcrop makes the reconstruction of the geologic structure for a small field area difficult or uncertain. A reconstruction has to take in account that structures suggested for the area have to be correlatable with structures along strike. The problem is a lack of detail in some parts of the adjacent larger areas, but the advantage is that the most likely geological interpretation for both the smaller and the large area can be obtained.

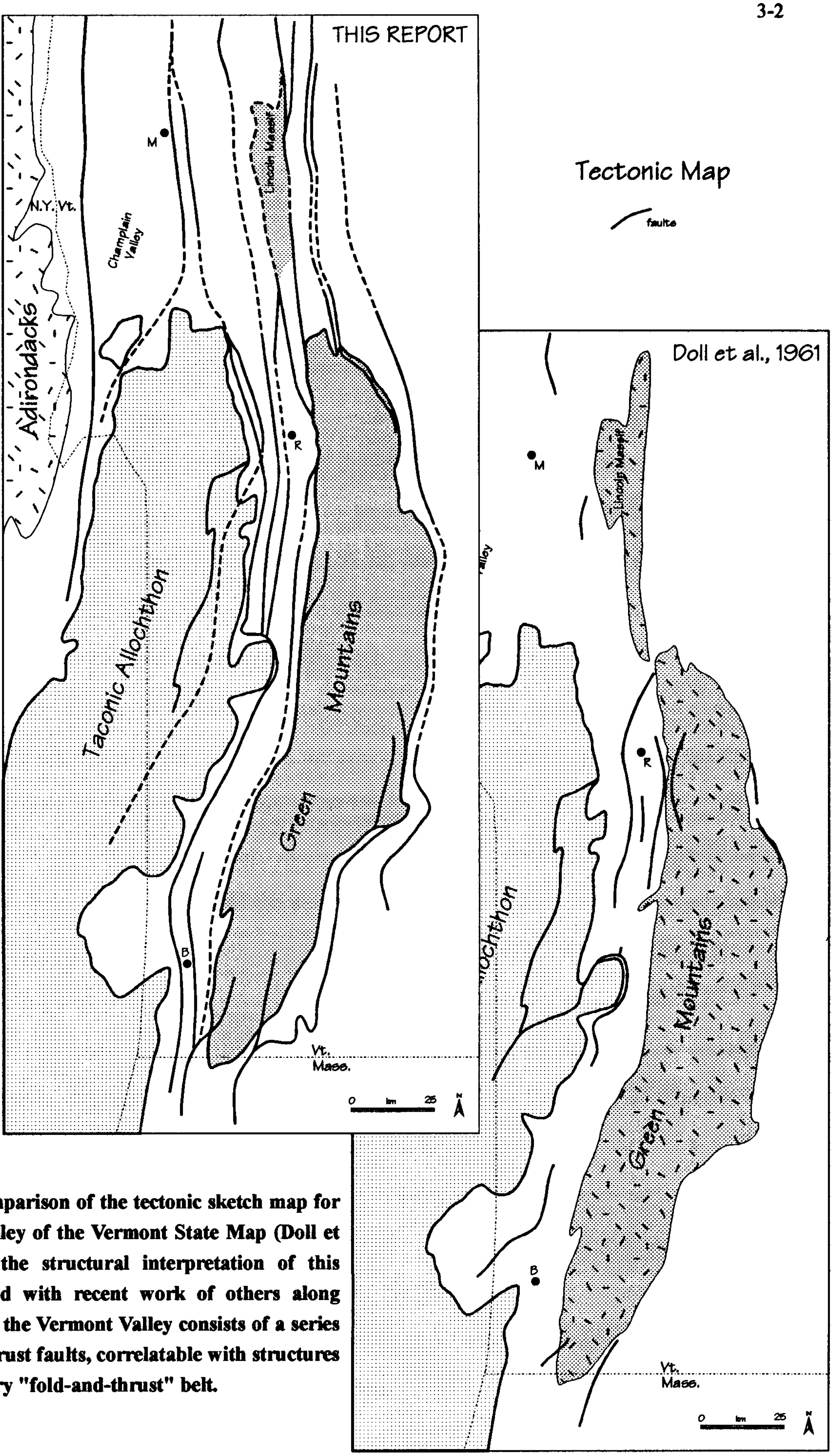


Figure 3.1. **Comparison of the tectonic sketch map for the Vermont Valley of the Vermont State Map (Doll et al., 1961) and the structural interpretation of this report integrated with recent work of others along strike. Note that the Vermont Valley consists of a series of continuous thrust faults, correlatable with structures in the Middlebury "fold-and-thrust" belt.**

The Vermont Valley is in my view probably underlain by a duplex consisting of several thrust faults that are difficult to demonstrate in the carbonates and the black phyllites, but highly suggested by the structural deformation and lithologic relations which can in most places only be explained by faults. A pre-duplex deformation generation is proposed, displacing carbonate sequence rocks over normal fault exposed basement, developing a ductile high strain zone containing basement-derived lithologies. Map and stratigraphic evidence suggests a more or less coherent marble slice, carried west with the Taconic Allochthon over the carbonate shelf duplex. The carbonate duplex and overlying marbles have been overridden in the east to some extent by an out-of-sequence thrust zone, carrying the complexly folded siliciclastic cover, overlying unconformably the Precambrian Grenville basement. As shown on the geologic map the field area is divided into three major units, each separated from each other by a major thrust (*Figure 4.8.*). The carbonates of the shelf sequence form a folded duplex, including large coherent basement and basement-cover slices and the black phyllites of the Hortonville Formation. The shelf duplex is overridden by the basal thrust of the Taconic Allochthon carrying along the base an attached coherent marble slice. Both the folded shelf duplex and the overlying marbles and lithologies of the Taconic Allochthon were then cut and overridden by late out-of-sequence thrusts, belonging to the Taconic Frontal Thrust System, carrying the Green Mountain Grenville basement and the Cheshire / Mendon siliciclastics.

The lithostructural geometry in this thrust belt is very complex and the structural interpretation is an attempt to express one possible solution for the area. This means that there is probably more than one structural solution possible to explain the field relationships as exposed; however the simplest reasonable interpretation is chosen here, even though in some respects it is not satisfactory. The faults shown on the map are a minimum needed to explain the map pattern in the field area. The development of the structural history of the Vermont Valley is next discussed in this chapter, followed by a regional synthesis of the geology of the marble belt.

3.2. Tectonic Deformations

The structural synthesis requires three different deformation generations D_1, D_2, and D_3. The schematic model that describes each thrust system with its effect on the structural geometry and evolution is described below.

3.2.1. pre-D_1 Deformation

When the leading edge of the continental margin was just about to reach the trench of the converging volcanic arc to the east, the continental rise terrain to the west of the volcanic arc responded with uplift (flexural bulge passage), followed by the collapse of the continental shelf and tectonically controlled subsidence. Chapple (1973) and Thompson (1967) argued that the continental shelf was deeply eroded and developed a karst surface, followed by block faulting and rapid subsidence and deposition of the black phyllites of the Hortonville Formation. The pre-black phyllites normal fault and the associated depositional unconformity is called the "Tinmouth Disturbance" (Thompson, 1967; Zen, 1961) in the field area, thought to be the beginning of the Taconic Orogeny (Baldwin, 1982). In fact the base of the proposed unconformity consists locally of a volcanic unit ("Baker Brook volcanics") (Thompson, 1959, 1967). This study suggests a major high strain zone instead, consisting of a mylonitic basement-derived greenschist, rejecting the idea of a major unconformity between shelf sequence and black phyllites. There are no stratigraphically unconformable relations between black phyllites and carbonates exposed in the field area. This includes the Whipple Marble occurrences in the map area, whose stratigraphic position and origin are therefore questionable.

In contrast Rowley & Kidd (1981) and Bradley & Kusky (1986) argue against deep erosion and rapid syn-normal faulting black phyllites deposition, because the off-shelf deep water sediments of this age do not contain the coarse detritus that would result. The Medial Ordovician (?) black phyllites of the Ira / Hortonville Formation rest across tilted and block-faulted beds down to and including Precambrian basement. The subducting ocean floor is commonly deformed by a peripheral bulge that forms as an elastic response to flexure of the down-going slab (Bradley & Kusky, 1986). Following platformal deposition during Cambrian and Early Ordovician times, the shelf was uplifted and block-faulted ("Tinmouth Phase of the Taconic Orogeny") and then buried beneath black shales and turbidites of the Walloomsac (Ira / Hortonville) Formation. Rowley (1982) presented a model for the relationship between black phyllites and the local contact with shelf units and underlying basement, being a normal fault contact. Normal faults commonly develop during initial stretching phase of continental rifting, and due to flexural bending during subduction of an Atlantic-type margin just prior to collision. Displacement of these normal faults range in offset up to 1 to 2 km (Bradley & Kidd, 1991), enough to sometimes expose the underlying Precambrian basement. The interpretation of a pre-folded normal fault explains the regionally occurrence of misinterpreted unconformities, lacking all structures common for it, e.g. a conglomerate at the base.

The complex structural and stratigraphic relationships result from the superposition of collision-related shortening on the pre-existing normal-fault-bounded sequences. I interpret the basement slices as completely normal-fault bounded fault blocks, that were tilted and rotated by probable listric normal faults (Rowley, 1982) and then overridden by the first advancing low angle thrust faults (T_1). Evidence for this relationship results mainly from stratigraphic comparison exposed by unfolding this contact (*Figure 3.2.*). Field evidence is obscured by overprinting of later thrust faults reactivating these normal faults. However the occurrence of a very distinct dark gray dolomite and outcrops of a breccia-type dolomite close to the eastern contact of the basement slices with black phyllites is interpreted as being the remnant of a normal fault breccia, re-healed by a later thrust fault (*Figure 3.3.*).

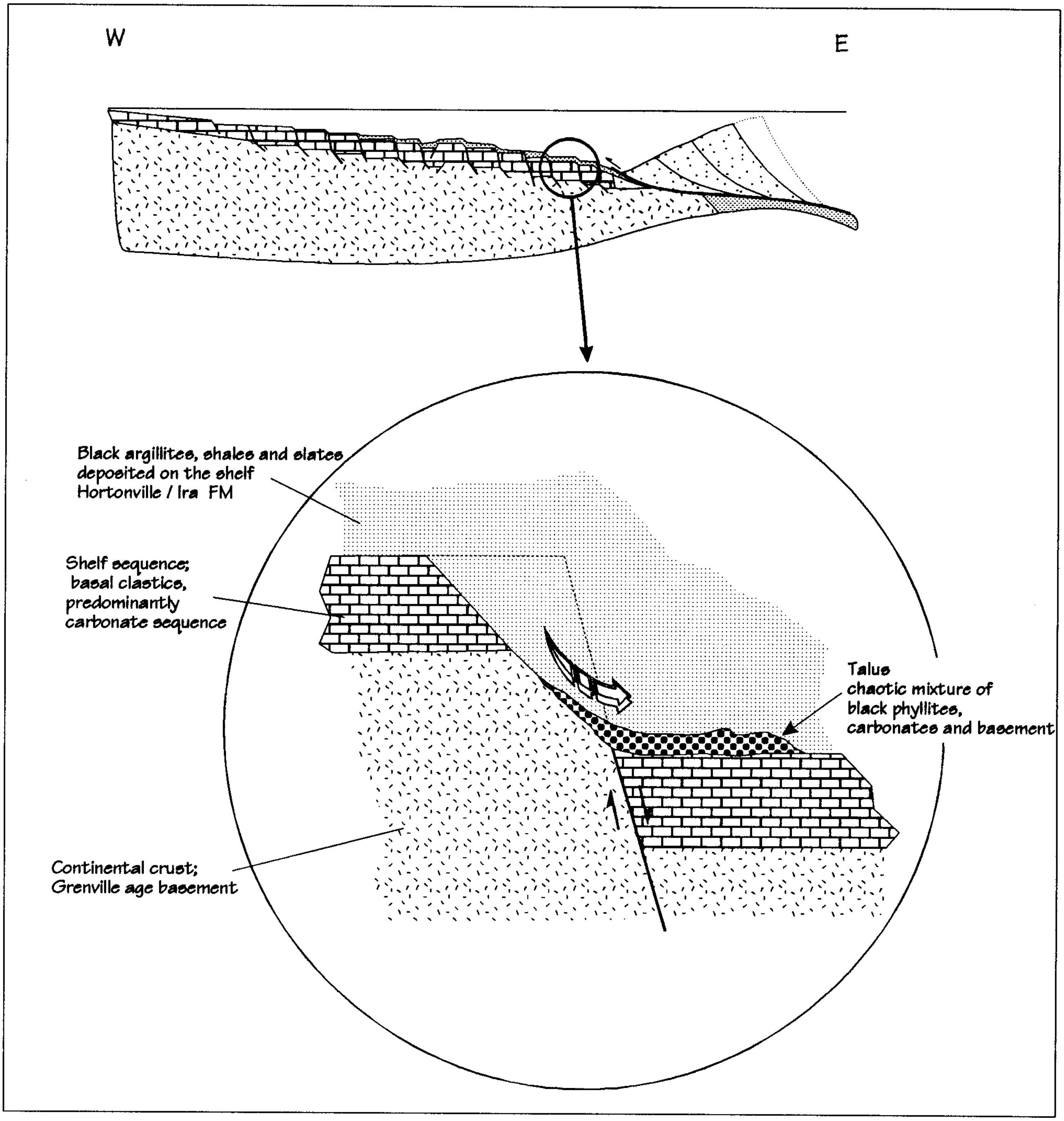


***Figure 3.2.* Normal faults as a result of block-faulting of the collapsing carbonate shelf. The displacement along normal faults may reach up to 2 km, enough to expose basement and carbonate rocks next to basement and basement next to black phyllites. Syn-depositional sedimentation of black shales has buried the fault scarps; this relationship may easily be misinterpreted as an unconformity ("Tinmouth unconformity").**

Figure 3.3. **Picture of re-healed dolomitic fault breccia interpreted to be a remnant of the block-faulted normal fault breccia. The fabrics clearly show brecciated material in a dark dolomitic matrix. The appearance of this rock is however massive. A large outcrop of this rock is along the West Hill Road [F4] where the road passes a small bridge.**

3.2.2. D_1 Deformation

The Baker Brook Thrust represents a ductile high strain zone derived from a plutonic protolith which occurs along the eastern contact of the black phyllite terrain with the carbonate belt of the Vermont Valley in the field area. Outcrops of the mylonitic greenschist represent a major thrust zone of ductile deformation that is well exposed along the east slope of the north-south trending intermediate ridge separating the Tinmouth Valley and the Vermont Valley. These structures have previously been traced only a short distance and interpreted as a "volcanic" unit, belonging to the basal Ira Formation. I interpret this rock unit as a tectonically derived mylonitic greenschist, separating the black phyllites of the Hortonville Formation in the west, from the carbonate shelf sequence in the east. There are several good exposures of this distinct rock unit in which the fault relationships of the mylonite and adjacent rocks can be studied. The rock fabrics are very complex and overprinted by later deformation. However the fault zone rocks are easily identifiable in the field by the distinct greenish color and highly foliated fabrics and can be traced from exposures in Danby north to cliffs west of Clarendon. These structures belong to the first deformational stage with a westward directed shortening of the arriving accretionary wedge moving in front of the colliding volcanic arc. An excellent exposure of the fault contact is found in the South Wallingford marble quarry (*Figure 3.4.*); the north wall of the quarry reveals a perfect profile through the contact and shows the incredible deformation within the adjacent marbles, dolomites and black phyllites.

3.2.2.1. Macroscopic Structures

The South Wallingford marble quarry is located in a large marble sliver extending about 4 km along strike, abruptly truncated north and south and bounded west and east by faults. The large scale structure is a westward-overturned fold with its hinge line almost

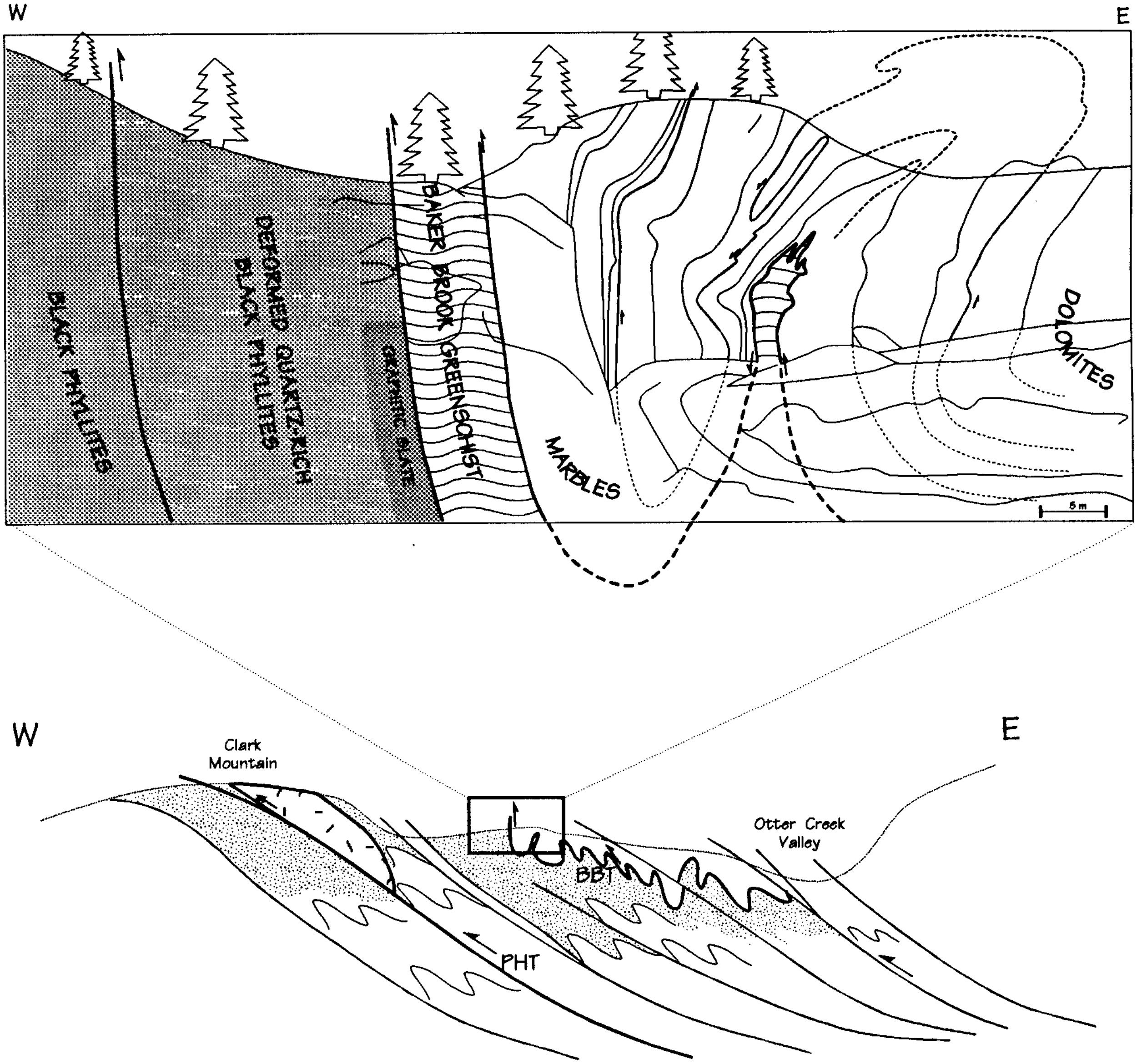


Figure 3.4. **Sketch to explain the detailed relationships along the west side of the carbonate belt in the South Wallingford marble quarry of the Vermont Valley. The Baker Brook Thrust (BBT) separates black phyllites in the west from carbonate rocks in the east. Pine Hill Thrust (PHT).**

horizontal. However the structures within this fold are strongly deformed and obscured and demonstrate the incredible deformation which must have taken place in the carbonate shelf.

A section from east to west along the north cliff of the quarry starting from Route 7 reveals a sequence from intermediate dolomite, white marble presumed to be a member of the upper Shelburne, into the Blue Marbles. In the north-west corner large cliffs expose the contact with the greenschist. From the contact to about 20 meters to the west, the quartz-rich black phyllites are exposed. This excellent exposure demonstrates major deformation within the rock units, thrusts, repetition and thickening by imbrication within the carbonates. The marble is clearly cut by several faults which have been obscured by later recrystallization during metamorphism. The contact of the marble with the greenschist is exposed along the west cliff in the north-west corner of the quarry and in a tightly folded patch in the north cliff. West of the greenschist-marble contact, quartzose black phyllites, a very distinct dark black graphite-rich slate and normal black phyllites are exposed (*Figure 3.5.*). The greenschist varies in thickness along strike from about 15 meters to 50 centimeters, and feldspar clasts are commonly less abundant in the greenschist of the South Wallingford quarry and smaller in size than for example at the exposure at the Baker Brook Falls.

The South Wallingford quarry is the only good exposure in the field area that reveals the contact between greenschist and carbonate sequence. At this locality the adjacent carbonates to the east are also exposed, and this makes it possible to study directly related deformational structures in the carbonates without the risk of misinterpretation of secondary structures. The adjacent marbles, which are mylonites too, show a strong transposed foliation consisting of small dark and light bands of about 0.5 to 2 cm thickness, isoclinal folds and thrust-repeated slices with the same consistent sense-of-shear as obtained from microscopic structures. The prominent mineral stretching lineation plunges steeply to the south on the foliation. Both faces of the cliffs (north and south) in

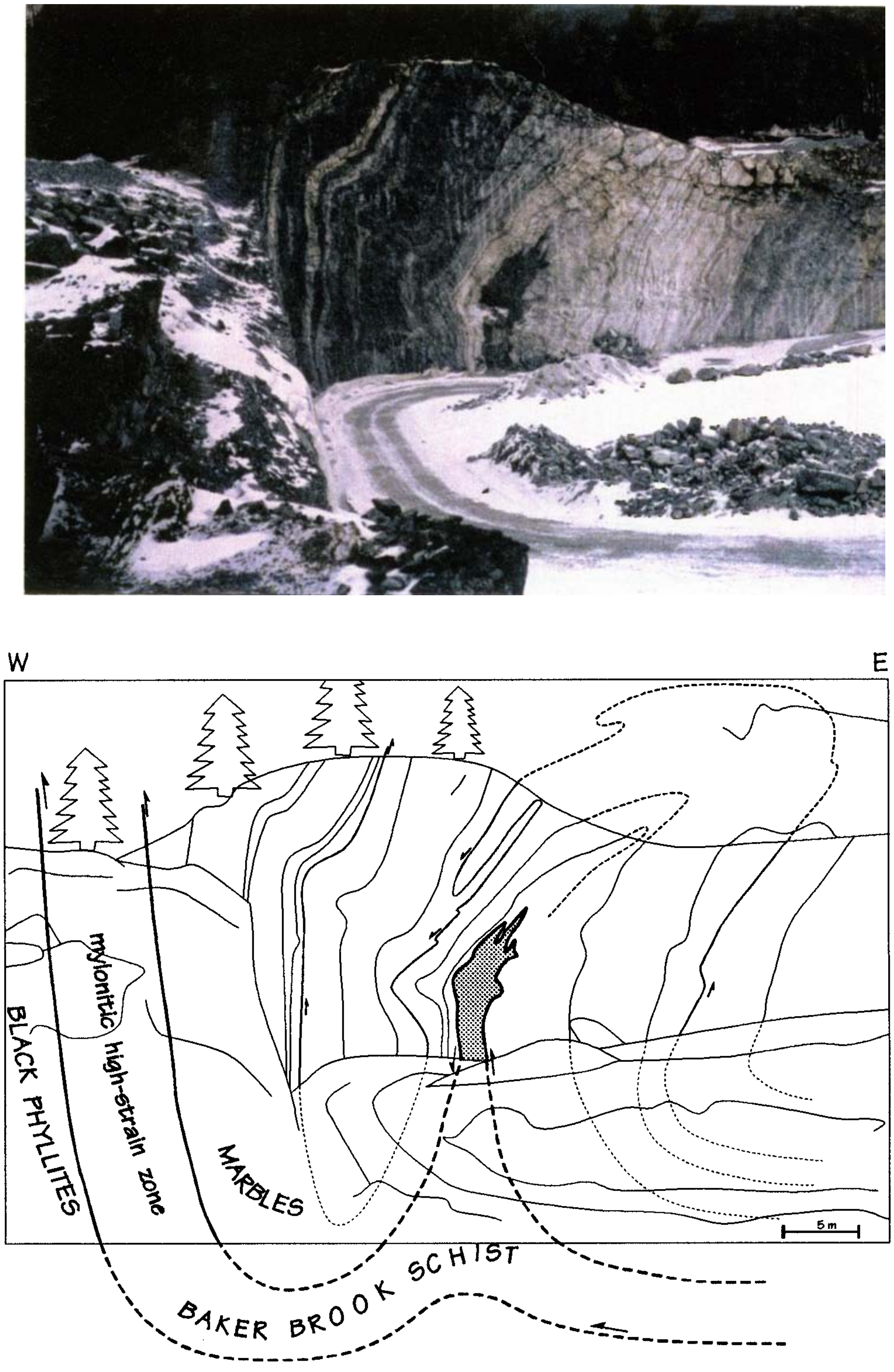


Figure 3.5. **Picture is showing the complicated structure within the marbles and dolomites. Isoclinal folding, overturned locally to the cast. This outcrop exposes the thrust contact (east over west) of an inverted section of the shelf sequence over black phyllites, separated by the Baker Brook Greenschist. North face of South Wallingford marble quarry.**

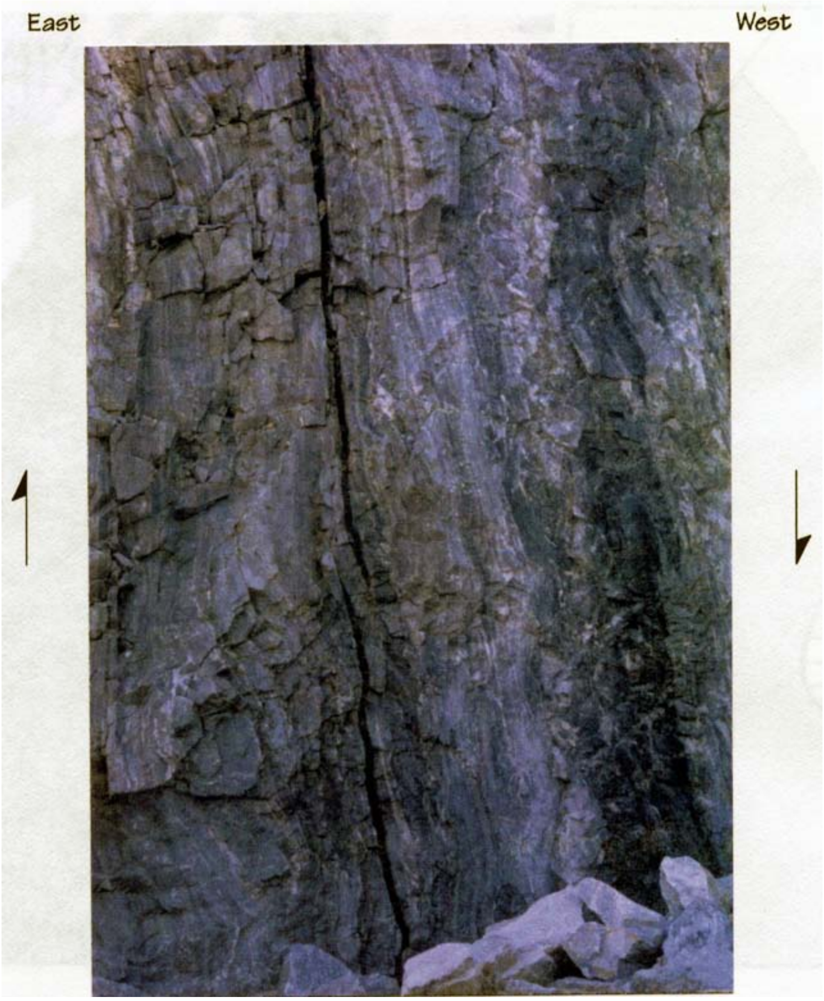


Figure 3.6. **Picture of the south cliff in the South Wallingford marble quarry showing the strongly foliated mylonitic marble with asymmetrical isoclinal folds and tail-like structures sheared off in thrust direction (east-over-west). The darkest layer within the cliff is a dike. The width of the picture is about 5 m.**

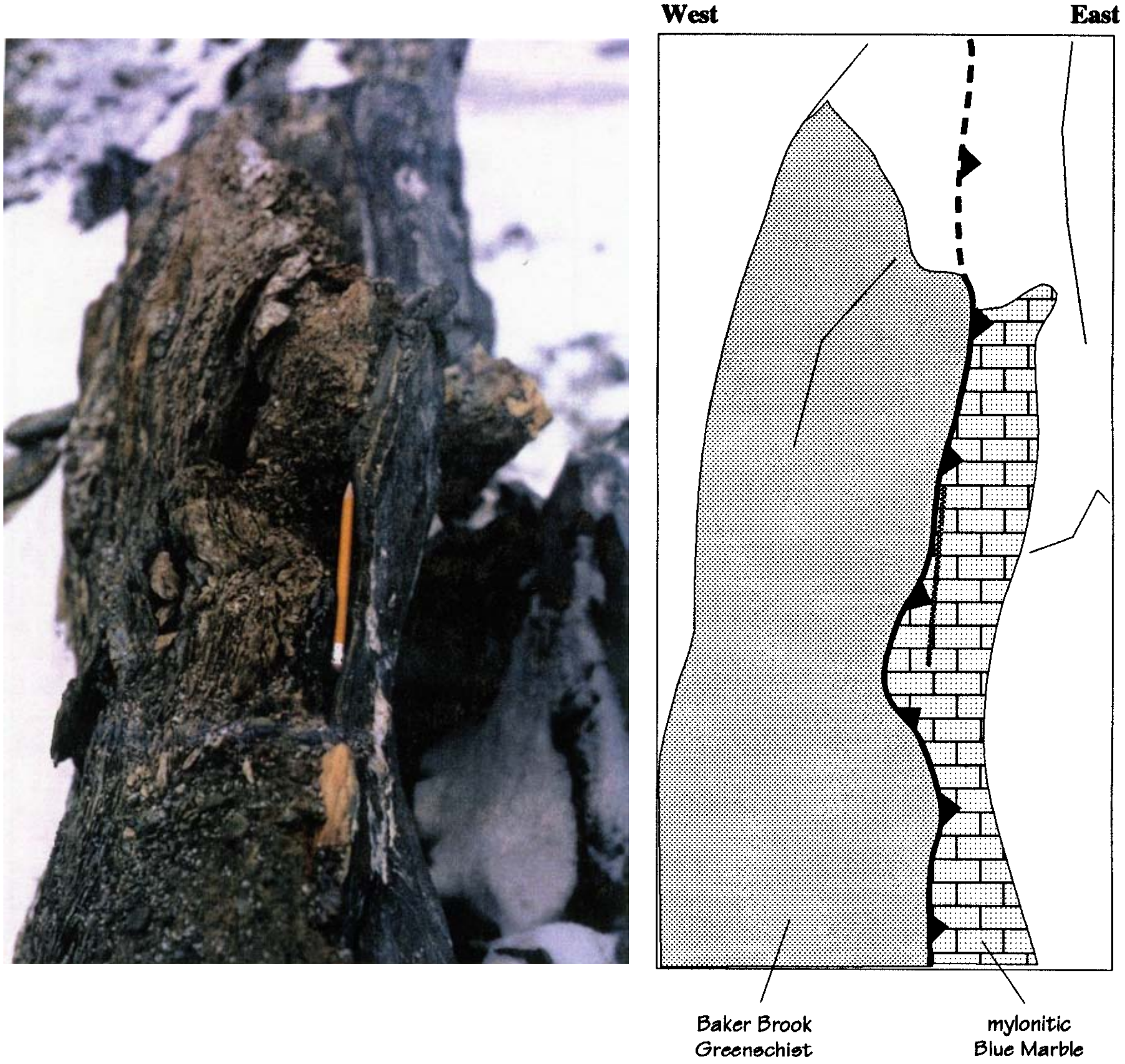


Figure 3.7. Outcrop picture of the vertical sharp thrust contact between the Blue Marble sequence and the Baker Brook greenschist of the mylonitic high strain zone in the South Wallingford marble quarry. Shear indicators suggest an east (marble) - over - west (greenschist) sense of shear. Pencil is 15 cm.

the quarry along strike show asymmetric folds; in many cases asymmetrical folds and sliced layers indicate the direction of shear (*Figure 3.6.*). These structures vary in size from microscopic mm-scale to outcrop scale, to 100 meter scale, as observed in large fold structures beneath Dorset Mountain.

The contact between the mylonitic greenschist and the marbles is extremely sharp, suggesting exclusively ductile deformation within this fault zone (*Figure 3.7.*). Thin sections from this contact were used to demonstrate carefully the shear sense without the influence of overprinting deformations.

3.2.2.2. Microscopic Structures

The highly strained character of the marble shows best where alternating layers of gray and light-gray marble are found. These layers consist of very fine-grained calcite grains showing under the microscope small isoclinal folds, resulting in thickening of layers. The micro-thickening is basically the same process responsible for the large scale thickenings in the marble units (e.g. beneath Dorset Mountain). The shear surfaces between the alternating layers are usually not quite parallel to each other, but truncate older structures (foot wall) along micro faults. Locally single larger calcite porphyroclasts show asymmetrical pressure shadows with a consistent sense of shear. (*Figure 3.8.*). The sense of shear on these surfaces is consistent with the overall sense of shear.

Microscopic kinematic indicators throughout the Baker Brook high strain zone record thrust (east-over-west) movement. In this section I demonstrate the microstructural evidence for thrust displacement along the Baker Brook Thrust, displaying east-over-west shear fabrics, that are consistent with the thrust interpretation of macroscopic fault structures and the interpretation for the tectonic history of the Vermont Valley. Most of the macroscopic structures are displayed in the rocks adjacent to the greenschist, but the microscopic structures are best identifiable in the greenschist itself. The characteristic fault rock and its fabric that are observed are documented below.

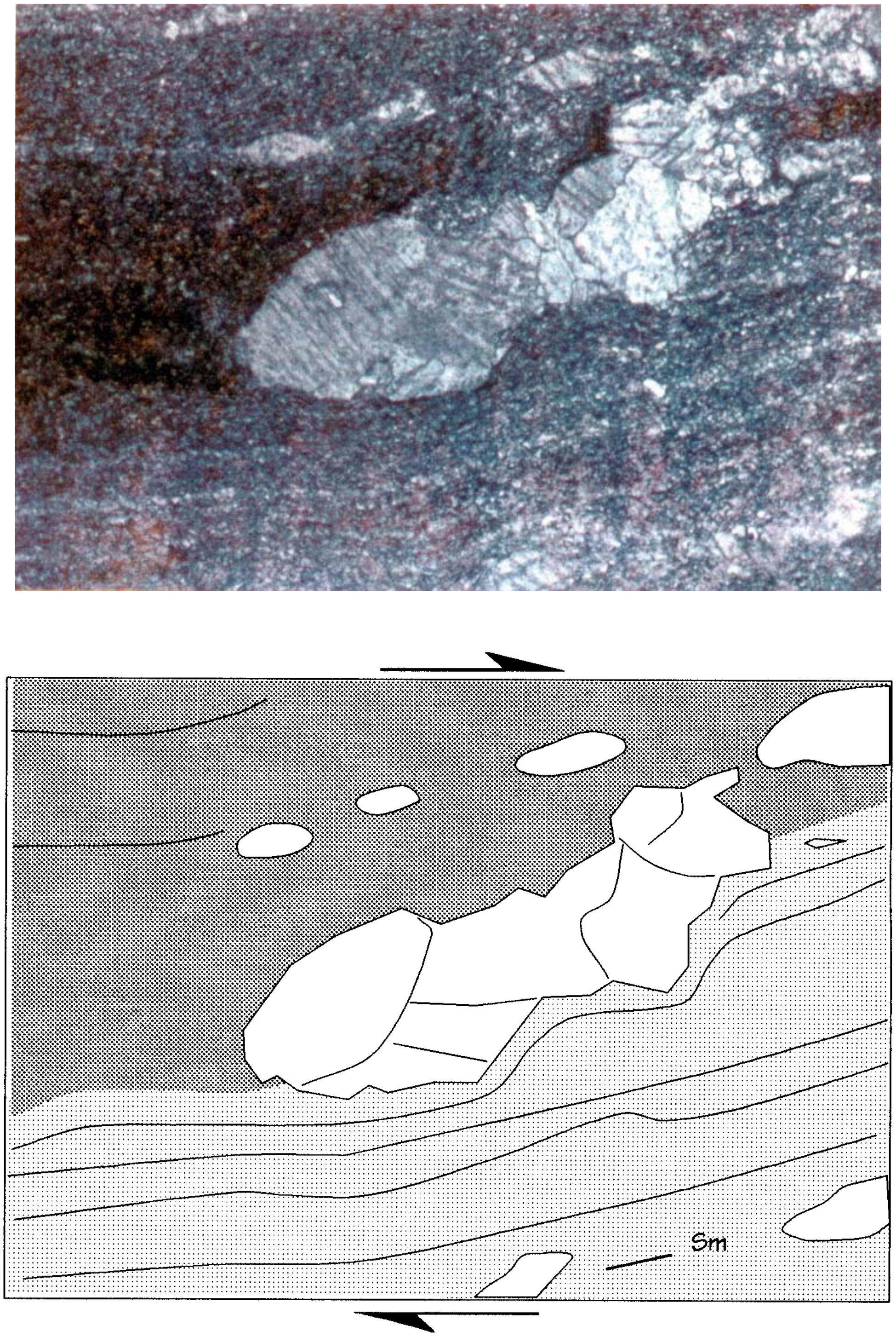


Figure 3.8. **Thin section of mylonitic marble, containing calcite porphyroclasts in a very fine-grained calcite matrix, displaying truncation of different shear surfaces and asymmetrical pressure shadows. The "cross-bedding like" truncation is structural and can not be used to determine stratigraphic up. Sm=mylonitic foliation. Width of photo 5 mm.**

Locally, angular to subangular clasts of weakly-deformed coarser feldspar fragments, derived from intermediate-silicic plutonic rocks are observed. The megacrysts, presumed to originate from the Grenville basement, are predominately feldspathic porphyroclasts, ranging from 0.3 to 3 cm in diameter. The weakly deformed feldspar clasts show dilatant fractures that are sealed and filled with recrystallized quartz. Quartz grains show subgrains, rotation-recrystallized new grains with minor grain-boundary migration recrystallization and asymmetrical grain shape fabrics. The anastomosing mylonitic foliation is best developed where larger fragments of weakly deformed feldspar megacrysts are preserved within the matrix. Those feldspar clasts and locally large quartz grains developing subgrains are surrounded by the fine-grained quartz-sericite-chlorite-carbonate matrix; epidote is the predominant associated mineral (*Figure 3.9.*). Well developed sense of shear indicators include asymmetric quartz-carbonate-chlorite-muscovite pressure shadows around remaining isolated feldspar porphyroclasts, asymmetric carbonate porphyroclasts, displaced fractured feldspar grains and weakly developed S-C fabrics (Simpson & Schmid, 1983) (*Figure 3.10.*). However the best observable shear criteria in the samples are feldspar porphyroclasts with a σ-type, and less commonly δ-type, asymmetrical shapes relative to the foliation plane. Where mica is abundant, a fine-scale S-C fabric is observed, however in most places the fabric is obscured by a later crenulation cleavage and can be used as sense-of-shear indicator only with care. The initial stage of deformation in the Baker Brook Thrust Zone resulted in fragmentation of the coarse-grained gneiss (?), as evidenced by the numerous relict porphyroclasts of feldspar observed in the fault zone. The feldspar clasts are commonly fractured but seem to be mainly unrecrystallized and are the best and most consistent sense-of-shear indicators. The brittle deformation of the feldspar seems to reflect an early stage of deformation of the fault zone development. Shear-sense indicators determined from such indicators in the deformation zone suggest relative movement of the upper plate toward the west along the mylonitic layering (convergent fault movement).

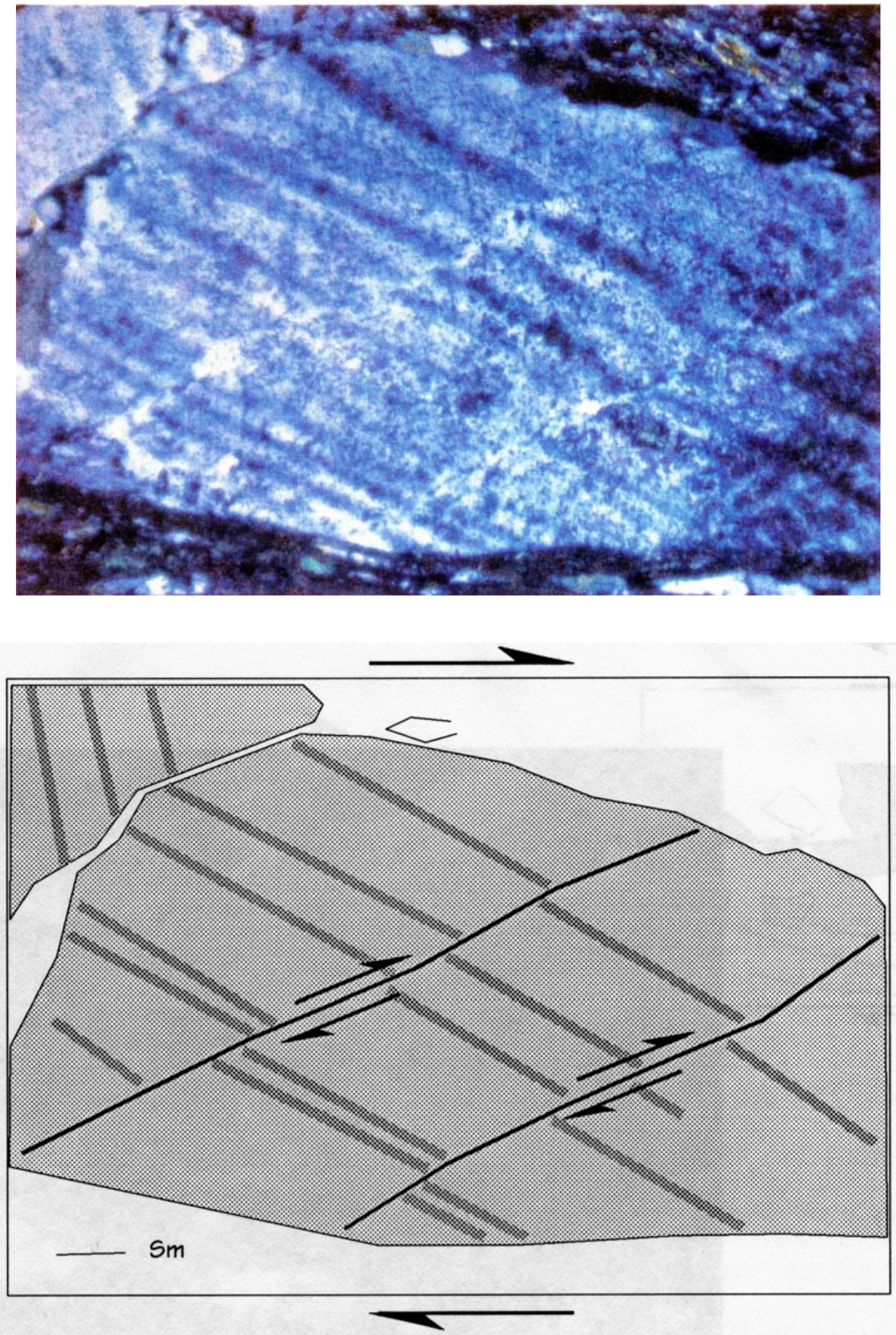


Figure 3.9. **Micro cracks in feldspar megacryst offsetting the twin lamellae. The feldspar megacryst shown in the picture is only a part of a 25 mm long micro clast showing consistent weak deformation and recrystallization in micro cracks. Consistent shear indicators show a clear east-over-west (top to the right) thrust sense of shear for the Baker Brook Thrust. Width of photo is 3 mm. Sm=mylonitic foliation.**

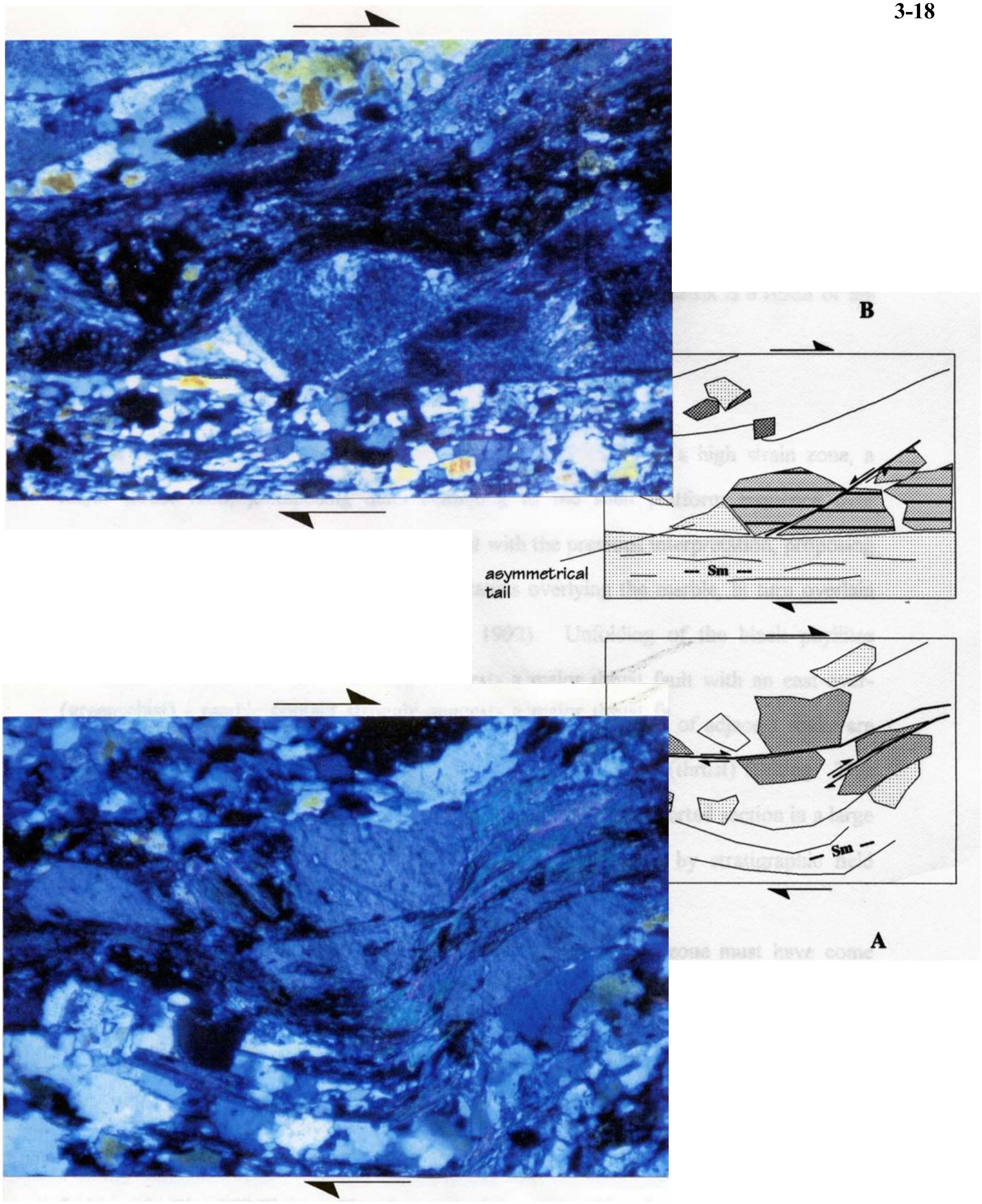


Figure 3.10. **Photo of typical top-to-west deformation features in mylonitic greenschist demonstrate thrust sense of shear for the Baker Brook Thrust. A: Sliced calcite grain showing clear offset. B: Feldspar megacryst with asymmetrical tail and antithetic offset along internal fractures. Sm = mylonitic foliation. Note also the sharp fault contact below the feldspar and the mylonitic matrix. Width of photo is 3 mm.**

The pervasive mylonitic foliation is common throughout the Baker Brook Thrust zone. Examples of this fabric are exposed where quartz is strongly recrystallized and forms a very planar mylonitic fabric with well-developed quartz rods. Isolated porphyroclasts display a strong and consistent asymmetry, indicating an east-over-west sense of shear along the fault zone. The anastomosing mylonitic foliation in the matrix is a result of the abundant feldspar clasts.

3.2.2.3. Discussion

The re-interpretation of the Baker Brook greenschist being a high strain zone, a major thrust fault, juxtaposing units belonging to the shelf platform sequence over Ordovician black phyllites, is in strong contrast with the previous interpretation, proposing a unconformably depositional contact of volcanics overlying the marble, in turn overlain by the black phyllites (Herrmann & Kidd, 1992). Unfolding of the black phyllites (greenschist) - marble contact strongly suggests a major thrust fault with an east-over-west sense of shear (*Figure 3.11.*). Mylonites and fold structures of adjacent rocks are consistent in geometry and movement history with compressional (thrust) faulting. This interpretation assumes that the marble sequence to the east is an inverted section in a large scale overturned nappe-type fold structure, which is supported by stratigraphic field evidence.

The protolith for the plutonic fragments in the high strain zone must have come from a relatively "close" source, exposing basement rocks. The restricted distribution of the mylonite zone suggests that the basement protolith is derived from the normal fault contact, exposing basement. This interpretation is supported by the fact that the high strain zone appears to be related to the distribution of basement slices brought up by later faults as the Pine Hill Thrust. The character of the greenschist, shows higher chlorite and feldspar content, larger grain size and overall greater thickness of the thrust zone if there is a basement slice exposed to the west. This suggests that the protolith for the high strain

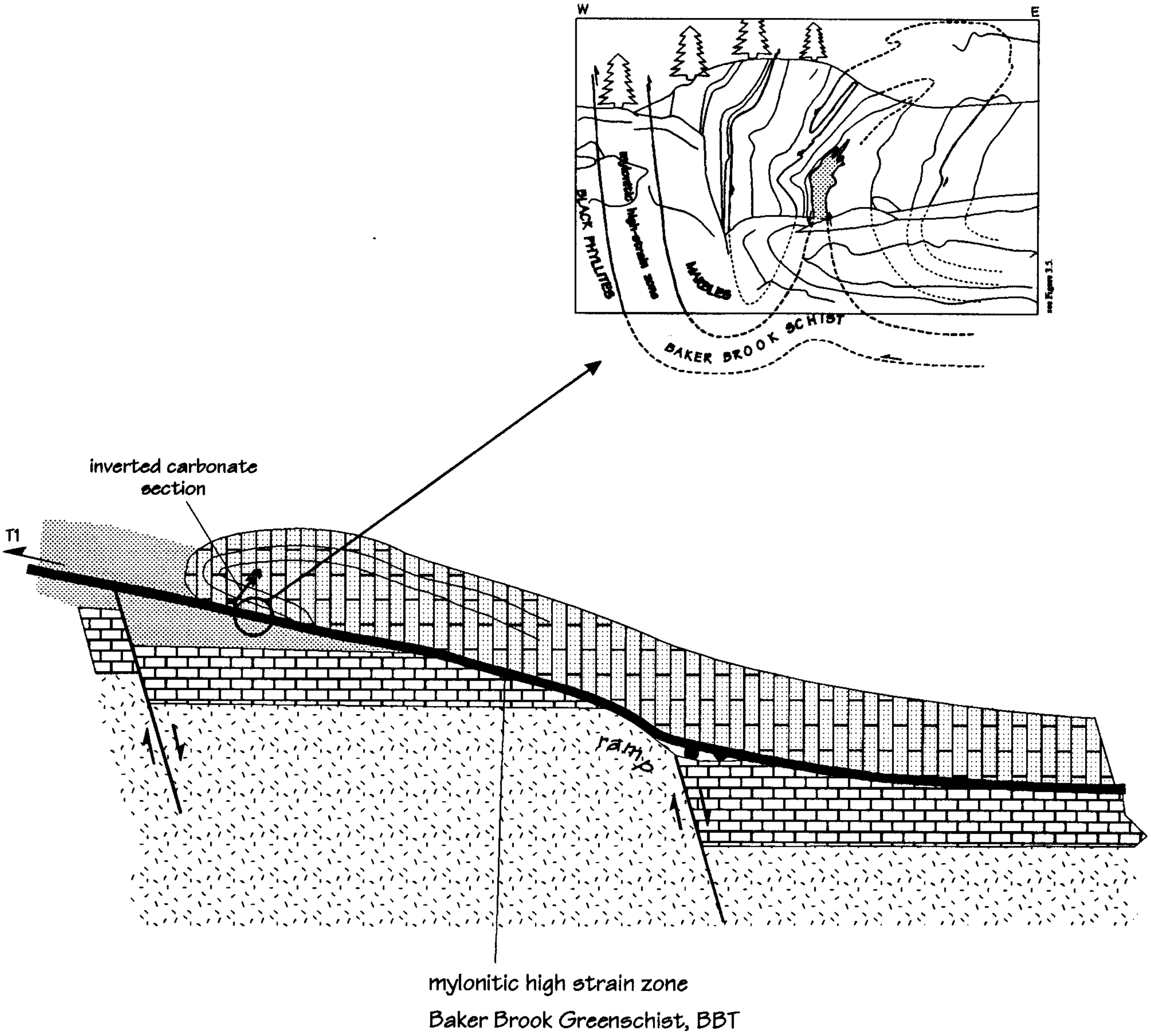


Figure 3.11. **The sketch shows the unfolded relationships inferred from the complex structures of the South Wallingford marble quarry. Large nappe type overturned folds were thrusted to the west, being the first westward directed collision related structures of the Taconian orogeny. The displacement must have been substantial to explain the metamorphic character of the myonitic high strain zone developed when an overturned carbonate section was thrusted over the normal fault exposed fault scarp and emplaced on black phyllites.**

zone might be derived from those basement slices. The normal fault at that location must have been a major fault with substantial displacement, exposed basement must have been brought up discontinuously along strike, resulting in the now established distribution of basement slices and remnants of the high strain zone. It should be pointed out that the greenschist is obscured and clearly cut by faults of the shelf duplex and therefore an intact fault zone can not be mapped in many places.

3.2.3. D_2 Deformation

The sequence of development of any thrust belt requires the successive development of duplex thrust faults. These subsidiary faults link the two glide horizons, the floor and the roof thrusts (Boyer & Elliott, 1982). Field evidence in the field area supports the idea that a duplex underlies the Taconic Allochthon to the west, the Vermont Valley and also extends beneath the Green Mountain massif, since faults along the western flank of the Green Mountain massif are suggested by this report, and also can be supported by COCORP seismic reflection data (Ando et al., 1984). Most faults dominating the Vermont Valley belong to the carbonate shelf duplex. The Dorset Mountain Thrust (roof thrust) is the major detachment surface along which the thrust stack of the Taconic Allochthon was emplaced to the west, responsible for the development of the shelf duplex.

3.2.3.1. Duplex Floor Thrust (T_{2f})

It is extremely difficult to recognize fault zones in the shelf sequence, juxtaposing carbonates against carbonates, or fault zones in the phyllites. However the knowledge of the complicated structure in the carbonates from the few places where fault relationships can be demonstrated supports the idea of an extremely imbricated sequence with major thrust faults. Faults within the carbonates are mainly based on lack of stratigraphic relationships along strike while drawing the geologic map, which is in some places not satisfying, but necessary. Conformable contacts were preferred where possible, but in most cases continuity along strike can not be demonstrated; the inferred faults are in many places parallel with stratigraphic contacts.

Examples of the complex structure within the carbonates have already been demonstrated in *chapter 3.2.2.* in the South Wallingford marble quarry. This exposure is probably the most important in terms of showing that the internal structure of the carbonates may be extremely difficult to define solely from non-quarry outcrops. A large road cut along Route $7_{G5/6}$ shows thrust-repetition of beds in the carbonates, exposing slices of the Dunham and Monkton Formation. Thompson (1959) shows a conformable stratigraphic sequence from the Monkton Formation all the way up to the Bascom Marble with this outcrop and exposures farther west (*Figure 3.12.*). In contrast I interpret this exposure as a good example demonstrating imbrication and sequence-repetition by thrust faults. Another good example for the very complex structure in the carbonate sequence is a quarry in Wallingford_{H1}, that shows beautiful folded carbonate beds interlayered with quartzite beds, exposing fault surfaces along the dark banded phyllitic layers (*Figure 3.13.*). The sequence of those two exposures is almost identical. The base of the faults in the folded sequence is in many cases a dark gray, very fine-grained, pyrite rich phyllite unit, locally with a schistose component.

The occurrence of a propagating shelf duplex beneath the emerging accretionary wedge of deep water sediments, is a common and geometrically necessary explanation in many thrust-and-fold belts (Boyer & Elliott, 1982). The carbonate platform is overridden by the Taconic Allochthon, forming a hinterland-dipping duplex by stacking the Cambrian carbonate sequence with its overlying deep water sediments, the black phyllites of the Hortonville Formation. Basement might have been detached from the overridden basement footwall by "footwall plucking" (Platt & Leggett, 1986) and incorporated into the duplex. Another possibility to derive basement and incorporate it into the duplex stack is when the thrust system moves up a footwall ramp through basement. A horse block of

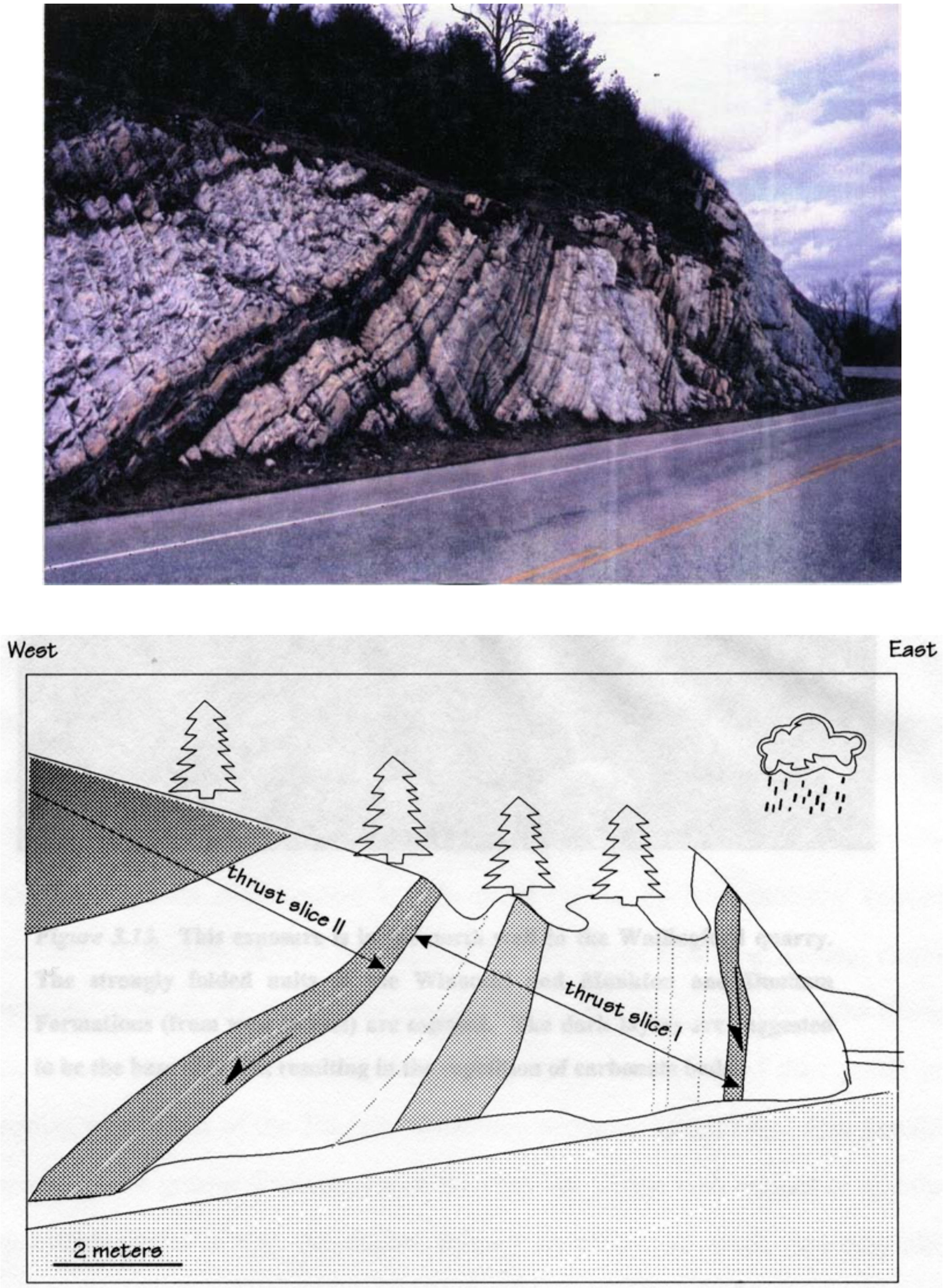


Figure 3.12. **This roadcut 2 miles south of Wallingford along Route 7 shows repetition of beds by thrust-faulting (thrust slice I = thrust slice II). Thompson (1959) shows a complete section from the Monkton quartzite through the Winooski, Danby and Shelburne Formations in outcrop to the west of the road cut, which now is poor, and a continuous stratigraphic section through the units is highly interpretative.**

Figure 3.13. **This exposure is in the north wall in the Wallingford quarry. The strongly folded units of the Winooski and Monkton and Dunham Formations (from west to east) are exposed. The dark layers are suggested to be the base of faults, resulting in the repetition of carbonate beds.**

Precambrian basement breaks of from the ramp and is transported along an imbricate fault. This model is favored because that the structural relationships in the Vermont Valley imply the existence of a large footwall ramp, in order to explain the drop in structural level west of the Pine Hill Thrust and especially for the geometry of the eastern margin of the Taconic Allochthon. Therefore I suggest that the floor thrust of the moving duplex has overridden the normal faults of the block-faulted shelf, further complicating the structures of the duplex in the Vermont Valley. From the stratigraphic relationships (basement against black phyllites) we know that a normal fault must have existed, with a displacement large enough to expose basement. It is suggested here that the Pine Hill Thrust is one of the link thrusts of the duplex, linking the floor thrust to the roof thrust (McClay, 1992), which has cut a horse, while overriding the normal fault scarp, into the footwall, detaching slices of basement and carried it to a position between carbonates and black phyllites of the duplex (*Figure 3.14.a.*). The displacement along the thrusts of the shelf duplex is relatively small, suggesting a hinterland dipping duplex, except for the displacement along the Pine Hill Thrust bringing basement up to the structural position of the black phyllites, which occur on the west side of the basement. This exceptional greater displacement is difficult to explain by later thrusting (out-of-sequence thrust ?), because there is no evidence for substantial fault displacement cutting later structures, especially the Ordovician marbles transported along the sole of the Dorset Mountain Thrust. An out-of-sequence thrust bringing up basement and then paralleling the overriding roof thrust of the Taconic Allochthon seems to be unlikely. One possible model to explain the greater displacement of the Pine Hill Thrust with respect to all other duplex imbricate faults is that the duplex formed an antiformal stack structure after ramping over the steeply dipping normal fault. After climbing the frontal ramp, the roof thrust curves into an antiform. The horse, including basement slices, is still dipping towards the hinterland, but brought up to a higher level with respect to later formed horses. Basement must be brought up so far to rest on black phyllites in the west, which

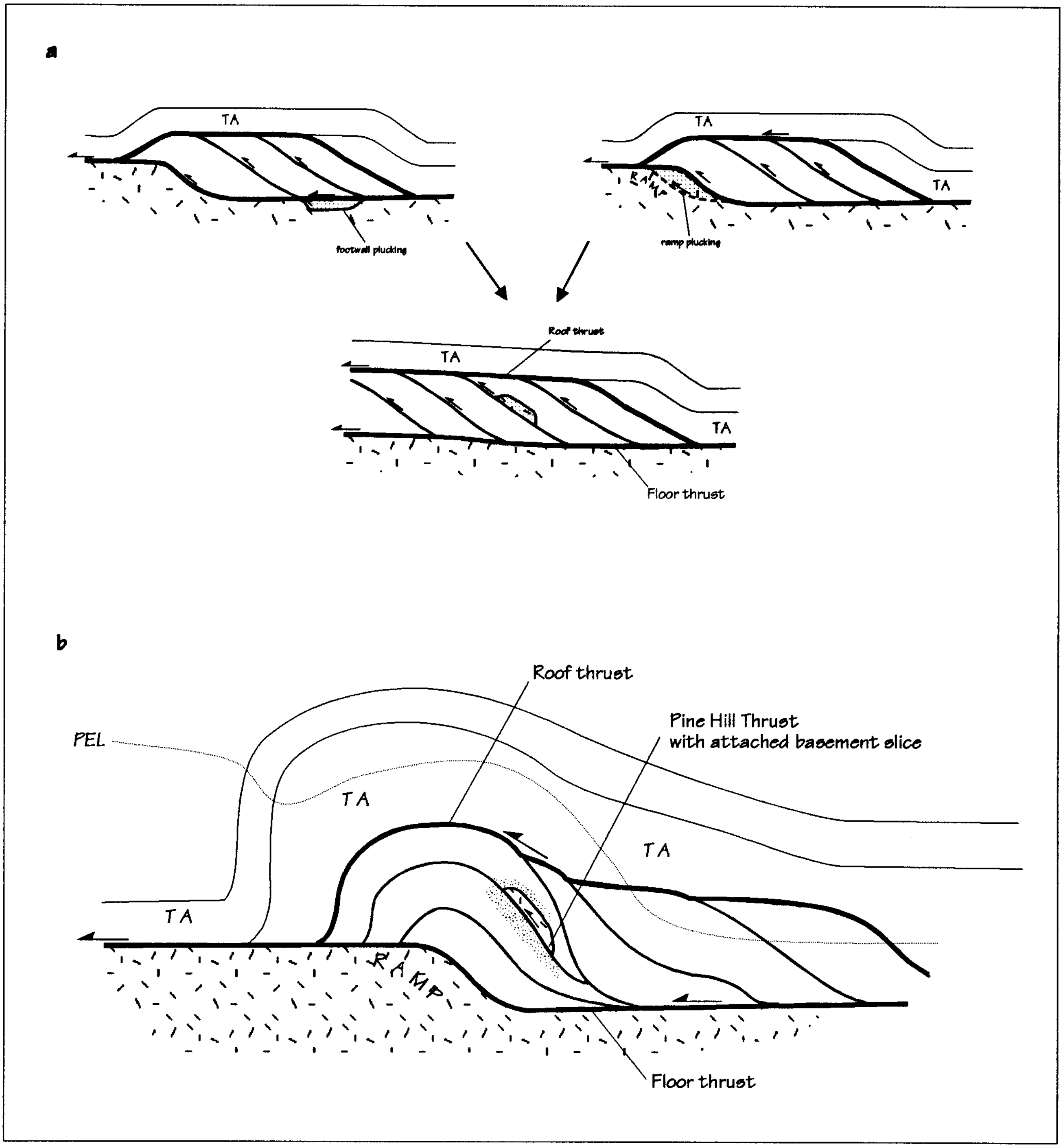


Figure 3.14. **a. Schematic geometry of duplex structure progessively incorporating basement into the thrust stack by ramp plucking or footwall plucking. b. A ramp would force the hinterland-dipping duplex to form an antiformal stack. Displacement along earlier faults (east) is greater and attached basement slices would be brought up to a higher structural level. TA - Taconic Allochthon, PEL - Present erosion level for Dorset Mountain, ignoring that a marble slice attached to the roof thrust must have truncated the upper structural level of the duplex in order to sit directly on top of basement.**

structurally overly the Cambrian carbonate sequence. The black phyllites on the eastern side of the basement slice have probably not been transported significantly along the contact with respect to the basement slice. The basement / black phyllite contact is proposed to be the "original" normal fault / depositional contact as discussed in *chapter3.2.1.*, although there might have been a re-activation of this fault contact by later deformation. The sketch in *Figure 3.14.b.* gives a schematic view of the very complex structures of the various slices in different structural levels, by explaining it with an antiformal stack geometry; this is hypothetical but in my view the most plausible explanation for the structures of the Vermont Valley.

It is also possible that the Pine Hill Thrust has been re-activated in the last stage of the Taconian orogeny by a simple thrust fault following the old fault trace, while folding the inactive shelf duplex by late T_3-thrusts belonging to the Frontal Thrust System, to accommodate further shortening. These faults might have truncated overlying structures.

The only well known fault in the Vermont Valley is the Pine Hill Thrust, first recognized by Wolff (1891), placing Precambrian basement and Cambrian rocks of the Mendon Formation and Cheshire quartzite against shelf carbonates or black phyllites of the Hortonville Formation. Where black phyllites are placed against black phyllites, the trace of the fault is not clear, however I interpret areas of very quartzose black phyllites and slivers of Blue Marble to be brought up by the Pine Hill Thrust or branches of it. Especially south of Danby Hill the trace of the fault is unclear. The displacement along the fault must have been quite substantial, but is compatible with any structures west of Dorset Mountain. I believe that the Dorset Mountain Thrust, carrying the marbles of the Vermont Valley, has not been cut by later thrust faults. The Pine Hill Thrust must have been the major fault of the shelf duplex, but restricted to this deformational event and not, as suggested by Rowley & Kidd (1981), Stanley & Ratcliffe (1985), and Ando et al. (1984), a major late thrust fault along which the imbricated basement of the Green Mountains was transported to some extent to the west.

Faults of the shelf duplex clearly truncate earlier D_1-structures in the Vermont Valley. Several outcrops show sections of dolomite and/or quartzite between 10 to 100 centimeters thick, "interlayered" with strongly foliated greenschist of the Baker Brook Thrust Zone (*Figure 3.15.*). Best exposures are at Danby North Road$_{E16}$ 100 m north where the road meets the power line, on a small ridge south-west of the junction of roads **Th.21** / **Th.19** / Route 7_{F14}, and behind the garage at Route 7_{F12}. All these exposures contain Cambrian dolomites, in thin layers repeated but separated by 1 to 10 centimeter thick layers of greenschist. The exposure at F14 shows repeated layers of dolomite, coarse bluish quartzite and coarse weathered blue marble in a zone of about 15 meters across strike; all beds dip about 30° to the east. I interpret this geometry as resulting from thrusts within the duplex, which imbricate the carbonates and the distinct greenschist of the Baker Brook Thrust, which forms a perfect marker to highlight later structures. The thin repeated layers give an idea of the abundance of thrust development within the duplex, and which is representative of all imbricate thrusts of the duplex. However, these truncation zones should also expose black phyllites within the carbonate slivers, but they do not. I believe that the exposed outcrops represent zones cut by the T_2-faults in a lower structural position, where carbonates still rested on carbonates.

Faults of this type are very difficult to demonstrate in the black phyllite terrain overlying the intermediate ridge between the two Valleys north of Dorset Mountain. A distinct melange unit as proposed for the Proctor area by Bierbrauer (1990) does not exist in the southern part. All dark blue marbles within the black phyllites of the Hortonville Formation are previously interpreted as belonging to the Whipple marble, a member of the Ira Formation. The Whipple Marble is clearly identified by fossils, as a Middle Ordovician marble. I believe the occurrences previously called Whipple Marble are not a member of the Ira Formation, but belong to the Ordovician marbles of the Blue Marble sequence. Several highly sheared marble slices within the black phyllites are very close to known faults zones, e.g. along road **Th.20**, west of exposures of the Baker Brook greenschist.

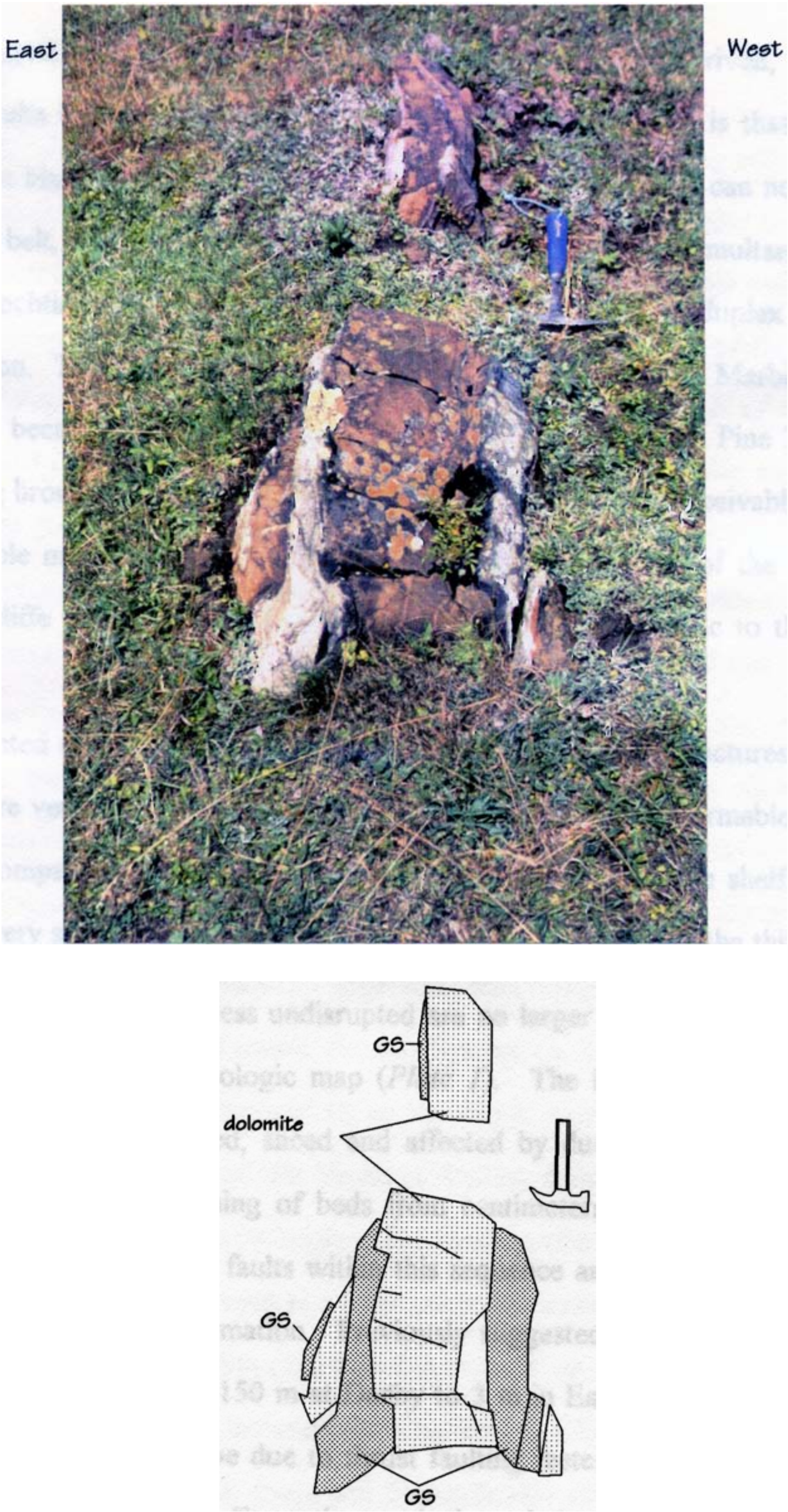


Figure 3.15. **Very common outcrop structure where thin layers (2 - 15 cm) of mylonitic greenschist, GS (T_1) are "interlayered" with dolomite and/or quartzite. The contact between dolomite and greenschist is interpreted as a fault contact. D_1 structures are clearly truncated and sliced by faults of the shelf duplex (D_2). Outcrop picture north of Danby.**

Therefore I suggest that the marble slices are in fact tectonically derived, attached to hidden thrust faults belonging to the shelf duplex (T_2). The problem is that the marble slivers within the black phyllites, brought up by imbricate thrust faults, can not belong to the main marble belt, because the marble belt is emplaced more or less simultaneously with the Taconic Allochthon, responsible for the development of the shelf duplex in a higher structural position. The map pattern supports the emplacement of Blue Marble slivers by imbricate faults, because exposed marble slivers line up, parallel to the Pine Hill Thrust, suggesting being brought up by a fault. However, it is alternatively conceivable that there might be a marble member of some extent within the black phyllites of the Hortonville Formation; Ratcliffe (1975) reports such material from the Walloomsac to the south in Massachusetts.

The presented outcrop examples clearly demonstrate that the structures within the carbonate belt are very complex and are far from being an intact conformable section as proposed by Thompson (1967). The competent units of the carbonate shelf have been imbricated to a very small scale, the exposed field relations suggest that the thickest slices which are internally more or less undisrupted are no larger than 20 meters across strike, not distinguishable on the geologic map (*Plate 1*). The incompetent beds, mainly the Ordovician marbles, are folded, sliced and affected by ductile deformation ("flowage") resulting in incredible thickening of beds from centimeters in one place to up to 100 meters in other places. Early faults within this sequence are not easily recognizable any more due to the ductile deformation. Previously suggested dramatically thinning of the Danby Formation from about 150 m at Danby to 3 m in East Dorset (10 km south from Danby), is proposed here to be due to thrust faulting instead of depositional variations. The situation of the Danby Formation and the whole carbonate sequence is very significant, because the Valley narrows between the steep western flank of the Green Mountains and the eastern flank of Dorset Mountain to less than 1000 meters, too narrow to fit the intact shelf sequence in this gap, even if all were vertical.

3.2.3.2. Duplex Roof Thrust (T_{2r})

The Dorset Mountain Thrust is the major detachment surface along which the thrust stack of the Taconic Allochthon was emplaced to the west. It is the major floor thrust of the Taconic Allochthon (Taconic Basal Thrust), which has overridden the carbonate shelf platform and is responsible for the deformation and the development of the underlying shelf duplex. As soon as the leading edge of the accretionary wedge of the Taconic Allochthon crossed the carbonate shelf edge, thin slivers of the carbonates were attached to the basal thrust surface and transported with the accreted stack to the west (Rowley & Kidd, 1981). I propose that the eastern side of the Taconic Range shows evidence that large carbonate slivers were attached here to the basal thrust surface, and that the ultimate floor thrust of the Taconic Basal Thrust System therefore occurs at the base of the marble sequence. The suggestion that allochthonous or parautochthonous slices of shelf carbonates are present at many places at the base of the Taconic Allochthon was already suggested by Rowley et al. (1979), but often confused with carbonate slivers along the base of most Taconic slices related to large-scale imbrication during the last stages of the collision, referred to as the Taconic Frontal System by Rowley & Kidd (1981). The Dorset Mountain Thrust is proposed to be the major single initial thrust surface, along which the entire marble belt of the Vermont Valley, from the Massachusetts-Vermont border to at least Brandon, and probably to the most northern exposure of marble north of Middlebury, has moved to the west as a large coherent, however internally imbricated slice (*Figure 3.16.*). Later imbrication (T_3) then has brought up carbonate slivers and in some places basement, for example between the Chatham and Giddings Brook slices and the Rensselaer and Giddings Brook slices and the carbonate slivers in the Taconic sequence west of the field area. Based on the highly deformed character of the marbles and suggestions for lithologic similarities of the rocks belonging to Dorset Mountain and units east of the Green Mountains massif (Stanley & Ratcliffe, 1985), the marbles must have

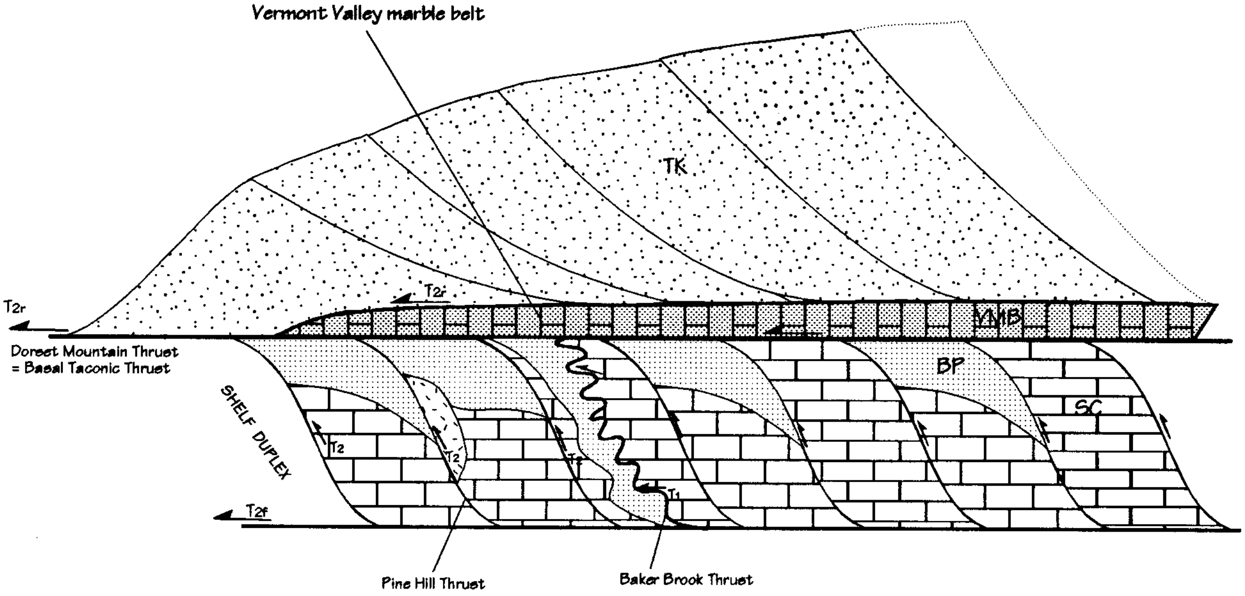


Figure 3.16. **The Dorset Mountain Thrust (T2r) carrying the entire Vermont marble belt to the west can be viewed as the downward extension of the Basal Taconic Thrust. Large carbonate slivers were attached to the sole of the Taconic Allochton, truncating all earlier structures of the platform shelf duplex.**
TK - Taconic Allochthon, VMB - Vermont Marble Belt, BP - Ordovician black phyllites, SC - Cambrian shelf carbonates.

been attached to the early thrust surface of the Basal Taconic Thrust and transported a substantial distance from the east.

All structures of the shelf duplex in the Vermont Valley including the basement slices brought up along the Pine Hill Thrust (especially the Mill Brook basement slice) were truncated by the marbles of the Dorset Mountain Thrust.

The area south of Danby Four Corners is poorly exposed and the map pattern shown on Thompsons (1967) map conjectural. Although the outcrop is not much better now I relocated old marble quarries shown on the geologic map of Bain (1912) south-west and south of Danby Four Corners. Correlation of these exposures with other outcrops in the field area support the suggestions of several workers (Bain, 1912; Dale, 1912) who proposed earlier the continuity of the marble belt as a single large coherent unit, as shown on Bain's (1912) geologic map; however it was not interpreted then as a tectonically derived fault slice. The exact location in this area of the fault contact between the phyllites of the Taconic Allochthon and the underlying marbles is in some places mappable, although the distinction between black phyllites of the Hortonville Formation and lithologies belonging to the Taconic Allochthon is easily confused and misinterpreted (Zen, 1964; Bierbrauer, 1990). The thrust contact between the Ordovician marbles and the carbonate shelf sequence can not be demonstrated and is interpretative (*Plate 1*), due to poor outcrop in Tinmouth Valley.

The extent of the marble sliver attached to the Taconic Basal Thrust is based on the distinct contrast of highly deformed and metamorphic versus less deformed and less metamorphic marbles and carbonates. The marbles from Dorset Mountain south through Arlington are more or less flat-lying which is in obvious contrast with the in many places steeply dipping rocks paralleling the Pine Hill Thrust. The structural relationships south of Danby suggest that locally slivers of the overridden less metamorphic shelf sequence were also attached to the Dorset Mountain Thrust and emplaced on top of similar looking carbonate units. The flat-lying carbonates of the Danby Formation in Mill Brook and south of Danby (Danby type locality), and slivers extending farther south beneath Dorset Mountain as a very thin sequence, are suggested to have been transported west with the Taconic Allochthon and the attached marbles. Those slivers were attached to the base of the main marble slice and transported only a small distance compared with the overlying marbles. The abrupt change in metamorphic grade and substantial differences in thicknesses between and within units of the Blue marble sequence and the marbles of the Shelburne Formation are also explained by minor thrust faults of this group. The necessity for such faults can be better demonstrated by contact relationships of smaller slices in the Proctor area (Bierbrauer, 1990).

Deformation of the Marbles

All marbles of the Vermont marble belt show intense deformation structures with tight folding and imbrication being responsible for extreme thickness changes along strike. The areas of extreme thickenings give the marble in several localities its economic valuable thickness, making the Vermont marble belt one of the most important marble deposits in the world (Bain, 1912). Due to its complex internal deformation, all data taken from one location must be viewed as a locally determined structure, making a correlation with other exposures difficult. In the field area there are only a few examples where substantial thickening is exposed. The most impressive locality is the Imperial Danby quarry on the east flank of Dorset Mountain near Danby; other examples are exposed in the South Wallingford marble quarry, dolomite outcrops along Mill Brook Road from Danby to Danby Four Corners, as well as in several other quarries in the Vermont marble belt. The importance of significantly locally thickened beds in the marbles has been under-estimated by all workers publishing in the quadrangle bulletin series for the Vermont Valley (Fowler, 1950; Hewitt, 1961; Zen, 1964; Thompson, 1967; MacFadyen, 1956), and who disregarded the detailed and convincing work done previously by Bain (1931, 1934, 1959), and Dale (1912, 1913, 1915). The deformation within the marbles has been named

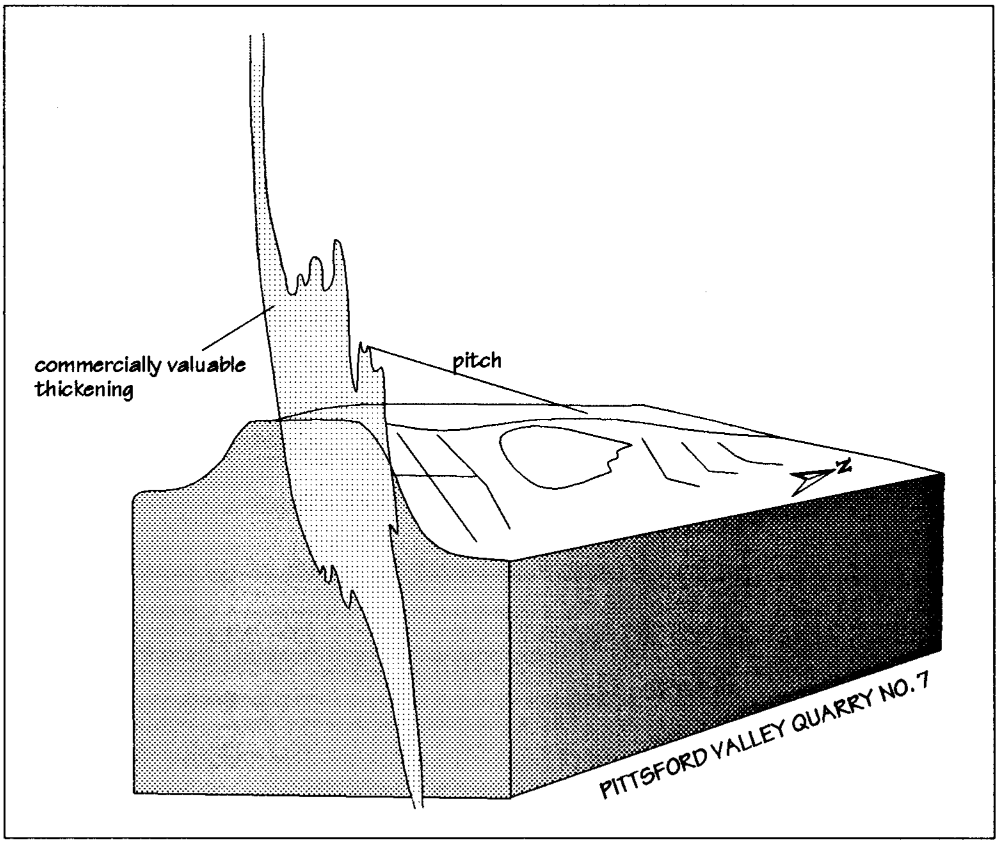


Figure 3.17. **"Flowage" fold at Pittsford Valley quarry no. 7. (after Bain, 1959)**

due to its ductile appearance "flowage folding", a term established by Bain (1931). Abnormally coarse texture with high local intensity of folding is illustrated by the Pittsford Valley, West Rutland and Danby deposits (Bain, 1934). The Brandon Italian marble beds on the west side of the Pittsford Valley quarries are thickened from 3 m to 45 m in the hinge of a "flowage" fold, accompanied with a local grain size increase of 0.3 mm. Most impressive thickening occurs in the Columbian deposit at the Danby mine beneath Dorset Mountain. Here the marble beds of this one distinctive unit have been thickened to over 160 meters on the east side of the Mountain, thinning south to approximately 30 meters. It should be noted that an experienced worker is able to distinguish beds thinned to centimeters, due to distinct characteristics seen in outcrop or bore hole cores. The commercial layers in the Columbian marble member of the Shelburne Formation of 23 meters (at this locality) are subdivided into 26 (!) distinguishable layers each having a different name and ranging in thickness between 2 centimeters to 3.5 meters (Ratte & Ogden, 1989). Unpublished reports of Bain (Report on the geology of the Danby deposits, 1929; The marble deposits of western Vermont, ????) demonstrate in several profiles and outcrop sketches the structure of the Danby marbles and now they can be explained by structures such as that of *Figure 3.17.*.

3.2.4. D_3 Deformation

Structures of the Taconic Frontal System are well established in the Taconic Allochthon and on and near its western margin (Rowley & Kidd, 1981; Bosworth et al., 1988, 1985; Bosworth & Rowley, 1984; Bosworth & Kidd, 1985). More easterly occurrences of these late thrusts have not previously been shown in the carbonate shelf rocks of the Vermont Valley and the clastics and basement of the Green Mountain massif. The existence of late out-of-sequence thrusts can only be inferred from large scale structural relationships of the Vermont Valley, the Taconic Allochthon to the west and the

Green Mountain massif to the east. In the field area the only major fault viewed to be a late thrust juxtaposed over part of the shelf sequence is the Green Mountain Thrust, consisting of a series of complex folded structures and thrust slices, along the western edge of the Green Mountain massif. The detachment of the Frontal Thrust System is probably the Champlain Thrust and must lie deep below all structures and have transported the Green Mountains as a slice to the west. In the field area the Green Mountain Thrust is of this age, but may have relatively minor displacement (a few kilometers) compared with its detachment surface, which is likely to have around 100 kilometers (Rowley, 1982). The possibility of a thrust here has long been discussed by several geologists (Bain, 1925; Dale, 1919; Gordon, 1916; Hawkes, 1941; Karabinos, 1988), but has never been established. Earlier workers favored a thrust along the west side of the Green Mountains in order to locate the root zone of the Taconic phyllites east of the Taconic Allochthon. Geologists in the 1950's and 60's (summarized in the Vermont State Map, Doll et al., 1961), however, proposed an essentially un-faulted margin of the Green Mountain massif, with the idea that the Taconic Allochthon was a gravity driven klippe and the Green Mountain massif an undisrupted anticline from which the klippe came. Recent mapping by Ratcliffe (1992, pers.comm.) has shown that the Green Mountains reveal more or less intact cover-basement relationships with no major truncations within the massif, as already proposed for the western Lincoln massif by Dellorusso (1986) and Dellorusso & Stanley (1986). Other interpretations proposing the existence of major thrust faults in the Green Mountain massif juxtaposing basement and cover in a series of slices as presented by Karabinos (1988) are rejected by recent new mapping Ratcliffe (1992, pers.comm.), however thrust faults along the western flank of the Green Mountain massif are suggested in the southern part by Ratcliffe et al. (1988). The difficulty in distinguishing between cover and basement is great and might easily lead to differing opinions about lithologic relationships. Lithologic continuity along strike does not exist, and discussion about whether certain dolomite-marble and quartzite units belong to the Precambrian or the Paleozoic still continues. Demonstration of which major process was responsible for the non-continuity along strike of cover units, either complex extensive folding (Ratcliffe, 1992, pers.comm.) or imbrication, is difficult within the belt of siliciclastic cover rocks, but this uncertainty has no major effect on the interpretation of the structural development of the western margin of the western margin of the Green Mountains in the area mapped. The highly disrupted western flank of the Green Mountains is suggested to be the result of complex folding and imbrication, and in particular due to an out-of-sequence thrust belonging to the Taconic Frontal System (T_3). Non-continuous beds along strike and repeated beds across strike are common in the siliciclastic sequence. Although direct evidence for a major fault system is not exposed, I believe that the observed structure can not be explained only by complex folding, but also requires at least one major thrust fault, with a fault zone probably west of the basement / cover unconformity seen high on the slope of the Green Mountain massif, and with the fault covered in most places by the talus of the steep flanks of the Green Mountain rocks.

Bierbrauer (1990) demonstrated out-of-sequence thrusts in the Proctor area bringing marble slices to higher structural positions. The Whipple Hollow Fault and the Proctor Fault can be traced southward, but with a quite different interpretation of the structural relationships than by Bierbrauer. Although he suggested a continuation of these faults into my field area, joining the Pine Hill Thrust, there is no evidence for late thrust faults within the carbonate sequence; alternative continuation traces for these faults are discussed in Chapter 4. Following my interpretation for the emplacement of the marble sequence as an attached slice along the sole of the floor thrust of the Taconic Allochthon, there is no evidence for substantial faults cutting Dorset Mountain or immediately west of it. In response to late thrust faults flanking the Vermont Valley, the shelf duplex must have been truncated by those faults, resulting also in the complicated deformation of the duplex and locally reactivation of its structures. A late stage folded duplex has never been proposed to be responsible for structures seen in the Vermont Valley but may be helpful to explain several problems with earlier interpretations.

The structures along the western flank of the Green Mountains have not been the focal point of this project. However the change from previous maps (Thompson, 1967; Doll et al., 1961) in structural relationships were so major, that it became apparent that an interpretation for the Vermont Valley also needs a new interpretation for at least the western margin of the Green Mountain massif. Another important fact is that there exist several detailed maps for parts of the western side of the Green Mountains, as well as several larger-scale structural interpretations that suggest it is significally faulted (Gordon, 1916; Hawkes, 1941; Kent, 1942; Dale, 1917; Karabinos, 1988; Ratcliffe et al., 1988). It is curious that these were all completely disregarded by the later interpretations. A re-interpretation for the Green Mountain western margin is attempted, but is based on too little field work to allow a complete interpretation for the entire length of the western flank of the Green Mountains. However field evidence suggests for this part of the Green Mountains that there are substantial imbrications and I favor strongly the existence of a thrust fault along the western base of the Green Mountains.

3.2.4.1. Kaolin / Manganese Deposits (k)

In addition, the kaolin deposit at South Wallingford, is strong evidence for a fault in this position. The remnants of a Manganese Mine occur at the foot of the western flank of the Green Mountains at South Wallingford along Homer Stone Brook. The kaolin deposit with the associated manganese and limonite of the Kinney Kobble Manganese Mine was worked 1888 and abandoned a couple years later. The existence of a broken chain of kaolin deposits more or less associated with iron ore and manganese minerals occurs along the western flank of the Green Mountains (*Figure 3.18.*) from Monkton to Pownal and includes outcrops at Monkton, Brandon (Forestdale), Rutland, South Wallingford, Tinmouth, North Dorset, Shaftsbury and Bennington (Jacobs, 1925). Many of them are close to the western border of the Green Mountain basement in the Vermont Valley. These occurrences suggest a possible relationship between the kaolin and a probable fault or Green Mountains Thrust system along at the base of the Green Mountains in the Vermont Valley (Ogden, 1969; Jacobs, 1925; Burt, 1927-28; Harder, 1910; Wark, 1968).

The material found at the described location is a light white very fine-grained kaolin clay (*Figure 3.19.*). Exposures are only found within the old mine shafts and dumped material next to the shafts. The contact between the clay and the adjacent rocks could not be found.

The deposit of the manganese bearing clay of the Kinney Kobble Mine is reported to be an approximately 100 meter thick clay layer in contact with quartzite to the east and limestone to the west (*Figure 3.18.1.*). The clay and the adjacent units have a nearly vertical dip (Harder, 1910). The outcrop of the deposit was over 350 m along strike by a width of about 65 m (Jacobs, 1926). In the Bennington area logs of borings into the kaolin report thicknesses of about 60 m (Burt, 1928). At South Wallingford an almost horizontal drift with a total length of 360 m was driven to reach the ore deposit, of which 160 m went through limestone. This ore vein is thought to extend some 5 kilometers north-south (U.S. Depart. of Agriculture-Forest Service, 1934, file 2360).

The kaolin has been assumed by most previous studies to be a residual product of the weathering of feldspathic material in place. In most cases, the deposits are located within or next to the Cheshire Quartzite, which is relatively free of feldspar and has a massive jointed character (Ogden, 1969). Therefore the only source for the origin of the weathering feldspar was thought to be the gneiss of the Green Mountains. This has to be ruled out because as demonstrated for the large deposits at Monkton, the Precambrian gneiss is quite a distance away from the deposits and can not be an "in place" weathering product. According to Ogden (1969) the kaolin is of a hydrothermal origin along a zone of faulting. It occurs as a result of the last major deformation in this area. Ogden argues the age of the kaolin to be Triassic, because the hydrothermal influence of magma

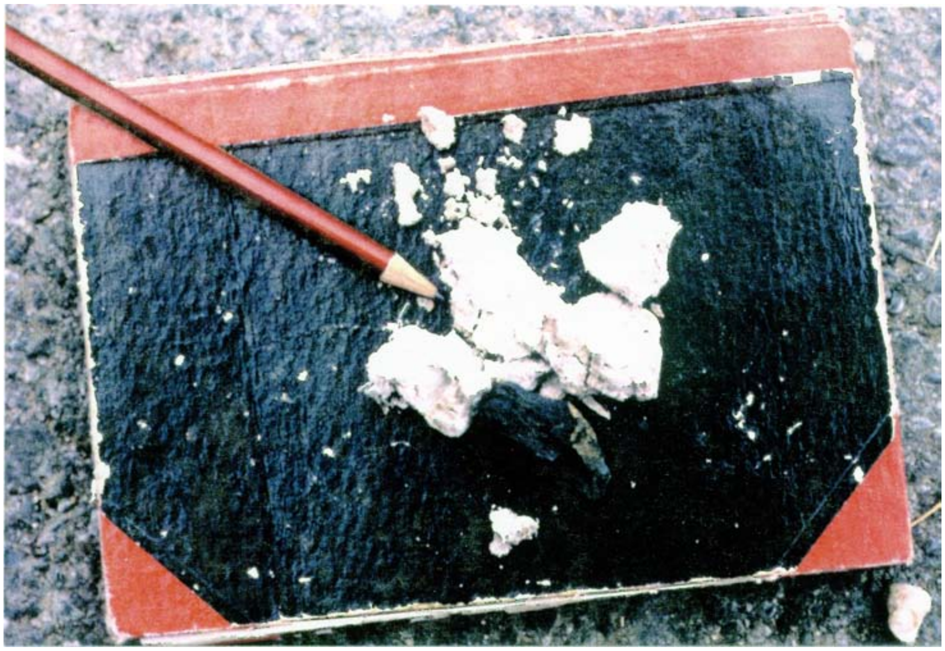


Figure 3.19. **Clean white kaolin clay with a piece of manganese oxide concretion found near the old mine shafts of the Kinney Kobble Manganese Mine at South Wallingford.**

bodies is considered to have resulted in the formation of the kaolin, and that is the age of the camptonite dikes in the area. According to Ogden (1969) the kaolin may have been from a deep-seated source, formed by alteration of feldspar contained in granite and then carried upwards and deposited in the upper part of the fractured zone by ascending thermal waters with reaction and replacement taking place.

Although there might be other possible structural interpretations for the location of the source of the kaolin, it seems likely that hydrothermal fluids are responsible for the origin of the kaolin; its occurrences supports the existence of a significant thrust fault between siliciclastic rocks and carbonates at the western front of the Green Mountain margin.

4. Regional Synthesis and Implications

4.1. Introduction

Recent work by numerous authors has resulted in the reinterpretation of many of the original ideas concerning the nature of the geologic history of Vermont and adjacent areas, as a result of plate tectonic-inspired interpretations. The notion that the Taconic Allochthon has been emplaced by "hard rock" mechanisms, and not as one or several gravity slides detached from their origin, lead to the proposal of the Taconic Frontal Thrust System, which is responsible for the existing stacking order of the Taconic Allochthon (Rowley & Kidd, 1981; Rowley et al., 1979). These faults were active after or during the final stage of the emplacement of the accretionary wedge. Bierbrauer (1990) emphasizes the importance of late, cross-cutting faults of the Frontal Thrust System (T_3) for the northern part of the eastern margin of the Taconic Allochthon. It is very likely that late T_3-thrust faults and related structures underlie the entire Vermont Valley and probably the Green Mountain massif. Mapping along the eastern margin of the Green Mountain massif has shown that the Precambrian basement has also been broken up into numerous basement thrust slices (Stanley & Ratcliffe, 1985; Dellorusso & Stanley, 1986). Most of the rocks of the central Vermont Valley represent a complex sequence of lithotectonic assemblages rather than a simple west-dipping homoclinal sequence. The previous interpretation for west-central Vermont with the "Middlebury Synclinorium" and the "Green Mountain Anticlinorium" (Doll et al., 1961) as a more or less un-faulted structure (*Figure 4.1.*), does not explain the structures observed.

In contrast this study suggests a very different interpretation for the structural evolution of the Vermont Valley and the Green Mountain massif (*Figure 4.2.*). The newly

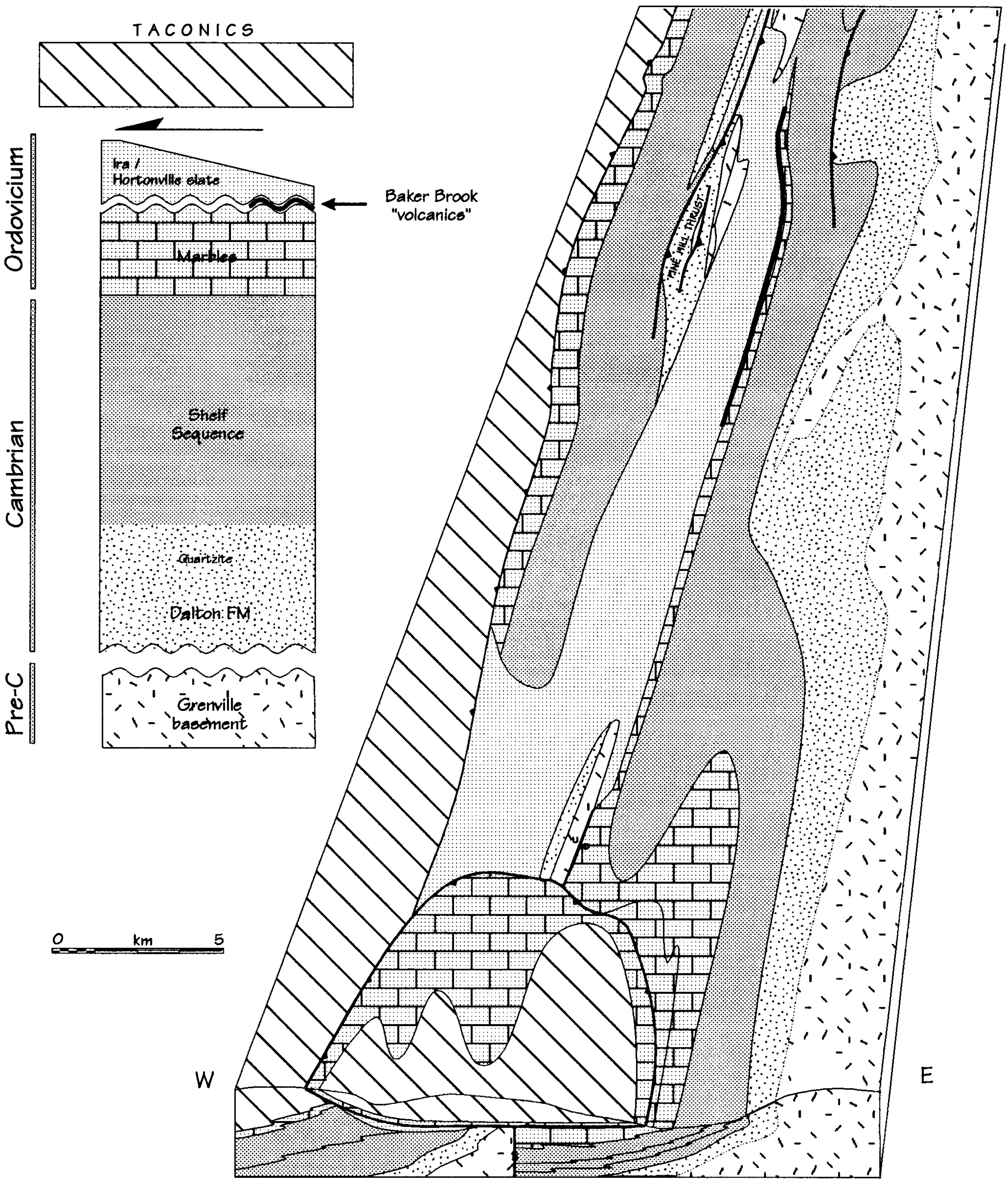


Figure 4.1. **Generalized geologic map of the field area in the Vermont Valley from Thrompson (1967). The only continuous fault in the field area is the Basal Thrust of the Taconic Allochthon.**

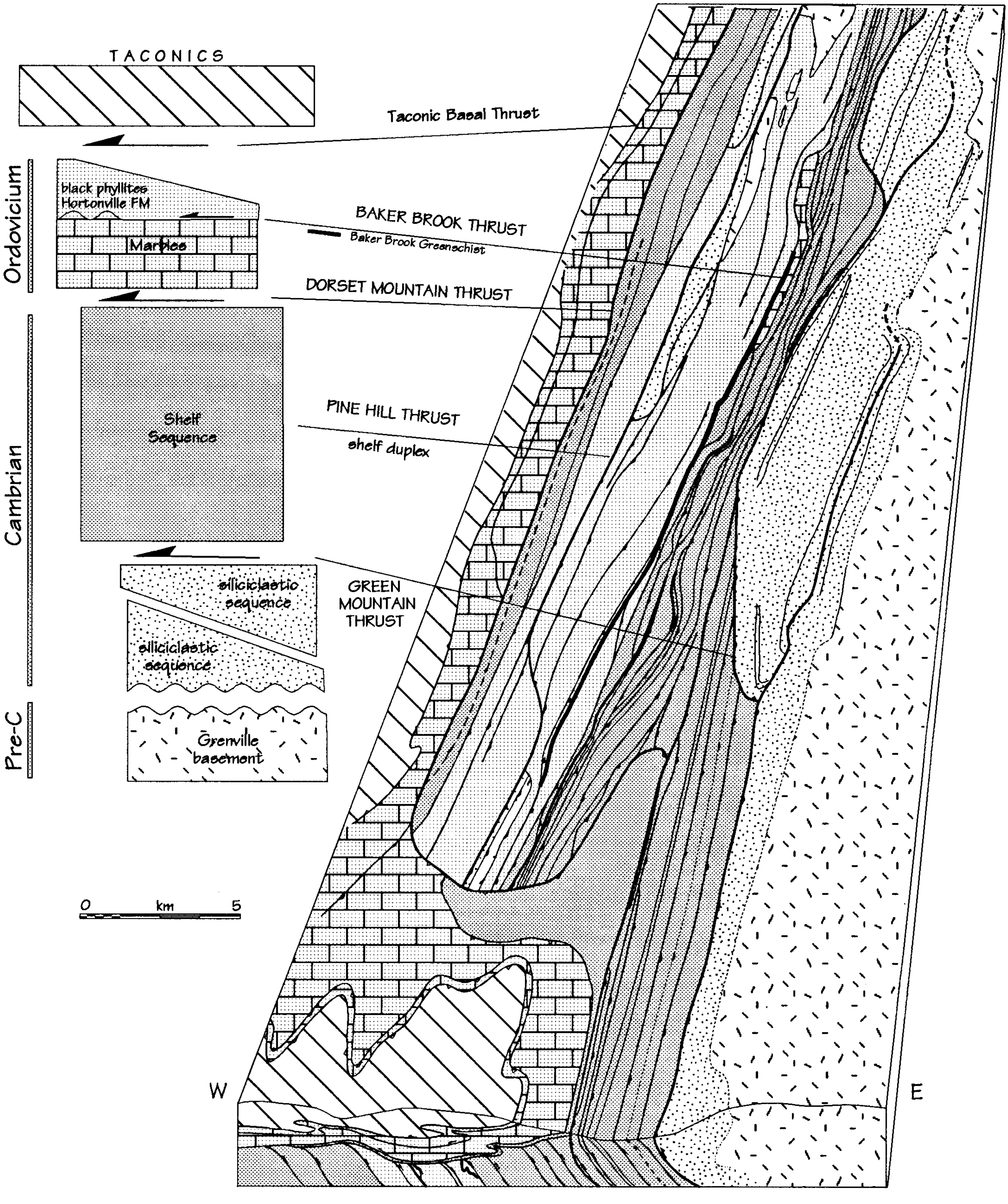


Figure 4.2. **In contrast to Figure 4.1. (Thompson's map) this geologic map shows my geologic interpretation of the field area in the Vermont Valley and along the western flank of the Green Mountain massif.**

discovered Baker Brook Thrust demonstrates early disruption of the carbonate shelf. The Paleozoic shelf sequence consists of several carbonate slices and slivers, belonging to the shelf duplex underlying the Taconic Allochthon and probably crystalline basement of the Green Mountains. The duplex system proposed correlates with similar structures of the "Middlebury Synclinorium", also a duplex fold-and-thrust belt (Washington, 1992). The Vermont marble belt is proposed to be a large more or less coherent carbonate slice, transported with the last emplaced slices of the Taconic Allochthon to the west. As shown on *Plate 3*, most faults can be correlated with structures elsewhere to the north and south of the Vermont Valley.

4.2. Faults of the Field Area

Four major thrust faults have been discovered in the field area that are important on a more regional scale and discussed below.

The main structure that stands out the most on the geologic map of the Vermont Valley (*Figure 4.6.*) is the occurrence of two north / south elongated black phyllite terrains of the Hortonville Formation, both cut by several thrust faults; both belts are part of the shelf duplex underlying the Vermont Valley. The eastern belt forms the intermediate ridge containing several discontinuous Precambrian basement slices brought up by the Pine Hill Thrust. The north-western belt contains several carbonate slivers, presumably brought up by late out-of-sequence thrust faults, that are associated with a melange zone including Taconic lithologies, rather than just black phyllites of the Hortonville Formation (Bierbrauer, 1990).

4.2.1. Shelf Duplex Imbricate Thrust Faults - Pine Hill Thrust

The Pine Hill Thrust belongs to the shelf duplex but is of particular interest, because Precambrian basement slices were brought up suggesting a greater displacement with respect to the adjacent duplex imbricate thrust faults. The western side of the Mill Brook basement slice (south-west of Danby) is in thrust contact with black phyllites of the Hortonville Formation (*Figure 4.5.*). The Pine Hill Thrust strikes north-south connecting all basement slices in the Vermont Valley before its truncation by Dorset Mountain in the south. The black phyllites west of the basement slices belong to the foot wall, whereas the basement slices and phyllites east making up the prominent ridge separating the Vermont Valley, belong to the hanging wall of the Pine Hill Thrust. This contact does not represent an unconformity between rocks of the siliciclastic sequence and overlying black phyllites of the Ira Formation as mapped by Thompson (1959, 1967).

To the north, the Pine Hill Thrust is well defined up to Boardman Hill (south-west of Rutland), from where the continuation farther north is not clear. The Pine Hill Thrust loses its definitive identity north of Rutland, where the distinction between black phyllites of the Hortonville Formation and the black schists of the Mendon Formation, as well as the distinction between basement units or units belonging to the cover, becomes very difficult (*Figure 4.6.*). The units east of Proctor and Pittsford (Doll et al., 1961) are interpreted by Brace (1953) as Upper Cambrian carbonates and Ordovician Marbles, whereas Keith (1942) and Karabinos (1988) interpret those rocks as Lower Cambrian units of the Mendon Formation. Keith (1932) shows a complicated north / south trending fault system north of Rutland, but none of the faults joins the Green Mountain Thrust system along the western flank of the Green Mountains. Depending on which rocks were included into the shelf sequence or the siliciclastic basement-cover sequence, the Pine Hill

Thrust might be truncated by faults along the western margin of the Green Mountains, or it may simply die out to the north.

The Pine Hill Thrust is clearly overridden by the Dorset Mountain Thrust at Dorset Mountain and its continuation to the south can not be clearly demonstrated (*Figure 4.6.*). This does not mean that the Pine Hill Thrust dies out directly after it disappears beneath the massif of Dorset Mountain; it would continue to the south, whether it is truncated by, or joins, the Dorset Mountain Thrust.

The basement slices are presumed to have been detached and incorporated into the duplex during its development. The reactivation of the duplex imbricate faults is very likely, to explain the higher structural position of the basement slices with respect to the carbonates and black phyllites of the duplex. Several other workers (Rowley & Kidd, 1981; Ratcliffe, 1992, pers.comm.) have suggested that the Pine Hill Thrust is related to a late event, juxtaposing attached basement along out-of-sequence thrusts. However there is no evidence that the Pine Hill Thrust truncates younger structures of the overlying Dorset Mountain Thrust (T_{2r}), with such a substantial displacement needed to transport basement on top of black phyllites. I believe that this structural relationship can be explained without the existence of a late major thrust fault (*Chapter 3.2.3.*) and I want to point out that the Pine Hill Thrust as referred to in this study is part of the shelf duplex and therefore an T_2-imbricate thrust fault of the duplex.

Although I do not find any evidence to believe that the massif of Dorset Mountain has been brought to its present structural position by late out-of-sequence thrust faults as suggested by Bierbrauer (1990), there is the possibility that there has been some late movement west of Dorset Mountain probably along a continuation of the Pine Hill Thrust as pointed out by Ratcliffe (1992, pers.comm.). This fault would have reactivated the duplex imbricate Pine Hill Thrust and then parallel the floor thrust of the Dorset Mountain Thrust (T_{2r}, Taconic Basal Thrust) before its truncation of the Dorset Mountain Thrust on the western flank of Dorset Mountain, hidden in the Taconic phyllites (*Figure 4.3.*).

Pine Hill Thrust suggested as out-of-sequence thrust

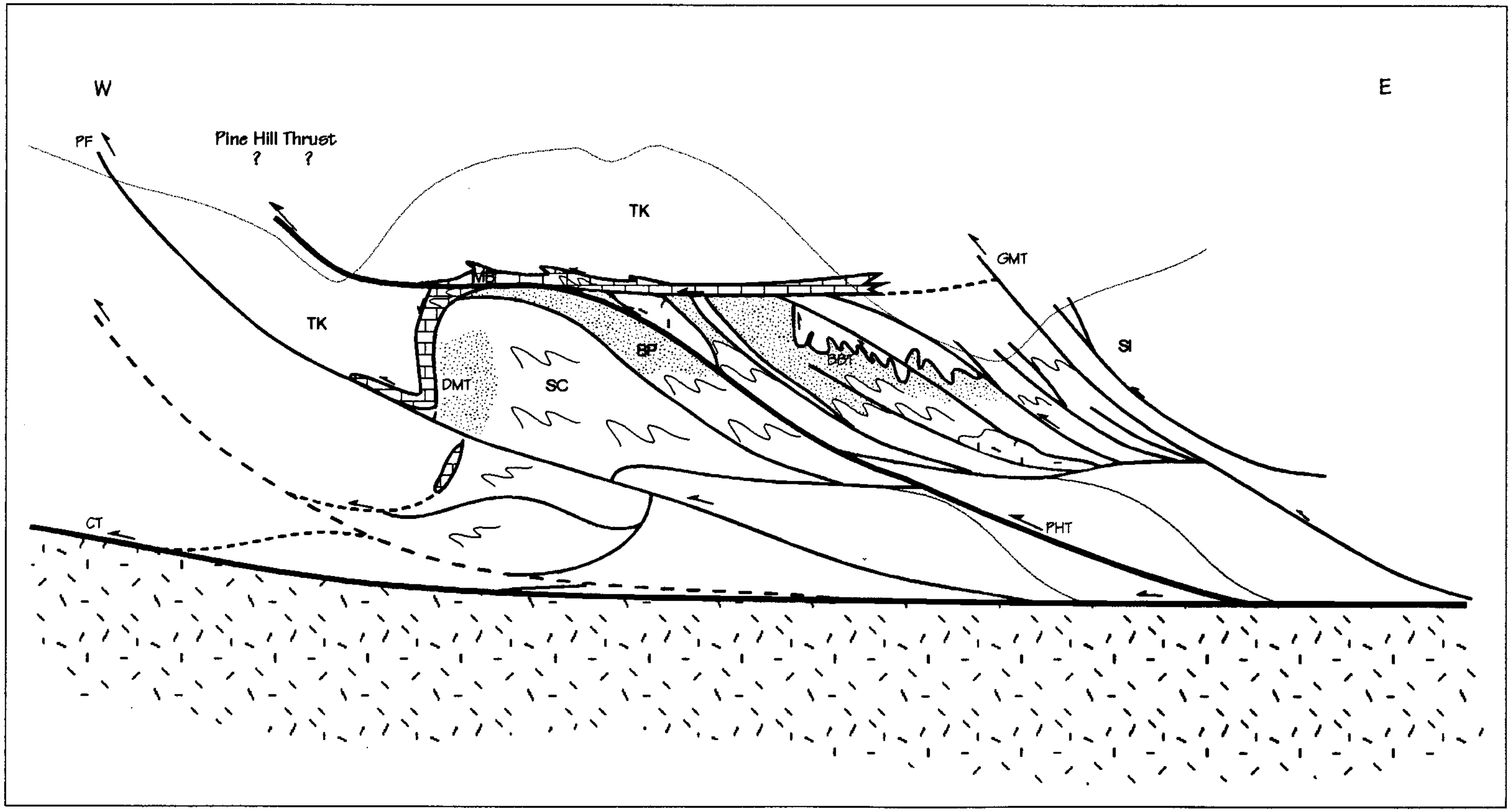


Figure 4.3. **Alternative profile with the Pine Hill Thrust shown as (at least in part) a late out-of-sequence thrust fault. The displacement along the Pine Hill Thrust suggests reactivation of an earlier duplex imbricate thrust with the already incorporated basement slice.**
Profile C-C' of Figure 4.9.. PF - Proctor Fault, DMT - Dorset Mountain Thrust (Whipple Hollow Fault), PHT - Pine Hill Thrust, BBT - Baker Brook Thrust, GMT - Green Mountain Thrust, CT - Champlain Thrust; TK-Taconic Allochthon, MB - marble belt, SC - shelf carbonates, BP - Ordovician black phyllites, SI - siliciclastic sequence.

North of Dorset Mountain, the truncation of the Dorset Mountain Thrust by this late out-of-sequence thrust fault would have been taken place above the present erosion level. The truncation of the Taconic foliation in combination with the occurrence of detached carbonate slivers west of Dorset Mountain as pointed out by Ratcliffe (1992, pers.comm.), clearly demonstrates late movement west of the Dorset Mountain massif. However the displacement suggested from the Taconic-marble thrust contact (Dorset Mountain Thrust) on either side appears too small to propose a major out-of-sequence thrust here.

The South Wallingford marble slices pose a geometrical problem. As stated earlier, I believe that the rocks of the Vermont marble belt have been carried with the Taconic Allochthon to the west and are detached from the underlying Cambrian carbonates. Besides the relatively large marble slices at South Wallingford, there have been several others mapped (e.g., at East Clarendon), east of the Pine Hill Thrust, as shown on the Vermont State Map (Doll et al., 1961). The South Wallingford marble is very similar to the marbles of the main belt west of the Pine Hill Thrust and identified as Blue Marble and upper Shelburne Marble, however those marbles at South Wallingford have never been mentioned by Bain (1959) as belonging lithologically to the main Vermont Marble belt. The South Wallingford marble slice and all other marble exposures east of the Pine Hill Thrust within the Cambrian carbonates of the shelf platform are presumably carbonate slivers, incorporated into the shelf duplex, with a similar composition but different origin than the main Vermont marble belt to the west.

4.2.2. Proctor Fault

Bierbrauer (1990) recognized two late out-of-sequence thrust faults at the north end of the black phyllite terrain west of the Pine Hill Thrust. The *Whipple Hollow Fault*, brings up the West Rutland marble belt as a fault slice and the *Proctor Fault*, a major thrust fault along the western carbonate belt, juxtaposes Ordovician marbles on black phyllites; both are presumed to be late east-dipping faults belonging to the Frontal Thrust System (*Figure 4.6.*). He believed that the Pine Hill Thrust belongs to the same thrust system and suggests that both faults might be branches of the Pine Hill Thrust, terminating in each other to continue south along the marble / phyllite contact, or truncated by the Pine Hill Thrust. I agree in part with the interpretation of Bierbrauer (1990) but prefer to continue the Proctor Fault westward into the Taconic Allochthon west of Clarendon Springs, since I believe that the Pine Hill Thrust is not necessarily a late thrust fault and there is no place to continue the fault south within the carbonates. However, the Proctor Fault could alternatively continue south through the swamps of Tinmouth Valley and be in fact responsible for the late truncations west of Dorset Mountain.

I suggest that the Dorset Mountain Thrust and the Whipple Hollow Fault are correlatable and join each other at about Clarendon Springs, and are the major floor thrust along which the entire Vermont Valley marble belt has been transported to the west.

4.2.3. Dorset Mountain Thrust / Whipple Hollow Fault

The Dorset Mountain Thrust belongs to the Taconic Basal Thrust, the major thrust in the Vermont Valley fault system. The Taconic Allochthon has been transported to the west by the Basal Thrust locally accreting large carbonate slices from the overridden shelf platform, that were attached to the sole of the moving thrust and transported to the west. Where carbonate slivers have been attached to the floor thrust of the propagating Taconic slices, the Basal Thrust System does extend down to the base of these slivers, named by me the Dorset Mountain Thrust. I suggest that the Dorset Mountain Thrust is a gentle westward dipping fault south from Dorset Mountain and a steeply westward dipping or overturned eastward dipping folded major detachment north of Dorset Mountain. The Dorset Mountain Thrust follows the contours of the Basal Taconic Thrust throughout the length of the eastern margin of the Taconic Allochthon. I suggest that the entire Vermont marble belt belongs to one, more or less coherent, carbonate slice transported to its present position with the Taconic Allochthon to the west (*Figure 4.6.* and *Figure 4.8.*).

South of Dorset Mountain, the Dorset Mountain Thrust separates the marbles and Taconic phyllites from the Cambrian carbonate shelf sequence. The belt continues to the southern end of the Green Mountain massif, where the Dorset Mountain Thrust and the carbonate units are truncated by thrust faults along the Green Mountain massif transporting Cheshire Quartzite and Mendon Formation to the west as shown on Doll et al. (1961) and Gordon (1913).

North of Dorset Mountain an interpretation for the trace of the Dorset Mountain Thrust is more difficult. Bierbrauer (1990) points out that the Whipple Hollow Fault is necessary because the distribution of map units along the eastern slope of the Taconic Range cannot be explained solely by a folded Basal Thrust. I agree with his interpretation that the eastern marble belt (Proctor marble belt) must have been brought up by a late thrust fault truncating the Dorset Mountain Thrust. However it is possible to explain the same structural geometry as proposed by Bierbrauer (1990) for the West Rutland marble belt, who shows an eastward dipping Whipple Hollow Fault bringing up the West Rutland marble belt, with an eastward dipping *overturned* thrust fault (T_2) (*Figure 4.7.*) shows the Dorset Mountain Thrust continuing to the north and joining the Whipple Hollow Fault as a steeply eastward overturned dipping thrust fault. The Dorset Mountain Thrust probably continues as far north as Middlebury, where it would die out where the marble units disappear, that are presumably affected by major faults of the Hinesburg Thrust and the Monkton Thrust Fault extending south as shown on Doll et al. (1961).

4.2.4. Baker Brook Thrust

The Baker Brook Thrust is the best mappable fault in the field area, extending north-south and paralleling the eastern margin of the eastern phyllite terrain (*Figure 4.6.*).

However, this high strain zone disappears north of South Wallingford. In the Wallingford gravel quarry, between Otter Creek and the intermediate ridge, several dumped large blocks of definite Baker Brook Greenschist have been found, but the contact was covered at the time of my visit and not located. The northernmost exposure so far located is west of Clarendon where the Greenschist is in direct contact with actinolitic Precambrian basement, similar to units found in the Green Mountain massif (Ratcliffe, 1992, pers.comm.). The Baker Brook Thrust probably continues farther to the north paralleling the black phyllite terrain.

The Baker Brook Thrust and the Pine Hill Thrust seem to be closely related to one another. Both thrusts, although of different thrust generations, are truncated by the Dorset Mountain Thrust, run parallel to the north, and both disappear about in the same area. It is possible that the Precambrian basement clasts found in the Baker Brook Greenschist are derived from the same basement slices later brought up by the Pine Hill Thrust. Therefore the normal fault exposed basement fault scarps may have been overridden by T_1-thrusts developing the mylonitic high strain zone derived from such a protolith. Later imbrication (T_2) of the shelf platform developed a shelf duplex propagating to the west, cross-cutting and incorporating the structures related to the T_1 events (*Figure 4.4.*). The floor thrust of the duplex might have been induced by the normal fault foot wall ramp, to cut off slivers of Precambrian basement. The exposed basement, overridden by the Baker Brook Thrust (T_1) and the floor thrust of the westward moving duplex (T_2), may have had the same detachment surface, which would explain the close association.

4.2.5. Faults along the Western Flank of the Green Mountain Massif

Thrust faults along the western margin of the Green Mountain massif are difficult to demonstrate directly. T_3-thrusts are suggested from the distribution of map units as well

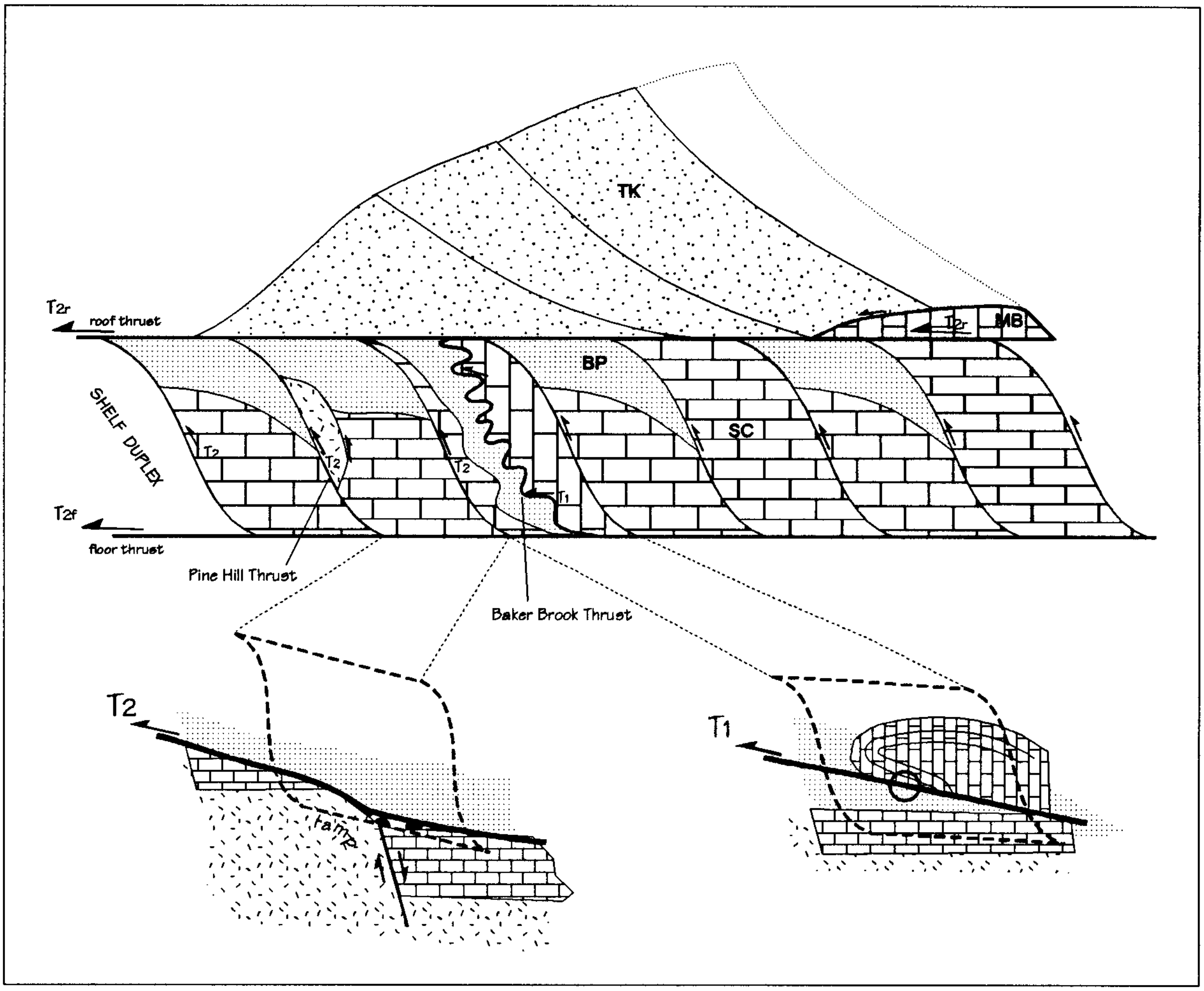


Figure 4.4. **Diagram shows the suggested incorporation of Precambrian basement slices by footwall plucking from the overridden ramp and the incorporation of the complete T1 (Baker Brook Thrust) contact as a horse in the propagating shelf duplex.**

TK - Taconic Allochthon, BP - Ordovician black phyllites, SC - shelf carbonates, MB - marble belt

as by topographic discontinuities. A complex folded T_2-duplex, instead of late T_3-thrust faults would not explain the map pattern. As shown on the geologic map of the field area (*Plate 1*), the map units along the western margin of the Green Mountains are discontinuous and vary substantially in thickness from place to place (Keith, 1942; Karabinos, 1987; Harding & Ebbe, 1987).

The main east to west traverse of a deep crustal seismic reflection survey (COCORP, Brown et al., 1983; Ando et al., 1984; Walsh, 1981) runs from near Clarendon Springs to Windsor, Vermont. The gross geometry of the eastward-dipping zone is one of a large thrust ramp that facilitated faulting of continental basement in the Green Mountains to higher structural levels, thus suggesting that the anticlinorium is a large hanging-wall structure or ramp anticlinorium (Ando et al., 1984). The structural interpretation also suggests highly deformed large satellitic massifs of Grenville basement, such as Chester Dome, Bronson Hill anticlinorium and the Lincoln massif (Dellorusso & Stanley, 1986), that are probably transported along intracrustal detachments. Reflections beneath the Taconic Allochthon are interpreted to represent Paleozoic shelf sediments similar to those of the Vermont Valley sequence, which possibly extend in disrupted fashion beneath the Precambrian rocks of the Green Mountains, suggesting a major basement overthrust (Brown et al., 1983), implying a considerable amount of displacement of basement rocks. Alternatively, the data under the Green Mountains may represent a fault zone within basement rocks expressed by a tectonically laminated mylonite or crush zone. In this case, the geometry can be accommodated by limited transport of the basement during thrust faulting.

From the map pattern of the field area and thrust faults shown along the western flank of the Green Mountains east of Rutland (Doll et al., 1961), juxtaposing basement and siliciclastic cover on Paleozoic shelf rocks, at least limited transport along the Green Mountain Thrust is suggested. Additional, perhaps limited, transport is supported by the geometry suggested for the Pine Hill Thrust in this study, as an early thrust fault. Recent mapping by Ratcliffe (1992, pers.comm.), did not find evidence for interleaving basement and cover rocks within the Green Mountains, rejecting the interpretation proposed by Karabinos (1988). However, I believe that a major thrust detachment could be hidden under the talus of the western flank of the Green Mountains, because of the distribution of discontinuous rock units I have found and suggestions of thrust faults along the western margin of the Green Mountain massif from deep seismic reflection studies (COCORP, Brown et al. 1983).

4.2.6. Summary for the Thrust Faults in the Field Area of the Vermont Valley

The simplified sketch of the geologic map of the field area (*Figure 4.5.*) shows the major units and structures seen now in outcrop, that are the basis for the following interpretation on a larger scale (*Figure 4.6.*). The area is subdivided into three major structural units:

I) the phyllites of the Taconic Allochthon in the west, with its attached marble sequence along the sole of the Basal Taconic Thrust System (Dorset Mountain Thrust).

II) the carbonates and black phyllites, and locally basement, of the strongly disrupted shelf duplex in the Vermont Valley.

III) the complex folded and imbricated siliciclastic sequence along the western margin of the Green Mountains.

The exceptional significance of the Baker Brook Thrust is related to its protolith, which is derived from Precambrian Green Mountain basement, suggesting substantial displacement and an earlier deformation stage than of the shelf duplex development. Unit II is simplified, showing only major thrusts of the imbricate stack belonging to the shelf duplex. The western flank of the Green Mountain massif (unit III) is cut by a late out-of-sequence thrust system, imbricating the complex folded cover and basement rocks preserved. These late thrusts are also responsible for folding of all older structures including the shelf duplex. Reactivation of older faults in this stage may be responsible for crosscutting relationships difficult to explain solely with T_2 (duplex) structures.

One reason for this chapter is to correlate the structural evolution proposed by Bierbrauer (1990) with the structural interpretation found in my field area. The structures complement one another so that an interpretation for the whole northern Vermont Valley is now possible (*Figure 4.6., 4.7., 4.8., 4.9.*).

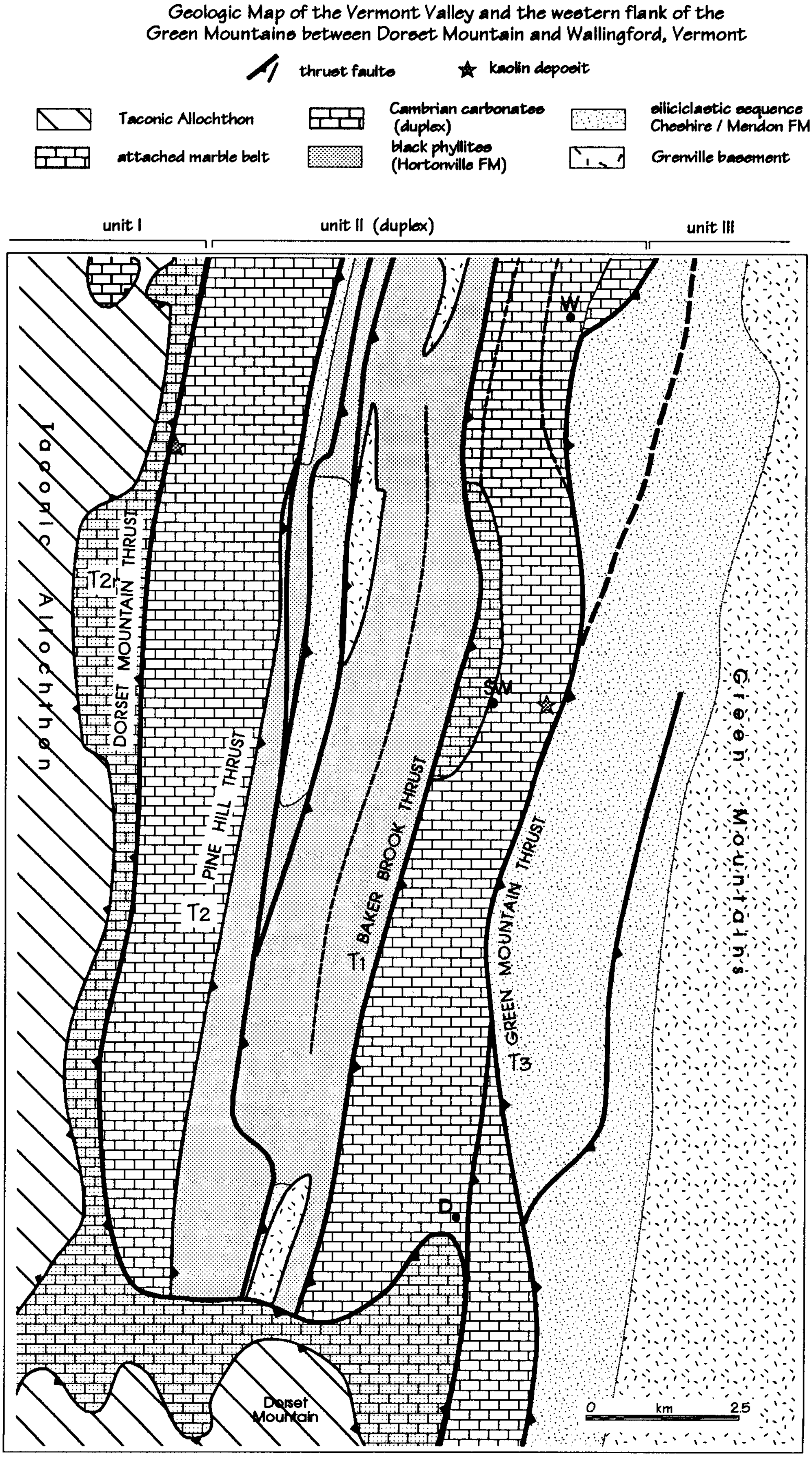


Figure 4.5. **Simplified geologic map of the Vermont Valley and the Green Mountain massif between Danby and Wallingford, Vermont. Within the shelf duplex (unit II) only major thrust faults are shown.**

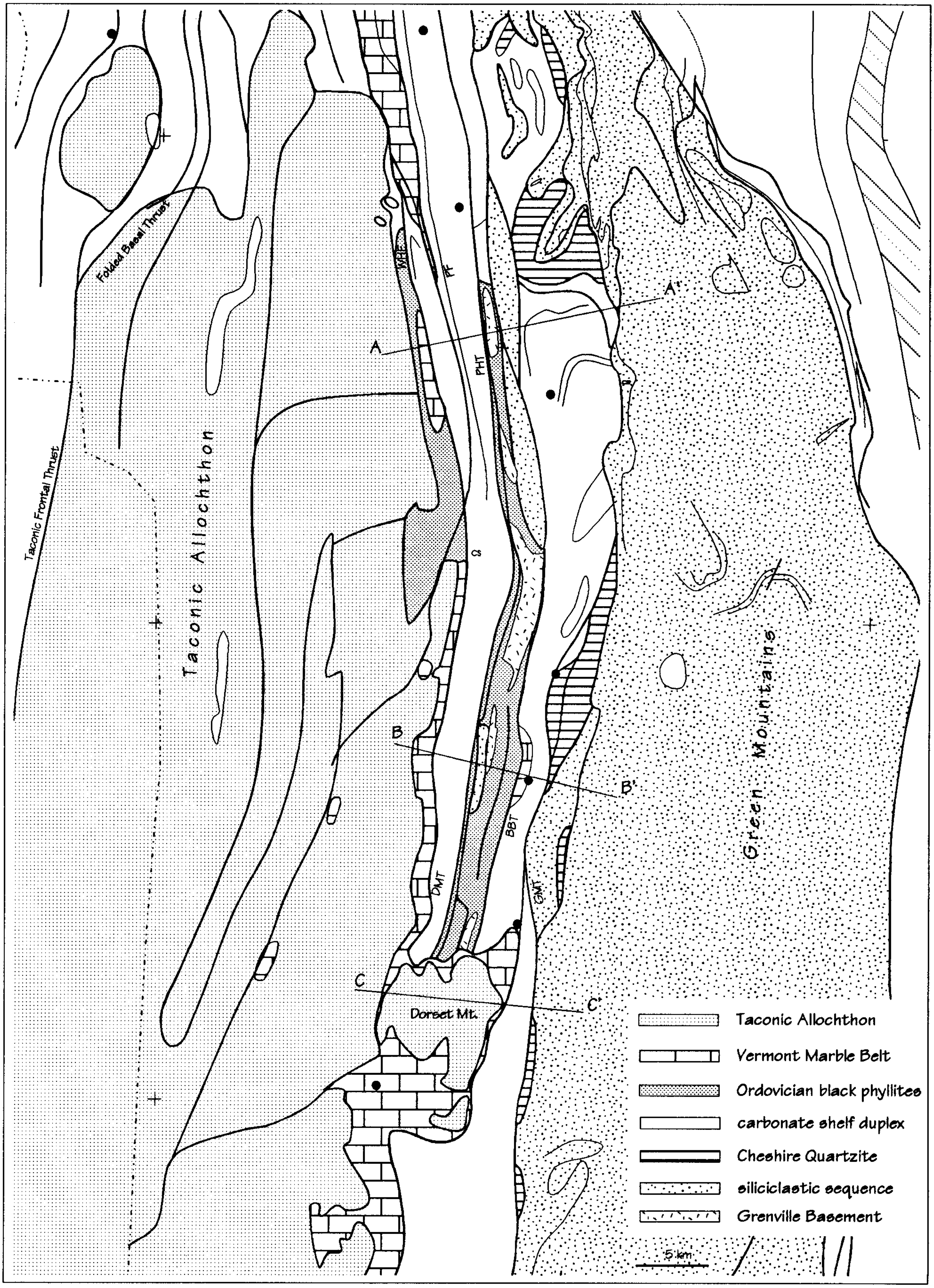


Figure 4.6. **Generalized lithotectonic map of west central Vermont showing the regional structural interpretation of the Vermont Valley and the western flank of the Green Mountain massif (see also Plate 4). Thick lines represent thrust faults.**

DMT-Dorset Mountain Thrust, BBT-Baker Brook Thrust. PHT-Pine Hill Thrust, GMT-Green Mountain Thrust, WHF-Whipple Hollow Fault, PF-Proctor Fault

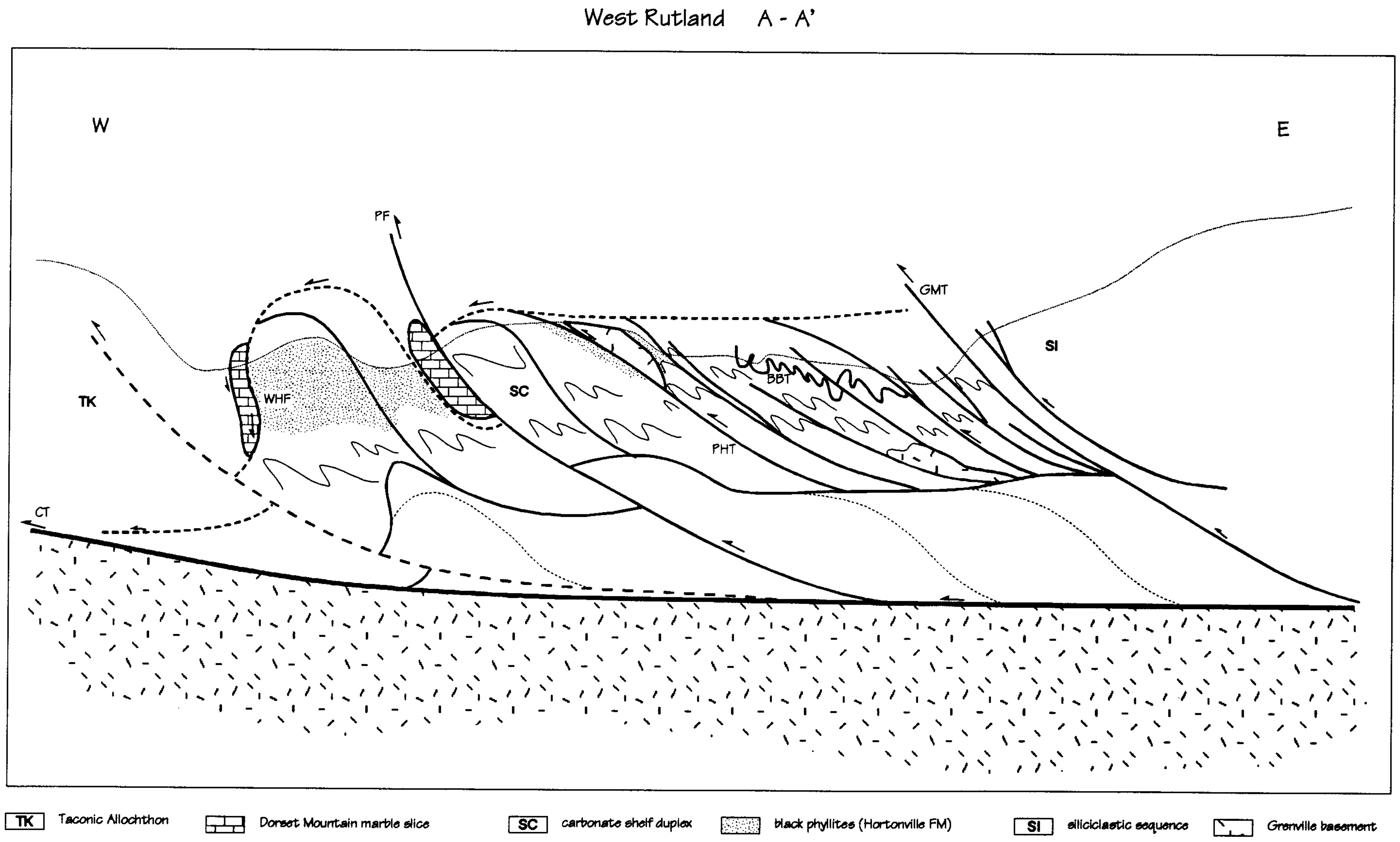


Figure 4.7. **Profile WEST RUTLAND, A-A'. PF - Proctor Fault, WHF - Whipple Hollow Fault = DMT - Dorset Mountain Thrust, PHT - Pine Hill Thrust, BBT - Baker Brook Thrust, GMT - Green Mountain Thrust, CT - Champlain Thrust**

South Wallingford B - B'

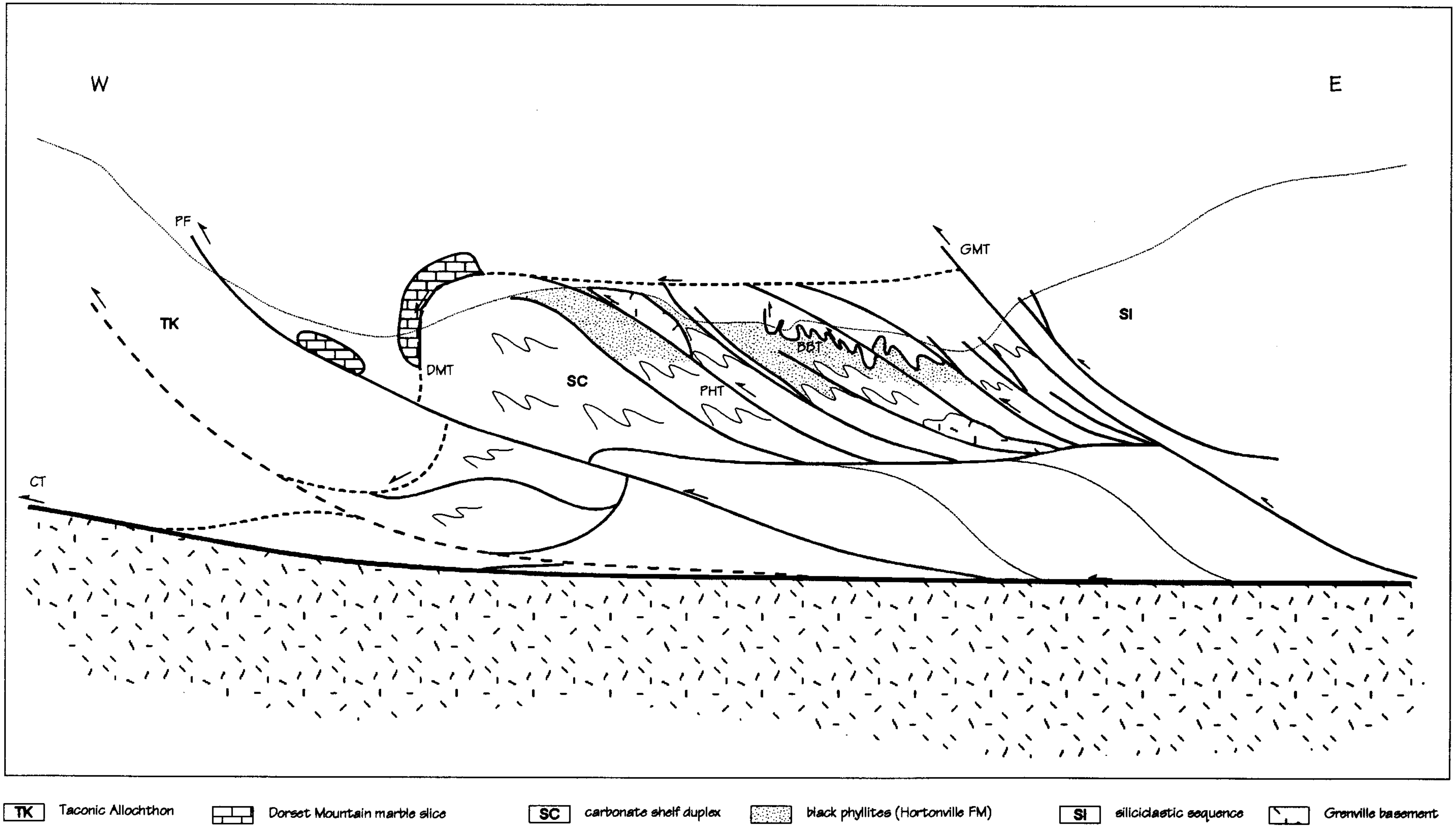


Figure 4.8. **Profile SOUTH WALLINGFORD, B-B'. PF - Proctor Fault, DMT - Dorset Mountain Thrust (Whipple Hollow Fault), PHT - Pine Hill Thrust, BBT - Baker Brook Thrust, GMT - Green Mountain Thrust, CT - Champlain Thrust**

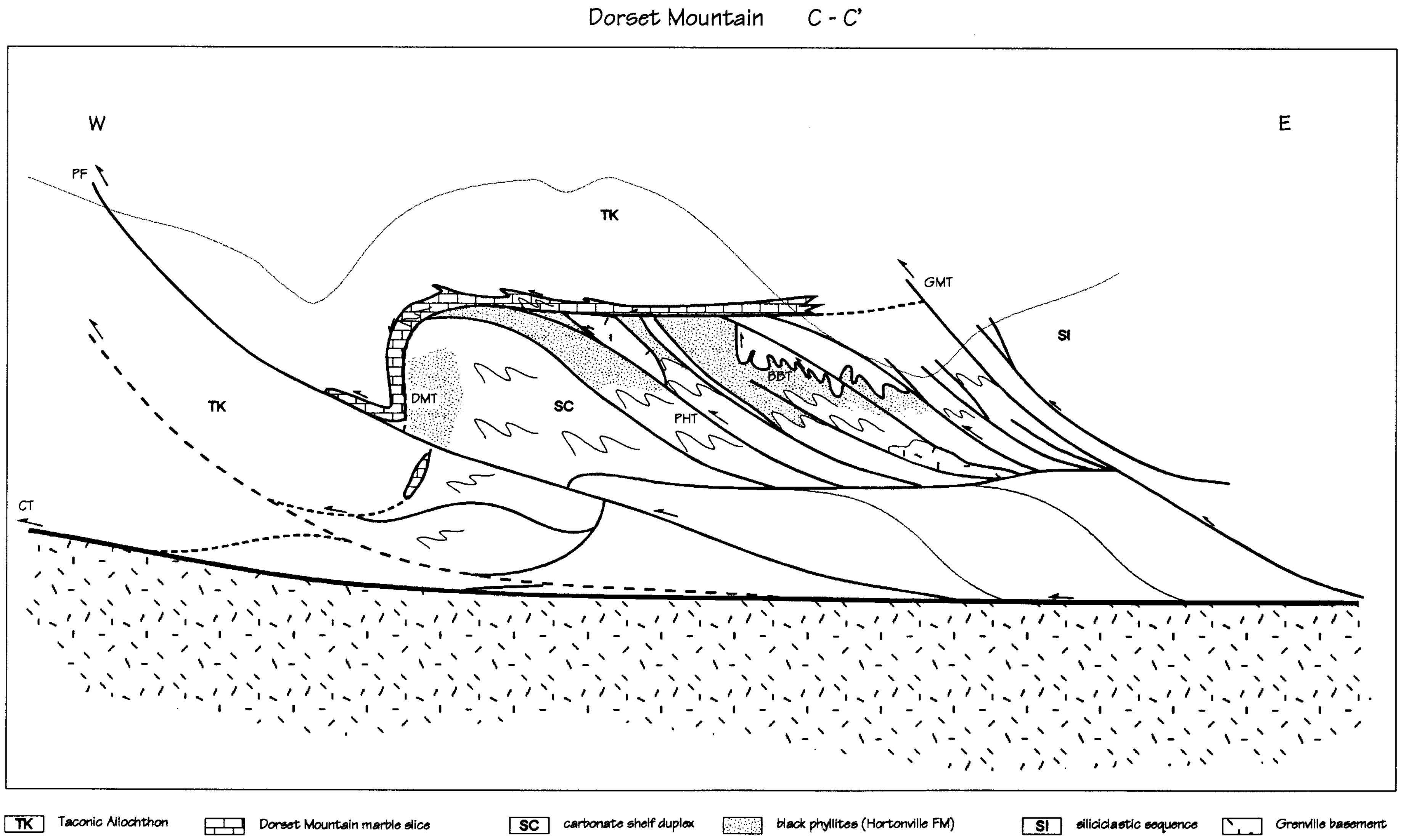


Figure 4.9. **Profile DORSET MOUNTAIN, C-C'. PF - Proctor Fault, DMT - Dorset Mountain Thrust (Whipple Hollow Fault), PHT - Pine Hill Thrust, BBT - Baker Brook Thrust, GMT - Green Mountain Thrust, CT - Champlain Thrust**

4.3. Geologic History

The model presented here for the structural evolution of the field area in the Vermont Valley and its exposed carbonate shelf, black phyllite and locally Precambrian basement rocks, is an attempt to apply modern structural and tectonic knowledge to one of the longest studied parts of orogenic belts in the world and to explain its complex structure. The synthesis of the tectonic history of the Vermont Valley is based on the information presented in the previous chapters. Deformation and metamorphism associated with the Taconian and probably Acadian orogenies has overprinted most of the primary features in these rocks and cross-cutting relations may vary from one location to the other. The very poorly established stratigraphy, with many open questions, affects also the structural interpretation, which in turn can result in gross misinterpretation of the regional structure. Detailed mapping and analysis of the rock fabrics reveals the sequence and boundary conditions that are the most important in their evolution. The following simplified diagrams represent one complete possible sequence of events. The diagrams include structures for which there is not direct field evidence, because of poor outcrop, complex structure, and so forth. The discrete studied events described are not meant to imply that these events were necessarily separated by pauses in deformation, but are meant to be snapshots during a continuous process (*Figure 4.10.1., 4.10.2., 4.10.3., 4.10.4.*).

The Proterozoic basement rocks have suffered intense deformation and metamorphism during the Grenvillian orogeny of which only minimal evidence has remained in the rocks of this area due to retrograde metamorphism and overprinted foliations. The Late Proterozoic to Early Cambrian rifting of the basement complex resulted in the deposition of the cover sequence that now mantles the Grenville Mount Holly complex. The shallow marine sequence consisting of westward transgressing, basal siliciclastics of the Mendon and Cheshire Formation represents the first deposits derived from the adjacent basement rocks preserved in this area. These units are then overlain by the thicker sequence of the carbonate shelf platform of the passive continental margin of North America. The deformational and metamorphic history of the area is associated with the Middle Ordovician Taconian, and, at least on the east side of the Green Mountains, with the Devonian Acadian orogenies.

SCHEMATIC TECTONIC EVOLUTION OF THE STRUCTURES IN THE VERMONT VALLEY

Figure 4.10.1., Figure 4.10.2., Figure 4.10.3., Figure 4.10.4.

STAGE I

pre D_1 - Deformation — The westward moving volcanic arc starts forming the stack of an accretionary wedge containing the deep water sediments of the continental rise / slope, and being responsible for the progressive subduction-related drowning of the passive margin of North America. In response to the bending of the subducting slab, the shelf sequence and locally underlying basement were block-faulted by normal faults (displacement up to 2 kilometers), followed by rapid sedimentation of black shales (and locally turbidites) (Walloomsac / Ira / Hortonville FM), resulting in the burial of the block-faulted shelf and basement.

These early normal fault contact relationships are probably responsible for the major structural pattern of later deformational stages. The contact relationships between the Precambrian basement slices and black phyllites do not necessarily support a major regional unconformity and deep erosion, named the *Tinmouth Unconformity* (Rodgers, 1971; Thompson, 1967) in the field area. This contact is viewed as a buried talus-denuded normal fault scarp following Rowley (1982); however deposition during normal faulting, as well as later re-activation along westward-directed thrusts, may have obscured and complicated the contact relations in places.

STAGE II

D_1* - *Deformation — After the leading edge of the propagating accretionary wedge reached the continental shelf platform, large westward directed overturned folds and/or nappe type structure formed and was transported over the block-faulted and black phyllite-covered previous carbonate shelf. This stage is associated with the development of the Baker Brook Thrust. The nappe overrode the Precambrian basement, exposed along normal fault contacts, and the fault developed a ductile high strain zones including basement-derived material. The fault trace must have cut up into the footwall of the normal fault and continued into the overlying black phyllites.

STAGE III

D_2* - *Deformation — With the further propagation of the Taconic Allochthon to the west, beneath the moving floor thrust of the accretionary prism the shelf duplex developed, locally incorporating plucked basement slices from the base of the thrust. Earlier thrust surfaces were folded and included as horses in the duplex; e.g. the basement slices with their normal fault contact relationships and horses including the complete Baker Brook Thrust contacts. It is proposed that large slivers of Grenville basement were detached and incorporated in the duplex. Note that in the initial stage all duplex thrusts do have approximately the same displacement and the basement slices as well as Cambrian carbonates were not truncated. Further propagation of the duplex over the footwall ramp must have reactivated older fault surfaces, being responsible for the relatively greater displacement along the Pine Hill Thrust. The final stage of the emplacement of the Taconic Allochthon, involved large carbonate slivers, which were detached from the overridden shelf platform, attached along the sole of the floor thrust of the moving basal thrust of the Taconic Allochthon and then highly deformed and metamorphosed. The Basal Taconic Thrust, now structurally including the marble slice (Dorset Mountain Thrust), truncates all older structures. This stage is responsible for the further imbrication of the already stacked carbonate shelf with re-activation of older structures and the development of new faults resulting in the very complicated present structure of the Vermont Valley.

STAGE IV

D_3 - Deformation — Continued convergence and shortening of the continental crust gives rise to imbrication of the continental basement and overlying structures. The Taconic Frontal System is the late stage imbrication of all earlier structures and responsible for out-of-sequence thrust faults, carrying detached carbonate and/or basement slices and juxtaposing complete sections; strong associated folding of the shelf duplex and all other structures is suggested. Late stage imbrication seems to be necessary to account for the present distribution of rock units and may be especially responsible for the complicated structures of the western margin of the Green Mountain massif and its cover rocks.

SCHEMATIC TECTONIC EVOLUTION OF THE STRUCTURES IN THE VERMONT VALLEY

Deformation Sequence:

pre D1: block-faulting (normal faults)
syn-depositional black phyllites (Hortonville FM)
Talus along foot of fault scarp

D1: pre-shelf duplex thrust fault, placing an overturned carbonate section over black phyllites, separated by the developing mylonitic high strain zone Baker Brook Thrust (east over west, BBT)

D2: Development of the shelf duplex from overridding first Taconic slices, incorporation of basement by footwall plucking. Pine Hill Thrust (PHT). Emplacement of the last slices of the Taconic Allochthon, carring large coherent attached marble slices along the sole of the Basal Taconic Thrust to the west. Dorset Mountain Thrust (DMT)

D3: Late out-of-sequence thrusts belonging to the Taconic Frontal System, folding of the shelf duplex and overlying Taconic slices, juxtaposing units along the western flank of the Green Mountain massif. Green Mountain Thrust (GMT)

Passive atlantic-type continental margin of eastern North America in Early / Middle Ordovician time:

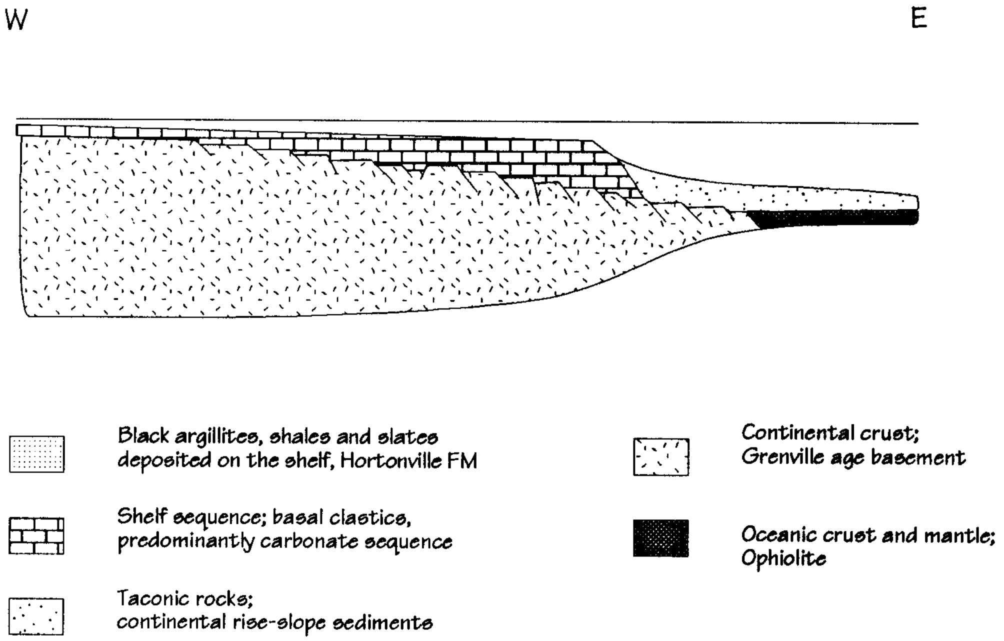
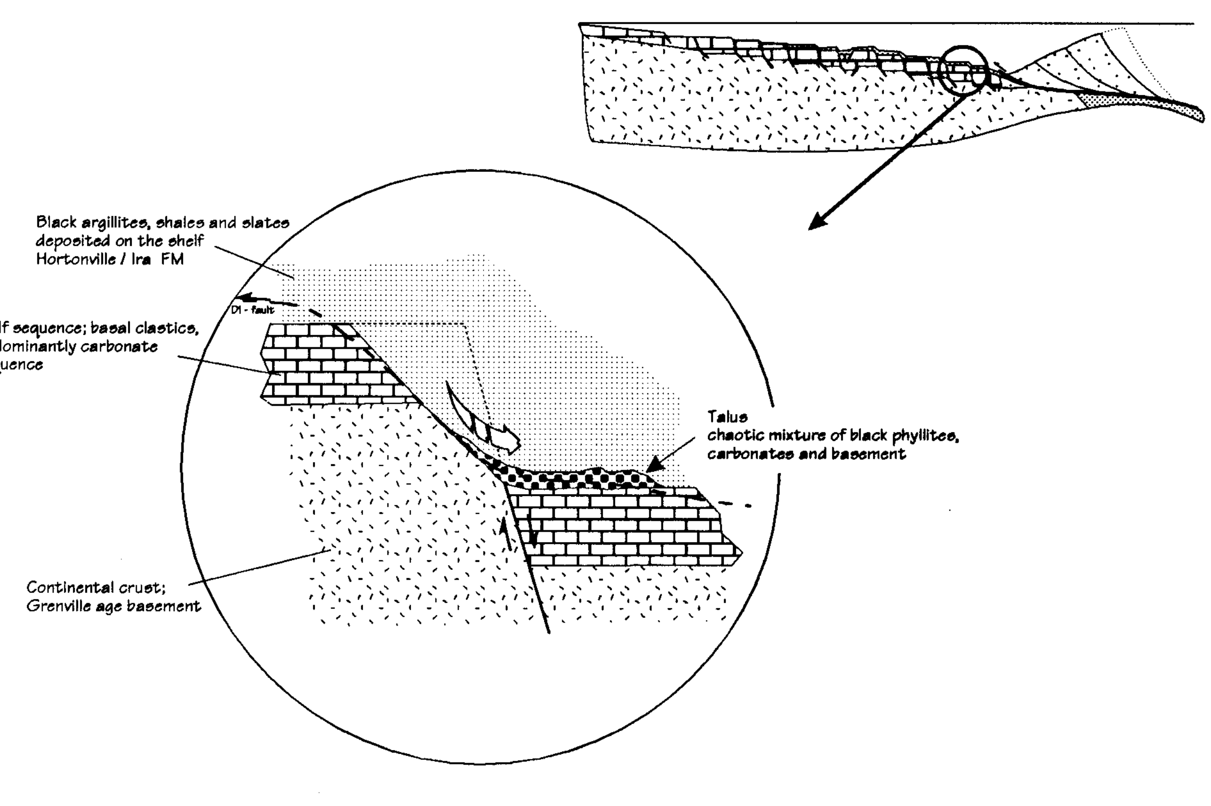


Figure 4.10.1.

STAGE I:



STAGE II:

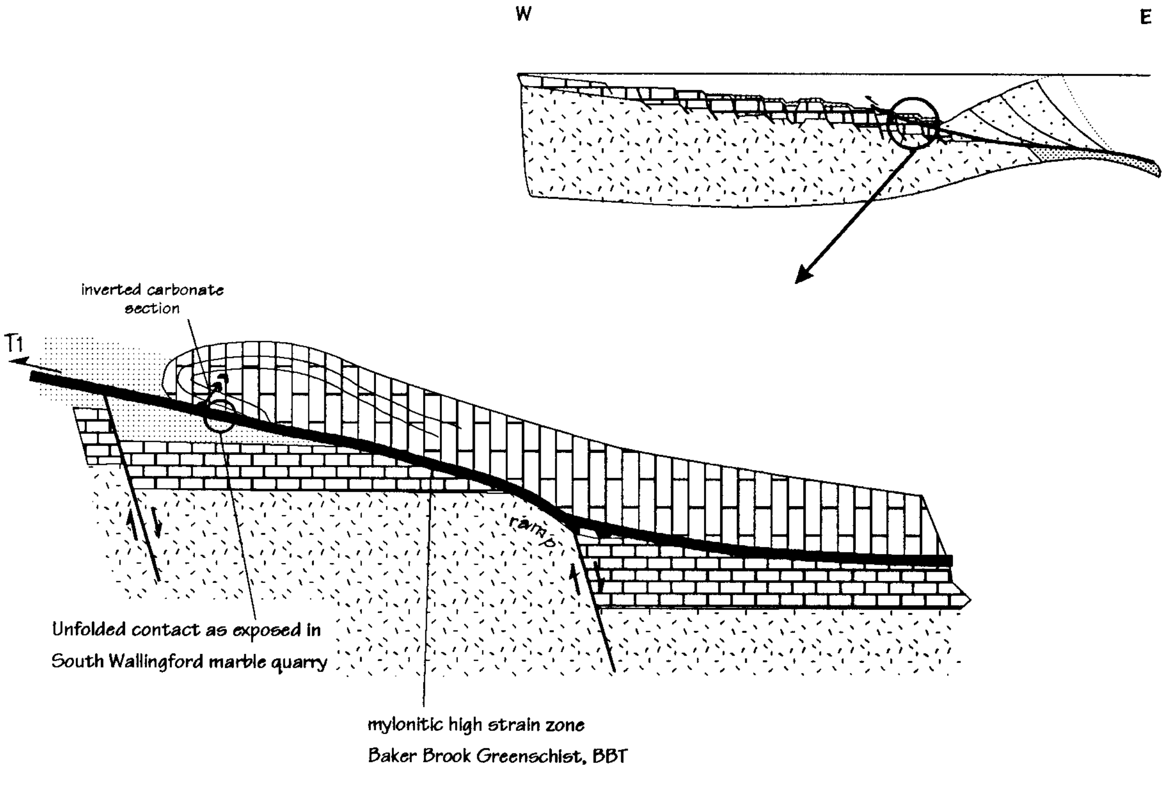
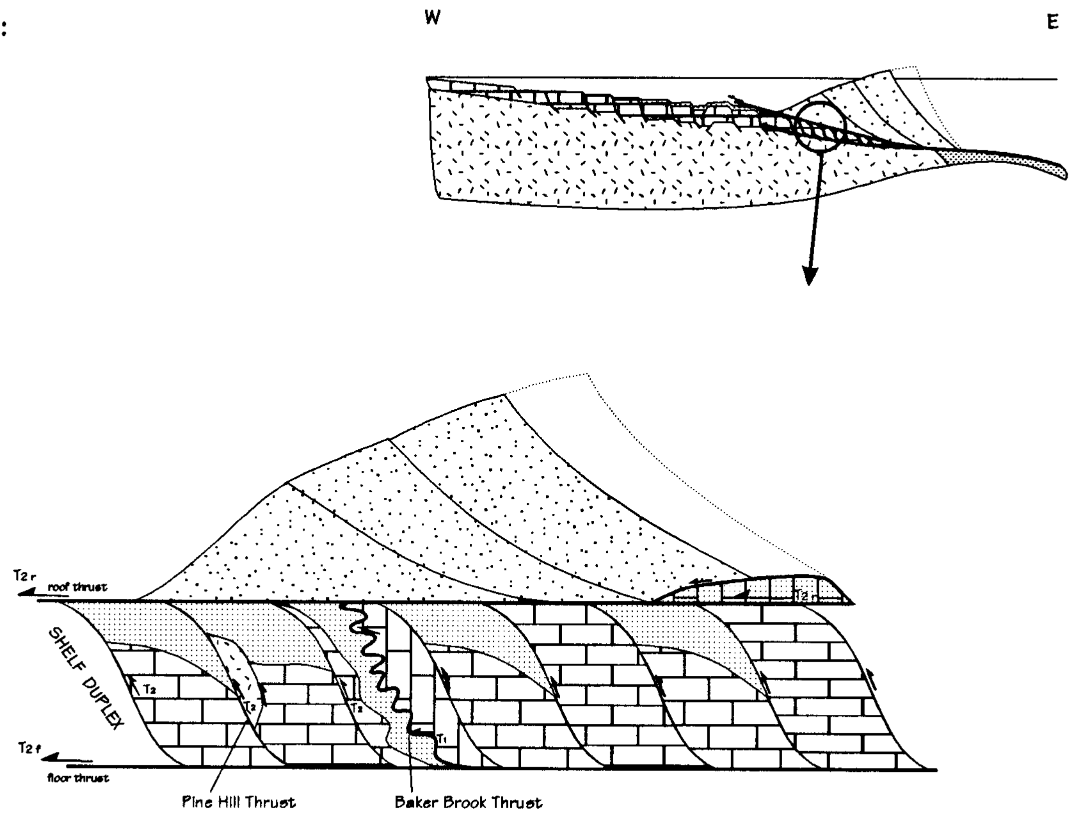


Figure 4.10.2.

STAGE III:



STAGE III (final):

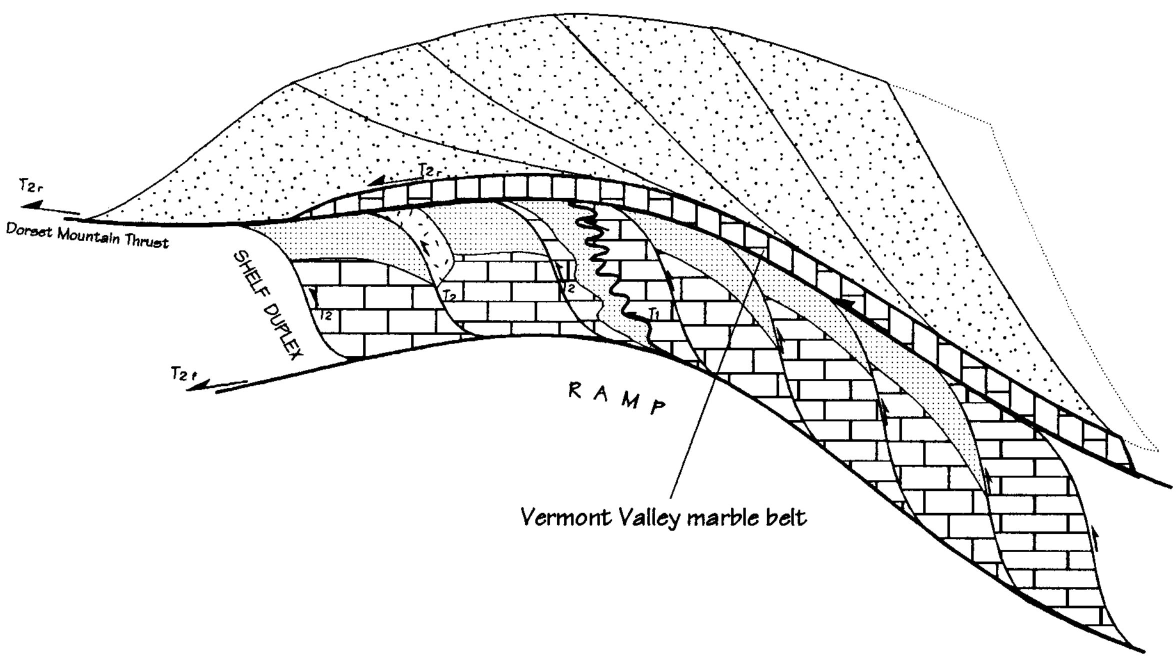


Figure 4.10.3.

STAGE IV:

present day structural relations for the Vermont Valley,
the adjacent Green Mountain massif and the Taconic Allochthon

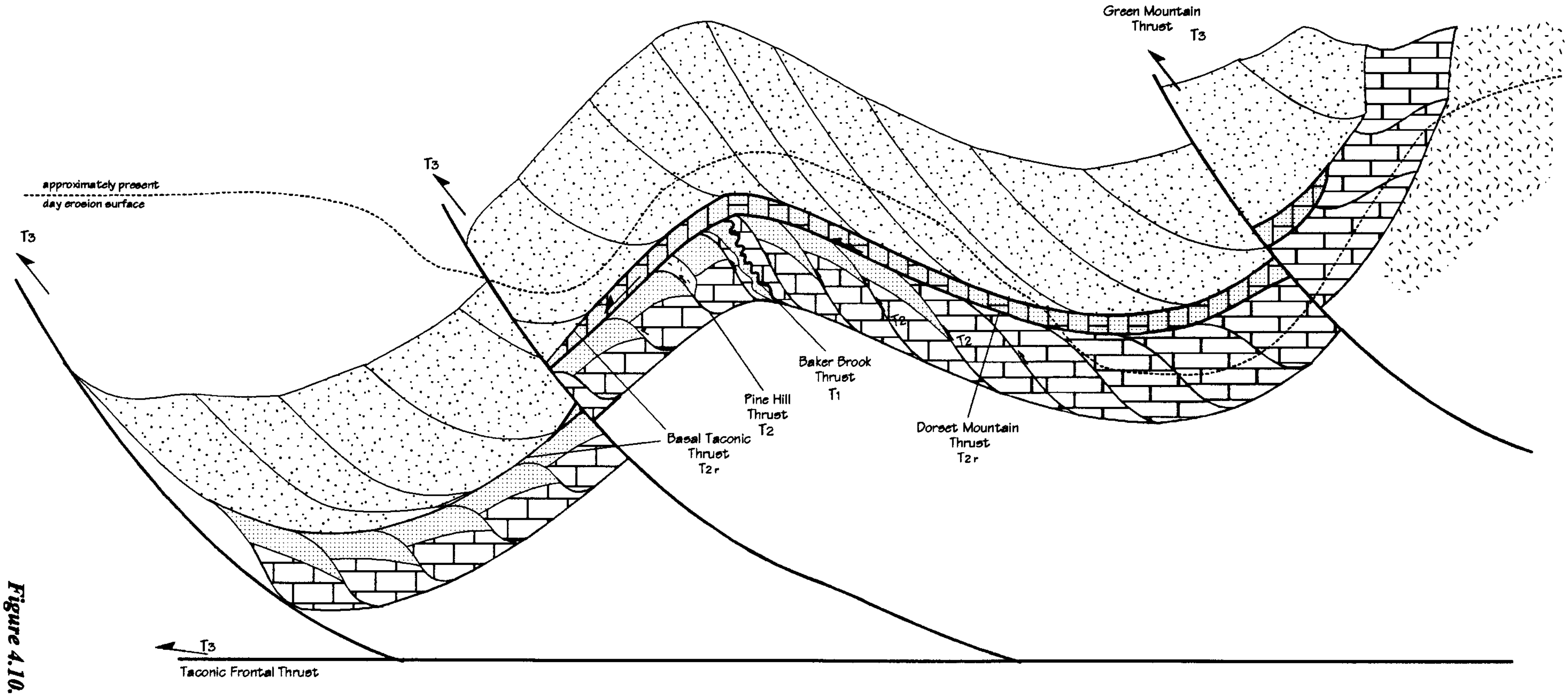


Figure 4.10.4.

References Thesis

As pointed out in this study there is a multitude of "forgotten" literature available, especially from around the turn of the century and later. In order to give later workers the most widespread reference to work with, I included all references on the thesis topic in this reference list, marking the ones I have cited in the text with a *.

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