THE GEOLOGY OF TACONIC THRUST SHEETS AND SURROUNDING CARBONATES OF THE WEST CENTRAL VERMONT MARBLE BELT, NORTH OF RUTLAND, VERMONT

Abstract of

a thesis presented to the Faculty

of the State University of New York

at Albany

in partial fulfillment of the requirements

for the degree of

Master of Science

College of Science and Mathematics

Department of Geological Sciences

Kay Bierbrauer

1990

ABSTRACT

The carbonates of the Vermont Valley and the overlying rocks of the Taconic sequence have been generally believed to lie on the east limb of a major unfaulted syncline (Middlebury Synclinorium). In this view a westward dipping, north-south trending basal Taconic overthrust must be exposed somewhere along the eastern margin of the Taconic Range.

In contrast, this study based on detailed mapping at the north end of the Taconic Allochthon suggests that a folded overthrust surface is only locally seen in fensters; more commonly the basal obduction surface of the Taconic Allochthon has been truncated by later cross-cutting thrust faults. In the study area these newly recognized east dipping faults are the "Whipple Hollow Fault" and the "Proctor Fault". These two faults postdate the initial Taconic overthrust and must belong to the Champlain thrust system of which another fault forms the frontal thrust of the Taconic thrust belt towards the west. Where exposed the basal thrust is characterized by a thick melange unit and isolated slivers of shelf carbonates. The melange underlies wide areas which had previously been mapped as part of the authochthonous shelf sequence. Other areas which were also believed to represent these authochthonous phyllites have been identified as characteristic black pelitic Taconic lithologies. The redefined Taconic rocks also include typical green and greenish gray phyllites of the Cambrian Bull Formation. It indicates that the Middle Ordovician shale unit which conformably to unconformably overlies the carbonate shelf west of the Taconic Range is not yet, or perhaps only locally, exposed at the present erosion level of the Vermont Valley. In addition the easternmost equivalents of this unit must have been tectonically removed and incorporated into the basal melange. Where a lithological correlation with the Taconic stratigraphy is not possible the remaining black phyllites are probably Middle Ordovician in age; still these phyllites have been incorporated into the overlying melange and must be viewed as allochthonous. The rocks of the study area underwent a progressive deformation path which can be subdivided into three different stages (D_1 to D_3). During each stage a characteristic thrust system (T_1 to T_3) was active. D_1-deformation describes the stacking of the Taconic lithologies

in an accretionary imbricate fan thrust environment (T_1). This early deformation is associated with a prominent slaty cleavage (S_1). Large-scale F_1-folds, if present, would be strongly refolded and tightened so that they are not detectable. Obduction of the composite T_1-thrust stack onto the carbonate shelf resulted into a small-scale imbricated T_2-marble/phyllite schuppen structure. The propagation of this duplex has produced large-scale folds. F_2-structures are associated with a main regional crenulation cleavage (S_2). Progressive shortening during D_3-deformation culminated in foreland directed thrust faults (T_3). A second crenulation cleavage (S_3) is related to this late thrusting event. The regional application of the observed thrust geometry strongly suggests that the Middlebury Synclinorium is unlikely to be an unfaulted structure. In particular this study suggests major north/south trending, eastward dipping late thrust faults for the entire length of the eastern Taconic margin and the Vermont Valley. The "higher Taconic slices" are also believed to be related to this period of thrusting; this out-of sequence imbrication by later faults explains the existing "stacking controversy" among Taconic geologists.

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ACKNOWLEDGMENT

Over the past two years many people have contributed their time understanding and knowledge to my education. I am grateful to the Department of Geological Sciences for providing space and equipment for this study. Thanks for all the friends and students for the time we spent together.

I am most grateful to Dr. William Kidd who introduced me to the study area. He contributed a lot to this work during our discussions of the Taconic geology in the field and indoors. I also owe Dr. Winthrop Means for his time to examine hand samples and thin sections and for short and helpful lectures on structural problems. I also want to thank Dr. George Putman and Dr. Gregory Harper for their suggestions of improvement.

During my stay in Vermont I experienced the hospitality, kindness and friendship of Chris Anderson and Andrew Snyder who provided me with much more than a campsite. Thank you for the great time at Fire Hill Farm.

Finally I want to thank my parents for their love, support and encouragement during my study and Heidi for her warmth and love during all stages of my work.

State University of New York at Albany

College of Science and Mathematics

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The thesis for the master's degree submitted by

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THE GEOLOGY OF TACONIC THRUST SHEETS AND SURROUNDING CARBONATES OF THE WEST CENTRAL VERMONT MARBLE BELT, NORTH OF RUTLAND, VERMONT

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CHAPTER 1

INTRODUCTION

1.1. Location of the field area

The present study investigates the structural and stratigraphic relations at the north end of the Taconic Allochthon in west central Vermont. Figure 1 shows the location of the field area.
The area mapped is approximately 5.5 by 3.0 kilometers, sited along the eastern margin of the Taconic Range. It is located north of Whipple Hollow about 1.5 kilometers west of Florence and 9 kilometers north of West Rutland. About 3 kilometers northwest of the field area the Taconic mountains end abruptly and the terrain slopes down into the Champlain Valley. From this point the allochthon trends approximately 200 km southward as a narrow (20-30 km) elongated belt. At the northern end of the Taconic Range the Vermont Valley lies between the Taconics and the Green Mountains to the east.

1.2. Regional Geology

During the Middle Ordovician Taconic orogeny a major fold and thrust belt developed along the eastern margin of the North American continent. Large nappes containing deep water sediments and dismembered ophiolites (Rowley, 1983) were thrust westward onto the early Paleozoic carbonate shelf. The Taconic orogeny documents the disruption of the former passive continental margin and is seen as the earliest phase of the Appalachian/Caledonian orogeny. The Taconic event is probably related to the collision of the North American craton with an island arc (Chapple, 1973; Rowley and Delano, 1979) or a micro continent (Rowley, 1983; Samson, et al., 1989; Delano et al., 1990). The initiation of the Taconic thrust sheets over an eastward dipping subduction zone was first suggested by Chapple (1973), and Rowley and Delano (1979) who modified an earlier plate tectonic model of Bird and Dewey (1970). The earlier model suggested a westward dipping subduction zone with Andean type

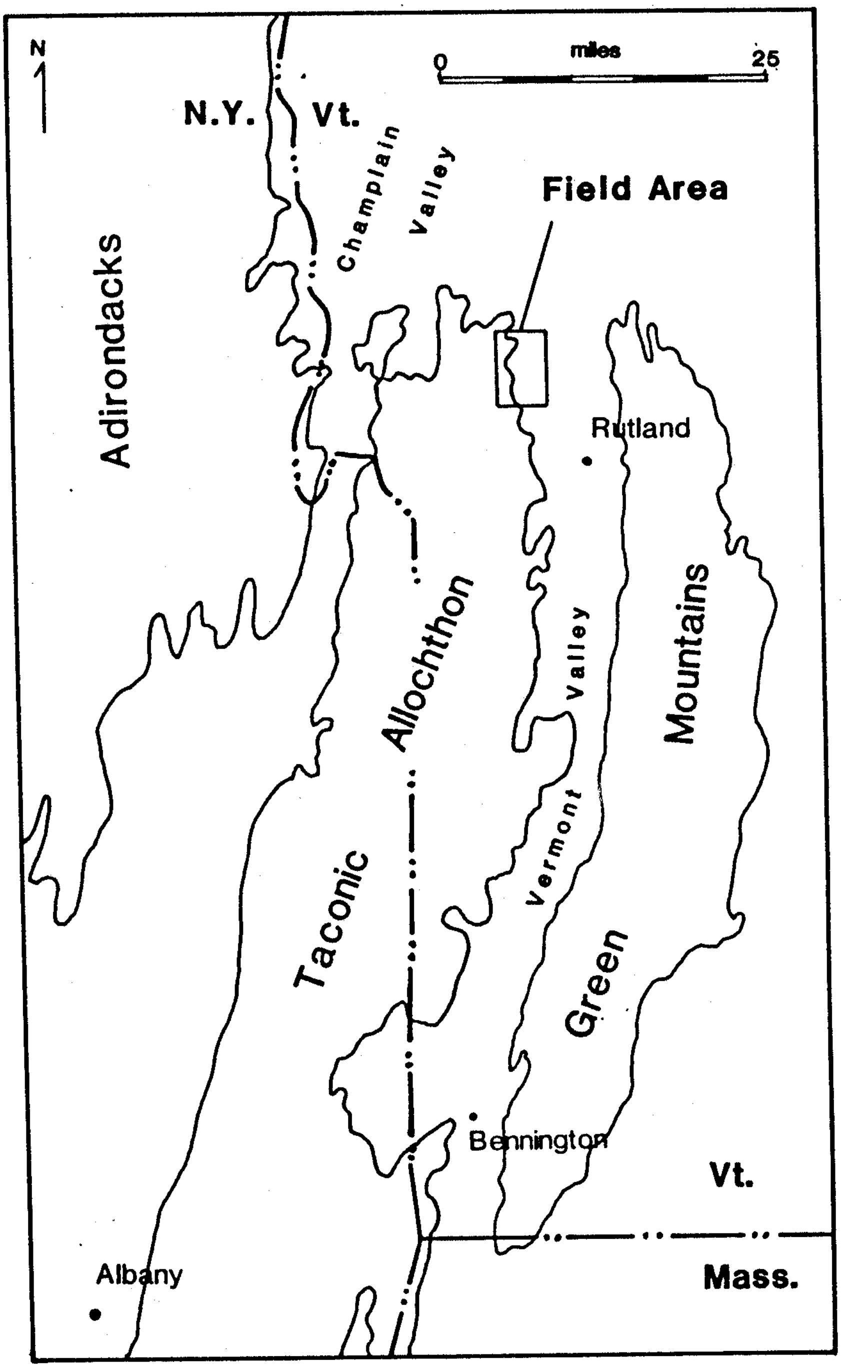


Figure 1: Location of the field area

margin assuming a marine foreland basin between the continent and the magmatic arc.

The Taconic Allochthon itself consists of sediments of the former continental slope and rise apron. These sediments were probably the last slices stacked in an accretionary prism environment which developed in front of the westward moving island arc/micro continent.

Rowley and Kidd (1981) proposed an east to west stacking order for the Taconic slices 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. This was in contrast to Zen`s (1967) "diverticulated" west to east younging direction for the Taconic slices. Zen`s view was followed by Potter (1972) and is still favored by Stanley and Ratcliffe (1985). The controversy probably exists because Zen and others overlooked the significance of different thrust generations. For example, some of Zen`s major thrust slices (Zen, 1967) could be the result of second order thrusting. A later thrusting event would in fact "diverticulate" the initial stacking order which was the event that Rowley and Kidd (1981) attempted to describe. In their model of the Taconic Orogeny late thrusts belong to the Frontal Thrust System and cross-cut the folded Basal Thrust; it is the Basal Thrust that accomodated the initial obduction onto the shelf (Rowley and Kidd, 1981; Rowley, 1983). Major regional thrusts like the Champlain thrust and the Green Mountains basement cored thrust sheet also belong to the Frontal Thrust System.

Figure 1 shows the Taconic Allochthon lying sandwiched between Precambrian basement of the Adirondacks west of it and the Green Mountains in the east. The Green Mountains probably cut off the Taconic Range from the main accretionary prism sequence further to the east. Today only an erosional remnant of the former extensive Taconic fold and thrust belt is exposed. Especially east of the Green Mountains, the geology has been strongly modified by deformation and metamorphism during the Acadian. West of the Green Mountains the general geology and the allochthonous origin of the Taconic Mountains are well known. However, the thrust relationship between rocks of the allochthon and carbonates of the shelf sequence is not everywhere fully understood. This relationship may very well change along the strike of the eastern margin of the Taconic Range because of the complexity of the thrusting events.

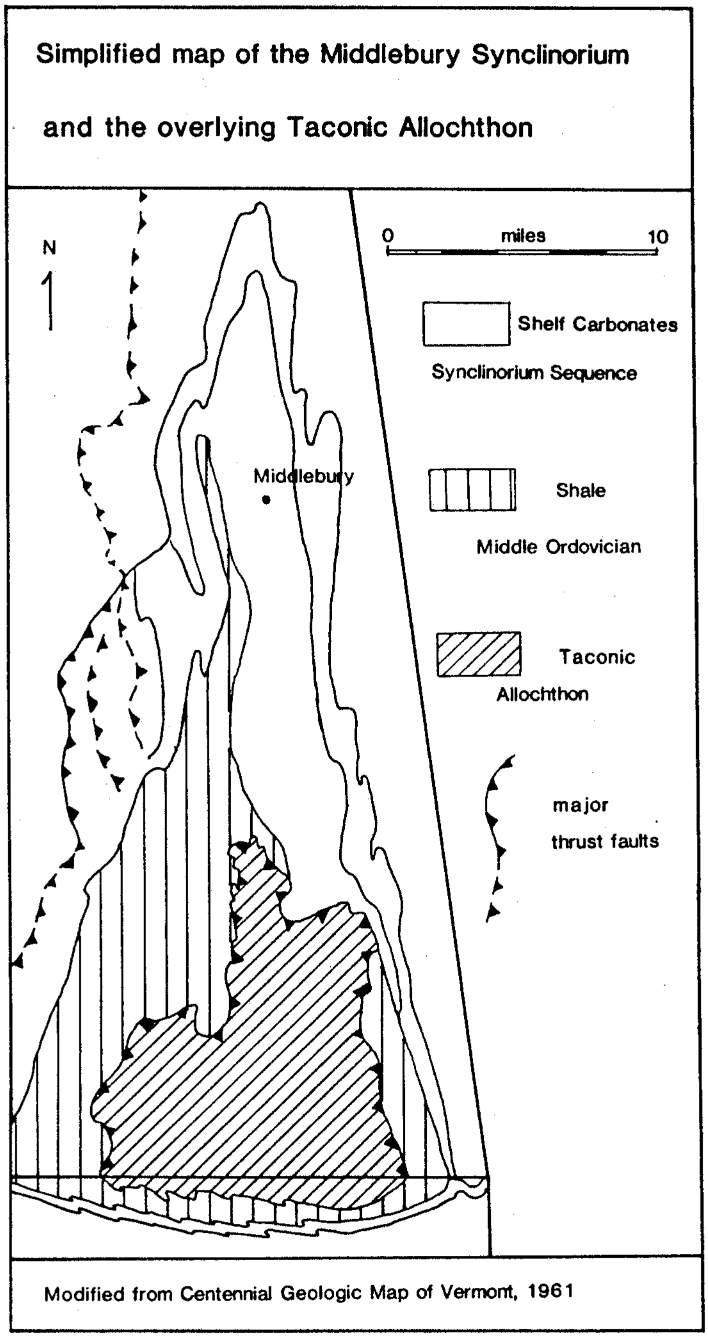


Figure 2: Regional Geology

1.3 Previous Work and Geological Problems

Figure 2 shows the structural relationship between the Middlebury Synclinorium and the Taconic Allochthon as shown on the Centenial Geologic map of Vermont (1961). The rocks of the shelf sequence form the authochthonous Middlebury Synclinorium (Cady, 1945) in which at least the lower slices of the allochthonous Taconic rocks have been supposedly emplaced by gravity sliding (Cady, 1945; Zen, 1961, 1967, 1972; Bird, 1969). This interpretation was mainly based on the presence of wildflysch deposits and associated soft-sediment deformation along the margin of the allochthon. Prior to the emplacement of the slices a Middle Ordovician hemipelagic dark shale unit was deposited in the developing synclinorium. As shown on Figure 2 this sequence was believed to occur almost everywhere between the platform carbonates and the Taconic sequence. It was this concept which led Cady (1945), Fowler (1950), and Zen (1961) to the conclusion that the Taconic overthrust must be hidden in similar looking phyllites at the north end of the Taconic Allochthon. Fowler (1950) and Zen (1961) suggested that the Middle Ordovician slates and phyllites which overlie the shelf sequence are not distinguishable from black Cambrian rock units of the Taconic sequence. As the north end of the allochthon is characterized by a thick sequence of dark phyllites and no convincing evidence of thrusting was found by those authors, this explanation was quite reasonable. In terms of gravity sliding, a sharp tectonic contact was not necesarily required as discussed by Zen (1961).

The gravity emplacement hypothesis was later rejected since hard rock thrusting had been successfully demonstrated as the main emplacement mechanism of the Taconic Allochthon (Rowley et al., 1979; Rowley and Kidd, 1981; Bosworth and Rowley, 1984). The two stage thrusting sequence of Rowley et al. (1979) has already been mentioned.

Washington (1981) suggested a north/south trending thrust fault through the core of the Middlebury Synclinorium and questioned the general unfaulted synclinal structure. The distribution of carbonates of the Proctor marble belt, which extend into the field area, are probably also controlled by faults related to the Frontal Thrust System. This interpretation would be very different from the traditional view in which the carbonates of the Vermont Valley are considered to be the southward continuation of the east limb of the Middlebury Synclinorium (Cady, 1945; Zen, 1961). The large area, small scale mapping of Fowler (1950) and Zen (1961) was insufficient to demonstrate the exact thrust relations at the north end of the allochthon. The geology is also complicated by a large carbonate slice, the "Florence Nappe" which extends high up into the surrounding phyllites (Zen, 1961).

A detailed study of the area chosen was intended to reveal more of the complex structure and lithology of the region.

In this perspective the approach to the field area was two-fold:

1) Detailed mapping of the stratigraphic units within the extensive area of black phyllites, as well as in the adjacent typical Taconic units and the carbonates of the shelf sequence.

2) Determination of the fold and thrust geometry of the area including the exact location of the basal thrust surface if possible.

Results from the field area are later used to propose a modified view of the north eastern margin of the Taconic Allochthon and the Vermont Valley.

Field work was done during a two month field camp in the area in June and July of 1989. Additional work was undertaken during weekends of the following fall and in the spring of 1990.

CHAPTER 2

LITHOLOGY

2.1. Introduction

Depositional processes of passive continental margins are characterized by lateral changes and result in large variations of lithostratigraphic units.

Keith and Friedman (1977) following an initial suggestion by Bird and Dewey (1970) proposed a slope-fan-basin-plain model for the shelf-derived Taconic sediments which is characterized by a variety of depositional processes on the slope and within submarine canyons.

Therefore considerable facies changes across and along strike in the allochthon must be expected. The units which are now preserved in the Taconic Allochthon have also experienced a complex deformation history and stratigraphic relations are difficult to define. If the fold and thrust geometry of a region is not well known in turn the inferred stratigraphy will be less constrained. On the other hand apparent stratigraphic relations may be used to obtain a structural interpretation elsewhere. Most of the field area is underlain by dark phyllites and the stratigraphic as well as the structural relations between Ordovician and Cambrian rock units were more or less unknown. On the existing maps of Fowler (1950) and Zen (1961) black phyllites were often separated based on an assumed, necessarily existing thrust boundary instead of using lithological characteristics. As a result lithologic descriptions of Cambrian phyllites of the allochthon and rocks of the Middle Ordovician flysch sequence are almost identical and cannot be applied for future studies.

In general the lithostratigraphic column for the eastern region of the Giddings Brook slice is less well constrained as a result of more complex structure (Rowley et al., 1979). Nevertheless, a well defined stratigraphy exists for the western region and a lateral change to the east has also been outlined by the same workers. Where possible, correlations with this stratigraphy seem to be most appropriate. The problems mentioned above make it difficult to map out well defined stratigraphic units from maps and descriptions of earlier workers. Metamorphism into very similar looking phyllites and the complex infolding of all rock units into the thrust belt, complicate the assignment of small outcrops to any particular formation. Therefore each outcrop has first been mapped in a descriptive way and stratigraphic units have later been defined with the help of sawn slabs and intensive sampling. Looking at sawn rock samples during fieldwork has proved exceptionally helpful in distinguishing phyllite units later on in the field. All the different rocktypes which have been recognized are described and discussed and also correlated where possible. An overview of the stratigraphy which has been used and defined by earlier workers is shown in Figure 3 for the Ordovician shelf carbonates. The most commonly used stratigraphic names for the Taconic sequence are summarized in Figure 4. It should be emphasized that some of the stratigraphic relations east of the Taconic Allochthon have been obscured by thrusting, especially those units which were distributed closest to the initial thrust surface between the shelf and the overriding accretionary prism.

Period	Series	group	Cady (1945) West-Central-Vermont	Cady and Zen (1960) Sudbury/Brandon	Fowler (1950) Castleton Area	Zen (1964) Castleton Quadrangle
Ordovician	Middle	Trenton	Hortonville Shale	Hortonville Slate	Hortonville Formation	Ira Formation
			Glens Falls Limestone	Limestone of Mid-Ordovician Age	Whipple Marble	Whipple
					(unconformity)	(unconformity)
			Orwell Limestone		Orwell Limestone	
		Black River	? ?		? (disconformity ?) ?	
		Chazy	Middlebury Limestone	Middlebury Limestone	Middlebury Limestone	
			Beldens Formation	Beldens	Beldens Formation	
			Weybridge Member of Beldens Formation	Burchards	Burchards Limestone	
			Crown Point Limestone			
	Early	Beekmantown	Bridport	Weybridge	(disconformity ?)	Chipman Formation
			Bascom Formation	Bascom Formation	Bascom Formation	Bascom Formation
			Cutting Dolomite	Cutting Dolomite		
			Shelburn Marble	Shelburn Marble	Boardman Formation	Shelburn Formation

Figure 3: Overview of the Ordovician Shelf Carbonates

2.2. Carbonates within and adjacent to the Slate belt

2.2.1. The Proctor/West Rutland marble belt

The Taconic thrust sheets structurally overlie the early Paleozoic carbonate platform. West of the Taconic Range the platform rocks dip gently to the east and are conformably overlain by black Ordovician shales and slates. This shale unit indicates a change from shallow water carbonate deposition to deep water flysch sedimentation and thus demonstrates increased subsidence of the shelf during this time. East of the allochthon equivalent carbonates of Cambrian to Early Ordovician age underlie the Vermont Valley between the Taconic Range and the Green Mountains. The carbonates of the Vermont Valley have been metamorphosed to dolomite and calcite marble. Extensive quarrying of these marbles was the dominant industry of the whole region at the turn of the century. The West Rutland marble belt south of the mapping area probably produced the most valuable marble during that time (Dale, 1912). Just east of the mapping area the Old Hollister quarries are narrow but very deep openings which may illustrate well the quarrying technique. At this location the marble beds dip 80 to 90 degrees to the east and a single bed has been followed down to a depth of 316 feet (Dale, 1912). In West Rutland the quarries had to follow the beds in an anticlinal structure. Tunneling underground was a common practice in most of the quarries. Today all the quarries around West Rutland, Proctor, and Florence are abandoned and either closed or filled with water. Several smaller quarries are located within the field area, two of them in the southeastern part of the kidney-shaped "Florence Nappe" (plate 1). The carbonate patch which extends northward from the main quarry section (Florentine quarries) has a complex internal structure and is referred to as Florentine sheet. The Florentine sheet is bounded by the Florentine Fault and the Proctor Fault as shown on plate 1. At least three carbonate units can be distinguished in the Florentine sheet. The same units also occur in the "Florence Nappe" east of Biddie Knob. No faults have been found within the "Florence Nappe"; if this is a correct structural interpretation, it may be used to establish a possible stratigraphic relationship for the units within that structure.

2.2.2. Whipple Marble (Owh)

Unit 1 Blue Gray Marble (Owh1)

A massive dark blue to blue gray marble can only be seen in the quarries of the field area. The marble is commercially useful because it usually contains thick beds of calcite marble with only a few intervening dolomite beds. The marble occurs in either a massive dark blue kind or a blue gray type streaked with a very fine and complex folded bedding lamination. The relation of both types can not be established as the quarries are filled with water and the remaining walls are weathered and coated dark black and can usually not be reached. Either type can be seen in large blocks adjacent to the quarries which have been left by the marble companies. The blue gray marble occurs in the lower part of the "Florence Nappe" and has also been quarried at the Florentine Quarries. It also occurs in two very small openings about one mile north of the main quarry section. The rock owes its dark blue and gray colors to various amounts of graphite present in the beds (Dale, 1912). In thin section the graphite is seen as black particles. Otherwise the rock is a pure calcite marble containing minor amounts of quartz.

Unit 2 Gray Marble with beds of Dolomite (Owh2)

The massive blue gray marbles at the Florentine Quarries are in thrust contact with the phyllites as well as with adjacent carbonates. Therefore a stratigraphic relationship to the following unit can not be established at this location. In the "Florence Nappe" they are followed by a thick unit of gray marbles with interbedded layers of dolomitic marble. The dolomitic beds range from one to several feet thick and they may be difficult to distinguish from similar beds of the Lower Ordovician Bascom Formation. The dominant marble outcrop at Fire Hill characterizes this higher formation in the carbonate slice. The thicker, buff or dark looking dolomitic layers weather out in relief and occasionally form small ridges. On fresh surfaces the dolomite is dark gray which according to Fowler (1950) is different from dolomites of the Bascom Formation.

Unit 3 Black and Gray Marble (Owh3)

This carbonate unit is very distinct from the other marbles because of the black color and the typical weathering of the grayer unit into gray-white carbonate sand. Both units occur together, lensing into each other. The black variety can be seen to grade into a black calcareous shale at two locations where the black marble is underlain by the gray unit. Therefore the black carbonates may be slightly younger and mark the transition to shale sedimentation.

The black unit has a very fine grained texture and minerals can hardly be identified in a thin section. The black color may be due to a high content of carbon-rich materials.

Correlations and discussion of the Whipple Marble

The exact age of the carbonates described so far is uncertain. All three units together have been mapped as Whipple Marble by Fowler (1950) who placed the Whipple at the base of the Hortonville Slate above a Trenton unconformity. Zen (1961) followed this interpretation but his Whipple consists only of the dark black and sandy weathering carbonates (unit 3), whereas unit 1 and 2 have been interpreted by Zen as the Lower Ordovician Bascom formation. Unfortunately no reliable report of fossils exists from the carbonates in the field area. Although Fowler and Zen discussed the possible age of these formations, the map pattern I have determined is inconsistent with their stratigraphic description. Moreover both authors assumed a conformable relation between carbonates and phyllites and this necessarily required a regional unconformity below the Whipple. Some of the statigraphic interpretations were mainly based on that assumption.

As unit 3 locally grades into calcareous phyllite it is probably of Middle Ordovician, possibly Trenton age. The thickness of the unit can hardly be determined. In the "Florence Nappe" only the base of the sequence is preserved, whereas the patch in the Florentine sheet is bounded by thrust faults. South of where the powerline crosses the road to Fire Hill the beds are nearly vertical and a minimum thickness of 20 meters is exposed. Cady (1945) called the upper limestone unit underneath the Hortonville Slate the Glens Falls limestone following Ruedemann (1912). This limestone belongs to the Ordovician

Trenton group and overlies the Orwell limestone. Ruedemann (1921) describes two facies of the Glens Falls which are compatible with unit 3 of the field area. These are: "a gray crystalline limestone beneath and a bluish-black partly shaly limestone above". Cady`s Trenton group was adopted by Fowler who correlated the Whipple with a member of the Glens Falls limestone. Unit 3 could be an equivalent of the Glens Falls, but still the correlation of unit 1 and 2 remains unclear. However, they must be slightly older and probably are Black River to Early Trenton in age, or perhaps Chazy.

In the early classification of the marble industry the marble of the Florentine quarries belonged to the uppermost graphitic beds of Trenton age (Dale, 1912). Zen`s suggestion that the Florence Nappe and part of the Florentine sheet are of Lower Ordovician age must be rejected mainly because unit 3, which elsewhere has been mapped as Whipple by Zen, occurs in the "Florence Nappe". Moreover the typical blue gray marble from the quarries in the field area is very different from the gray marbles of the Bascom formation. The darker color of the dolomite beds had already been pointed out by Fowler (1950). The Whipple Marble in Fowler`s sense is an appropriate general term because the correlation with other units has proven to be difficult. However, the unit should be subdivided into three members of the Whipple marble as outlined above. In this study the Whipple is considered to be a spatial equivalent of the uppermost shelf sequence. It is very likely Black River/Trenton in age but it is also possible that the Whipple is slightly older than equivalent units further west. It is also entirely possible that parts of the Whipple are coeval with early Hortonville shale elsewhere, but the Whipple should be discussed as a separate lithologic unit for lithostratigraphic purposes. Whipple also occurs in the West Rutland marble belt at the base of the Taconic Allochthon (Fowler, 1950; Zen, 1961) and further south a few smaller slices occur in the slate belt (Zen, 1961, 1964).

A conformable relationship between Whipple and overlying shale unit has not been observed. Whipple is either associated with melanges or in thrust contact with other slate units. The relations in the area do not help to answer the question whether a Trenton unconformity exists or not. Nevertheless, normal faulting in the outer shelf during this time may have caused local unconformities within the Black River and Lower Trenton (Bradley and Kusky, 1986).

2.2.3. Early Ordovician Marbles of the Bascom and Chipman Formations (Ob, Och)

The name Bascom Formation was introduced by Cady (1945) to define the units that overlie the Cutting Dolomite. In the marble belt south of Brandon however, the Bascom losses its identity due to metamorphism, as pointed out by Cady. Thompson (1967) mapped not only Bascom after Cady but also included the overlying Beldens Member of the Chipman Formation (Cady, and Zen, 1960). Theokritoff and Thompson (1969) defined the Bascom as a blue gray, gray and white marble, locally with dolomite mottling (Beldens Member), and containing interbeds of gray, yellow, or orange weathering dolomites. Fowler (1950) mentioned the abundance of sandy phyllite, phyllite and sandstone and Zen (1964) reported phyllites and white siliceous partings, as well as characteristic calcareous siltstone beds in addition to standard Bascom lithologies. According to Zen the white marble of the Bascom is restricted to the base of the formation. In the present area the Bascom is less well defined than in the Hindsburg Synclinorium of the northern Champlain Valley, where Cady (1945) distinguished four lithologic zones in this formation. At the north end of the mapping area (outcrop 1 on plate 1) thick gray marble occurs next to brown weathering marble with gray streaks about 1.0 to 0.3 centimeters apart which weather into raised ridges. A brown weathering calcareous sandstone also occurs which probably shows cross beddding. In a sawn slab the streaked marble is white and the more siliceous beds are gray. A thin section of the rock shows that the white marble contains a lot of quartz. The gray layers consist of very fine grained quartz and plagioclase, opaque materials and only minor amounts of calcite. Detrital micas are possibly present besides a number of metamorphic layer silicates within these fine clastic layers. The calcareous sandstone is also very fine grained and consists of quartz, feldspars, layer silicates, calcite,and a lot of accessory materials. Larger opaque flakes, possibly hematite, define a foliation that can be seen in a hand sample. Another rock variety is a blue gray, brownish streaked quartzite with intervening thin white calcareous layers. This typical clastic facies within the marbles has been descibed elsewhere. It is Dana`s striped stratum (1877) and was mentioned by Cady (1945) as a waymark because of its characteristic weathering surface. In Cady`s stratigraphy it is the Weybridge Member of the Beldens Formation. Cady and Zen (1960) renamed the Beldens into the Chipman Formation and included the Beldens and Weybridge as two of four members. The Beldens Member of the Chipman Formation also occurs in the field area close to the Weybridge lithology. It is a bright, orange, buff weathering dolomite which is interbedded with snow white marble (Cady, 1945).

Although the Chipman Formation was described in detail by Cady and Zen (1960) in the Sudbury Slice, these easily identified units are included in the Bascom formation on Zen`s maps from 1961, and 1964. The Weybridge of Cady (1945) was placed in the Ordovician Chazy group. In the later publication (Cady and Zen, 1960) the Chipman Formation including the Weybridge Member is the uppermost part of the Lower Ordovician and is of Beekmantownian age. However, the Chipman overlies the Bascom and occurs at the north end of the field area in thrust contact with Taconic phyllites. The Chipman should not be included within the Bascom where both units can be distinguished because a more detailed map pattern helps to interpret the overall structure of the region.

Black phyllites have not been found within the Bascom Formation of the field area. Besides gray marble and interbedded dolomites a thick unit of interlayered gray and white marble is characteristic for what has previously been mapped as Bascom (Fowler, 1950; Zen, 1961). It is not clear whether these are local variations in the Bascom or represent a different sequence. As no other correlation is reasonable and at least the Bascom Formation of Thompson (1967) includes gray and white marbles, they are included within the Bascom Formation.

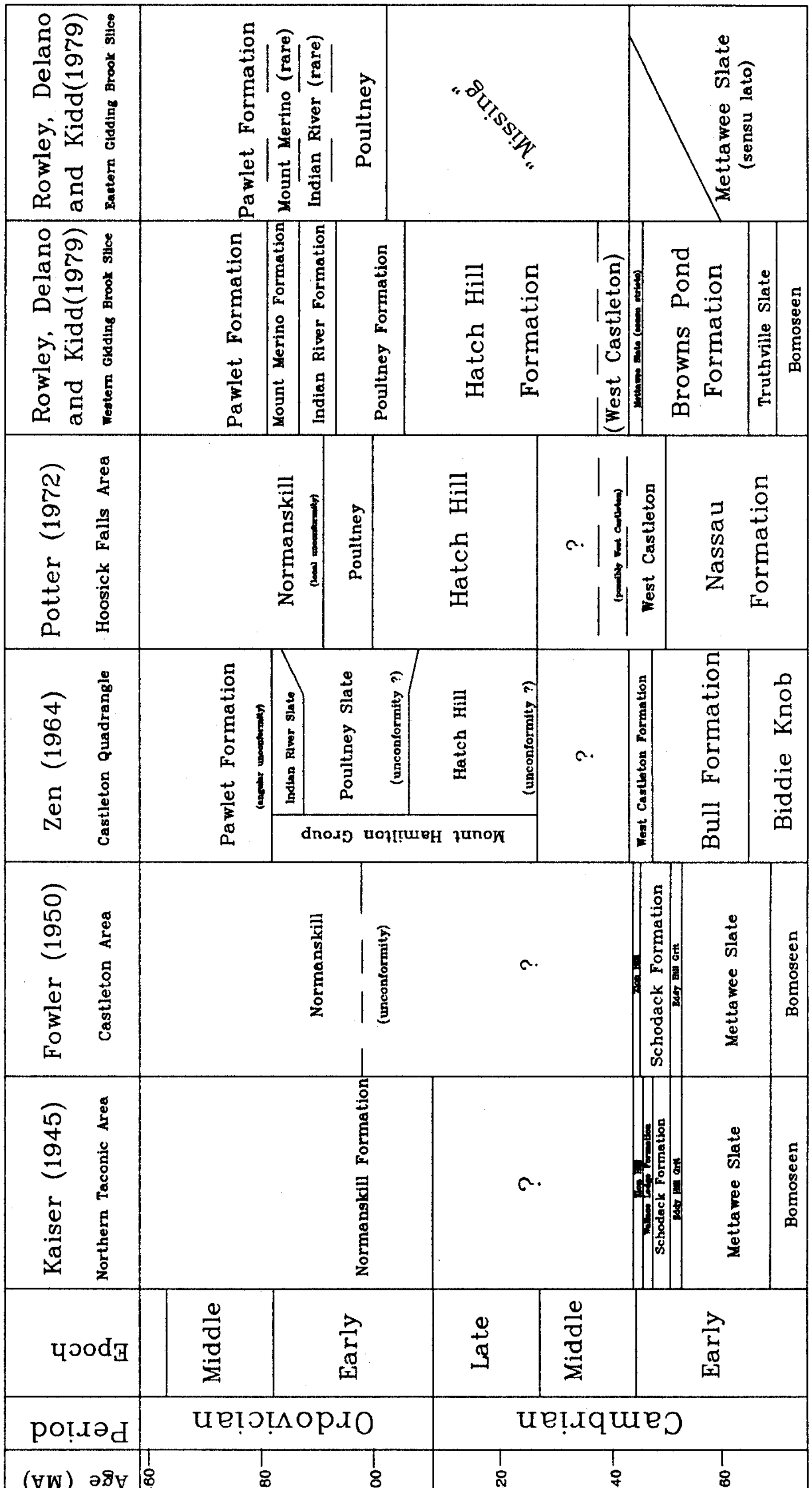


Figure 4: Overview Taconic Sequence

2.3. The Phyllite Terrain

The difficulty in separating black phyllites in the field has been outlined by Zen (1961). The conclusion however, that the Taconic overthrust is hidden in similar looking phyllites of Lower Cambrian and Ordovician Trenton age is much too simple.

Black slates and phyllites occur throughout the Cambrian of the Allochthon in the Browns Pond and Hatch Hill (including the West Castleton Formation), as well as in the base of the Early Ordovician Poultney, and in the uppermost Pawlet flysch (Rowley et al., 1979; Rowley, 1983). Theoretically either formation can be in thrust contact with the Trenton Shale assuming a complex structure for the region. Moreover, Pawlet flysch and Trenton Shale must be somehow related during the collision event and obduction of the allochthon. It is possible that an early syntectonic (Pawlet) sequence was overridden and later accreted to the allochthonous wedge in the deeper part of the subduction zone. If such a sequence is now exposed on the east side at the base of the Taconic Range, it in fact explains the similarity of black phyllites with Taconic and Hortonville (Trenton) affinities. In this view it is not necessary to separate allochthonous from authochthonous phyllites. On the other hand a distinction should be made between passive continental rise sediments and later syntectonic flysch. Moreover, it is reasonable to distinguish early and late syntectonic deposits. The disruption of the former continental rise and incorporation of Taconic slices into the accretionary prism must be somewhere recorded within the pre-obduction sedimentary record. These rocks may look slightly different from the main flysch and the melanges which are associated with the obduction of the prism onto the shelf. Unfortunately it is quite difficult, may be impossible, to demonstrate an exact age relationship between these rock units.

Taconic phyllites and flysch sequence are described and discussed in this section. However, the interpretation of some phyllites is mainly based on the concept mentioned above rather than following the`authochthonous versus allochthonous method` of earlier workers.

2.3.1. Green Taconic Units : Bull Formation (Cb)

The colored slates of the Taconic Allochthon refer to green and purple Lower Cambrian units which can best be seen in the large outcrops along Route 4 from Fair Haven N.Y. to West Rutland Vt., thus crossing the Allochthon from west to east. Some of the more common names for these lithologies include the Nassau Formation and Mettawee Slate Facies (Cushing and Ruedemann, 1914), and the Bull Formation (Zen, 1961). In the present area, besides the larger outcrops of the Bull Formation, a few very small patches of green phyllites occur within black and dark gray units. If a conformable relationship exists, the green patches may be used to define the age of the surrounding black phyllites as long as the green or purple colors are acceptable indicators for the Cambrian age of a unit. The literature does not report green or purple slates\phyllites which conformable overly the Trenton Limestone at any type locality. Where the structural relationship is clear the total of the overlying unit is of black color. This fact was convincing enough for Fowler (1950) to map isolated patches of Mettawee Slate within the Hortonville in Whipple Hollow north of West Rutland. On the other hand the same patch of greenish gray phyllites was interpreted by Zen (1961) as a stratum of the Ira Formation rather than part of the Taconic sequence. The conclusion must be either to ignore Zen`s interpretation or to admit that Cambrian and Ordovician phyllites can by no means be distinguished. Prof. William Kidd (per.com.) says that he knows of no location where green lithologies occur in unquestionable Middle Ordovician slates. Therefore all green units are included within the typical Taconic sequence.

Still, the exact stratigraphic position of the green/black contrast is not always clear. In the small isolated patch of predominantly dark gray and black phyllites east of the Florentine quarries a small outcrop of soft green phyllite has been discovered (outcrop 2 on Plate 1). The rock appears identical to phyllites of the Cambrian Bull Formation. However, it is associated with black phyllites which are similar to those described in the interbedded phyllite and quartzite sequence (page 27). The stratigraphic relation of the black/green boundary at this location is not known; it may also be tectonic in origin. As the entire phyllite patch above the Whipple Marble is believed to represent the Basal Thrust (section E on plate 1), extremely complicated relations are not unlikely.

Rowley et al. (1979) describe two Cambrian black/green boundaries, the first below the Browns Pond and a second above this formation, but the upper green/maroon unit (the Middle Granville slate) is very thin (≤ 50 m) and minor in extent compared with the rest of the Bull/Mettawee. Moreover the Early Ordovician Poultney Formation is characterized by Rowley (1983) as "variegated gray, medium to dark gray, green, and lesser maroon slates and silty quartzites". Rowley`s description of the "white to light gray , silty to fine sandy quartzites" of the Poultney may also match the interbedded phyllite and quartzite sequence. However, hand samples of the Poultney of the western region look very different from these phyllites.

A second very small outcrop of green phyllite occurs close to an outcrop exposing a kind of Eddy Hill lithology (outcrop 3, plate 1) as described on page 22. Therefore the surrounding black and gray phyllites very likely belong to the Browns Pond Formation. It is also possible that small patches of green phyllites locally occur elsewhere in the stratigraphic column where they have not yet been recognized. This uncertainty should be noticed but must be accepted.

In any case these phyllites are definitely part of the Taconic Allochthon. The Bull Formation in the present area consists of very fine grained, soft, well cleaved phyllites with typical rusty orange weathering cleavage planes. The rock itself weathers white, brown or orange. Moreover, the softness of this phyllite is very distinct from all other formations (except, for some exposures that are probably parts of the Browns Pond). Locally a silver gray variety has been found. The silver gray color results from coarser micas within the cleavage planes and the rock is almost transitional between a phyllite and a schist.

Besides the soft phyllites the Bull Formation includes many small quartzite layers. These are usually white or light green and resemble very fine grained, well-sorted quartz sands. The thickness of the layers varies from 0.3 to a few centimeters but the finer bedding lamination is usually folded, disrupted and locally transposed. Rowley et al. (1979) called the soft better cleaved member of the Bull formation the Truthville Slate which conformably overlies the Bomoseen and is the upper member of the Mettawee Slate Facies. Greenish quartzites are also associated with the Truthville which are different from the Bomoseen Wacke. Lithologies which may resemble the typical Bomoseen Member of the Bull Formation (Rowley, 1983) have not been found in this field area and that agrees with the suggestion (Rowley et al., 1979) that there is a facies change towards the east into finer slates and phyllites.

The clean thin quartzites in the present area are probably distal turbidites which have accumulated in a submarine fan environment, whereas the thicker bedded Bomoseen Wacke was perhaps primarily confined to submarine canyons of the upper and lower continental slope.

Fowler (1950) reports greenish gray slates from the upper Mettawee slates that he interpreted to mark the transition to the overlying black Cambrian slates.

In the field area thick units of gray, dark gray, and greenish gray phyllites, as well as minor amounts of black phyllites are locally associated with the Bull Formation. It is possible that the boundary to the overlying Browns Pond is not always sharp. However, the occurrence of black phyllite is probably more typical for the latter. On the other hand a large area of unquestionable Bull/Mettawee lithologies has been discovered on the prominent ridge between West-Rutland and Proctor, approximately 1.5 kilometers northwest of Beaver Pond near Proctor. At this location soft green phyllites grade, over a distance of several hundret meters, into dark gray units which finally grade into a thick sequence of soft black phyllites. The black phyllites are identical to the green rocks, except for the darker color. Thin quartzites do not occur within this area of the Bull Formation. This thick sequence of darker materials is unusual for the typical Bull/Mettawee and two possibilities may explain the observation:

1) The dark gray to black units are equivalents to the Browns Pond Formation and indicate a transitional change from the underlying Bull into the overlying Browns Pond.

2) The darker units belong to the Bull Formation and either represent a local variation or otherwise indicate a further facies change towards the east from purple, green, and minor black phyllites into green, gray and predominantly gray/black to black equivalents. Because no black units are known anywhere within exposures of unquestionable Bull Formation, this is a less likely explanation.

2.3.2. Black Taconic Units (Overview)

In the eastern Giddings Brook Slice the predominantly green Cambrian and/or late preCambrian Bull Formation is followed by a dark Cambrian sequence of black and gray phyllites, quartzites, calcareous quartzites, a limestone member, and an additional Cambrian black/green boundary. In the stratigraphy of Rowley et al (1979) the oldest black unit is the Browns Pond Formation, the overlying but thin purple and green lithology is the Middle Granville Slate and the upper black Cambrian slates are included in the Hatch Hill Formation (Figure 4). In contrast, Fowler`s (1950) black Cambrian sequence consists of the Eddy Hill Grit, the Schodack Formation, and the Zion Hill Quartzite but no additional green/purple slate unit.

Zen (1964) named almost the entire black Cambrian succession West Castleton Formation and defined the overlying Hatch Hill to be of Late Cambrian age and therefore marking the transition to the Ordovician Poultney Formation. This interpretation is different from the earlier published stratigraphy (Zen, 1961), where the West Castleton is only Early Cambrian in age.

Kaiser (1945) already suggested the occurrence of green and purple slates within the black Cambrian slates. Kaiser`s Wallace Ledge Formation is approximately 100 feet thick and occurs between the Schodack Slate and the overlying Zion Hill Formation. The Zion Hill quartzite itself is a little troublesome because Zen (1961) includes this quartzite in the Bull Formation. Nevertheless, the Zion Hill was defined by Cushing and Ruedemann (1914) and also described by Kaiser (1945) and Fowler (1950) in some detail. It is very likely an equivalent to Dale`s Ferruginous Quartzite of Late Cambrian age. Moreover, Kaiser (1945) clearly states that the Zion Hill, as well as the Wallace Ledge Formation, are absent in many places elsewhere in the allochthon. It not clear where Rowley et al. place the Zion Hill but as discussed here it would be Hatch Hill. It should be noticed that Zen (1961) also considers his Zion Hill to be Dale`s Ferruginous Quartzite. The discrepancy concerning the Zion Hill is of minor importance because the typical thick quartzite is not present in the field area. According to Prof. Kidd (pers. com.) the Zion Hill of the type section occurs where Zen puts it, in the Bull Formation but other occurrences mapped by Kaiser, and others, are of Hatch Hill.

However, Kaiser`s Wallace Ledge and the Middle Granville Slate of Rowley et.al (1979) may indeed be the same unit although the stratigraphic position is slightly different. Wallace Ledge and Zion Hill of Kaiser mark the end of the Cambrian, whereas the Middle Granville Slate occurs in the Lower Cambrian. The problem cannot be solved from literature research but it may illustrate the complexity of exact stratigraphic relations. A single unnoticed thrust fault within any of these units may result in a variety of stratigraphic interpretations. Nevertheless, a few distinct lithologies which have been described from many places within the allochthon can be used to define the Cambrian age of black phyllites.

2.3.3. Eddy Hill Type Lithology

Graywacke and quartzite units have been reported from many places within the Cambrian slates. All units are of various thickness and have most commonly been described as "lensing" or channel filling deposits. They are therefore best included as a member of the typical slate unit in which they occur. In the present area the abundance of these units is important to demonstrate a Cambrian age for phyllites which have previously been mapped as Ordovician Hortonville Slate (Fowler, 1950) and Ira Formation (Zen, 1961, 1964).

Many of these quartzites are difficult to identify with a type unit, nevertheless the Eddy Hill Grit has a typical character in the field area. The rock consists predominantly of quartz with a few larger grains up to 0.5 cm across and is of dark gray to black color. The average grain size is 0.3-0.5 mm of grains lying in a finer grained quartzitic matrix. Detrital micas, plagioclase and pyrite are also abundant. Most of the grit is very rich in opaques within the matrix and also wrapping around single grains. This is what gives the rock its dark appearance. On fresh surfaces the quartz grains appear black because of the black coating material. Quartz grains range from well rounded to very angular, are unstrained or show undulose extinction, yet others exhibit well developed subgrain boundaries. Similar rocks have been described as Eddy Hill Grit (eg.Kaiser, 1945; Fowler, 1950) as an equivalent to Dale`s Black Patch grit (1899). These quartzites are typical dark gray and consist of quartz grains in a matrix of calcareous material. The Eddy Hill type lithology is included as a calcareous quartzwacke member in the Browns Pond Formation of the stratigraphic column for the Giddings Brook Slice (Rowley et al., 1979). In their classification the wackes occur in gray and black slates which follow the Metawee Slate facies and therefore define the first green/ black boundary within the Taconic lithology. This corresponds exactly with the position where Kaiser and Fowler placed the Eddy Hill grit. For the north end of the slate belt Kaiser (1945) described the Eddy Hill grit to be a narrow zone of thin bedded dark quartzites. In the field area the quartzites are less dominantly calcareous though minor amounts of dolomite have been found in thin section. The grit occurs in gray and black phyllites of or equivalent to the Browns Pond Formation. These phyllites are included in Kaiser`s Eddy Hill formation. Equivalent quartzites can also be found as blocks and pebbles within the melange unit.

2.3.4. Browns Pond Formation (Cbp)

Eddy Hill Grit and surrounding phyllites must belong to the Browns Pond Formation following the stratigraphy of Rowley et al. (1979). The phyllites vary in a wide range from black, dark gray to pale gray. They are either massive, hard and poorly cleaved or well cleaved and soft, elsewhere well cleaved hard and fissile. The bulk of the phyllites which occur with the Black Patch/Eddy Hill Grit are massive black and dark gray rocks locally interbedded with thin (0.3 to 2.0 cm) fine grained black and gray quartzites. All types of phyllite weather white, brown, or locally reddish and may occur together, in no particular stratigraphic order. However, the lower Browns Pond may possibly be characterized by softer, well cleaved phyllites. Two extensive outcrops show this lithology (4 and 5, on plate 1).
The fine to silty rocks are of light gray, dark gray and black color. Locally a faint color contrast in the outcrops may represent bedding, but on the other hand the layers are difficult to trace in outcrop and larger-scale fold structures have not been observed. As already discussed for the Bull Formation, it is not exactly clear in which formation this lithology should be placed. On the map it is included within the Browns Pond Formation because of the absence of characteristic green units and because similar rocks also occur in close association with Eddy Hill Grit. It is also possible that the Browns Pond is

characterised by two different facies and that the massive sandy type phyllite and Eddy Hill Grit were confined to submarine canyons and smaller channels. The finer gray and black phyllites may still be transitional to the Bull Formation.

Another distinct unit, the Mudd Pond Quartzite, has been described for the Browns Pond Formation (Rowley et al., 1979); this quartzite was included into the Bull Formation by Zen, (1961). The "clean medium to coarse grained thick bedded" Mudd Pond Quartzite of Rowley et al. (1979) also occurs in the field area. Several larger outcrops of Mudd Pond Quartzite lie along the boundary between the Browns Pond Formation and the disrupted phyllite and quartzite sequence (type 1 melange as described on page 28) and demonstrate the extensive occurrence of this quartzite lithology. The relation to the surrounding phyllites of the melange unit is not everywhere very clear.

The Middle Granville Slate on top of the Browns Pond can not be seen or at least not clearly defined in the field area.

2.3.5. Hatch Hill/West Castleton Formation (Chw)

In this study the name Hatch Hill/West Castleton Formation is used to define the black phyllites which are not included in the Browns Pond Formation but which are also believed to be of Cambrian and Late Cambrian/Early Ordovician age. The Hatch Hill of Rowley et al. (1979) in the western Giddings Brook Slice includes all units above the Middle Granville Slate and below the Early Ordovician Poultney Formation. Zen`s West Castleton (1961, 1964) and the Beebe Limestone are part of the Hatch Hill Formation. Hatch Hill lithology is apparently missing in parts of the eastern Giddings Brook region (Rowley et al., 1979) but equivalent units are present further to the east mapped as Schodack Formation by Fowler (1950) and West Castleton Formation (Zen, 1961). However, the Hatch Hill described for the western Giddings Brook region contains very characteristic thick dolomitic quartz arenites which are definitely missing in the field area, except for those described at the end of this paragraph. Therefore the name Hatch Hill may be misleading because dolomitic quartz arenites are usually associated with this formation. Instead a thick sequence of black phyllites is present and the

Hatch Hill/West Castleton Formation in the easternmost Giddings Brook area contains most of the black phyllites which are probably not distinguishable from units of the Middle Ordovician flysch sequence. Nevertheless a Hatch Hill equivalent must exist in the east and a facies change into undifferentiated black shales of the West Castleton and Hatch Hill Formations is likely.

The Beebe Limestone for example which belongs to the West Castleton member of the Hatch Hill can be used to distinguish Cambrian from Middle Ordovician phyllites. The Cambrian age of the Beebe Limestone (Keith, 1932) is well established by a number of fossil localities (Zen, 1961). Zen describes it as "a black, fine grained, massive limestone, weathering dark gray, and crisscrossed with calcite veins", but also as " massive, dark bluish-gray and weathering light blue". This color has also been reported by Kaiser (1945). Unfortunately, the limestone has litle significance for the mapping area. A bluish gray highly deformed quartz rich limestone containing calcite veins has been found in only one outcrop which is unquestionably located within the allochthon (outcrop 6 on plate 1). The surrounding phyllites are black, fissile, brown or rusty weathering, and locally graphitic. A more sandy phyllite, non fissile but well cleaved, in addition to a fine grained, non fissile, well cleaved dark gray type are also seen in this outcrop. Other phyllites found in the Hatch Hill/West Castleton Formation are more massive poorly cleaved and of blue to bluish black color. They contain thin white (0.1-1.0 cm) dolomitic quartzites which weather brown and give the rock a banded appearance. Other phyllites only contain thin quartzite layers and no dolomite.

In general the Hatch Hill/West Castleton Formation is characterized by a variety of predominantly dark phyllites which may not always have successfully been distinguished from similar rocks of other allochthonous formations. However, this uncertainty does not really affect the interpretation of the overall thrust geometry as long as Hortonville/Ira lithologies have been correctly separated.

At the north end of the field area a very distinct quartzite and graywacke lithology is exposed (outcrop 7 on plate 1) which is interbedded with black and dark gray phyllites. It is a massive, gray to greenish/gray dolomitic quartz wacke with thin layers of greenish argillaceous material. The rock contains quartz, dolomite, plagioclase, iron oxides, micas, and chlorite. Another variety consists predominantly of quartz, few micas, and very coarse dolomite grains. In fact this rock contains so much dolomite that it almost looks like a quartz rich dolomite marble. In addition a non-calcareous quartzite occurs which contains small layers of albite porphyroblasts as seen in thin section. These porphyroblasts have no stratigraphic significance and have been found in other lithologies. In close association with these units a thick bedded dolomitic arenite occurs which exhibits a very thick (1-3 cm) crust of rusty weathering material. These layers must belong to the Hatch Hill Formation. The greenish/gray quartz wacke on the other hand would be less typical for the Hatch Hill. The rusty weathering wacke, however, and the dark color of the surrounding phyllites strongly suggests that the lithology in question must be treated as a sub-facies of the Hatch Hill, rather than as a Zion Hill equivalent.

2.3.6. Poultney Formation (discussion)

The Poultney formation consists of the lowest Ordovician slates which are found within the Taconic sequence. The formation was defined by Keith (1932) as white weathering gray slates and cherts. Although the Poultney slates have been described by most authors as very distinct units the lithostratigraphic variation of the formation appears to be quite exceptional. According to Potter (1972) the Poultney Formation can be divided into the White Creek Member (dark gray to black slates containing ribbon limestone, thin bedded limestone, dolostone, and quartzite) and the Owl Kill Member (siliceous argillite and very fine-grained hard slate) which forms the bulk of the formation. Equivalent units of Rowley et al. (1979) are the Dunbar Road Member (fissile, thinly cleaved, dark gray to black slate with interbedded thin micritic and sometimes silty limestone) and the Crossroad Member (hard, non-fissile often chalky weathering variably colored slates, finely color laminated slates and interbedded silty quartzites, quartz arenites and chert) for the western Giddings Brook area. In the eastern region the lower Poultney is missing and the remaining section shows dark gray and black (locally green) slates and argillites with thin white weathering, silty to fine-grained clean often finely laminated arenites, and rarely, white weathering black chert layers (Rowley et al., 1979). The Poultney Formation has not been mapped by Fowler (1950) and Zen (1961,1964) in the present area. However, the short review of this formation may indicate the character of the Poultney if present in the field area. It probably does not contain limestones but consists predominantly of dark gray and black hard phyllites containing clean silty to fine-grained quartzites and possibly thin chert layers. It may also contain greenish gray phyllites which in association with the fine silty quartzites would be difficult to distinguish from the Bull Formation. Although not mapped by Fowler (1950) and Zen (1961) the Poultney Formation very likely contributes to some of the darker phyllites in the field area. The small patches of green phyllites which have been discussed earlier possibly could belong to the Poultney instead of the Bull Formation. A possible candidate for the Poultney Formation has been mapped as an interbedded phyllite and quartzite sequence, but a definite stratigraphic correlation to the Poultney cannot be proven.

2.3.7. Interbedded phyllite and quartzite sequence (Op ?)

The correct stratigraphic interpretation of this unit is very important for the structural synthesis of the field area, because where found, it generally appears structurally between typical Taconic lithology and a melange type of rock. It also occurs between Taconic rocks and the carbonate slices where the melange unit is absent and Taconic rocks are not in direct contact with the carbonates.

The rock may be best described by its layering character. It consists of silty quartzites and intervals of dark gray to black phyllites. The whole rock may be called a phyllite. The layering is often modified due to deformation and strong pressure solution during metamorphism. More competent and thicker quartz rich layers are well preserved, whereas argillaceous intervals show a fine metamorphic lamination more or less parallel to bedding. Pinch and swell structures are locally found in the quartzitic beds. The appearance of the rock in outcrop depends on the abundance and thickness of quartzite layers which weather buff or gray to white and sometimes stand out in relief. This gives the rock a dull appearance which otherwise is a gray to black brown and rusty weathering phyllite. The thickness of the quartzite beds varies considerably but generally is from 0.5 to 3 cm. Thicker beds up to 5 cm occur locally. The intervening phyllite layers vary in the same range but in some places the rock grades into a wholly phyllite composition. Because of the relatively large amount of fine quartz sand the rock is very massive and often breaks along bedding planes. On the other hand where arenite beds are more or less absent it is a well cleaved phyllite which only exhibits the strong metamorphic lamination. The normal rock type contains about equal amounts of quartz arenites and argillaceous material.

2.3.8. Disrupted phyllite and quartzite sequence (Melange unit: M1, M2)

In a very small outcrop this unit may not be noticed and distinguished from the sequence described before. Basically it consists of the same lithology with the difference that no layers can be traced in outcrop. Instead the rock consists of fragments and pebbles of siltstone and quartzite interbedded in a pervasively sheared black phyllite matrix. The pebbles are of the same fine grained quartzite lithology as in the unit described above. It is a brown and rusty weathering black phyllite characterized by very irregular and craggy surfaces, commonly curved and anastomosing into each other. This is caused by the intersection of at least two more or less prominent foliations and also by cleavage refraction along the clasts. The pebbles are typically gray to white and can be recognized on intersecting surfaces. Although the lithology is very similar to the previous sequence an increase in organic material may be noticed as the matrix is darker and locally graphitic. Moreover the matrix is the dominant component of the unit. The writer believes that this unit is closely related to thrusting and it will later be described structurally in more detail. The sequence should be termed a type 1 melange as used by Bosworth and Vollmer (1981) who distinguish a type 1 melange from a type 2 melange in the sense that the former does not contain "exotic blocks". Type 2 melanges may be further subdivided depending on the nature and affinity of the blocks they contain. The term "exotic" is probably not well defined and has been used with various implications. In this study "exotic block" characterizes a rock fragment which does not belong in the formation which defines the matrix of the melange unit. A disrupted layered sequence may therefore be termed a type 1 melange unless it became mixed with other very distinct stratigraphic units of different origin, or with units from a different stratigraphic position.

Figure 5: Type 2 melange containing a block of quartzite.

Type 2 melanges which dominantly contain pebbles and blocks of black quartzite also occur in the field area. Other fragments in the type 2 melanges consist of a few larger fragments of the silty quartzite lithology similar to those which have been described for the non-disrupted succession, and, rarely, calcareous nodules.

It should be pointed out that blocks are generally only a minor component of the melange unit, which otherwise consists of either black phyllite with quartzite pebbles or of a pure black, often graphitic phyllite. Therefore type 2 melanges are difficult to distinguish from type 1 melanges and may have been found preferentially where large outcrops exist. Because many of the outcrops are small it is likely that type 1 has been mapped instead of type 2 and "exotic" blocks are hidden in some of the localities. Nevertheless the two melange units units have been distinguished where possible. Another observation indicating the existence of both types is seen in the non- disrupted phyllite and quartzite sequence which locally grades into its highly disrupted equivalent. Southeast of the "Florence Nappe" a type two melange zone extends in an approximately north/south elongated belt of several larger outcrops. This zone contains very large blocks of Eddy Hill type quartzite up to 3 meters across. Figure 5 shows a "small" block of quartzite at this location. The smaller blocks and pebbles are also of the same lithology. The size of some of the blocks is much thicker than equivalent beds found in the Browns Pond Formation. The predominance of blocks of black and gray quartzite and the occurrence of phyllite and pebble grit elsewhere may suggest that at least parts of the melange sequence had formed from the disruption of Taconic units. There is no question that the non-disrupted phyllite and quartzite sequence as well as the melange units have been mapped as Ira Formation by Zen (1964). Blocks and pebble grit are described in Zen`s Forbes Hill Conglomerate. Potter (1972) describes a similar unit, the Whipstock Breccia, from the Hoosick Falls area about 50 miles south of Rutland. The breccia occurs as lenses in the Walloomsac slate which is an equivalent to the Ira formation of the present area, and contains small intraformational silt fragments and large blocks of carbonate. Slices of carbonate comparable in size to the "Florence Nappe" are also included in the Whipstock Breccia. Zen (1964) revived Keith`s Ira Slate for the black Middle Ordovician phyllites east of the Taconic Range because these units cannot be traced into the Hortonville Formation of the western Taconic region. Nevertheless, his structural interpretation of the Ira is identical to that of the Hortonville. In this map area most of what has previously been mapped as Ira Formation is Taconic and the remaining phyllites are possibly older than the Hortonville Slate west of the allochthon. They are probably very early syntectonic deposits accreted underneath the main Taconic thrust plate. It is also possible that most of the phyllite/quartzite lithology is a distal equivalent of the Poultney Formation as discussed earlier. However, the unit described forms a thick melange sequence and does not closely resemble the authochthonous Hortonville Slate west of the Taconic Range.

2.3.9. Middle Ordovician Phyllites

The Hortonville Slate and Ira Formation in the sense of Fowler (1950) and Zen (1961) as stratigraphically (conformably to unconformably) overlying the authochthonous shelf carbonates essentially do not occur in the field area. Equivalent units may have been incorporated into the melange sequence. A few outcrops which lie structurally below the basal thrust surface exhibit a black graphitic well cleaved fissile phyllite which does not contain pebbles of quartzite or other fragments. These particular phyllites could be Middle Ordovician in age.

2.4. Igneous Rocks

Diabase dikes are more or less characteristic for the region. Dale (1912) describes a few dikes where they cross-cut the marbles of the Vermont Valley. Several dikes occur in the phyllite ridge between Proctor and West Rutland and in the adjacent marbles. These dikes are definitely late features as they are not affected by metamorphism and show no deformation (Dale, 1912). A small dike about two feet thick has been found in a small quarry in the phyllite along the Whipple Hollow road near the southern end of the field area (outcrop 8 on plate 1). The dike cannot be traced more than a few meters and the outcrop will subsequently be destroyed by future quarry activity. A thin section from this dike shows plagioclase, brown hornblende, augite, magnetite and secondary calcite in an intersertal texture.

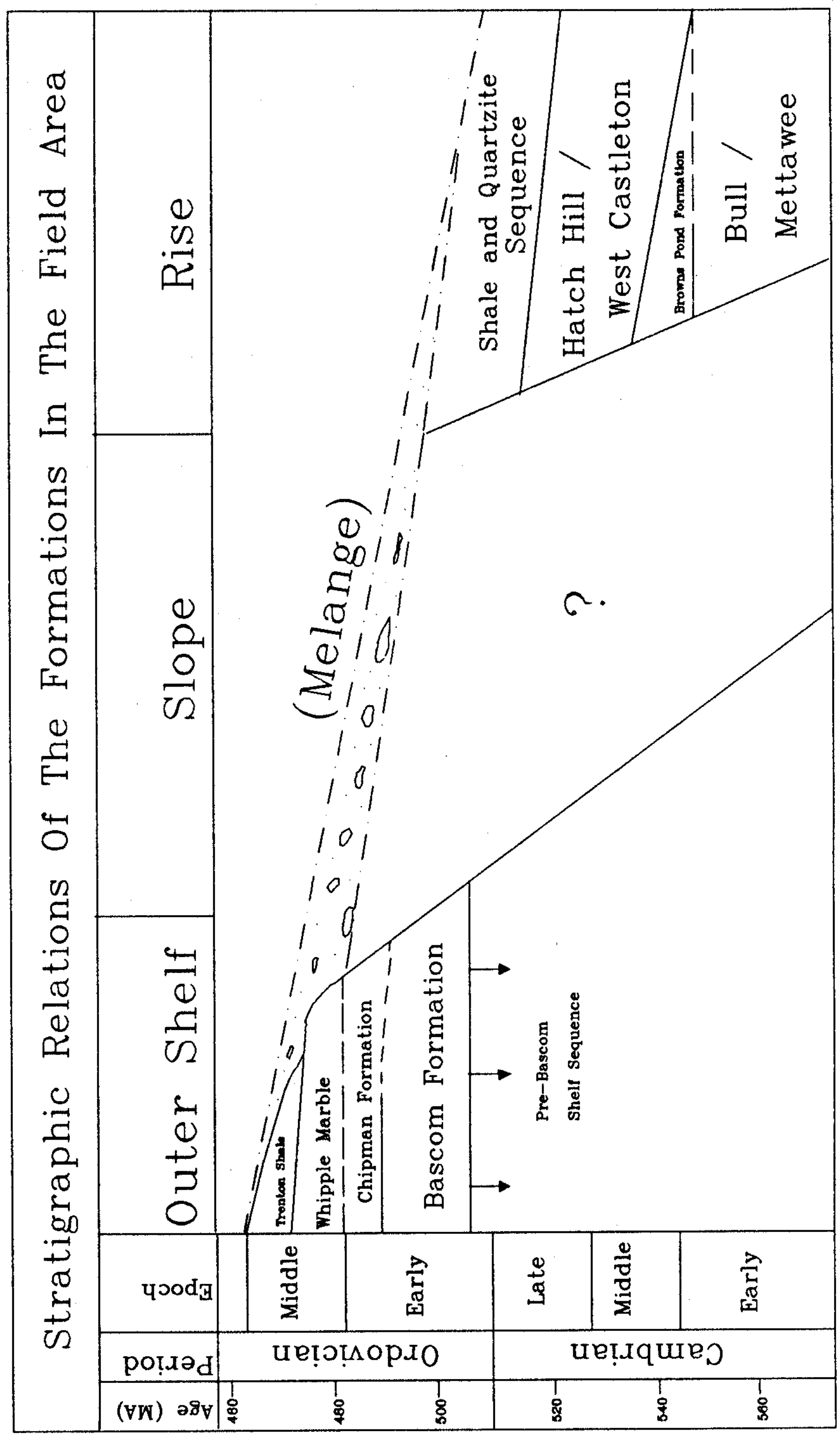


Figure 6: Stratigraphy of the field area

2.5 Summary and Discussion of the stratigraphic units of the field area

Only fragmentated sections of the Taconic lithology are preserved within the thrust sheets of the map area. Therefore some of the formations which have been described are probably very incomplete. In some places stratigraphic relations are highly interpretative and result from the comparison with better defined formations elsewhere in the allochthon. It is not possible to determine the thickness of individual units better than the maximum thickness which is exposed. Nevertheless, the previous descriptions show that many characteristic Taconic lithologies are present. Other rocks very likely resemble distal facies equivalents of other Taconic units which have been described further to the west. Instead of finding thick sequences of Middle Ordovician phyllites, the study area is characterized by more Taconic lithologies than previously thought; in addition most of the remaining black phyllites consist of type 1 and type 2 melanges. These melanges are not restricted to narrow fault zones, and type 1 melanges, especially, are distributed as thick sequences in close association with Taconic lithologies.

Figure 6 shows the proposed stratigraphic relations for the area. Compared to Rowley et al. (1979) the late Early Ordovician Indian River and Mount Merino Formations are definitely missing. The existence of the Early Ordovician Poultney is proposed but cannot be proven. Obviously the disrupted phyllite and quartzite sequence is lithologically not much different from the interbedded Phyllite/quartzite sequence. If the latter is Poultney the former may be related to mid-Ordovician thrusting and the incipient stacking of Taconic slices. This would in fact explain the lack of Indian River, Mount Merino, and also Pawlet Flysch from most of the eastern Taconic regions. However, the age problem of the melanges is more complex. Melanges of different ages can tectonically become mixed and the older melange may be incorporated into the developing one. Moreover, melanges may also form locally in fault zones which cross-cut older melange units.

Since the thrust geometry is quite complex such relations are likely to exist in the field area. The quartzite pebbles in the melange unit are unlikely to have been derived from the Hortonville Slate and are apparently related to the incorporation of older, pre-Middle Ordovician deposits. Phyllites which conformably or unconformably overlie the carbonates have not been found except for the two locations where the Whipple Marble grades into a calcareous phyllite. Other rocks which are very likely Middle Ordovician (probably earliest Middle Ordovician in age) and which do not represent a melange have rarely been found. These phyllites may crop out underneath the "Florence Nappe" and in front of the Whipple Hollow Fault.

Two explanations for the apparent lack of these phyllites are possible:

1) The rocks were tectonically removed during the early stages of Taconic overthrusting and developed into a thick basal melange sequence.

2) The Middle Ordovician phyllites which probably lie underneath the Taconic Allochthon have been truncated by rocks of the carbonate sequence along faults of the Frontal Thrust System. Subsequently the phyllites are restricted to fensters in the Taconic thrust belt.

A combination of 1) and 2) would explain why carbonate slices along the basal thrust surface are most commonly found in direct contact with Taconic phyllite and that the basal thrust surface is elsewhere defined by a very complex and thick melange sequence.

In contrast to Zen (1964) and Fowler (1950) no authochthonous Middle Ordovician phyllites have been identified. All units are considered to be allochthonous in origin. Black phyllites which probably resemble the Hortonville Slate are so minor in extent that they are better included in the melange sequence. As mentioned earlier most of the eastermost Hortonville must have been incorporated into the basal melange.

CHAPTER 3

STRUCTURE

3.1 General Statement

The present area consists predominantly of phyllites and thin bedded (mm to several cm) phyllite/quartzite lithologies. Thicker arenite beds, as well as beds of graywacke, ranging from a few to several feet thick, occur in a few places. Bedding can usually be seen in the thicker and competent layers, whereas no traceable depositional layers occur in the phyllites, which are characterized by the prominence of cleavage surfaces. Lithological layering if present is boudinaged, transposed or highly crenulated and often modified by pressure solution effects. In some of the Taconic phyllites a secondary layering is so well developed that it may be mistaken for primary bedding. In the carbonates, bedding is more prominent, but it may be difficult to find in outcrops of highly deformed sections, especially where thick, competent dolomite layers are missing. All rock units are folded but the observation of folds is more or less restricted to small scale structures because the overall outcrop is poor. Only a few larger outcrops exist which are located in the cores of overturned synclines. Centimeter-scale folds can be seen in many outcrops and are either late crenulation folds of D_3 generation or predate the regional folding event (D_2) and are of D_1 generation. Some of these folds may be syndepositional slump folds but because of the extreme shortening during later deformations this can by no means be demonstrated. Meter-scale folds are very difficult to assign to the correct deformation event because the beds which show these folds mostly lack associated axial plane cleavages. Cleavage planes are often folded also indicating a poly-deformation history. Thrust faults are generally very difficult to recognize but are much better defined where phyllites are in contact with the marble belt and in places where a melange is present. In addition major faults are often characterized by topographic expressions such as linear steep ridges or flat swampy areas.

Figure 7: Bedding in wacke of the Hatch Hill Formation.

3.2. Outcrop-Scale Structures

3.2.1. Bedding

Bedding is a useful indicator for structural relations. It may be used to determine the younging direction in a folded sedimentary pile; moreover folds and fold styles can directly be observed where bedding planes are distinguishable. In the field area bedding is usually present in the carbonates and mostly absent in the phyllites of the Taconic sequence. Thicker arenite beds occasionally occur in the phyllites but although some of the beds are quite thick these layers never continue for more than a few meters. The quartzite beds are definitely channel fillings rather than continuous horizons; the folded beds often weather into small ridges or elswhere emerge in a small outcrop above the surrounding phyllites. Figure 7 shows bedding in a rusty weathering wacke which probably belongs to the Hatch Hill Formation. Bedding is rarely so well exposed as seen in the outcrop of the photograph. Other quartzite lithologies are more homogeneous and bedding planes are less well defined.

A color contrast within the phyllites may easily be mistaken for bedding. Although a lithological contrast of depositional origin can never be ruled out, the color changes observed in the phyllites are very likely a result of metamorphism. This is clearly seen in the large road cuts along US Route 4 between West-Rutland and Castleton where green and purple phyllites interfinger in complex patterns which cannot be primary bedding. Therefore color changes within the phyllites, especially where little outcrop exists, should be treated very cautiously. A compositional change or a change in grain size in addition to a color contrast is a more reliable indicator for bedding. However, metamorphic differentiated layers may still be mistaken for bedding planes as discussed in 3.2.2.

Fine-scale lithological layering is much more common than thicker bedded sedimentary layers. Where present this lithological layering is rarely less deformed than shown on the image of a sawn slab in Figure 8. The interbedded phyllite and siltstone layers are likely distal turbidites and of sedimentary origin. The layers are usually highly deformed, boudinaged and transposed and also modified by pressure solution effects along cleavage planes.

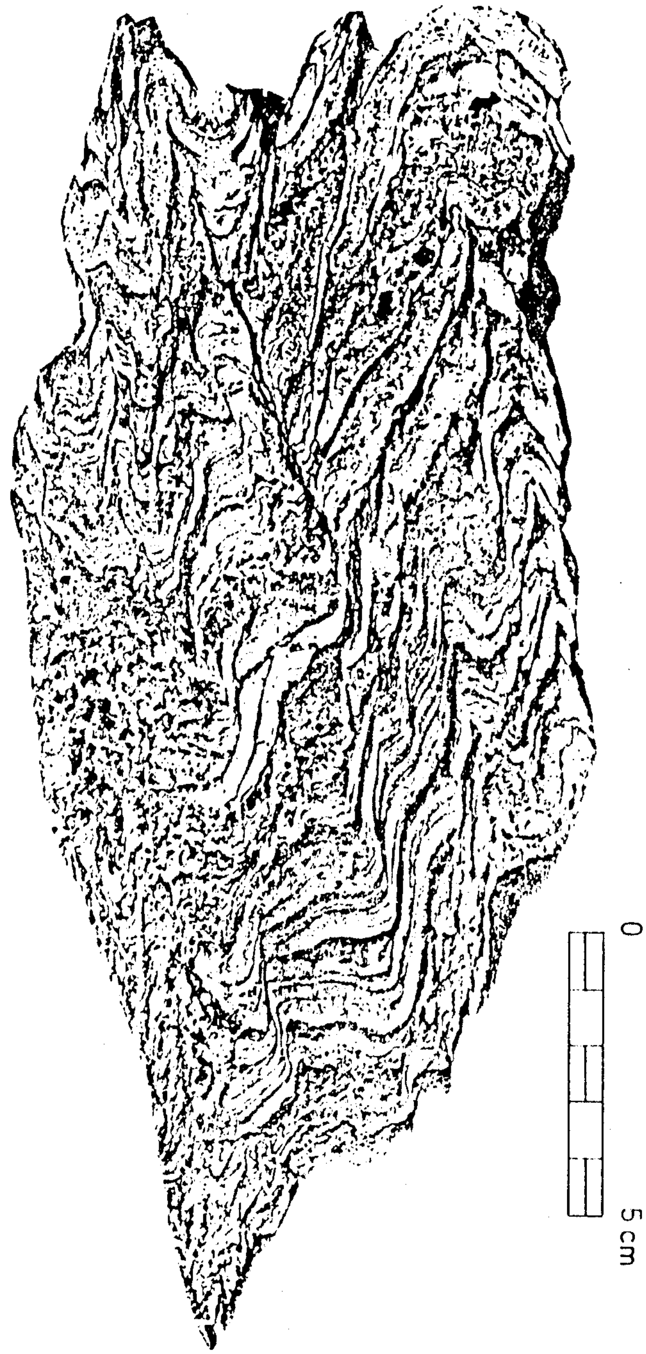


Figure 8 : Image of a sawn slab : Lithological layering in a sample of the Cambrian Bull Formation. White layers are silty quartzites; darker domains represent shaly partings.

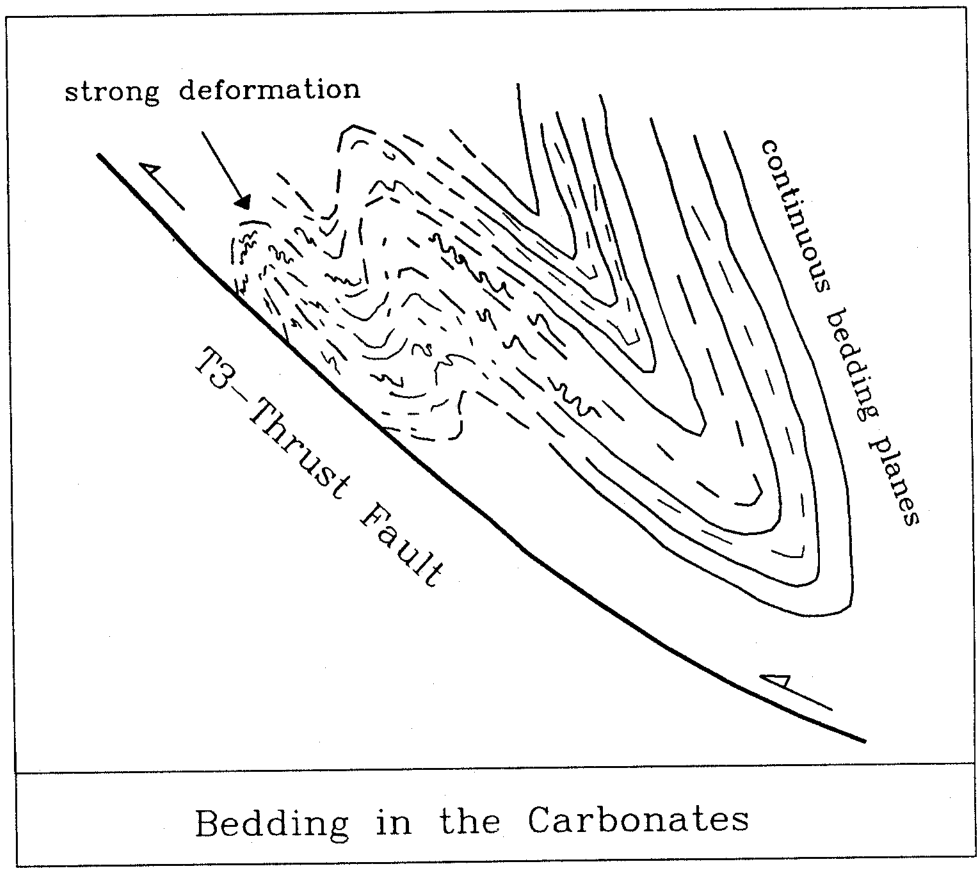


Figure 9: Control of cross-cutting thrust faults on the deformation and preservation of bedding planes in the carbonates.

Bedding in the carbonates is more prominent than in the phyllites. On the other hand the limestones and dolomites have been metamorphosed to marble, have probably also experienced pressure solution reactions, and are locally as much deformed as some of the phyllites. The preservation of bedding planes throughout a deformation event probably depends on the initial competence and thickness of the layers besides the overall pressure and temperature control, presence of fluids, etc during deformation. In addition, the structural position in a fold as well as the distribution of cross-cutting thrust faults may have a major control on the preservation of bedding surfaces after deformation, as illustrated in Figure 9.

In general dolomite beds appear to have deformed more brittly than adjacent beds of calcite marble. Beds of dolomite are easily recognized; they are commonly fractured and healed with calcite or quartz. Veining is usually absent in the neighbouring calcite marble. Thus, the calcite beds must have deformed in a more ductile manner and bedding planes are strongly deformed or not observable. In other places the entire marble is so highly deformed that boudinaged pebbles and blocks of dolomite float in a complex laminated matrix of calcite marble. Such a highly deformed outcrop is shown in the photograph of Figure 10.

Bain (1933) called the highly deformed appearence "Flowstructure" in order to emphazise the extremely ductile behavior found in some of the marbles.

Figure 10: Strongly deformed marble showing boudinaged blocks of dolomite in a more ductile behaving matrix of calcite marble.

3.2.2. Differentiated Layering

In addition to primary sedimentary structures a secondary metamorphic layering is commonly present in the phyllites. These metamorphic differentiations are closely related to cleavage development and therefore can be distinguished into two groups, due to S_1 and S_2. The earliest differentiation lies in the S_1 cleavage plane and simply results from clay- and quartz rich domains. In hand specimen it can be noticed as a very fine and thin white lamination of the quartz rich layers. Very often this lamination can only be seen on a sawn surface of a hand sample and can hardly be identified in the field. This lamination is present in phyllites of the Taconic Sequence and also in the melange unit.

In contrast to the S_1-lamination, the S_2-crenulation cleavage can differentiate much thicker layers. These layers may actually be mistaken for sedimentary laminations or beds. The layering has probably developed most strongly where pressure solution and material transfer was acting along discrete crenulation planes. In black phyllites the differentiated layers are always defined by darker clay-rich and white quartzose layers. In the green/greenish phyllites of the Bull Formation quartz- and chlorite rich layers form these laminations. On intersecting surfaces this differentiation may produce a prominent chlorite lineation. A thin section shows that besides chlorite a large number of opaques are concentrated in the chlorite domains. The opaque materials must be responsible for the dark color of the layers.

3.2.3. Cleavage

Three tectonic foliations are present in the rocks of the field area (S_1, S_2, S_3), which display a variety of cleavage morphologies (as for example seen in Figure 11).

S_1 is a penetrative early cleavage which is present in many of the phyllites. This early cleavage is usually crenulated by the main regional cleavage S_2 although this cleavage has very often developed parallel to S_1 and simply overgrown the pre-existing fabric. The main regional cleavage is thought to lie approximately axial planar to the larger folds which are suggested from the geological map. S_2 is locally crenulated by a second crenulation cleavage S_3.

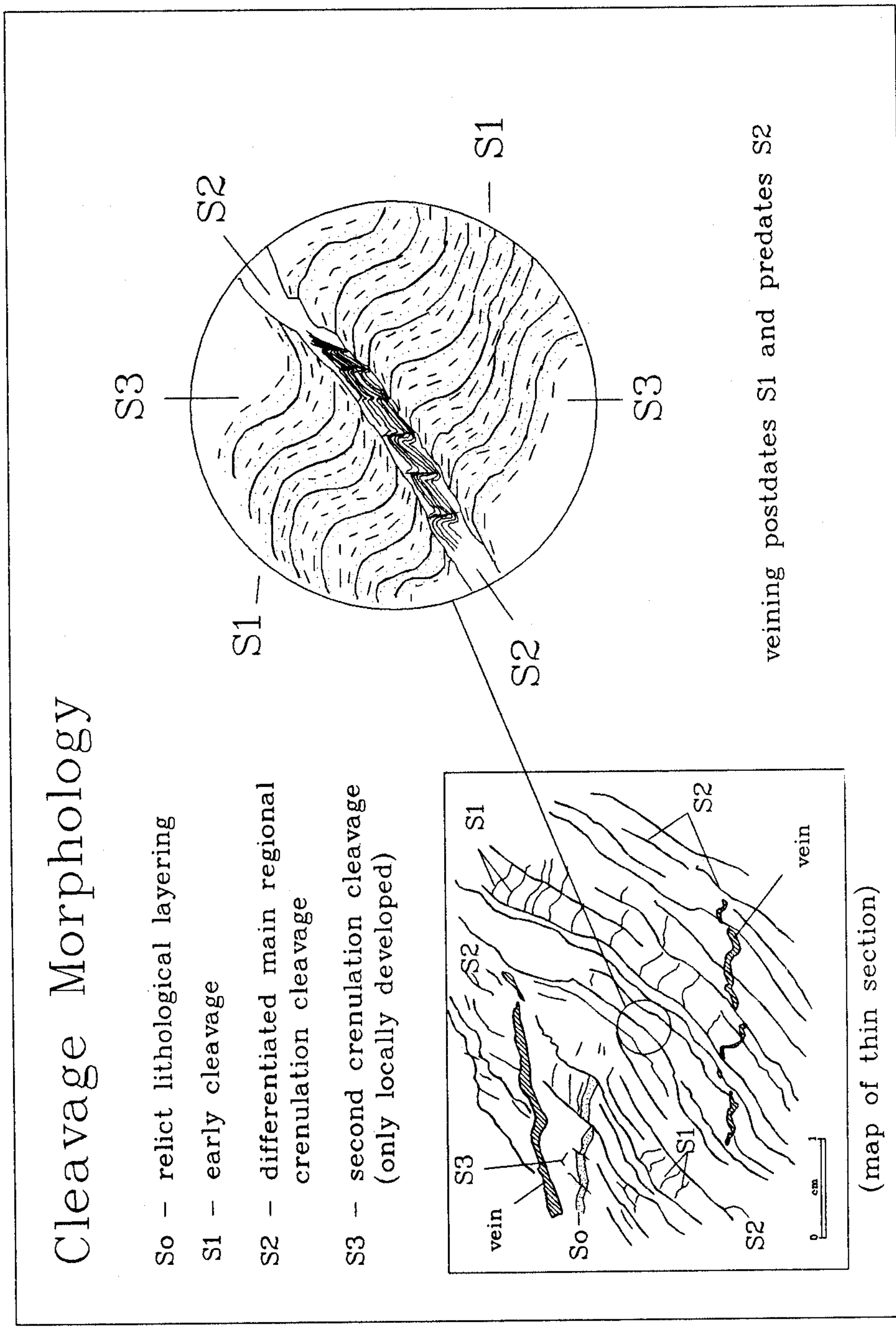


Figure 11: Cleavage morphologies in thin section

The presence of three cleavages does not necessarily indicate three separate tectonic events. Williams et al. (1969), for example, describe an axial plane cleavage which had developed prior to consolidation of Devonian sediments from New South Wales, Australia. Williams (1977) also pointed out that an axial plane foliation may locally overprint itself. The number of cleavages observed in a few outcrops may therefore not always be representative for the entire region. Fine grained pelitic rocks, especially, as explained to me by Prof. Winthrop Means, are extremely sensitive to incremental changes in the direction of principal stresses and associated strains and may locally develop weak crenulations and otherwise unexplained intersection lineations. If on the other hand the observed cleavage relations are more or less consistent over a wide area, each foliation is likely to represent a certain stage in the deformation history of the region. In a progressively developing thrust belt, cleavage formation is probably variable with respect to space and time. It could be possible that the main regional cleavage (S_2) developed in already obducted sediments, while S_1 was still forming in a deeper part of the accretionary wedge (Figure 12). Moreover, most of the western Taconic region probably never experienced S_1 cleavage development as S_1 was very likely restricted to considerable depth and metamorphic conditions in the former subduction zone. On the other hand the rocks which probably experience S_1 cleavage development will be the last to move onto the shelf compared to the younger more recently accreted sediments. As the second cleavage (S_2) is thought to be related to thrust folding during incorporation of carbonate slivers and the obduction of the accretionary prism onto the shelf (Figure 25) such relations would be explained. In this view the numerical order of cleavages only implies a different stage within the deformation history and each stage is not necessarily considered to define a single synchronous event.

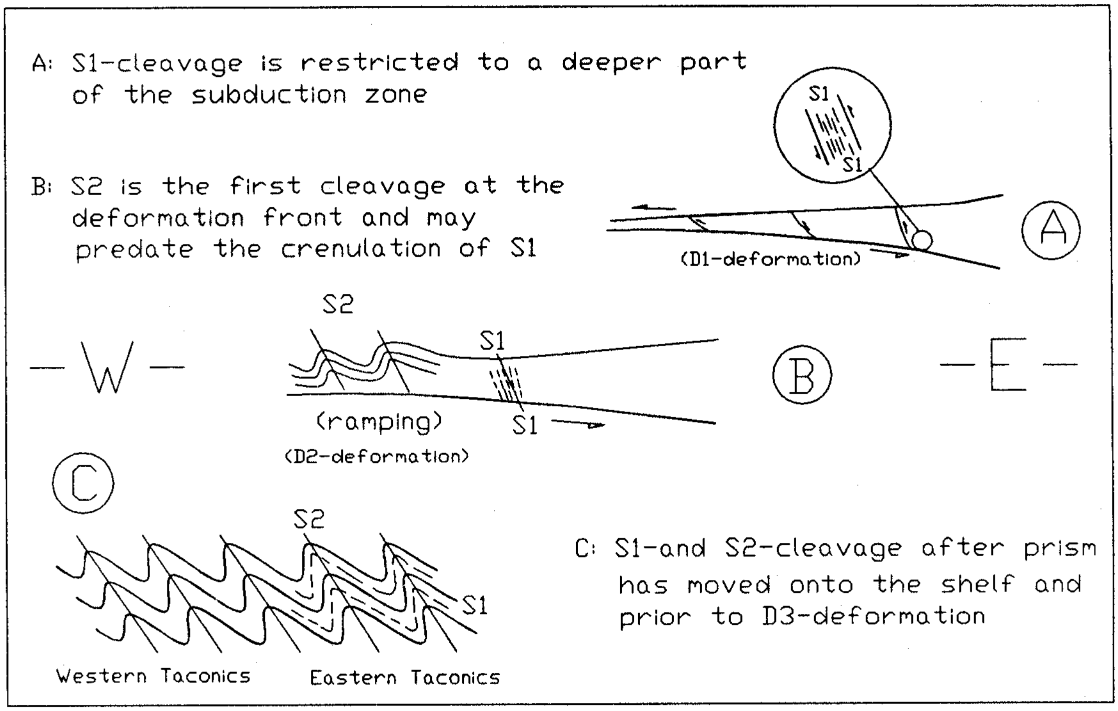


Figure 12: Possible relation between S_1-and S_2-cleavage

Early Cleavage (S_1)

In the western Taconic region the main regional cleavage (S_2) is the first tectonic foliation (Rowley, 1983). It is referred to as "S_2" because this cleavage represents the axial plane to folds of the "main regional deformation event" (D_2). Earlier folds of D_1-generation pre-date the S_2-cleavage development but according to Rowley (1983) the F_1-folds lack an associated S_1-axial plane cleavage. In the field area the S_2 is also considered to lie axial planar to larger regional folds and the similarity with Rowley`s deformation history is quite evident. The early cleavage in the field area is likely to represent the missing S_1-cleavage in the western Taconic region. However, the character of this early cleavage is probably more complex and S_1 may not only be viewed as the axial plane foliation to folds which predate the "regional folding event" of Rowley (1983). It has not been possible to demonstrate conclusively that S_1 lies axial planar to an observable fold. As a matter of fact this may be because folds are rarely seen within the phyllites. On the other hand where sedimentary laminations (S_0) are present S_1 appears to have developed more or less parallel to the former. A close observation from a number of thin sections shows that S_1 is approximately parallel to S_0 (where present). S_1 has not been found at a high angle to So but it is possible to demonstrate an obliquity of 10 to 15 degrees in a few places. It remains difficult to decide whether S_1 is an axial plane foliation associated with tight folding during D_1-deformation or not. This relationship may be difficult to prove because F_1-generation folds have probably been refolded, disrupted or highly deformed by the later deformations. On the other hand it is hard to understand why S_1 has never been found to transect sedimentary laminations at a high angle as expected to be seen in the hinge region of these folds. Although strongly modified by later deformations such a relation ought to have been observed in a few hand samples or thin sections. A penetrative and strongly developed early foliation in the absence of a regional folding event is probably not uncommon for accretionary complexes and is possibly recorded in the rocks of the field area. This suggestion results from the following considerations. Williams (1977) in a review paper about foliations discusses what he calls the "dewatering hypothesis". This hypothesis resulted from the suggestion of several workers that cleavages may form due to the combined effects of depth of burial

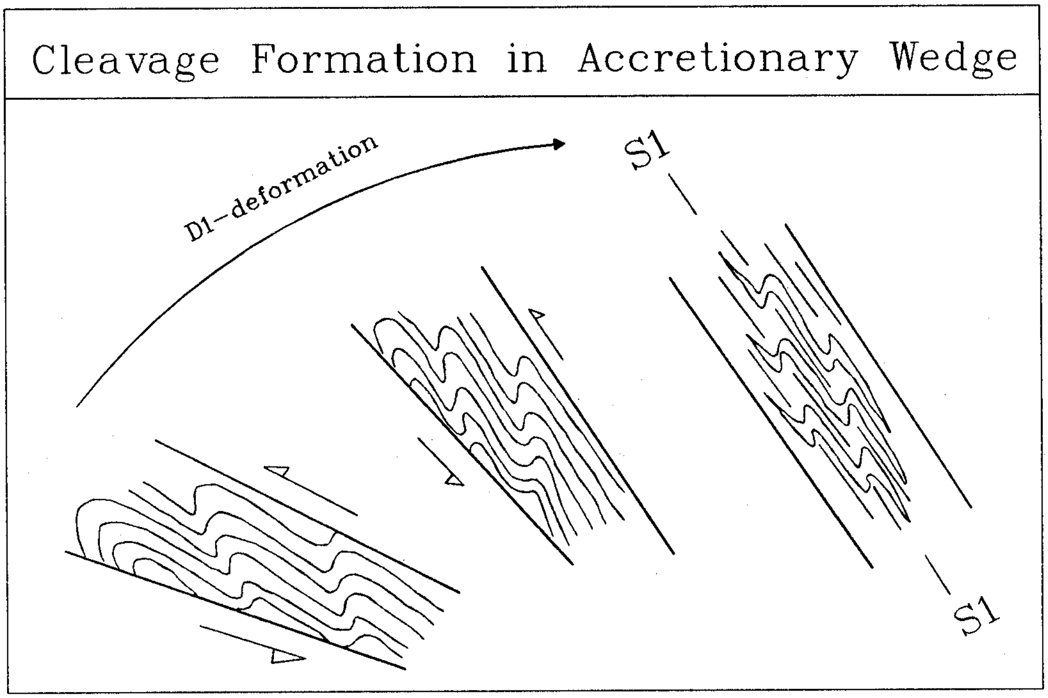


Figure 13: Cleavage development during D1-deformation in a deeper part ot the accretionary prism

and deformation. Williams concluded that the dewatering hypothesis is certainly not the general mechanism for cleavage development; however, he took into account that lithification under diagenetic conditions followed by pro-grade metamorphism may produce a strong foliation. Powell and Rickard (1985) report a well developed foliation that pre-dates a differentiated crenulation cleavage related to the first generation of mesoscopic folds from Bermagui, Australia. This was a different structural interpretation compared to Williams (1972) who considered this early foliation to be a late structure inheriting a depositional orientation. This problem is quite difficult to approach but it is important to recognize that, under special circumstances, a simple "dewatering" compaction, shaly parting-derived, fabric may develop into a metamorphic foliation which is not different from a typical slaty cleavage or axial plane foliation. Sediments which are accreted into a sedimentary wedge may be characterized by pre-existing dewatering or compaction fabrics. Once incorporated into the prism these rocks experience a progressive deformation path and, probably, metamorphic conditions in a deeper part of the prism. A possible mechanism for S_1 cleavage development is illustrated in Figure 13. However, too little is known about cleavage development in accretionary wedges and my study of this early cleavage is not conclusive enough to discuss this problem any further. A detailed study of the early foliation found in my area would perhaps reveal more information about the nature of cleavage formation in accretionary prisms. It would be a promising project because the Taconic Allochthon from west to east appears to display a variety of structural levels of a former accretionary wedge. The conclusion for the rocks of the field area is that S_1 represents a strong metamorphic fabric. It is possible that S_1 is an axial plane foliation to early accretion related folds. On the other hand S_1 may also be the result of metamorphism during progressive overprinting of a pre-existing compaction fabric and\or otherwise may result from shearing and progressive compaction and shortening approximately normal to an older sedimentary layering under metamorphic conditions.

Figure 14: Core of main regional syncline overturned towards the west. To the right of compass S_0 bedding lamination can be seen. S_2-main regional cleavage is a poorly developed fracture cleavage trending from the upper left to the lower right. The S_1-cleavage lies subparallel to S_0 and is strongly folded and crenulated in this outcrop (location 9 on Plate 1).

Figure 15: Outcrop showing the prominence of the S_1-cleavage and S_0 lithological layering in the core region of a larger fold of D2 generation. The S_2-main regional cleavage is more or less absent.

Figure 16: Possible range of fanning S_2-cleavage in core of main regional fold. The phyllites in the photograph belong to the Cambrian Bull Formation.

Main Regional Cleavage (S_2)

The second cleavage is an axial plane foliation to the larger folds of the area and is superposed on the pre-existing cleavage S_1. Strictly, S_2 is a main regional crenulation cleavage. S_2 cleavage morphologies are extremely variable and strongly depend on the lithological characteristics of the rocks. Three outcrops, each located in a west vergent syncline of D_2-generation, are shown in the photographs of Figures 14, 15, and 16. In Figure 14, the S_2-cleavage is a poorly developed fracture cleavage because of the abundance of many fine quartzite layers and a more "sandy" shale matrix. A thin section has been prepared from a sample to the right of the compass which was cut approximately in the plane of the photograph. A lithological lamination is defined by dolomitic quartzite layers and the early cleavage S_1 lies subparallel to S_0. The S_2-crenulation cleavage can easily be identified in thin section and locally refracts where it crosses the compositional layering.

The outcrop shown on Figure 15 is from the same locality, however, in this photograph the main regional cleavage is apparently missing and the outcrop is dominated by S_0 and S_1 related structures. In strong contrast to this location Figure 16 shows a fold in the fine grained pelites of the Bull Formation where S_2 has developed into a prominent axial planar fanning cleavage. The dip angle of this prominent foliation varies, as indicated in the diagram below, over a considerably wide range and this feature may be what causes difficulties for the correct assignment of cleavage generations, especially because the dip of the folded S_1 cleavage can vary within the same range. In many places a cleavage which appears to be a strongly developed main regional foliation is possibly seen in favor of the pre-existing S_1 cleavage. The exact relations between the two foliations may not always be clear as indicated on the photographs of Figure 17 and 18. The outcrop in Figure 17 shows a well developed cleavage dipping 50 degrees to the east and approximately parallel to a thicker quartz-rich sedimentary layer. In the entire outcrop the dominant cleavage appears to be locally bent and curved like sedimentary layers often are on a limb of a fold. Ignoring this observation and the possibility of a prominent layer parallel cleavage S_1, the photograph would suggest a strongly developed bedding parallel main regional cleavage (S_2). If present, S_1 on the other hand would have the same orientation

Figure 17: Well defined cleavage planes approximately parallel to the quartz-rich bed in the lower left corner of the photograph. The distinction between the S_1-cleavage and the S_2-axial plane cleavage is not always possible (see text for discussion).

Figure 18: Strongly cleaved phyllite which probably exhibits the S_1-cleavage instead of the main regional cleavage (S_2). Cleavage planes are bent and slightly folded in this outcrop.

as the cleavage shown on the photograph. Therefore either S_1 or S_2 is exposed in this outcrop, or more likely, both foliations are present. S_1 may cause the slightly curved and folded cleavage planes, whereas the S_2-main regional cleavage could be responsible for the disruption and fracturing of these planes. This interpretation of the outcrop favors the overall prominence of S_1-related cleavage planes at this location which lies 50 meters east of the outcrops shown in Figures 14 and 15. A similar situation is seen in the phyllites of the photograph of Figure 18. Here a single prominent foliation dips about 45 degrees to the east. The cleavage surfaces of the entire outcrop also appear to be somehow bent or probably folded and in the absence of any lithological marker in the fine grained lithology the distinction between S_1 and S_2 is a difficult question. The presence of a dominant cleavage of S_1-generation is suggested from other localities in the field area. During the early stages of my field work I was influenced by the suggestion of Rowley et al. (1979) that the Taconic phyllites are characterized by two eastward dipping cleavages and that the main regional cleavage is locally crenulated by a more steeply dipping cleavage. A number of outcrops in the field area, however, show a reversed relationship and a steep dipping foliation (60-80 degrees to the east) is being crenulated by a moderately dipping cleavage (40-55 degrees to the east). This relation was not understood until the presence of three cleavages became apparent. These outcrops strongly support my conclusion that S_1 and S_2 are the two prominent cleavages seen in the rocks of the field area.

Second Crenulation Cleavage (S_3)

In thin sections the S_2 or S_1 cleavage is often crenulated on a very fine scale. The third cleavage (S_3) on the other hand has rarely been found to represent a penetrative fabric, comparable in morphology to the S_1 and S_2 cleavage planes. A possible explanation could be that S_3 is commonly of a zonal type and in addition is only weakly and very locally developed. In a few places however, S_3-crenulations are extremely strongly developed and as a result the entire outcrop may be dominated by cm-scale crenulation folds. These outcrops appear to occur preferentially near T_3-thrust faults and suggest that the S_3-crenulations are related to this deformation. An example of this late cleavage is shown in

Figure 19: S_3-crenulation cleavage dipping towards the east with prominent cm-scale crenulation folds. S_3 is superposed on S_0-lithological layering and the associated S_1-cleavage.

Figure 19. S_3 is strongly developed and crenulates S_0 and the associated early cleavage (S_1). The crenulation cleavage dips about 65 degrees to the east but as the main regional cleavage S_2 is not clearly seen at this location the interpreted S_3-cleavage could possibly represent the former. On the other hand the cleavage morphology which is associated with small-scale crenulation folds appears to be different from the typical main regional axial plane cleavage (S_2). This structure is probably related to shearing and very likely a result of T_3-thrusting. The trend of S_3 crenulation folds is very consistent throughout the mapping area and the fold axes plunge almost exclusively 5-15 degrees to the south (Figure 20).

3.2.4. Veins

Veins have not been studied in a systematic way because where present these are usually strongly deformed, boudinaged, and disrupted in a way very similar to the structures which are associated with the deformation of lithological layers. This observation strongly suggests that most of the veins pre-date the regional folding event and perhaps have formed during or just before D1-deformation in the accretionary environment. In the thin section illustrated in Figure 11 for example, very fine quartz veins are approximately oriented parallel to the S_1-cleavage and are clearly crenulated by the second cleavage (S_2). As the veins post-date the early cleavage (S_1) these must have formed in between S_1- and S_2-cleavage development.

Other veins may be related to the regional folding event and the Basal Thrust System which was active during D_2-deformation. Because veining could have occured throughout the deformation history some outcrops may display a rather complex pattern of deformed veins; representative examples are illustrated in Figures 21 and 22. The location shows the core region of a syncline (near where it is truncated by the Proctor Fault) at the north end of the field area (section A on plate 1). Figure 21 illustrates a set of boudinaged quartz veins which are oriented in the plane of a strong foliation. The quartz veins/boudins define a dominant apparent stretching lineation trending from the left to the right (south to north) in the photograph.

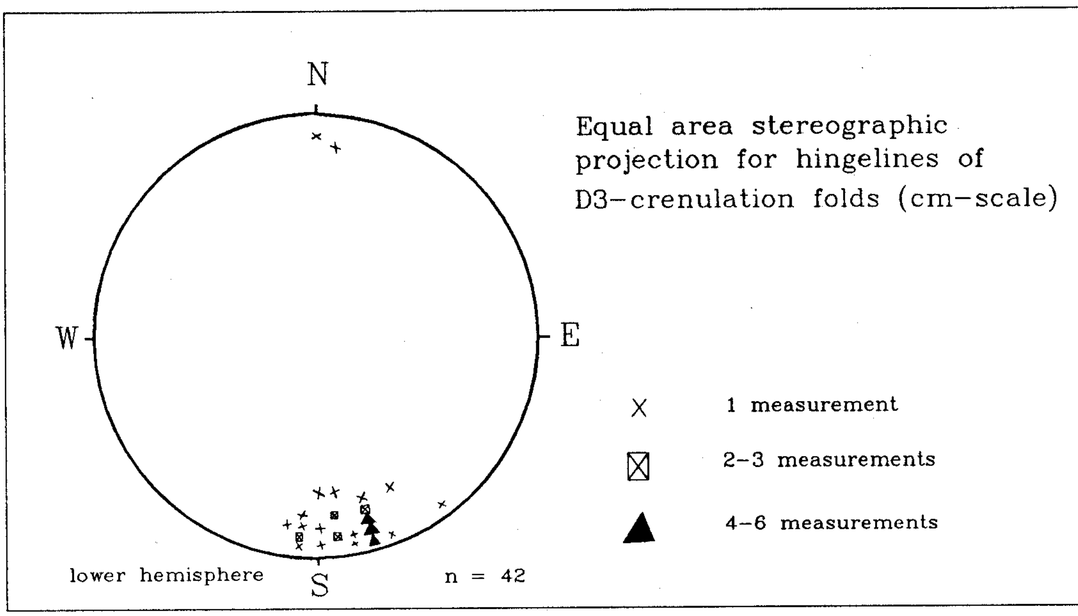


Figure 20: Orientation of S_3-crenulation folds

Figure 19: Deformed and boudinaged quartz veins. Prominent stretching lineation is oriented approximately north/south (left to right).

Figure 22: Outcrop showing a complex deformation pattern of quartz veins. In the absence of lithological layers some of the veins exhibit small D_3-crenulation folds (center of photograph).

In Figure 22 the quartz veins and quartz boudins are strongly folded. Different generations of quartz veins are likely to be present. To the right of the hammer and in the center of the photograph the quartz veins, in the absence of any lithological layers, define cm-scale D_3-crenulation folds. A detailed structural study of most of the quartz veins would be very time consuming and would probably not contribute conclusive results for the regional structural interpretation. On the other hand the presence of quartz veins is helpful to recognize the extent of deformation in some of the outcrops.

3.3. Larger-Scale Structures

3.1 Folds

It has already been mentioned that the observation of folds is restricted to outcrop-scale structures. Larger outcrops often display the core region of a larger, main regional fold. These folds are asssociated with the main regional crenulation cleavage S_2 (Figure 14 and 16). The map pattern of my geological map appears to be be controlled by this folding event except for fault related structures. Also these folds have probably been tightened during D_3-deformation. The possibility of larger accretion-related folds which are related to the S_1-cleavage has been discussed in the previous section. Folds of this generation which exceed the scale of a few meters have not been found in the field area. Larger refolded folds are either not present, not observable, or otherwise too small to be detected given the inevitable inaccuracies of the geological map. Large folds which form during the accretion of sediments into an accretionary wedge are possible and have for example been described by Moore and Karig (1976) from the Shikoku subduction zone, southwestern Japan; nevertheless the Taconic sedimentary wedge in the field area exhibits D_1-accretion related fold structures only on a relatively small scale compared to the dimensions of the regional folding event. However, larger F_1-folds may easily be concealed in the majority of fine grained pelitic rocks.

Folds which unquestionably post-date the regional event are restricted to cm-scale crenulations and do not disturb, disrupt or modify the pre-existing D_2-structures. In summary, larger folds can only be related to the main regional folding event. The main regional folds trend approximately north/south

Figure 23: Core region of a D_2-anticline refolding D_1-related structures in the lower right corner of the photograph.

and are interpreted to be generally west vergent and more or less asymmetric as seen on the sections of the geological map. The outcrop in the photograph of Figure 23 shows an anticlinal structure of D_2-generation. Due to the quartz-rich lithology the fold is observable but lacks a well developed axial plane foliation. The complex crumpled structure in the lower right half of the photograph probably predates the fold itself and was refolded by the latter. The structure is very likely of D_1-generation. Although the map appears to indicate a larger north plunging anticline at the north end of the field area this pattern can also result from a non-horizontal initial orientation of the Basal thrust surface prior to the folding event.

3.3.2 Thrust Faults

Many thrust faults are responsible for the juxtaposition of the stratigraphic units in the field area. The existence of the Taconic overthrust was the starting point for this study. A simple thrust relationship between the Taconic rocks and the shelf carbonates on the other hand does not adequately explain the complexity of the region. Instead three thrust generations are responsible for the distribution of the map units (plate 1) . The faults which are shown on the geological map are the minimum which is necessary to explain the map pattern and the occurence of the melange units. Many more smaller faults are possible and have either not been observed or may be hidden in areas of poor outcrop. Thrust faults may result in a variety of lithostructural geometries and the structure of a thrust belt can therefore be very complex. The basic rules for the development of thrust systems have been described in detail (e.g. Chapple, 1978; Boyer and Elliot, 1982; Butler, 1982). The application of any of these models must be based on a detailed geological map and the location of a sufficient number of fault zones. These requirements are quite difficult to satisfy for most of the region. Uncertain stratigraphic relations in the field area have been discussed earlier. Moreover, it is extremely difficult to recognize fault zones in the phyllites, unless very distinct units have been displaced. Even where the lithologic contrast is sharp and phyllites are in thrust contact with carbonates, this relationship is not always easily determined. The distribution of type 1 and type 2 melanges are probably the strongest evidence for tectonic movement. Still, it is by no means possible to draw a perfect solution in any of the cross sections on the map. Very often more than one structure is possible. The solutions shown on the map represent the simplest reasonable interpretation and an attempt to be more or less consistent along-strike in the mapping area. The structural synthesis requires three different thrust generations T_1, T_2, and T_3 which are defined below.

The schematic models which describe each thrust system should illustrate the development of the determined map structure. However the actual geometry is probably more complex, especially in detail, and modified by local variations in style and propagation of the faults.

T_1-Thrusting

According to Rowley and Kidd (1981) the Taconic slices had already been stacked into a composite thrust sheet prior to the overriding of the shelf. This view is a good working hypothesis because the allochthon itself is a more or less homogeneous structure compared to the chaotic transition zone that occurs between the non-disrupted shelf sequence and the allochthon. A comparable melange zone is missing in the Taconic sequence which suggests that the allochthonous wedge had formed in an earlier thrust regime. Thick wedges of sediments for example accumulate at the leading edge of overriding plates in many modern convergent settings (e.g. Karig and Sharman, 1975; Moore and Karig, 1980;). An equivalent model of thrust accretion for the Taconic slices has been proposed by Rowley and Kidd (1981). Although the deep structure of accretionary prisms is not fully understood (Moore et al., 1985) the basic accretion is thought to develop in a simple leading edge imbricate fan geometry (e.g. Moore et al., 1985; Moore and Byrne, 1987). Figure 24 shows a plausible scenario in which the Taconic slices are being stacked in the inferred T_1-accretionary thrust system. T_1-thrusts should have become progressively older and more steeply dipping from west to the east. All thrust faults sole into a basal decollement (T_{1B}) which separates the downgoing from the overriding plate. As summarized by Moore et al. (1985) it has been suggested that the accretionary style may also involve duplex structures. Although possible these would probably be difficult to demostrate for the Taconic Allochthon.

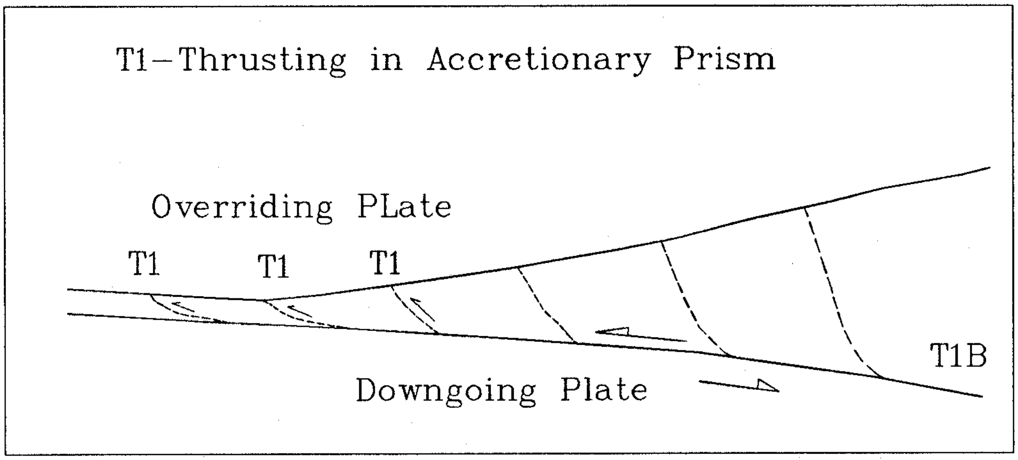
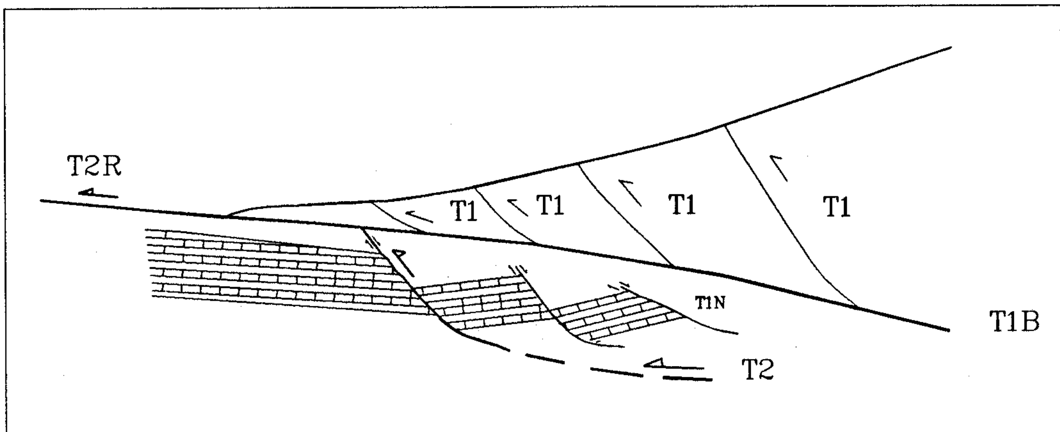


Figure 24: T_1-faults of the accretionary thrust system sole into the basal decollement (T_1B) which separates the overriding from the downgoing plate. The faults become progressively older and more steeply dipping from the left to the right (west to east).



T1	:	first generation thust faults
T2	:	second generation thrust faults
T1B	:	first generation basal decollement
T2R	:	roof thrust for second generation thrust duplexes
T1N	:	normal faults of first generation

Figure 25: Transition from T_1-thrusting into the Basal Thrust System (T_2). Incorporation of slivers of the shelf carbonates and the development of thrust duplexes underneath the basal roof thrust (T_2R).

The development of duplex structure is more characteristic for the T_2-Basal Thrust System as shown in Figure 25. In general T_1-faults which have formed within the accretionary Taconic wedge can hardly be recognized in outcrop. Stratigraphic inhomogeneities observed over a wide area such as a thick sequence of stratigraphically older rocks on top of younger Taconic units may indicate a larger slice boundary within the accretionary stack (unless the whole or a large part of the structure is upside down due to recumbent folding).

Such a T_1-thrust relationship is thought to exist in the field area. Still the fault can only be mapped by the observed black/green boundary in the phyllites. Thrusting in an accretionary environment is probably not restricted to a small zone. Moore and Byrne (1987) present a mechanism for melange formation and the stratal disruption of accreting sediments. They suggest a thickening of the fault zone as the deformation propagates into adjacent undeformed sediment. This is supposed to be the result of strain hardening, local drop in pore fluid pressure and the reorientation of faults during deformation. These mechanisms are possibly most important in submarine accretionary prisms where young and poorly unconsolidated sediments are rapidly deformed and dewatered (Moore and Byrne, 1987). The model may be true for the youngest Taconic sediments during the incorporation into the prism. Many of the older slope and rise sediments were probably well lithified before the onset of the Taconic orogeny. Neverthless these mechanisms perfectly explain the disrupted phyllite and quartzite sequence which is likely to have formed during T_1-thrusting. The accretion processes which have been described from subduction zones (e.g. Moore and Karig, 1976) and DSDP cores from forearc regions (e.g. Lundberg and Moore, 1986) suggest that in addition to large-scale slice boundaries a lot of small-scale stratal inhomogeneities within the Taconic sequence may be related to T_1-thrusting. An example of outcrop-scale disruption is shown in Figure 26. The fault zone is obvious because of the presence of a thick quartzite layer. In the more homogeneous phyllites secondary layering and cleavage development make the recognition of T_1-structures almost impossible.

Figure 26: Outcrop-scale stratal disruption possibly due to T_1-thrusting in the accretionary prism. The structure is only seen because of the presence of the thicker arenite bed

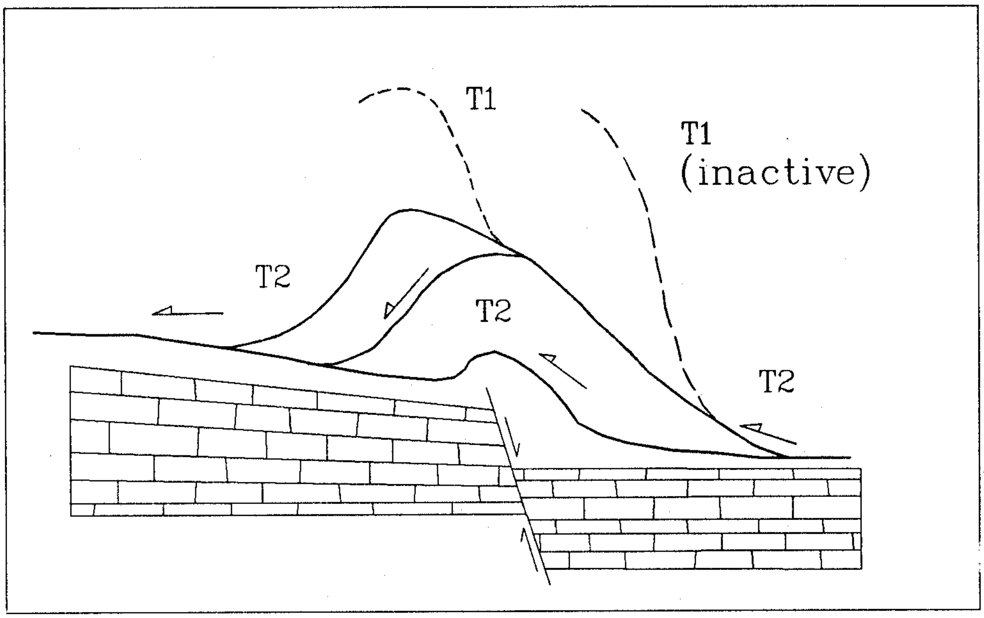


Figure 27: Propagation of the Basal Thrust System over the shelf. Possible development into an antiformal stack duplex structure after ramping over a steep dipping normal fault. After climbing the ramp the system would continue as a foreland dipping thrust duplex on the following flat.

T_2-Thrusting

The Basal Thrust of Rowley and Kidd (1981) represents the obduction surface of the allochthon onto the shelf. In this study the Basal Thrust is not treated as a single surface but as a thrust system in itself. The basal T_1-thrust decollement subsequently moves onto the shelf and develops into a roof thrust for all faults of T_2-generation which form during the incorporation of shelf carbonates underneath the main thrust. The size of the Florence Nappe and other carbonate slivers reported elsewhere (e.g. Zen, 1961; Potter, 1972) justify this interpretation. Figure 25 is a cartoon which illustrates the transition from T_1-Thrusting into the Basal Thrust System (T_2) and a possible explanation of how carbonate slices become attached to the Basal thrust. During the accretionary thrust stacking of T_1-generation, time-coeval normal faults cause the downfaulting of the outer shelf (Bradley and Kusky, 1986). Later, by the time the normal faults had been overridden by the prism, these were probably rotated and easily reactivated, reversed, and incorporated into the thrust movement. During further westward movement of the allochthon more and more shelf slivers may become incorporated into the system until the entire T_1-and T_2-thrust movement creates the present arrangement of the Basal Thrust System. During the transitional period both systems may have been active.

Figure 27 illustrates how the system could have formed into an antiformal stack duplex structure as described by Boyer and Elliot (1982). Such a structure is likely as the entire systems ramps over a major discontinuity on the shelf such as a steep dipping normal fault. After climbing the ramp the system would continue as a foreland dipping duplex on the following flat. This geometry could explain the complex structure in the carbonates generated by T_2-thrust faults as suggested for the Florentine thrust sheet. Moreover, the main regional folding which can be observed in both the carbonates and the Taconic sequence are very likely related to this deformation.

In the field area only the uppermost roof of the Basal Thrust is exposed in a window. This surface is marked by slivers of the Whipple Marble and by type 1 melange. This melange unit is probably a chaotic mixture of a slightly older T_1-basal melange and the Trenton Shale.

The actual thrust surface can be seen in a large outcrop at the north end of the field area. A detailed map of the outcrop is shown in Figure 28 (see plate 1 for location). It is the only real exposure of the Basal roof thrust, and is located in a steep elongated ridge where the exposure is not always easily accessible. On Fowler`s map (1950) and Zen`s map (1961, 1964) the carbonates are shown in a continuous patch and in Fowler`s interpretation the phyllites conformably overly the carbonates. Zen shows the carbonates thrust over the phyllite and relates this structure to the "Florence Nappe". A detailed inspection of this locality shows that the Basal Thrust Zone is exposed here. Structurally below the carbonates (cannot be seen in this outcrop) the typical melange unit is associated with the surrounding thrust of the carbonate slice. Along the elongated outcrop itself three isolated carbonate blocks can be located beside a larger carbonate slice. A direct contact between carbonates and phyllites has been found in a few places. The proposed conformable relationship of Fowler (1950), however, would be extremely difficult to reject in all but one place which is located above block 2 of carbonates shown in Figure 28. Figure 29 is a sketch of the structural relations seen at this location. The carbonates are separated from the phyllites by a folded quartz vein. The folded contact unquestionably truncates an older differentiated layering in the phyllite which parallels S_1. Kaiser (1945) had already mapped the Taconic overthrust in this outcrop because in his view all phyllites were part of the Taconic sequence. His interpretation was later rejected by Fowler (1950) and Zen (1964), but at least at this locality Kaiser was definitely right.

Although it is possible to find a thrust relationship at this location the outcrop rather impressively demonstrates how easy it is to conceal the Basal Thrust within phyllites. Fortunately the thrust surface is elsewhere defined by additional carbonate slivers or more often by the basal melange unit. Therefore the mapped boundary between this melange and Taconic lithologies also represents the basal thrust.

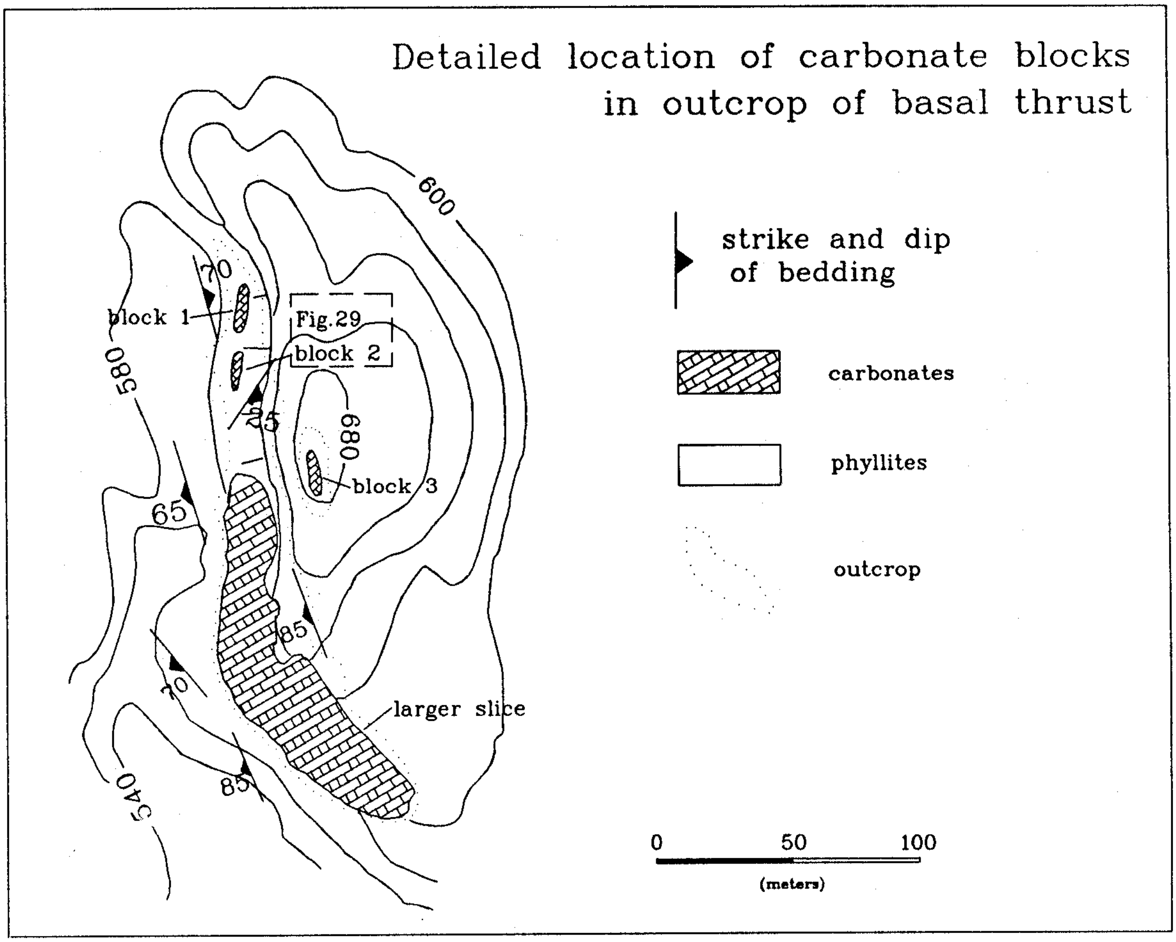


Figure 28: Outcrop map of an exposure of the Basal Thrust zone which is located at the north end of the carbonate patch north of the Florentine Quarries.

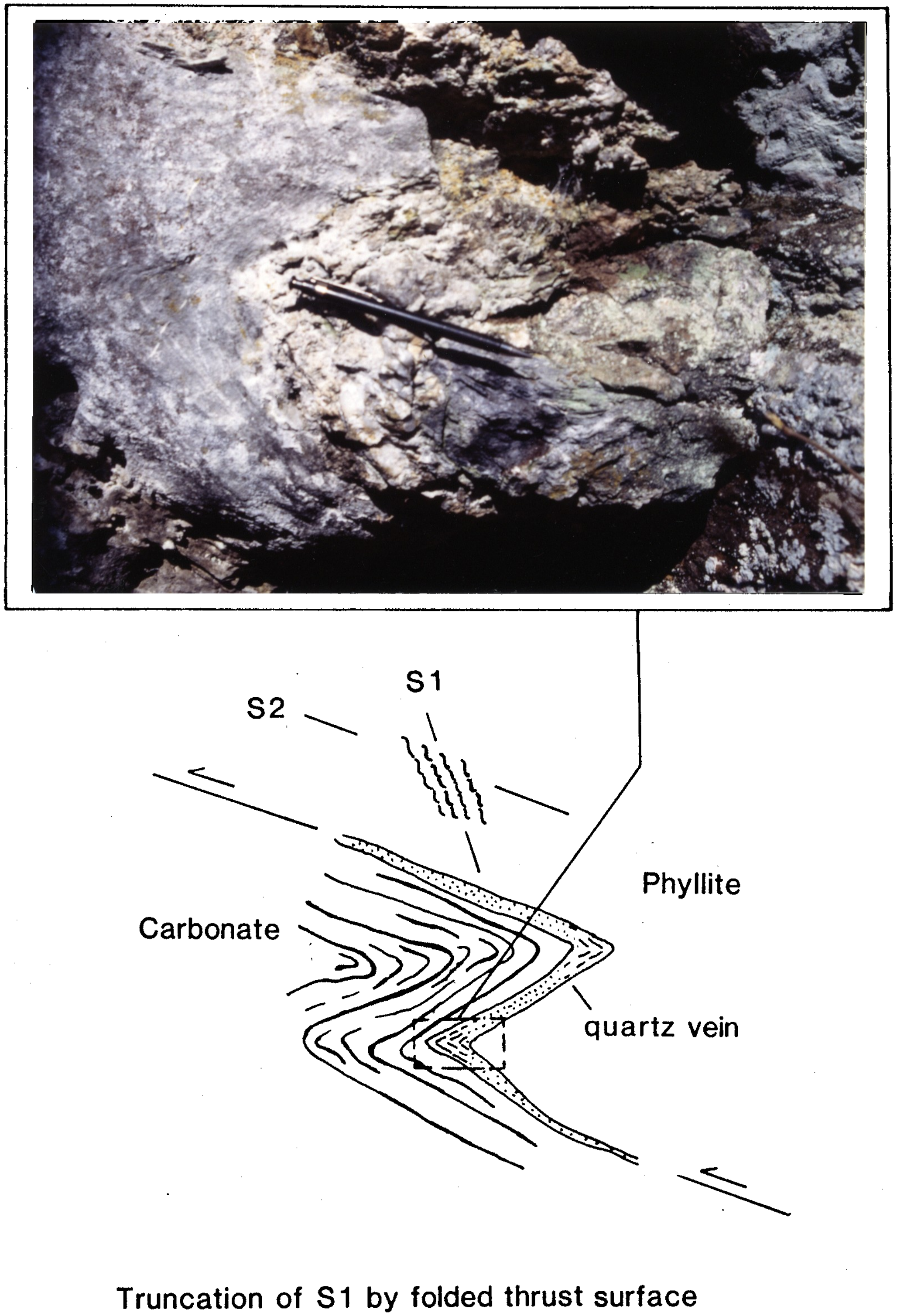


Figure 29: Example of the structural relations seen between a block of shelf carbonates and the surrounding phyllites at the exposure of the Basal Thrust zone which is shown in Figure 28.

T_3-Thrusting

The Frontal Thrust System of Rowley and Kidd (1981) truncates the folded basal thrust surface and is related to the final westward movement of the allochthon into its present geographic position. The Frontal Thrust System may be viewed as a response to the latest shortening during the collision event. During this period of thrusting the underlying continental basement must have been reactivated and incorporated into the thrust movement as suggested by Rowley (1983). Associated thrust faults of T_3-generation are also present in the field area where they truncate all older structures. The age of the faults is not constrained; they are probably related to the end of the Taconic orogeny and of late Middle Ordovician age (Rowley, 1983); however an Acadian age of this event cannot be ruled out because the structural observations only suggest a post Basal Thrust age relation.

The geometry which may result from the overprinting of the previous thrust faults by the Frontal Thrust System is illustrated in an extremely simplified diagram. T_3-thrusts cross-cut the entire T_2-thrust belt and therefore may displace a slice of shelf carbonate, which itself is overthrusted by Taconic rocks, above other units of the shelf sequence, and probably also over parts of the already emplaced Taconic sequence. In addition to faulting, the earlier folded basal thrust duplexes are tightened and slightly crenulated in between the T_3-thrust segments. Smaller branches in front of larger faults may further complicate the geology. Branches of the Frontal Thrust System are probably seen in the field area. Of course it is very difficult to speculate about the continuation of these faults into the sub-surface. The Whipple Hollow Fault can be a branch of the Proctor Fault which in turn may be a branch of the Pine Hill Thrust. The Pine Hill thrust is shown on older geological maps (Keith, 1933; Fowler, 1950) and was first reported by Wolff (1891). On the other hand all faults may sole into a deeper decollement. It is also possible that the faults are of slightly different ages and locally truncate each other during T_3-thrusting.

The cartoon of Figure 30 is only meant to illustrate the cross-cutting relations within the three thrust systems. A basal T_3-decollement is possible but not necessary for the development of the Frontal Thrust System. T_3-faults are suggested from the distribution of map units as well as by topographic

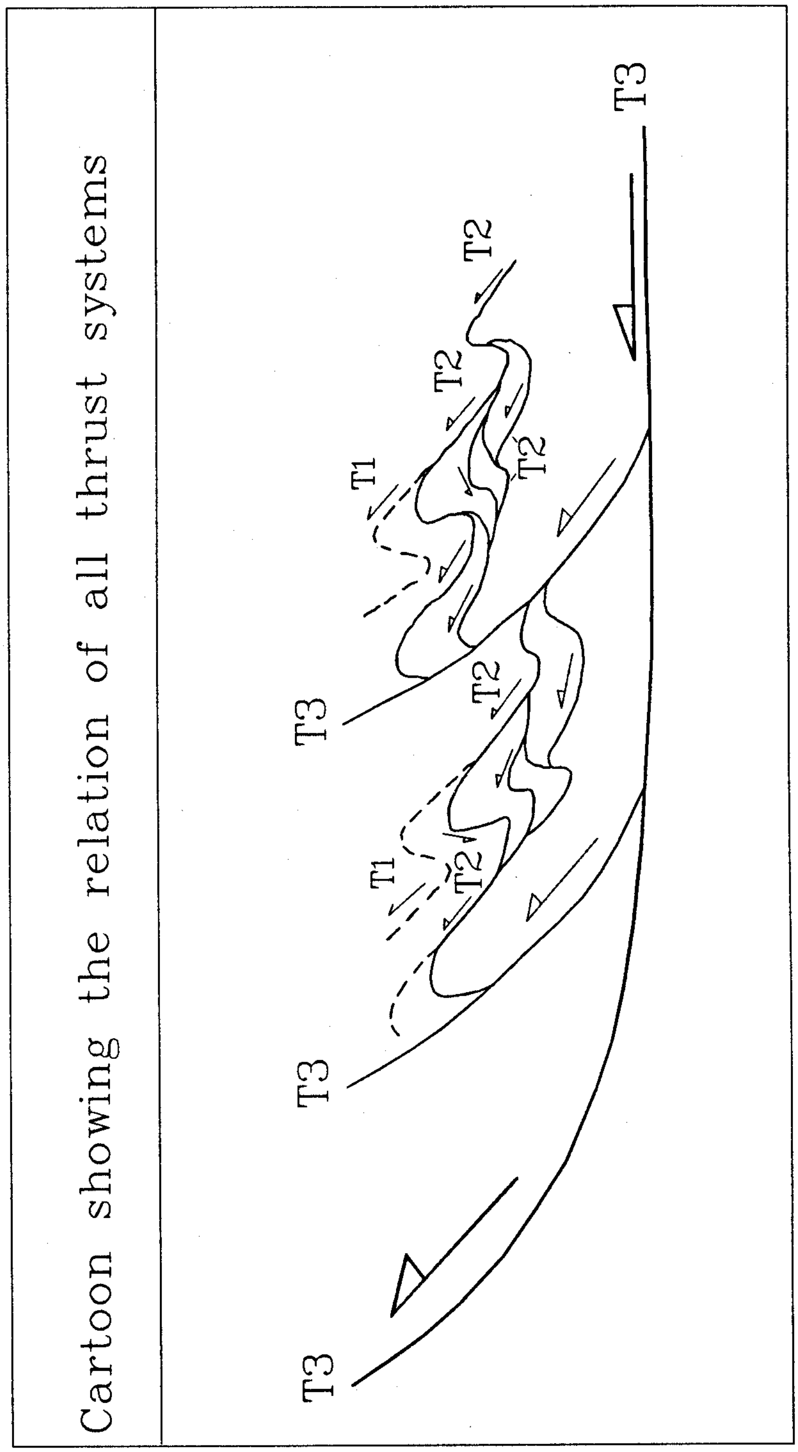


Figure 30: Schematic diagram illustrating the cross-cutting relationships of the different thrust systems.

discontinuities. A folded basal thrust relation instead of T_3-faults would not explain the map pattern.

Sumary for the evidence of thrust faults

Larger T_1 thrusts can only be inferred from the distribution of Taconic lithologies on the geological map. They remain conceptual as no convincing structural features are evident. Second generation thrust faults may locally be demonstrated where they truncate D_1 related structures such as for example illustrated in Figure 29. However, the difficulties in actually recognizing a T_2 generation thrust fault, even where the exposure is good has been outlined on page 71.

As the Basal thrust system was later folded, the traces of its faults are best read from the outcrop pattern of the associated melange. In areas where a larger patch of carbonates lies imbedded in the melange such a slice must also be bounded by T_2 thrust faults. In the absence of shelf carbonates the actual thrust geometry within the melange itself can hardly be determined. Highly deformed quartz veins are probably the only indicator for internal thrust faults if these are restricted to certain zones within the melange.

In general field evidence for the presence of T_1-and T_2-generation thrust faults is rare so that they become a consequence of the determined map pattern.

As D_3-crenulations are most strongly developed where F_2-folds appear to be truncated along faults they are probably the best hint for the presence of T_3-generation faults in addition to topography and the presence of north/south trending unfolded structural discontinuities.

3.4. Structure in the melange unit

Structural features found in the melange unit are helpful to establish a deformation chronology. The S2-regional cleavage for example would be absent if it had developed prior to melange formation. Therefore the identification of different cleavage generations within the melange sequence probably reveals information about the deformation history of the entire region. Melanges have often been characterized by non-regular cleavage surfaces which are usually the result of a single, penetrative anastomosing- or phacoidal cleavage. Typical examples have been described as due to "structural slicing" (Bosworth, 1984, 1989) for the western Taconic foreland, or had elsewhere been referred to as "argille scaliose", "sheared mudstone", "scaly clay" (e.g. Kleist, 1974), or "block in matrix ", "mud stone chaos" (e.g. Cowen, 1982).

There is multiple evidence to suggest that the nature of the unregular and anastomosing cleavage surfaces found in the melanges of the field area are not the result of a single penetrative deformation. The observed structures must be caused by the same three tectonic deformations which have been found in the Taconic phyllites. In some places the three associated cleavages probably postdate an earlier initial deformation of not fully consolidated sediments. However this is only suggested from a few samples which have been collected from the melange unit. In the bulk of the disrupted phyllite and quartzite sequence this phase is either only poorly recorded or the rocks were fully consolidated during the initial phase of deformation. Still, parts of the melange sequence have probably experienced an tectonically induced early phase of stratal disruption of not fully consolidated sediments and the subsequent accretion of these units underneath the sedimentary wedge during overthrusting.

In general soft sediment related deformations are somewhat enigmatic because the terms "soft, wet, fully consolidated, under-consolidated, partly consolidated, poorly consolidated" describe an extremely wide range of initial conditions for the sediments which are being deformed (for review e.g. Maltman, 1984).

This study does not intend to discuss any of these terms or to define the initial stages and degrees of dewatering of the rocks which have been incorporated into the melange sequence. Nevertheless I want

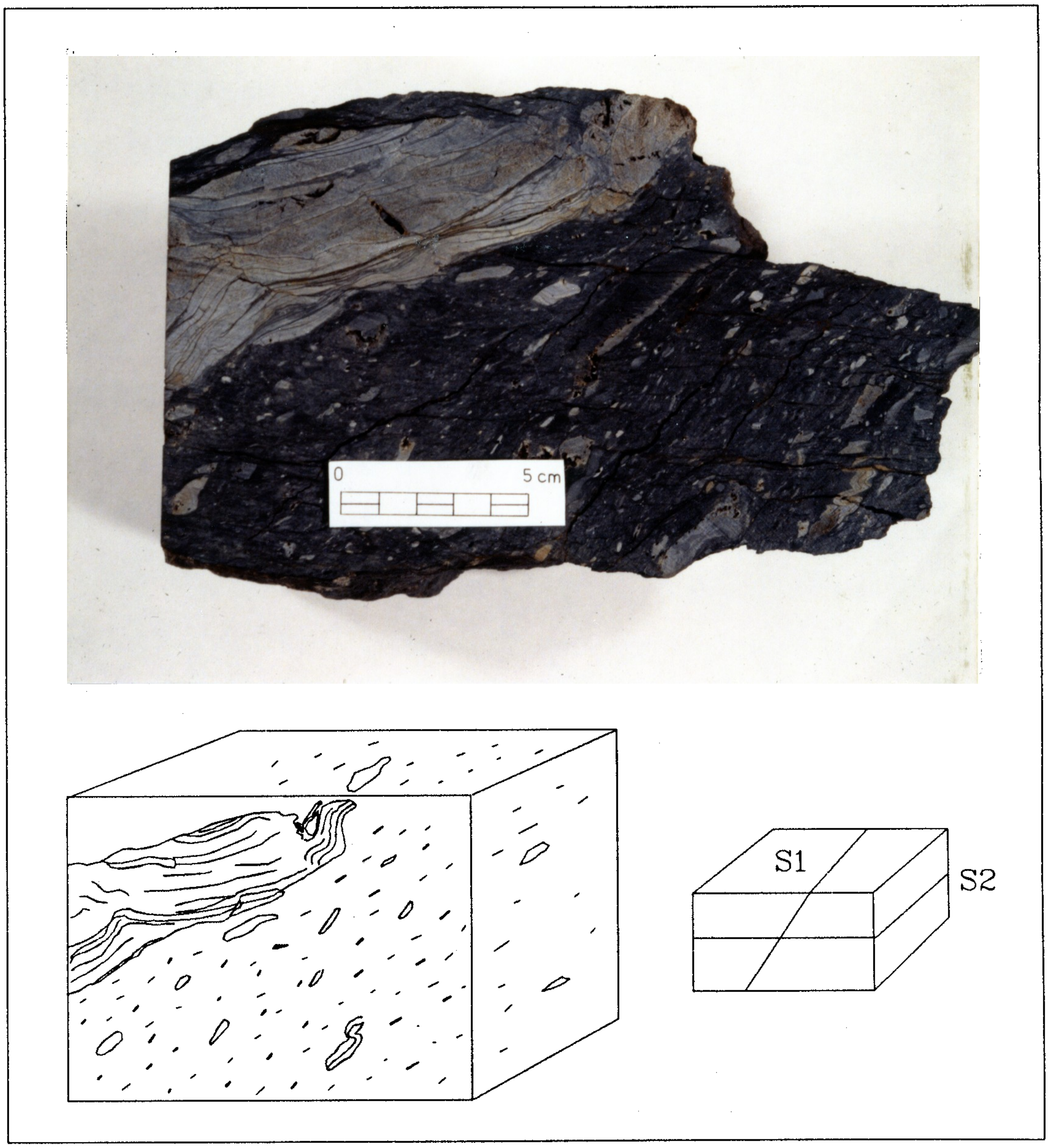


Figure 31: Typical hand sample of the melange sequence. Small pebbles of silty quartzite are elongated in the plane of the S_1-cleavage and define a stretching lineation.

to emphasize the possibility that structures found in the melanges of the field area may partly be the result of rapid dewatering and associated stratal disruption. Stratal disruption and the formation of melanges in association with sediment accretion has been reported from many recent studies (e.g. Lash, 1987; Moore and Byrne, 1987) and is also suggested from drilling results of the DSDP in active fore arc regions (e.g. Moore and Lundberg, 1986).

A typical example of the melange sequence is shown in the photograph and sketch drawing of Figure 31. Small pebbles of quartzite define a prominent stretching lineation and lie in the plane of the S_1-cleavage. On the photograph this cleavage can be noticed by little fractures which locally cause a fissility in the direction indicated by the small diagram below the photograph. A second cleavage (S_2) is oriented at a high angle to S_1 as also seen on the photograph and as indicated on the diagram.

It has already been outlined in section 3.2.3. that S_1 and S_2 are very often oriented in a very low angle with respect to each other (also Figure 17). This is probably the main reason for the anastomosing character of the cleavage surfaces in these melanges. Cleavage refraction along clasts, the prominence of S_1 related differentiated layers, as well as the shale/clast ratio may control the development and the character of the S_2 main regional crenulation cleavage.

The thin sections which have been studied from the melange unit indicate that although S_3 is commonly present it is less prominently developed compared to that in some of the finer pelites of the Taconic sequence. This is probaby caused by the inhomogeneities which result from the presence of clasts and the irregular character of the two prominent pre-existing cleavages S_1 and S_2.

The larger quartzite fragment which is seen in the upper left corner of the photograph in Figure 31 shows a complex internal structure. The fragment itself is more or less oriented in the S_1-cleavage plane, however, the internal network of layer-parallel and layer-normal fractures would be difficult to explain solely as a result of shortening normal to the S_1-cleavage plane. These features especially may document a rapid change of confining stresses and elevated pore fluid pressures in not fully consolidated sediments, prior to the development of the penetrative S_1 cleavage.

Figure 32 illustrates a thin section of another disrupted quartzite layer from the melange unit which exhibits a fine network of small fractures. These fractures are filled with clay particles and brown

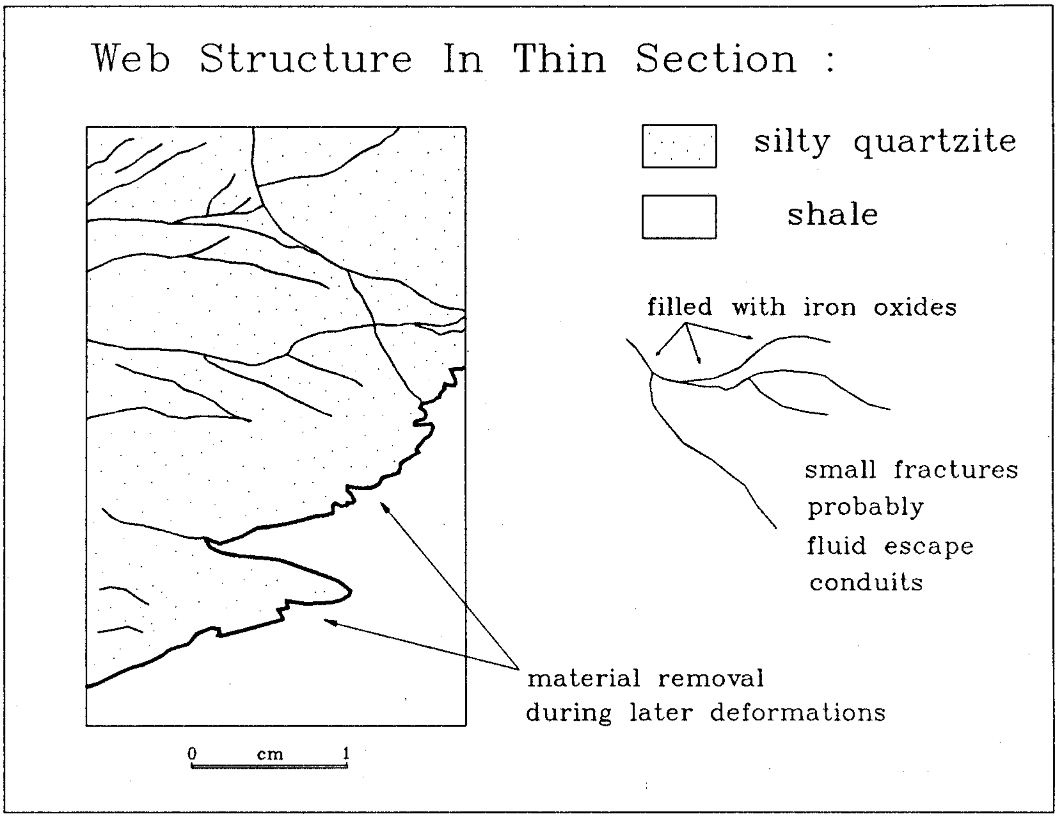


Figure 32: Web structure in a fragment of silty quartzite of the melange unit (type1).

reddish materials which are probably iron oxides. Cowen (1982) describes similar fractures from a disrupted sandstone layer of the Franciscan Complex containing extensional shear fractures. Lucas and Moore (1986) report "cataclastic shear zones" from DSDP core-studies which may also explain these features. Aalto (1989) calls equivalent shear zones "web structure" and these are also filled with iron oxides. According to Lucas and Moore (1986) and Aalto (1989) these fractures are characterized by grain breakage. Broken grains have not been found in any sample of the field area but they may have been removed during subsequent deformations and metamorphism. The net of fractures seen in Figure 32 is probably not caused by extensional shear fractures because no demonstrable offset can be noticed. These fractures may also be viewed as fluid escape conduits as described by Lucas and Moore (1986) for similar-looking structures. A second thin section is illustrated in Figure 33. Deformation of partly consolidated sediments may be indicated by two smaller clastic dikes.

The structures discussed here may either be the result of pre-tectonic slumping or probably caused by syn-tectonic stratal disruption of under-consolidated sediments.

However, more important, the thin section documents the presence of three tectonic foliations (S_1, S_2, S_3) in the melange unit and clearly shows that the S1-earliest cleavage is here definitely not caused by a strongly developed bedding parallel fisility. Additional evidence for the presence of all three tectonic foliations is documented in the photo micrographs of Figure 34 and Figure 35 because the presence of the three cleavages is of regional significance.

Summary and Interpretation of the Melange Unit

It has been shown that the three cleavage generations which are found in most of the Taconic phyllites are also present in the melange unit.

Stratal disruption and the preferred orientation of clasts in the plane of an early penetrative foliation (S_1) predate the regional slaty cleavage formation (S_2). S_1 and S_2, where more or less parallel, cause a complex anastomosing fracture cleavage. The S_3 cleavage is present in thin section but can hardly be observed in outcrops.

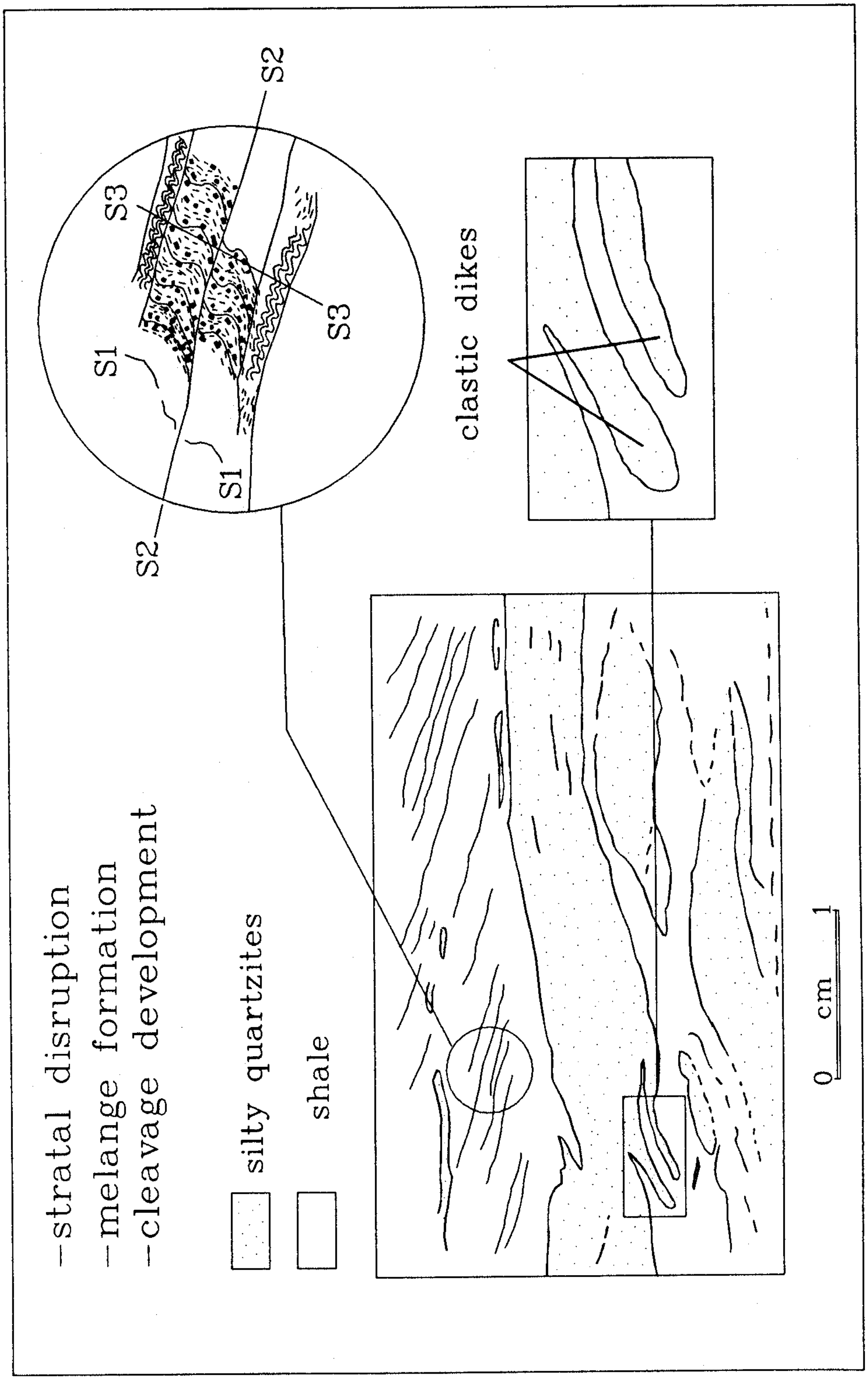


Figure 33: Example of a thin section from the melange unit (see text for explanations).

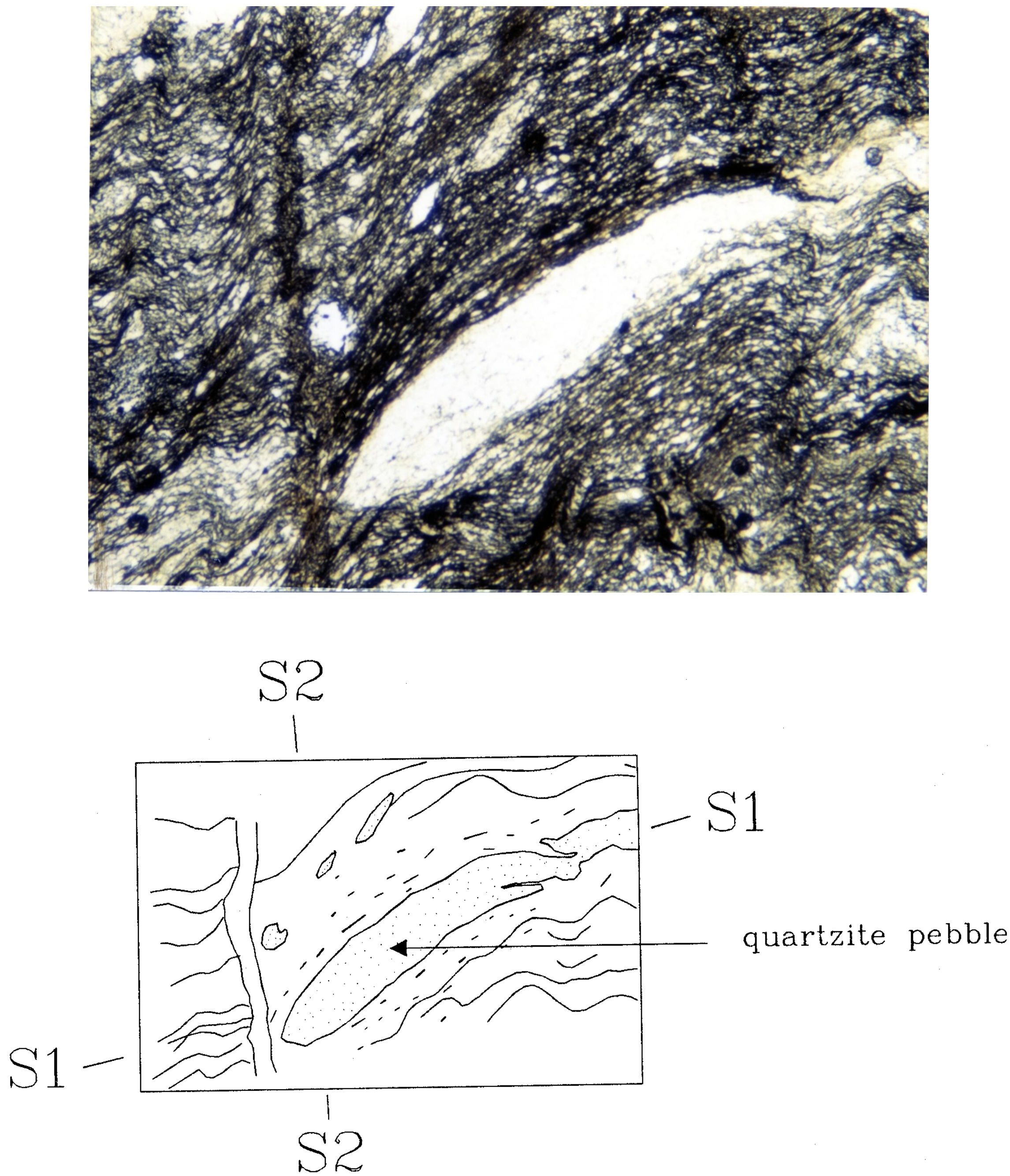


Figure 34: Photomicrograph showing the strong development of the early cleavage (S_1) in the melange unit. The quartzite pebble is oriented in the plane of the S_1-cleavage. A weak crenulation-cleavage (S_2) trends from the top to the bottom of the photograph.

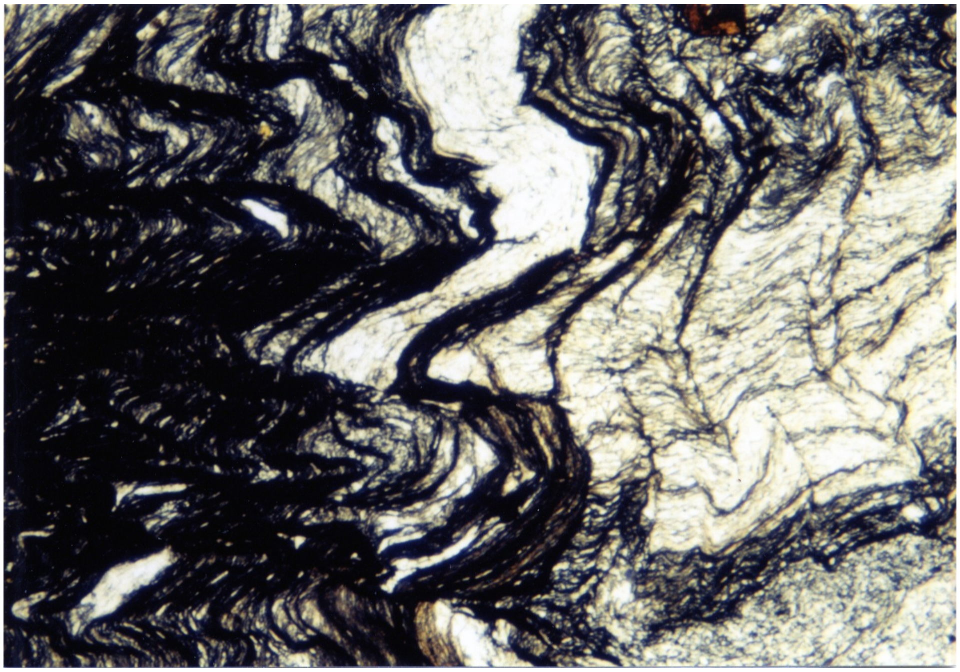


Figure 35: Photomicrograph of the same thin section as shown in Figure 34. In the right half of the photograph the S_2-crenulation cleavage is strongly developed. To the left a second crenulation is related to the S_3 cleavage. Figure 34 and Figure 35 have the same scale and the quartzite pebble in Figure 34 is approximately one centimeter long. The thin section which is illustrated in the two photomicrographs exhibits three variously developed cleavages in addition to differentiated layers. This morphology is characteristic for the entire melange sequence.

The cleavage generations which have been identified in the melange unit suggest that this sequence has undergone a similar deformation history compared to most of the Taconic sediments. In accordance with the origin of the cleavages discussed in 3.2.3. the melange sequence must have been incorporated into the accretionary wedge. The degree of stratal disruption and the presence of both blocks of Taconic affinity and blocks of the shelf sequence, suggests that the melange probably represents the basal T_1-decollement which developed into the Basal roof thrust. The presence of large carbonate slices which are surrounded by melanges of this type are best explained by the inferred thrust geometries as outlined in 3.3.2. For these reasons the folded contact between the melange unit and rocks of the Taconic sequence in the study area can be taken as indicator for the "Basal Taconic Roof Thrust".

On the other hand, stratal disruption and melange formation may also be found in sediments which have already been incorporated into the prism. It has been mentioned in chapter 2 that the phyllite and quartzite sequence locally appears to grade into the melange sequence. This implies that the Basal Taconic Thrust can not be viewed as a sharp tectonic contact because the nature of melange formation and associated accretionary processes suggests a gradation into a complex basal melange zone. It further explains why the location of this thrust surface has always been highly interpretative. In the present area the Basal Thrust must be seen as a thick and internally complex melange zone. A second important conclusion can be drawn from the structural analyses of the melange unit. The presence of the S_1 and S_2 cleavages suggests that the regional folding event must postdate the initial obduction of the allochthon and incorporation of carbonate slices into the melange unit.

3.5 Deformation History

The presence of three tectonic foliations, the map pattern established by this study, regional folds and outcrop-scale crenulations in addition to the multiple thrusting events with associated melange formation, suggest that the deformation history of the area is complex.

A "complex deformation" implies that there is a sequence of structures overprinting one another but,

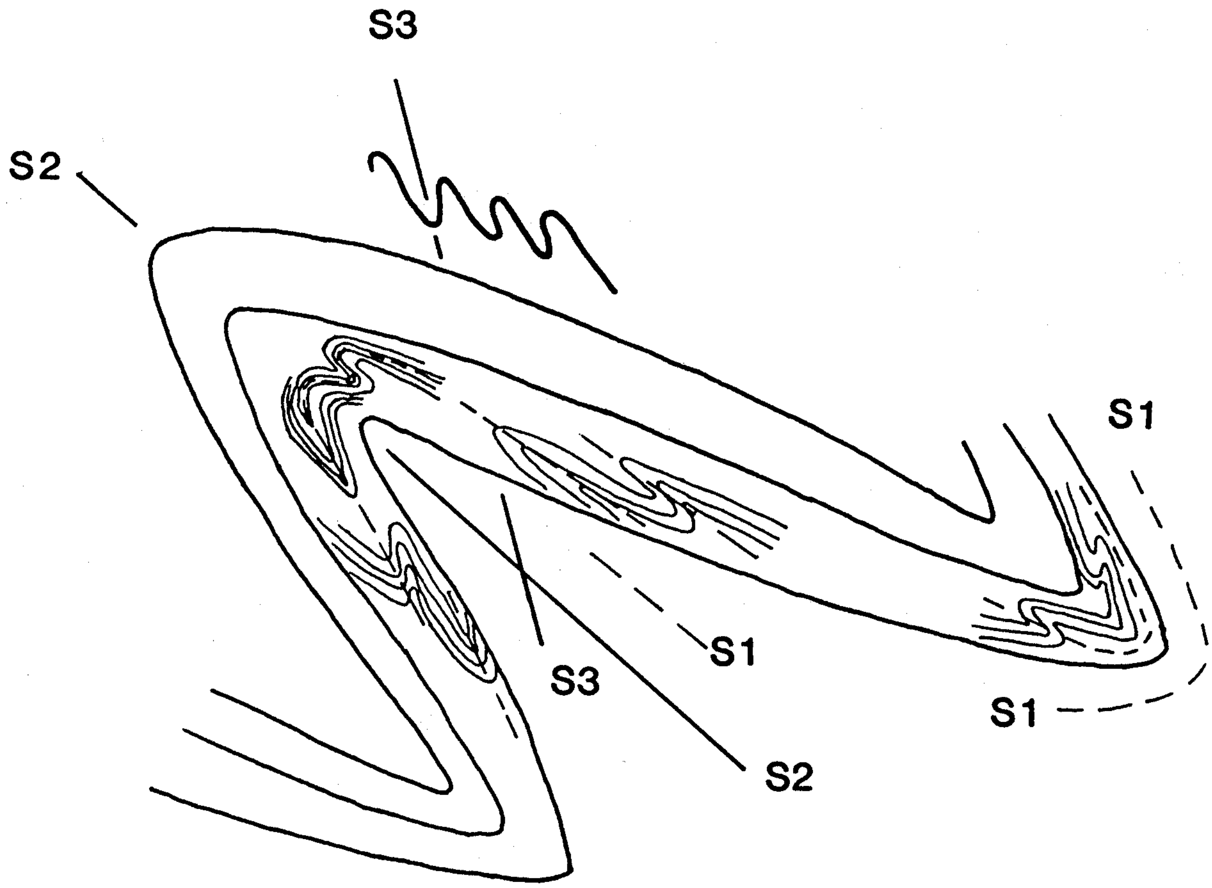


Figure 36: Diagramm showing the overlapping orientations of the three more or less east dipping cleavages S_1, S_2, and S_3. A folded appearance of the S_1-cleavage may not always be noticed. Where S_2 has developed as a cleavage fan the S_3-cleavage may be oriented sub-parallel to the main regional cleavage.
Note: Heavy lines do not represent bedding

more important, cross-cutting relations may vary from one location to the other. It further indicates that structures which are associated with different deformations may easily be mistaken, which in turn can result in gross misinterpretation of the regional structure. Figure 36 is a simplified diagram which illustrates the possible orientations among the different cleavage generations. The early cleavage (S_1) may be viewed as axial plane foliation in refolded strucutures of D_1-generation or instead as a modified bedding parallel dewatering fabric. The diagram shows how difficult it can be to assign outcrop-scale structures to the correct deformation event. The figure has no specific scale and the wave length of the main regional folds may range from a few tens of meters to several hundreds of meters. The dimension of D_1-and D_2-related folds is only schematic for the purpose of the illustration.

This section does not strictly describe a chronological order of events superposed on a rock body which is fixed in space and time. The deformation path outlined here attemps to relate folds, cleavages, and thrust faults in a sequence which is consistent with the structure of the geological map. Three major deformations can be distinguished which in a simple manner relate the three tectonic foliations with the three discussed thrust systems.

D_1 includes all processes and structures associated with the incorporation of the sediments of the former continental slope and rise into an accretionary prism. D_2 describes all obduction related structures and the disruption of parts of the outer shelf sequence and, finally, D_3-deformation results in foreland- involved and directed thrust faults. The transition from D_2- to D_3-deformation is not well defined. In fact T_3-thrust faults truncate D_2-structures; however, a progressive deformation which culminates into the formation of the late thrust faults is not unlikely. This is suggested by the more or less consistent and regular appearance of the main regional map pattern seen today which is difficult to be explained only by D_2-related thrust folding.

The deformation of sediments may begin shortly after deposition on the continental slope and rise where gravitational induced mass movement can result in typical slump structures and larger olistostromes (e.g. Moore et al., 1976). Slumps may result in the disruption or folding of primary sedimentary structures prior to any tectonic deformation. The Taconic sediments are likely to have experienced some kind of soft-sediment deformation such as reported by Rowley (1983) from the western Taconic region. D_0-deformation if distinguished should include all structures which have formed shortly after deposition on the slope and prior to the disruption and accretion of this environment. In contrast melange formation which is related to thrusting must be included into the D_1-deformation. This conceptual distinction between D_0-and D_1 related structures is a little problematic because in general larger submarine slides are commonly associated with some kind of tectonic activity and often pre-date or culminate into a tectonic event like the Taconic Orogeny. Olistostromes may feed into the leading edge of the accretionary front and become indistinguishable from tectonic melanges (Hsu, 1974; Moore, et al., 1976). If possible, the distinction between olistostromes and true melanges in the field area would be further complicated because the rocks are strongly deformed. Although D_0-deformation is likely to have occurred the D_1-deformation is the first clearly defined event of the region.

D_1-deformation involves a wide range of processes because it is related to accretionary tectonics. The leading edge of a sedimentary wedge is characterized by active thrust faults, folding, stratal disruption, soft sediment deformation, and melange formation whereas a deeper part of the accretionary prism may experience metamorphism and cleavage development. However, the processes found in accretionary environments are usually associated with the subduction of oceanic crust. During D_1-deformation and the disruption of the former continental slope and rise, the system already experienced "orogenic conditions" because continental crust had entered the former subduction zone. Therefore the Taconic slices may not necessarily be exactly comparable to subduction-related accretionary environments. It is probably this "orogenic component" during T_1-thrusting which caused the early cleavage S_1 to form in a relatively shallow level of the accretionary prism. D_1-deformation subsequently developed into D_2-deformation because the simple leading edge imbricate thrust system cannot continue during the following stages of the collision event. The formation of the different thrust systems has been discussed in 3.3.2. During D_2-deformation the propagation of the system is no longer possible without the development of larger folds (F_2) and additional thrust duplexes (T_2). As the Basal Thrust System which is active during this deformation is complicated by the incorporation of parts of the shelf sequence, the overall geometry and associated folds may vary considerably along the strike of the allochthon. Structures which have formed during this period of mountain building may locally vary considerably from what has been determined in the Proctor/Florence area.

The late thrusts of the Frontal Thrust System are only classified as a separate deformation event because these faults appear to truncate all older structures. The second crenulation cleavage (S_3) is not viewed as a an axial plane foliation to folds of this deformation. It is interpreted as the result of additional shortening and thrust shearing superposed on the structures which are caught between T_3-thrust segments.

Chapter 4

Regional Synthesis

4.1 Map Pattern

Carbonate Slices of the Basal Thrust System

The main objective of this study was to locate and characterize the "Taconic Overthrust". As seen on the geological map this fault zone does not trend in a north/south direction along the eastern margin of the allochthon as interpreted on older maps (Zen, 1961, 1964; Fowler, 1950).

The complexity of the field area is a result of the truncation of the Basal thrust by two later thrusts of the Frontal Thrust System. These faults are the Proctor Fault and the Whipple Hollow Fault. A third fault which is probably a branch of the Proctor Fault is referred to as the Florentine Fault.

For a general orientation the larger faults and thrust slices of the field area and the adjacent region are shown in Figure 37. At the south end of the map area the basal thrust is truncated by the Whipple Hollow Fault. This fault continues south to the West Rutland marble belt. In the central part of the map area the "Florence Nappe" forms the roof of a T_2-basal thrust duplex. The horses which define this duplex near the roof surface are either composed of carbonate slivers (especially Whipple Marble) or of melange. Therefore both units may be found in contact with typical Taconic lithologies. In the field area this contact is exposed in a window below the overlying Taconic rocks. At the north end of the mapping area the basal roof thrust is tightly folded and plunges northward underneath the main Taconic sequence. The east limb of this main regional fold is truncated by a late T_3-generation thrust fault (Florentine Fault), which localizes the occurrence of the carbonates of the Florentine quarries. In Zen`s view (1959, 1961, 1964) the marbles of the Florentine thrust sheet are part of the "Florence Nappe" and are back-folded into the east edge of the Taconic sequence. According to Zen, this

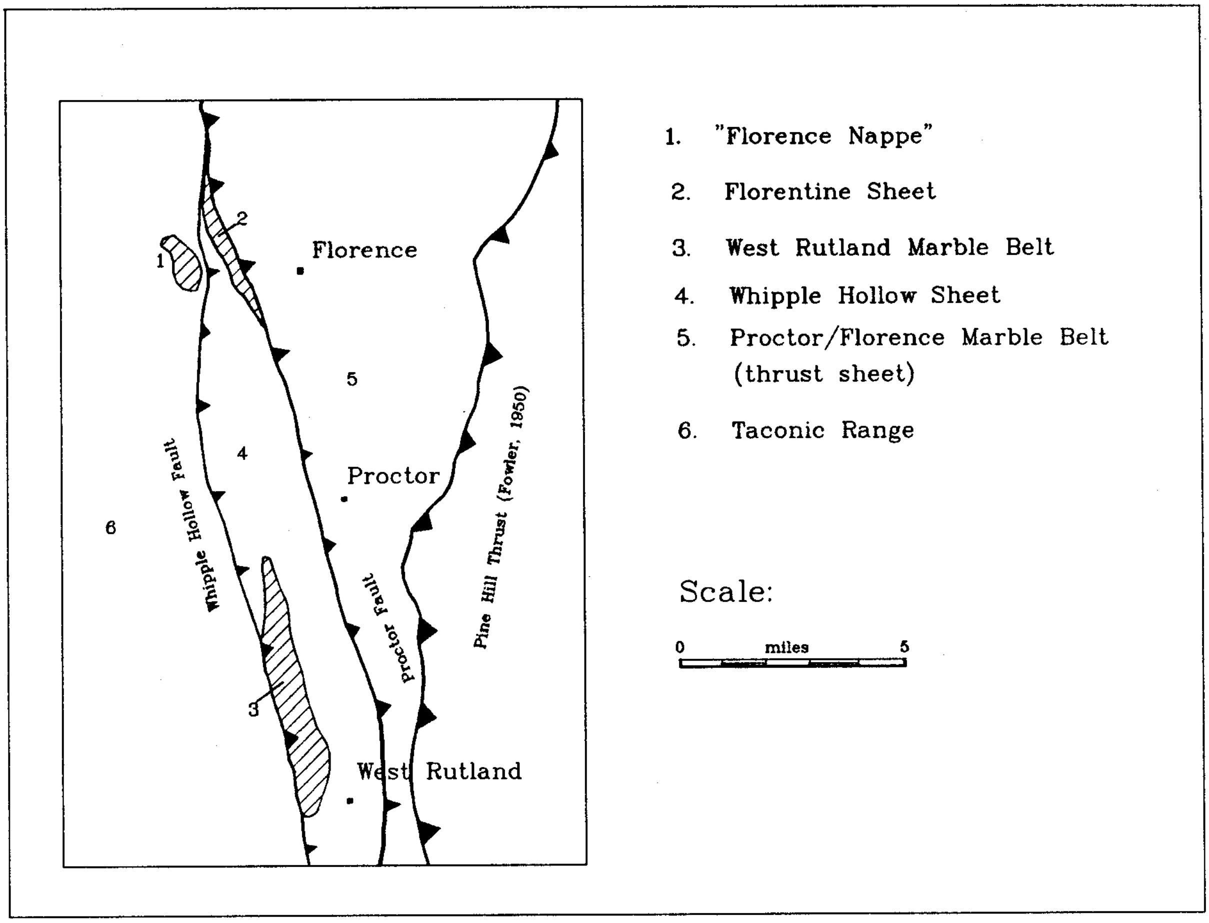


Figure 37: Major structural features and T_3-thrust faults of the region.

relationship shows the continuation of intense deformation in this area after emplacement of the Taconic Allochthon. The revised interpretation of this structure based on the mapping of this study is as follows:

The carbonates of Zen`s "Florence Nappe" belong to several different structures. It has earlier been indicated that most of the marbles belong to the Whipple and not to the Bascom Formation. Even if Zen`s assignment of the carbonates were correct, the discovery of Taconic lithologies and the presence of the Chipman Formation at the north end of the area are incompatible with his view of the "Florence Nappe". The kidney shaped carbonate outcrop at Fire Hill is a larger carbonate slice incorporated into the the Basal Thrust System. It is the type locality for the three units of the Whipple Marble as already suggested by Fowler (1950). The marble does not necessarily extend all the way up to an elevation of 1250 feet as shown on Zen`s map. Although the marble crops out at this elevation (with no exposure in between) it is more likely a result of folding as indicated in section E on plate 1. The entire kidney shaped pattern does not represent a syncline which overlies the phyllites on all sides as suggested by Zen. At Fire Hill the Whipple occurs in an anticlinal structure as originally interpreted by Fowler (1950). Southeast of Fire Hill at the locality of the two smaller quarries, the structure is a syncline (section E on plate 1). In this study the "Florence Nappe" is restricted to the kidney shaped marble patch. East of Fire Hill Taconic phyllites overlie the marble and the melange which is associated with the "Florence Nappe". The Florentine sheet is also underlain largely by Whipple Marble. The structure itself is decoupled from the main Proctor marble belt by the Proctor Fault whose presence is suggested by the phyllite patch east of the Florentine quarries. This patch is considered to be part of the Taconic sequence on the basis of the presence of green phyllites and the contact with the Whipple marble must be the Basal thrust folded in a syncline. To the east the syncline is truncated by the Proctor fault.

The Florentine marble patch on the other hand happens to truncate one of two carbonate slices at the north end of the area that define the basal thrust surface at this location (section B on the geological map). It is not a continuous marble patch which belongs to the Florence Nappe as mapped by Zen (1961, 1964).

Lower Cambrian Taconic Units

According to Zen (1959) the lower Cambrian Taconic sequence in the east flank of the Taconic Range north of the Castleton River is upside-down. It must have been the regional distribution of map units which led Zen to this suggestion. As Zen did not discuss the possibility of unnoticed fault relations within the Taconic sequence his regional synthesis requires an extremely complex fold style and fold geometry. The map pattern which has been determined during this study suggests that the structure is rightside up and that the distribution of map units is primarily a result of T_1-thrusting, later modified by the regional folding event, and finally redistributed by cross-cutting faults of the Frontal Thrust System. The importance of T_1-faults is simply suggested by the outcrop pattern of the Taconic units. Green Taconic phyllites of the Bull Formation occur at the top of all higher knobs in the region. They are most commonly underlain by black and gray phyllites of younger Taconic stratigraphic units. The possibility of an inverted conformable stratigraphic relation between the green and the black units would be inconsistent with most of the structural relations covered in this study. Moreover, the geometry of the Taconic black/green boundary, if a sedimentary contact in this area, would suggest that it had been folded by major north-northwest trending folds. Such folds would lack an asssociated unfolded axial plane foliation because all planar cleavage surfaces of the area strike approximately north/south and more commonly somewhat east of north (plate 1). The rocks both below and above this contact suggest north trending folds by the presence of at least one axial plane foliation. Therefore the distribution of the Bull Formation cannot be a result of the folding itself and must have been a pre-existing condition. The observed pattern is best explained by a folded large-scale accretionary thrust boundary of T_1-generation. Unfortunately T_1-thrusts are very difficult to recognize from exposure of these dominantly pelitic rocks. Even if the contact is actually exposed it might look conformable and could not be positively identified from outcrop evidence as a thrust fault. Thus the geological interpretation will always be influenced by the working hypothesis and the overall structural concept of the individual geologist. However, the map pattern and most of the structural observations, especially the recognition and detailed mapping of the melange units, require the existence of major, previously unnoticed, T_1-slice boundaries within Zen`s Giddings Brook Slice. This observation has some importance for the interpretation of Taconic structures along the eastern margin of the allochthon and raises questions about a few of of Zen`s regional structural interpretations.

The 800 feet hill south of the Florentine quarries has a very difficult structure probably more complex than shown on the geological map. The hill itself is the northern end of the prominent ridge between Proctor and West Rutland and forms a slice between the late Proctor/Florentine faults and the Whipple Hollow fault. Moreover, the hill approximately represents the structural level of the basal thrust surface. The whole complex is probably further complicated by T_1-generation thrusts which may be characterized by a highly complex structure where they sole into the former decollement. These circumstances may explain the more or less confusing distribution of type 2 melanges and isolated patches of green phyllites of the Bull Formation. The central hill may be considered as part of the Taconic sequence or instead as the upper part of the basal melange which could be dominated by Taconic lithologies. South of this hill and east of the Whipple Hollow Fault the occurrence of Taconic rocks is very obvious. The Bull Formation near Butler Pond has already been mapped by Fowler (1950). A second area is seen in a roadcut along the Whipple Hollow road approximately 1 kilometer south of Butler Pond and just north of the fork in the road (not covered by the map). The outcrop exhibits black and silver gray greenish phyllites interbedded with a massive, very hard clean viteous green quartzite typical of the Bull Formation. The little plateau 50 m west of the roadcut consists of purple phyllites which crop out over a large area. These belong unquestionably to the Bull Formation and are in the same way typical of the Bull Formation as similar phyllites and slates well exposed along US Route 4. The occurrence of the Bull Formation at this location in addition to other outcrops shown on the map suggests that the overlying phyllites of a second 800 feet hill north of Butler Pond also belong to the Taconic sequence. This hill shows almost no exposure; only one outcrop of homogeneous black phyllites has been found. All rock fragments collected from the ground were also black but more important no type 1 melange lithology has been observed. Although poorly exposed this hill is therefore very likely underlain by the Hatch Hill/West Castleton Formation.

4.2. Faults of the Proctor Quadrangle

Two faults which have been discovered in the field area are important on a more regional scale and are defined below.

The Proctor Fault

The Proctor Fault belongs to the Frontal Thrust System and strikes north northwest (N15W) through the entire Proctor Quadrangle. North of the field area the fault loses its identity in a big swamp and in the overall flat topography south of Brandon. To the south the fault can be extended into the West Rutland Quadrangle. Somewhere near West Rutland the fault must either terminate in the Pine Hill Thrust (Fowler, 1950) or continue further south along the marble/phyllite contact. The prominent ridge between Florence and West Rutland and which is underlain by phyllite is the foot wall of the Proctor fault whereas the marble belt of Rutland/Proctor/Florence is the hanging wall of the fault. The prominent phyllite ridge does not represent an unconformity between the shelf sequence and the overlying Trenton shale as mapped by Fowler (1950) and Zen (1964). The main argument against this hypothesis is that green phyllites which are unquestionably Early Cambrian or older in age (Bull Formation) are truncated by this fault in the field area. Moreover the Bull Formation is in thrust contact with the Proctor marble belt approximately 1 mile north of Proctor. These locations had previously been mapped as Hortonville- and Ira Phyllite (Fowler, 1950;Zen, 1964).

The Whipple Hollow Fault

The Whipple Hollow fault also belongs to the Frontal Thrust System, has approximately the same trend as the Proctor fault (N15W), and parallels the latter through most of the Proctor Quadrangle in Whipple Hollow. The Whipple Hollow Fault is located west of the prominent phyllite ridge and along the eastern margin of the Taconic Range.

The Taconic Range itself must be considered to be the foot wall of the Whipple Hollow Fault and the hanging wall consists of the phyllite ridge in the map area, but also, further south, of the West Rutland marble belt. The relation between the West Rutland marbles and the overlying phyllite ridge has not yet been determined by the author. An additional branch of the Frontal Thrust System is possible there as well as a folded Basal Thrust relationship. The Whipple Hollow Fault is necessary because the distribution of map units along the eastern slope of the Taconic Range and in Whipple Hollow itself cannot be explained solely by a folded Basal Thrust.

The fault probably continues south of West Rutland but the exact location is difficult to propose without additional field work. It is likely that the Whipple Hollow Fault terminates into the Proctor Fault somewhere around Clarendon Springs. On the other hand both faults may be truncated by the Pine Hill Thrust.

4.3 Implications for the Regional Geological Interpretation

The Taconic Allochthon consists of several major nested thrust sheets, a view which had been popularized by Zen (1961, 1967) and which since then became the fundamental working hypothesis for many Taconic geologists.

Our present understanding of the Taconic foreland fold-and thrust belt is probably best summarized in the structural and tectonic synthesis of the Taconic orogeny proposed by Rowley and Kidd (1981). Rowley and Kidd present a model compatible with modern accretionary systems and mountain building processes at convergent plate tectonic settings. Yet, a controversy about the stacking order of the Taconic slices still exists (Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985).

This study emphasizes the importance of late, cross-cutting faults of the Frontal Thrust System (Rowley and Kidd, 1981; Rowley 1983) for the eastern margin of the Taconic Allochthon and the Vermont Valley. It is further suggested that at least Zen`s Dorset Mt.-Everett Slice is bounded by faults of the Frontal Thrust System and that these faults were active after or during the final stage of the emplacement of the accretionary wedge. This explains why Stanley and Ratcliffe (1985) who had worked only in the "higher Taconics" concluded that there was a diverticulated stacking order.

The importance of late T_3-thrust faults has been outlined for the West Rutland/Proctor area. It is very likely that the entire Vermont Valley is underlain by T_3-related structures. This interpretation is in strong contrast to the traditional geological view of West-Central-Vermont and adjacent New York which assumes an unfaulted east limb of the Middlebury Synclinorium. On the other hand it is an accomodating solution of the stacking controversy and in addition explains the two-fold nature of the Basal Thrust surface. The suggestion of late, eastward dipping thrust faults along the eastern margin of the Taconic Allochthon is based on the following observations and interpretations.

In the northern Taconic region the folded Basal Thrust System is obviously characterized by a basal melange and isolated slivers of carbonates. This is probably very similar to the Hoosick Falls area (60 miles to the south) where Potter`s Whipstock Breccia and associated carbonate slivers represent the basal melange (Potter, 1972).

The structural relations between the Hoosick Falls area and Rutland appear to be quite different. Cambrian Taconic units directly overlie Early Ordovician shelf carbonates. Units like the Whipple Marble, the Hortonville Slate, or the melange unit are missing south of Dorset Mountain as shown on the Vermont State Geological Map and the more detailed maps it is based on (Thompson and Shumaker, 1967; Hewitt, 1961). On the geological map of the Pawlet quadrangle by Shumaker and Thompson (1967) the Dorset Mountain Slice is interpreted as a late thrust which clearly truncates other carbonates of the synclinorium sequence. The truncated shelf rocks, however are believed to dip westward underneath the Taconic Allochthon. Most of the carbonates are therefore interpreted to belong to the east limb of the overall synclinal structure of the shelf and the overlying Taconic Allochthon. Most of the Vermont Valley is covered by glacial deposits implying that many of the relations shown are highly interpretive and may easily be replaced by another interpretation.

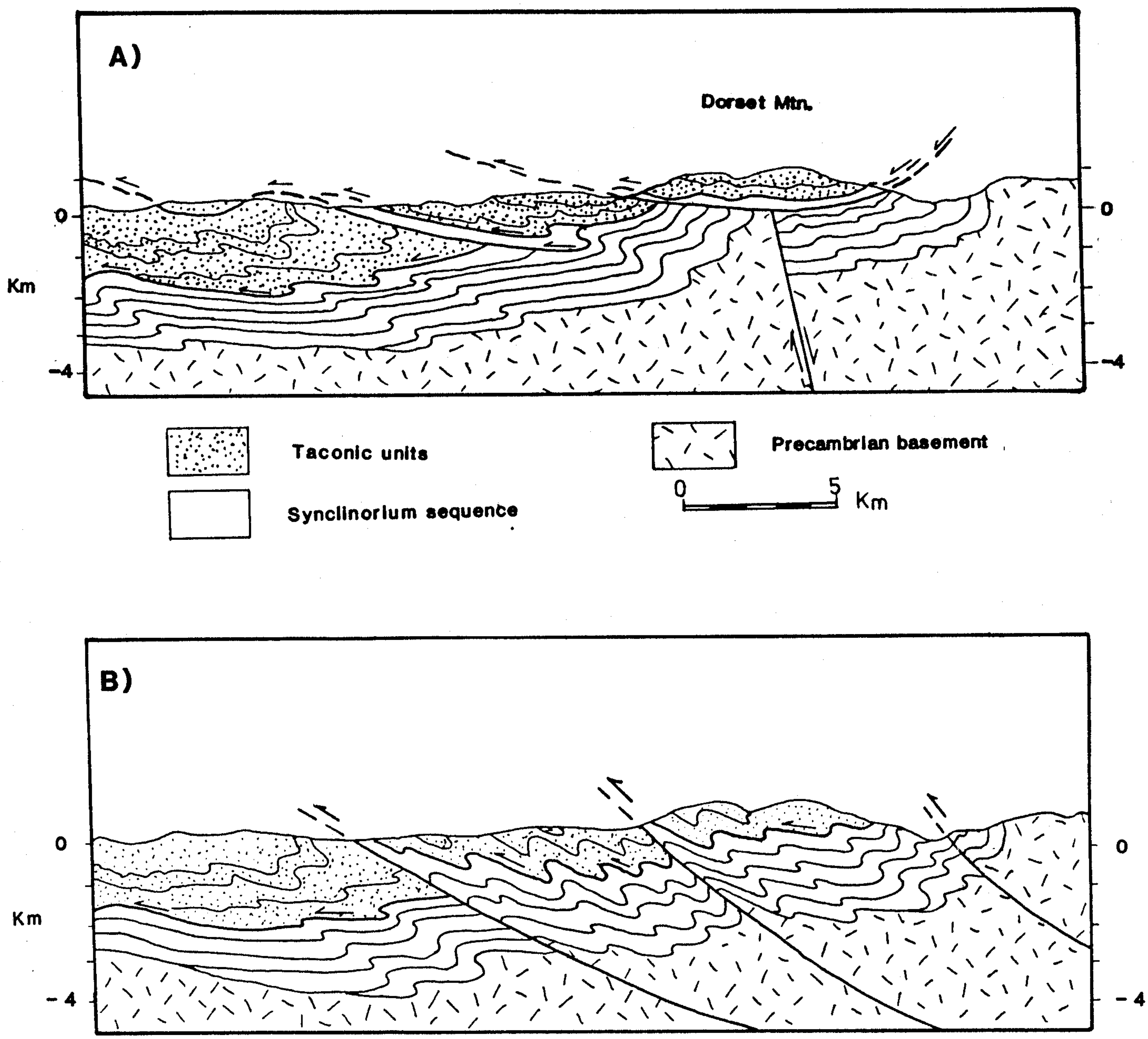
The thrust models which have been developed from this field area allow the removal of Hortonville Slate and parts of the carbonate sequence before a deeper Taconic part of the accretionary prism had moved onto the shelf (Figure 25). Therefore a direct thrust contact between Taconic rocks and the shelf sequences can be explained. This implies that the observed north/south variation in the nature of the Basal Thrust is probably a result of an initial west to east stuctural variation along the Basal Thrust

System. This hypothesis would suggest that those Taconic rocks which directly overlie the shelf sequence on a regional scale had been buried in a deeper part of the subduction zone. Such rocks have probably experienced higher pressure and temperature conditions and may exhibit a slightly higher degree of metamorphism than the phyllites of the field area. The author spent a day in the Cambrian Taconic units of the Everett Slice south of Equinox Mountain and north of West Arlington. The nature of the rocks which have been inspected tend to confirm this prediction. A considerably higher degree of metamorphism is suggested by the coarse mica grains which define a prominent foliation. Some of the highly foliated and mica rich rocks are probably better referred to as a schist. An increase in metamorphic grade from west to east but also from north to south has been suggested by Zen (1959). The higher metamorphic grade may be explained by other reasons too, but as discussed here it fits properly into the line of arguments.

The eastern Taconic Range and the Vermont Valley in this hypothesis do not represent the unfaulted east limb of a major syncline. Instead it is likely to be a zone which is dominated by east dipping faults of the Frontal Thrust System. The shelf rocks of the Vermont Valley are believed to be caught in T_3-generation thrust slivers and are very likely decoupled from those parts of the shelf which lie deeply buried underneath the main Taconic sequence. The Vermont Valley may be considered to be a rather complex thrust zone between the lower Taconic slices (e.g. Giddings Brook Slice) and the Green Mountain escarpment. Figure 38 illustrates a modified structural interpretation of the Dorset Mountain Slice compared to the interpretation of Thompson (1967). The proposed geology at this location is not substantiated by field work, however it is suggested from the regional application of my mapping results at the north end of the Taconic Allochthon.

This hypothesis explains the variation of the character of the Basal Thrust System along strike of the allochthon and the difference in metamorphic grade which is probably related to this variation. Finally it explains the stacking controversy which exists between prominent Taconic geologists.

(simplified after Shumaker and Thompson, 1967)



(revised interpretation of the eastern margin of the Taconic Allochthon)

Figure 38: Structural interpretation of the Vermont Valley. A: Interpretation of Shumaker and Thompson (1967). B: Revised interpretation of the author. The eastern margin of the Taconic Allochthon and the "east limb of the Middlebury synclinorium" are strongly modified by late thrust faults of the Frontal Thrust System.

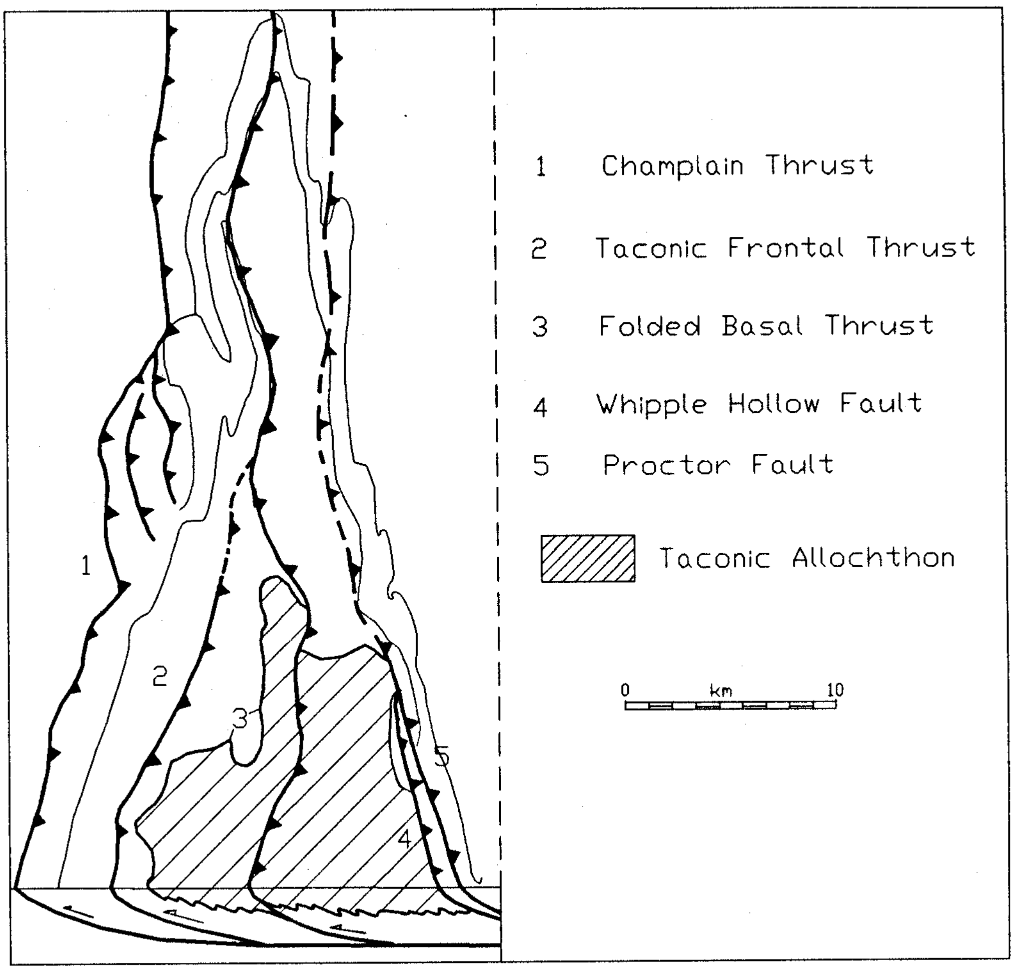


Figure 39: Schematic diagram showing a modified view of the Middlebury Synclinorium.

The development of a major syncline was required to explain a gravity driven emplacement for the Taconic Allochthon. The Taconic orogeny as pictured by Rowley and Kidd (1981) does not depend on this syncline. Even if the large syncline is viewed as a folded foreland basin caused by subduction and related flexural upbulging of the shelf to the west of this basin, this structure is unlikely to survive the Taconic orogeny without being cross-cut by foreland directed thrust faults.

North of the field area the overall structure of the Middlebury Synclinorium (Cady, 1945) may also be questioned to a certain extent. The Proctor fault must somehow continue into this structure. As indicated by all sections on the geological map the structural relations in the field area exclude the possibility that the Vermont marble belt at Proctor represents the southward continuation of the Middlebury Synclinorium (Cady, 1945; Zen, 1961, 1964). Washington's work (1981) near Middlebury, consistent with this suggestion, has already been mentioned in the introduction of this thesis. The conclusion must be that the overall synclinorium structure which is still commonly associated with the Taconic Allochthon and surrounding shelf carbonates is either not present at all or is at least extremely modified and redistributed by cross-cutting faults of the Frontal Thrust System. Figure 39 is a schematic diagram which illustrates a modified view of the Middlebury Synclinorium. It summarizes and translates the results of my field work into the regional geological setting. The Champlain thrust in front of Cady's Middlebury Synclinorium and faults like the Pine Hill Thrust near Rutland are more or less accepted as a part of this system. There is nothing particularly problematical in translating the intervening Taconic Range into the late Frontal Thrust System. The Taconic Allochthon should not be viewed as a composite thrust sheet; instead Taconic lithologies and rocks of the shelf sequence must be treated as a composite and complex fold and thrust belt.

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