Structural Analysis Across the Northeast Boundary of the Taconic Allochthon, West-Central Vermont

Abstract of
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Department of Geological Sciences

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ABSTRACT:

The Taconic Allochthon is an elongate belt of Cambro-Ordovician, argillaceous sediments with lesser occurrrences of calcareous and siliceous lithologies. These lithologically distinctive strata lie tectonically juxtaposed over a coeval medial-Ordovician carbonate shelf sequence. This geometry resulted from an arc-continent collision in which a westward-migrating arc (Ammonoosuc Volcanics) collided with an eastern North America passive margin and the accumulated accretionary prism of the forearc region was thrust onto the passive continental margin.

The present thesis examined the structural sequence at the north end of the Allochthon and the continuity of this sequence into the adjacent Parautochthonous Shelf strata. Structurally, the study area is quite complex and at least five phases of deformation can be distinguished.

In the study area, two "slaty cleavages" were found. The earliest (S_2), newly discovered during this research, strikes E/W and lies axial planar to the isoclinal, recumbent Ganson Hill Syncline. This is in turn transected by the NE-trending, "regional" slaty cleavage (S_3) which is well known from the western Taconics. This "later" cleavage is that slaty cleavage dominant in outcrop and shows a similar orientation for both the Allochthon and Parautochthon. The "slaty" cleavage in the Shelf Sequence,

however, has not been modified by later folding as has the Allochthon fabric.

In the Allochthon, the crenulation cleavage (S_5) is best developed near thrust zones although a weak crenulation lineation is present in nearly every outcrop in the study area. The NE-trending crenulation folds range from open to fairly tight, the latter being most common near thrusts. They are ubiquitously south-plunging with few exceptions.

The late crenulation cleavage is nearly absent within the Parautochthon. At only three places a weak crenulation cleavage was found within the carbonates. Coupled with the observations from within the Allochthon, this suggests that many of the late crenulation-age imbricate thrusts within the Allochthon sole or flatten to the Basal Thrust (Giddings Brook Fault) of the Allochthon.

An anomalous crenulation cleavage fabric is typically found in fault zones which developed synchronously with the crenulation F_5 folding. This anomalous discrete crenulation cleavage (named here S_4) post-dates the slaty cleavages (S_2 and S_3) and is generally transected by the NE-striking crenulation cleavage (S_5). The anomalous E/W striking fault zone cleavage (S_4) has an orientation normal to the fault plane or shear surface and the intersection lineation lies parallel to the transport direction as defined by chloritic and quartzose slickensides.

The magnitudes of strain associated with the Ganson Hill "early" slaty cleavage (S_2), the "regional" slaty cleavage (S_3) and the crenulation cleavage (S_5), were determined for a small number of localities using buckled quartz veins, reduction spots, and a combination of the t'_{alpha} method and buckled veins, respectively. The "early" slaty cleavage (S_2) shows a 74% shortening, the "late" slaty cleavage (S_3) shows 68-72% shortening and the crenulation strain (S_5) shows a variable shortening magnitude of 27-45% normal to the respective cleavages.

Microstructurally, the rocks of the Allochthon study area show all gradations of cleavage morphology due to varying proportions of silica and pelitic material. Slaty cleavage commonly appears as a differentiated layering or an anastamosing network of aligned phyllosilicates. The crenulation cleavages show a diversity of morphologies ranging from a discrete to a zonal fabric. New mica growth is typically seen in the cleavage domains. Microstructure of the Parautochthon is monotonous and cleavage is defined by stylolitic opaque seams and a weak grain shape foliation. In these rocks, mechanical twinning is present but evidence of recrystallization/recovery textures is common. Fault rocks from the Allochthon show microstructures indicative of complex growth patterns during deformation of quartz fibers and chloritic gouge material, in an environment dominated by high shear strains. Many specimens allow determination of shear sense by the geometry of cleavage rotation and the geometry of shear surfaces, analogous to those found in ductile shear zones

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CHAPTER 1 INTRODUCTION TO THESIS

The Taconic Allochthon is a north/south-trending elongate, lithologically distinct belt extending approximately 200 kilometers, from Sudbury, Vermont to Poughkeepsie, New York. The Allochthon spans a lateral distance between 20 to 30 kilometers at its widest points and the topography shows a maximum elevation of just over 730 meters within its boundaries. The Allochthon is composed of a thick sequence of interbedded argillaceous and arenaceous lithologies of late Pre-Cambrian (?) to medial-Ordovician age with lesser occurrences of calcareous and siliceous lithologies. These strata are of dominantly deep-water aspect and have been tectonically juxtaposed onto the shallow water Cambro-Ordovician shelf sequence dominated by carbonates and clastic sediments.

As determined by Zen (1967), the more obvious internal structure of the Allochthon is that of a series of six nested thrust slices, each possessing its own internal stratigraphy and structural features. From lowest to highest, they are: the Sunset Lake Slice, Giddings Brook Slice, Chatham-Bird Mountain Slice, Rensselaer Plateau Slice, Dorset Mountain-Everett Slice and the Greylock Slice. (See Figure 1.1) The structurally-lowest two slices, the Sunset Lake and Giddings Brook Slices, contain the most complete stratigraphy. Tectonically, the highest structural slices of the Allochton are the most far-travelled and are thought to have been carried piggy-back on the nascent, lowest structural slices as thrusting propagated to the west. Significant structural complexity exists within each slice, however, since detailed mapping (e.g. Rowley et al. 1979, Rowley 1979, Bosworth 1980) has shown that each of Zen's (1967) major slices are internally composed of numerous thrust imbricates or sub-slices. Within the Giddings Brook Slice, metamorphic intensity (within the chlorite-biotite range) increases to the east as does the development of the "late" structural elements, notably the crenulation age deformation structures. In the western Taconics, the rocks of the Allochthon have experienced a minimum of three deformation phases as determined using refolded-fold, transected cleavages and similar structural criteria. In the northeast Taconics, several more phases can be conclusively demonstrated as will be discussed in this thesis.

The Allochthon tectonically overlies a medial-Ordovician parautochthonous/autochthonous carbonate shelf sequence dominated by shallow marine clastics. This sequence is known as the Vermont Valley or Synclinorium sequence and represents the deposition of a coeval carbonate shelf of a lower Paleozoic ocean with the deep water sediments of the Allochthon. The present tectonic relationships are thought to have formed as a westward-migrating arc system (the Ammonoosuc Volcanics) overrode the continental margin as subduction occurred along an east-dipping subduction zone. (Rowley and Kidd, 1981) The Taconic

Allochthon can be regarded structurally as a lower Paleozoic accretionary prism which experienced a sedimentary history and deformational sequence analogous to modern convergent margins such as Taiwan and Barbados. Flysch deposited to the west of the advancing Allochthon records a progressive westward-younging of the graptolite zones within these sediments, and contains cleaved and deformed detritus from the Allochthon colliding with and overriding the shelf from the east.

FIGURE 1.1

STRUCTURAL SLICES OF THE TACONIC ALLOCHTHON

SHOWING OUTLINE OF STUDY AREA AND REGIONAL SETTING:

1-SUNSET LAKE SLICE

2-GIDDINGS BROOK SLICE

3-BIRD MOUNTAIN SLICE

4-CHATHAM SLICE

5-RENSSELAER PLATEAU SLICE

6-DORSET MT.--EVERETT SLICE

7-GREYLOCK SLICE

8-HOOSICK FALLS EMBAYMENT

9-EDGERTON HALF-FENSTER

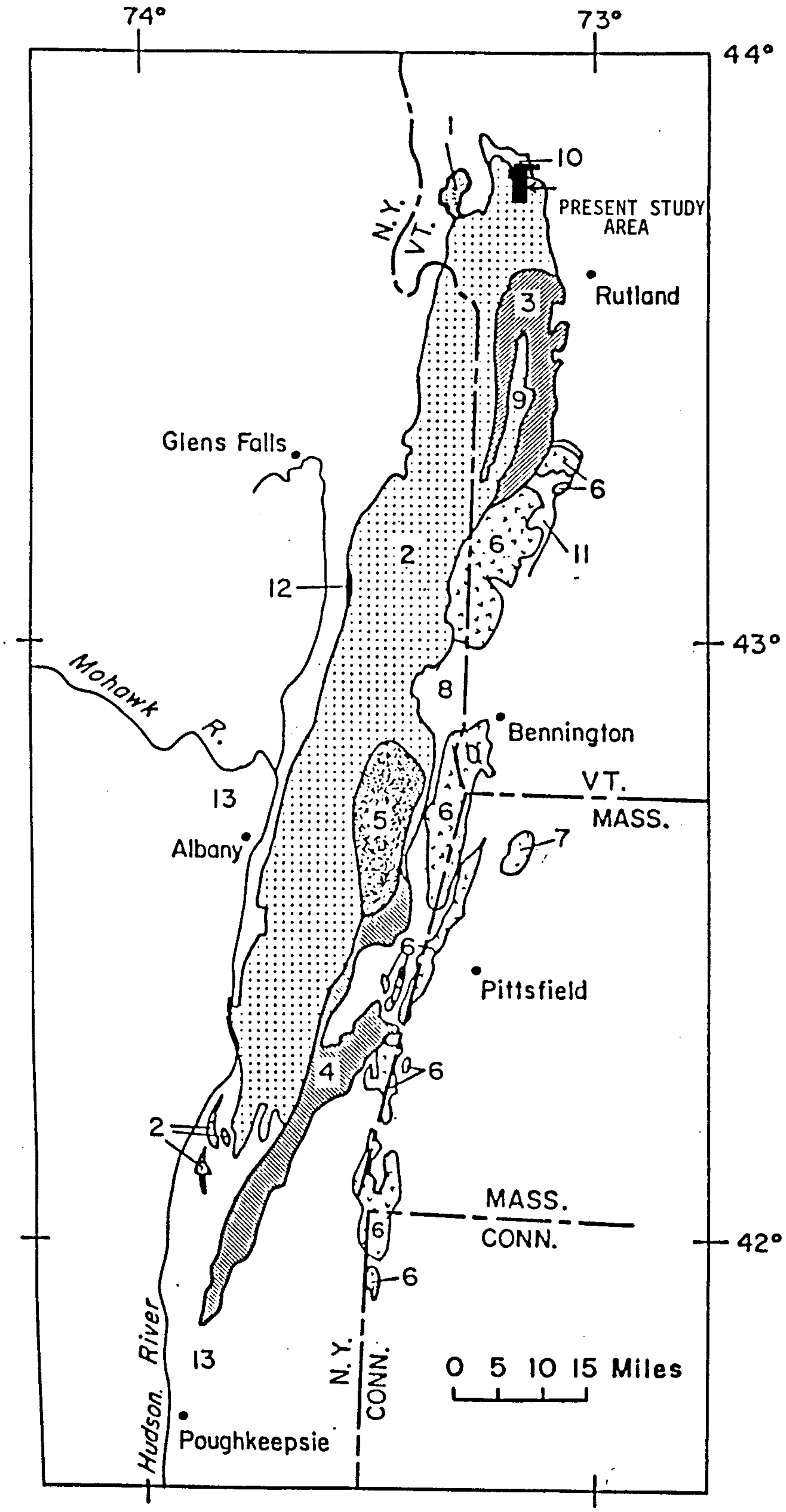
10-SUDBURY SLICE

11-DORSET MT. CARBONATE SLIVER

12-BALD MT. SCHUPPEN OR DUPLEX SYSTEM

13-AUTOCHTHONOUS SEQUENCE

(modified from Zen, 1967)



MODIFIED FROM ZEN, 1967

FIGURE 1.2--

LOCATION MAP OF THE STUDY AREA SHOWING
THE DOMINANT STRUCTURAL FEATURES AND KEY LANDMARKS:

1-GIDDINGS BROOK ANTICLINE (Zen, 1961)

2-PARSONS SCHOOL (now a private home)

3-HUBBARDTON GULF THRUST (Aparisi, 1984)

4-GANSON HILL SYNCLINE (Zen, 1961)

5-MUDD POND   6-WALKER POND

7- KEELER POND THRUST FAULT (Zen, 1961)

8-HINKUM POND   11-BEEBE POND

9-BURR POND   12-AUSTIN POND

10-KEELER POND   13-HUFF POND

14-WILLOW BROOK SCHOOL (now abandoned)

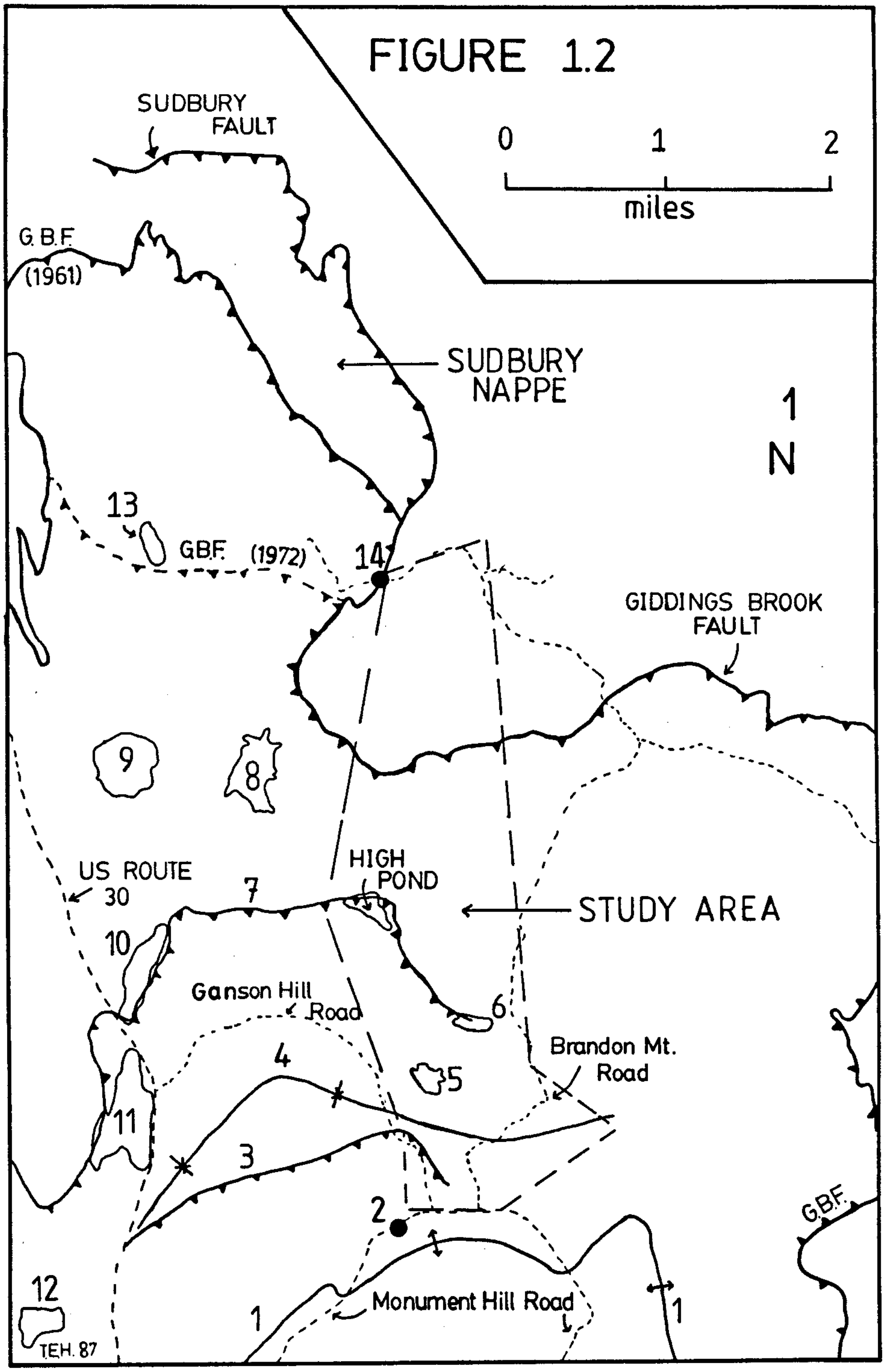


FIGURE 1.2
0
1
2
miles
SUDBURY
FAULT
G. B.F.
(1961)
SUDBURY
NAPPE
1
N
13
GBF.
(1972)
14
GIDDINGS BROOK
FAULT
9
8
HIGH
POND
US ROUTE
30
7
STUDY AREA
10
Ganson Hill
Road
6
4
5
Brandon Mt.
Road
11
3
2
GBF.
12
1
Monument Hill Road
1
TEH. 87

LOCATION OF STUDY AREA

The study area lies at the northeast end of the Allochthon approximately seven miles north of the Hubbardton exit on U.S. Hwy. #4 and approximately four miles southwest of Brandon, VT. The area is bounded to the south by Monument Hill road and to the north by the gravel road which passes the deserted Willow Brook School. The total area encompasses approximately 6.5 square kilometers. (See Figure 1.2) The exposure is quite good for the Taconic region, although some critical areas are covered by glacial cover and/or highly vegetated.

TECHNIQUES OF ANALYSIS

Mapping of the study area was performed on a scale of 1:10,000 using aerial photos (1:20,000, 1974) as base maps. Vehicle access was adequate, though minimal, to the majority of the study area and only the northernmost end of the area was unwooded. Logging and ski trails represent the only tracked access to most of the area. Compass traverses were essential and the best means of determining location in densely wooded areas where visibility is generally restricted to less than one hundred meters. Field work was carried out from early May until early July of 1986, followed by weekends during the Fall and Spring of 1986-87.

THE STUDY AREA

The study area was chosen for several reasons. The region shows excellent exposure for the Taconics, it straddles the Allochthon/Parautochthon boundary and contains several regionally important thrust faults, the Keeler Pond thrust of Zen (1961), the Hubbardton Gulf Thrust of Aparisi (1984) and the basal Giddings Brook thrust of the Allochthon, in addition to the root zone (?) of the Sudbury Nappe of Zen (1961). The regionally anomalous east/west trending Ganson Hill Syncline displays its easternmost closure within the study area.

The primary objectives of this study included: 1) a refinement of the prevailing deformation sequence constructed for the western Taconics, 2) a further examination of cleavage relationships within the E/W trending Ganson Hill fold complex, 3) an investigation of the nature of deformation within the Parautochthonous shelf sequence, 4) the continuity of structural relationships across the Allochthon boundary, and finally, 5) the microstructural characteristics of, and strain values associated with, the various structural elements in the study area.

The thesis is divided into five chapters: 1) An introduction to the thesis; 2) Stratigraphy of the study area; 3) Previous structural investigations in the region; 4) Structure of the study area; and 5) Strain associated with the various generations of cleavage.

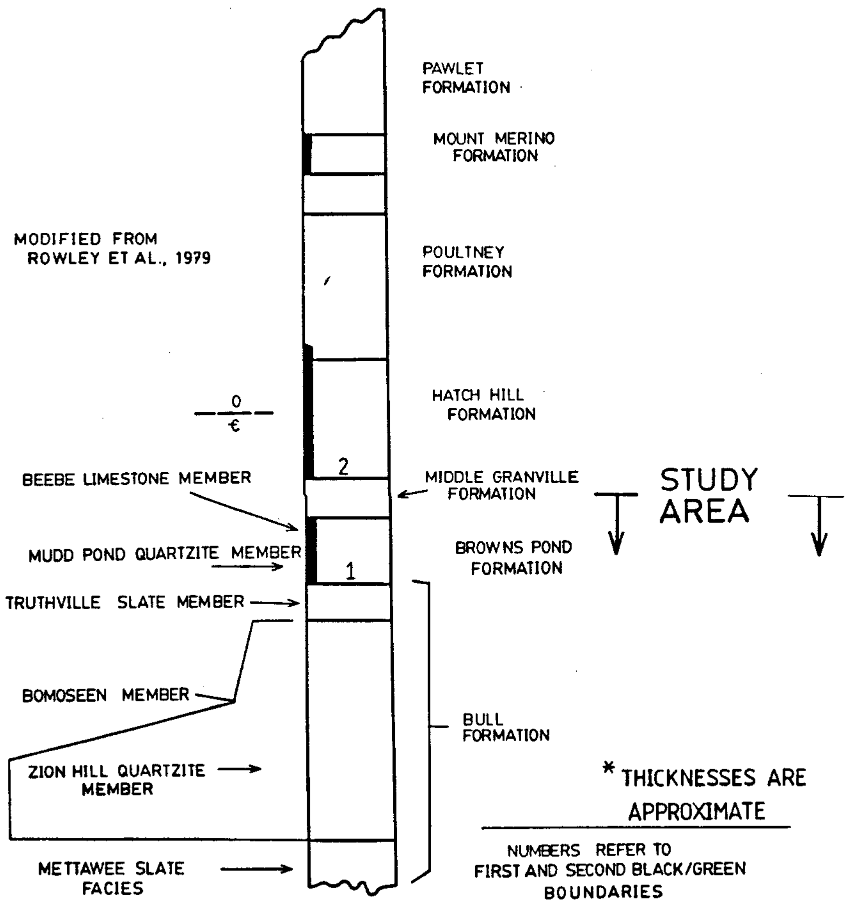
CHAPTER 2 STRATIGRAPHY OF THE STUDY AREA:

The stratigraphy of the Giddings Brook Slice is dominantly composed of argillaceous sediments with lesser occurrences of calcareous and siliceous lithologies. Only recently (Rowley et al., 1979) have the subtle stratigraphic variations within the Allochthon been well enough understood to permit detailed field studies of stratigraphic and structural variation. The present study did not attempt to add to the present knowledge of stratigraphic relationships within the Allochthon and the Parautochthonous shelf, and uses the framework suggested by Rowley (1983) and Zen (1961). This chapter is merely intended to discuss the observed stratigraphy and variations of this stratigraphy within the study area.

The study area within the Allochthon contains only the lowest Taconic stratigraphy, composed of the interbedded slates, siltstones and quartzites of the Bull Formation; Bomoseen Member, Truthville Member; the slates, quartzites and carbonates of the Browns Pond Formation, and the slates of the Middle Granville Formation(?). The Parautochthon stratigraphic framework used in the present study was that used by Zen (1961) and includes the black slate/pebbly conglomerate facies of the Ira-Hortonville Formation, the Forbes Hill Conglomerate member; and the carbonates of the Chipman formation; Weybridge Member, Burchards Member, Beldens Member. A stratigraphic column of the Allochthon stratigraphy and Parautochthon stratigraphy can be seen in

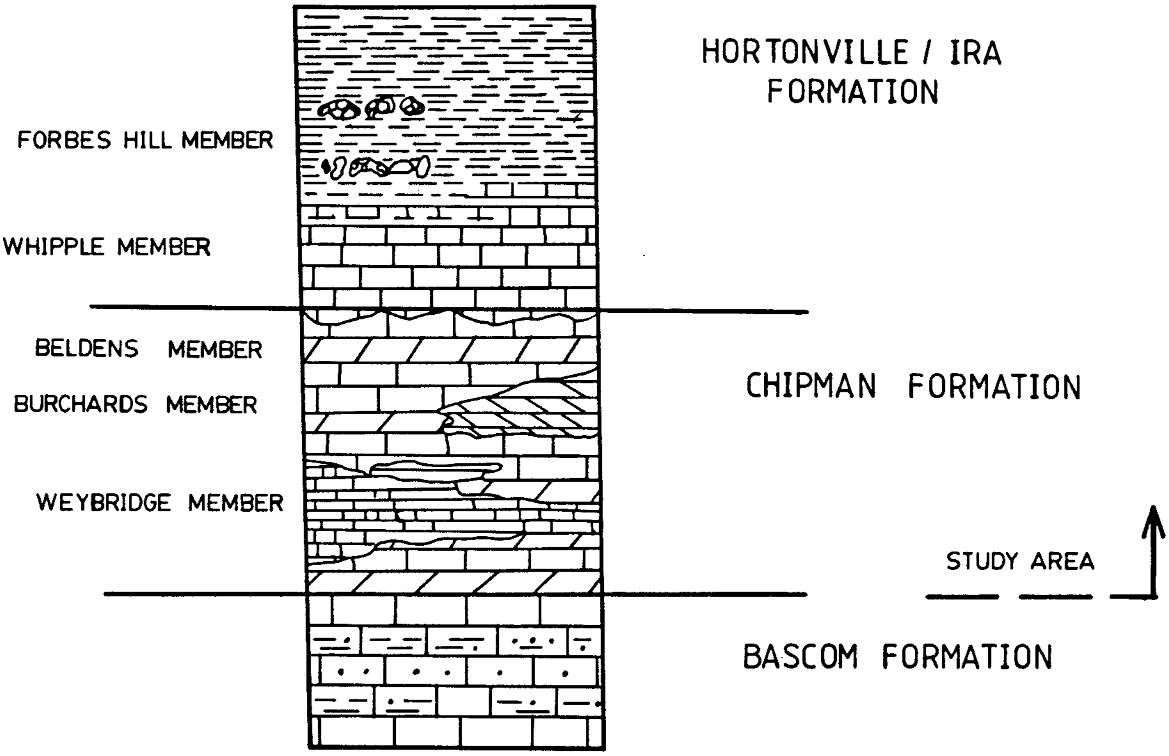
Figures 2.1 and 2.2. Those readers desiring more detailed stratigraphic descriptions and studies are referred to those found in Jacobi (1977), Rowley et al. (1979), Rowley and Kidd (1981), Rowley (1979; 1983) and Aparisi (1984). The present study was intended to address more structurally-related topics as described in the previous chapter (Introduction; Chapter 1) and which will be further discussed in subsequent chapters.

FIGURE 2.1 ALLOCHTHON STRATIGRAPHY



PARAUTOCHTHON STRATIGRAPHY

FIGURE 2.2



AFTER ZEN, 1961

ALLOCHTHON STRATIGRAPHY:

BULL FORMATION

The Bull Formation comprises the lowest stratigraphic units found within the Giddings Brook Slice. This formation contains the Truthville Slate Member, Bomoseen Member and the Mettawee Slate facies. Its upper boundary is marked by the first black/green boundary and the appearance of the darker Browns Pond Formation lithologies.

METTAWEE SLATE FACIES OF THE BULL FORMATION

This lithology distinguishes the thick sequence of interbedded purple, green and gray slates found at several positions within the Allochthon stratigraphy. Where the black slates of the Hatch Hill and Browns Pond cannot be demonstrated to enclose these slates, they are classified under the generic Mettawee facies as opposed to the Middle Granville member which will be used only where the sequence is well-constrained. As a consequence of undifferentiable interbedded purple, gray and green slates the Mettawee facies has been mapped at several levels of the Allochthon stratigraphy. As much as possible, this study attempts to restrict these slates to beneath the Bomoseen Member of the Bull Formation. The stratigraphic information required to more completely discriminate the nature of the Mettawee facies is generally complicated by poor exposure and complex structural imbrication found throughout the Taconics so the

Mettawee facies is adopted as a catch-all term for purple, green and light gray slates of unknown stratigraphic position.

In general, these rocks are purple, green and gray slates to mudstones and generally show well-developed slaty cleavage. Rowley (1983) separates this sequence into two lithofacies based on coarseness of the argillites and on associated lithologies. The lower lithofacies typically shows less well-developed cleavage as a result of coarser grain size and more abundant silica content. This lithofacies generally shows thin greenish-white weathering arenites and quartzites lying interbedded within the sequence.

The upper lithofacies, according to Rowley (1983), probably correlative with the Middle Granville slates, contains thin green micritic limestone layers interbedded with the slate and a more calcareous nature to the slates, which weather to a more brownish color.

Both of these lithofacies have been reported by Rowley (1983) to be interbedded on a mesoscopic scale. For this reason, such a distinction will not be attempted in this study, as the subdivision of the two lithofacies is not overly useful for mapping purposes.

BOMOSEEN MEMBER OF THE BULL FORMATION

The base of this lithology is distinguished by interbedded green and purple slate, probably the upper occurrence of the "lowest" Mettawee facies, similar to the

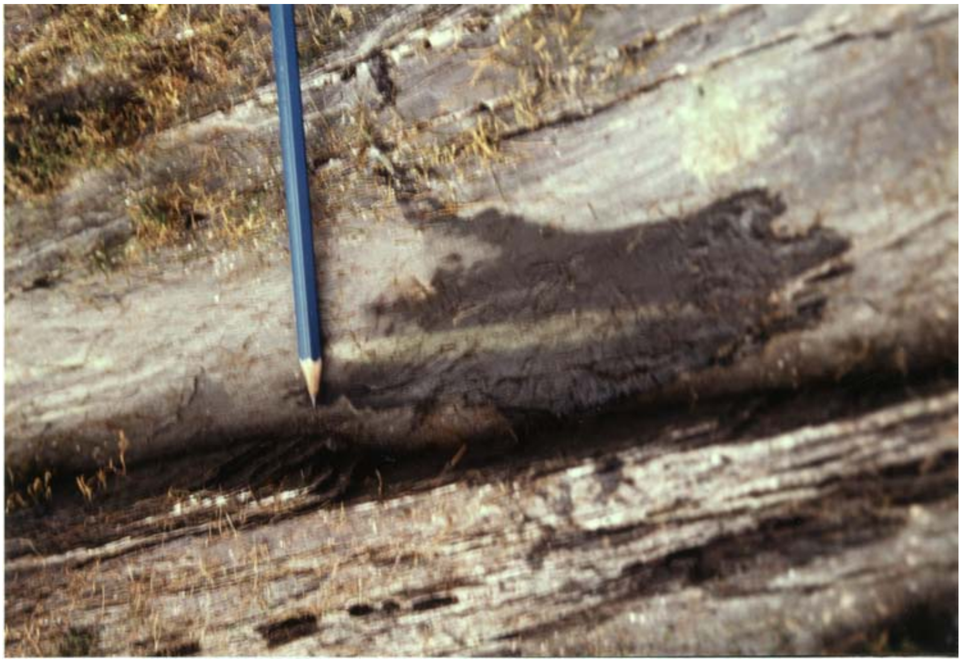


Figure 2.3
Green streak defining bedding in purple slates of Mettawee Facies, outcrop location WNW of Mudd Pond (423-5).

Figure 2.4
F_5 fold of interbedded arenites and green slates of Bomoseen Member, strata are upright here.
0.5 km NNW of Mudd Pond (423-7).

relationships found by Jacobi (1977) within anticlinal cores in the western Taconics. The bulk of the Bomoseen Member is more arenaceous and composed of a thick sequence of silty and shaly graywackes which are generally poorly-cleaved.

The cleavage in this rock is generally a spaced, anastamosing cleavage which is often weakly crenulated. One distinguishing characteristic of this lithology is the near absence of crenulation development except as a weak lineation on the slaty cleavage surfaces. This feature permits easy recognition of the "slaty cleavage" in the outcrop, whereas the crenulation cleavage is much less distinct, except where small-scale crenulation folds are present. There are, however, notable exceptions to this observation. The rock weathers to a light tan to a light gray and is olive green to light gray on fresh surfaces. Some thin massive silty green quartzite beds are often found interbedded within the graywacke but are apparently not restricted to any specific horizon of the Member. The most distinctive feature of this Member is the widespread abundance of mica-spangled surfaces visible in hand specimen. Jacobi (1977) reports a thickness for the Bomoseen Member of at least 240 meters in the Granville, NY region. The upper contact of the Bomoseen Member is marked by the appearance of a more greenish, slaty lithology, the Truthville Member. The Bomoseen Member is resistant to weathering and is commonly found forming ridgetops and steep bluffs. Excellent examples of this lithology in the study area can be seen along the Brandon Mt. Road, approximately one mile north of its junction with Monument Hill Road on the eastern side of the road, and on the south dipping topography of the steep knob just south of High Pond on the hanging wall of the Keeler Pond fault. These locations can be seen on the geologic map of the study area (see Chart I).

ZION HILL LITHOFACIES OF BOMOSEEN MEMBER

Lying within the Bomoseen is the Zion Hill lithofacies, a coarse-grained quartzite ranging locally to a pebbly-conglomeratic sub-graywacke as described by Aparisi (1984). She describes this quartzite as massive, pale gray to white-weathering and medium-gray to yitreous on a fresh surface. Grain size is variable from medium sand to coarse grit. This lithology is lensing and is easily confused with the Mudd Pond Quartzite. Several locations within the study area show thick Mudd Pond-like lithologies which are interbedded with light gray siltstones of the Bomoseen member. In the study area, the distinction between the Zion Hill and the Mudd Pond Quartzite (discussed later) was made on the basis of interbedded material, coarseness of grain size and color of the fresh surfaces. At places, both lithologies appear identical, especially where they lie interbedded with light gray slates which could be either a more siliceous Browns Pond lithology or a darker, more slaty Bomoseen lithology. The Zion Hill shows much less well-developed bedding but this is frequently-graded, in contrast to the Mudd Pond. All of these diagnostic features can be

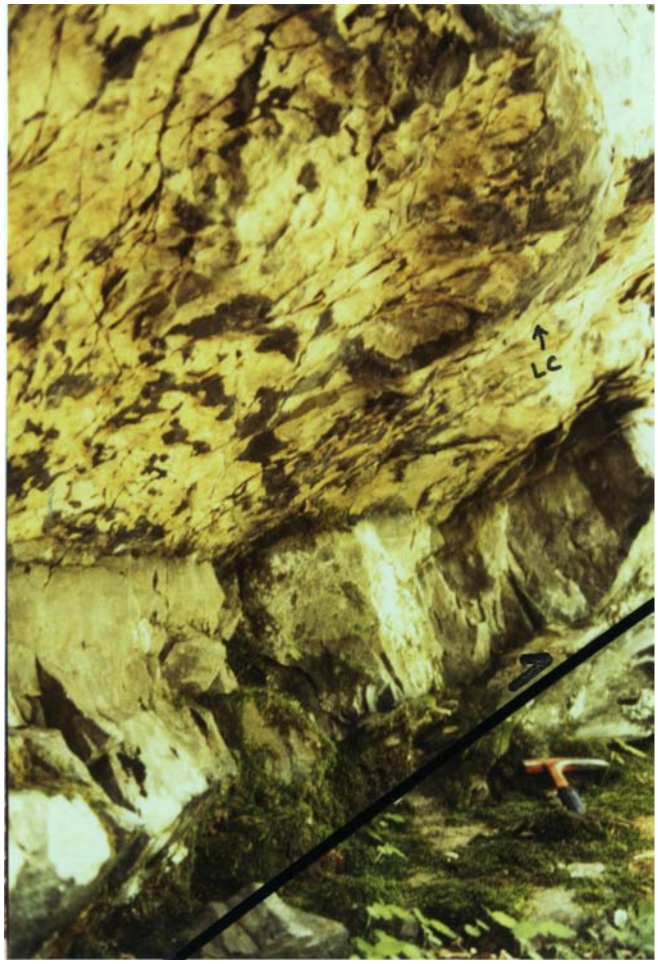


Figure 2.5
Zion Hill Quartzite with graded bedding (not visible in photo) and load casts. Load casts form the rounded protrusions on the upper surface in the photo. Thrust surface lies below hammer and is shown by the black line.
Outcrop forms extensive N-S bluff, NNE of Brandon Mt. Road/Monument Hill Road intersection.

Figure 2.6
Zion Hill Quartzite showing lenticular nature of lithology, same location as Fig. 2.5. Quartzite lies above thrust plane here and shows abundant cross-cutting veining.

shown to occur in both lithologies. Several locales can be found where dolomitic sandstone lenses lie interbedded with the Zion Hill quartzite. These lenses often contain calcareous clasts or nodules which appear to be highly flattened. Thickness of the Zion Hill is variable within the study area, ranging from 0.5 to 50 meters. The lithology weathers to rounded knobs and contains abundant cross-cutting white quartz veining.

TRUTHVILLE MEMBER OF THE BULL FORMATION

The Bomoseen Member is stratigraphically overlain by the Truthville Member, a micaceous olive gray to dark-greenish gray slate. This lithology is more uniform and shows only minor ribbon quartz-arenites near its base. This lithology outcrops poorly and is often marked by a topographic depression up section from the Bomoseen as described by Rowley (1983). This slate displays a well-developed slaty cleavage. It is exposed at the northwest corner of Mudd Pond in the study area.

BROWNS POND FORMATION

The Browns Pond Formation marks the lowest green/black boundary of Rowley et al. (1979). The Browns Pond consists primarily of grayish-black to black slates intermingled with thick quartzites, calcareous wackes, layered limestones and limestone breccia. Based on shelly fauna described from within the West Castleton formation (in part, the precursor to the Browns Pond in modern usage) Theokritoff (1964) has suggested a late early Cambrian age for rocks now included in this formation. All of these lithologies are present within the study area. These lithologies are not entirely restricted to the Browns Pond but their presence together allow discrimination of this unit.

Bedding within this formation is only distinguishable where calcareous horizons and quartzites provide significant contrast. The slates are generally silty and often calcareous. They weather brownish-gray to an olive-black and generally show small calcite crystals on cleavage parting surfaces. The cleavage is generally wavy and finely spaced.

MUDD POND QUARTZITE MEMBER OF BROWNS POND

In the lowermost levels of the Browns Pond, lie thick (up to 8 meters), lensing, light gray to tannish-gray, slightly rust-speckled quartzites named the Mudd Pond quartzite. The study area contains the type locality for this lithology along the western shores of Mudd Pond. Interestingly, on the southeastern shore, a nearly identical lithology can be found which lies interbedded with light gray wackes. This has been mapped by Zen (1961) as the Zion Hill lithofacies of the Bomoseen Member. Often, dolomitic sandstones are found interbedded within the unit as lenses or channels. According to Rowley (1983), lenses of the Mudd Pond may overlap in a vertical sense but are thought to be confined to the same general stratigraphic horizon. The most distinctive feature of this lithology are the interbedded dolomitic sandstone lenses and the abundant,

Figure 2.7
Mudd Pond Quartzite showing an F_3 (?) fold. Note irregularly-spaced fractures defining bedding on the limbs.

Figure 2.8
Mudd Pond Quartzite illustrating typical appearance of bedding and crosscutting veining, in addition to an interbedded more slaty lithology on the top of the outcrop. Outcrop lies to NW of Mudd Pond. (423-1A).

often cross-cutting veining that transects the lithology without any obvious preferred orientation. In places, the veining is at right angles to bedding but this relationship can be shown to vary significantly. The lithology is distinctive and regionally important, as it defines the closure of the Ganson Hill syncline. In outcrop, distinct parallel fractures can be shown which can be demonstrated as bedding. Supporting this observation is the highly variable spacing of the fractures which supports the idea that the fractures parallel bedding as opposed to having formed by tectonic processes. This lithology is easily confused with the Zion Hill Quartzite and is best distinguished from it on the basis of grain size, color and interbedded lithologies. The Mudd Pond is generally cleaner, finer-grained, is less-often graded, shows bedding planes more frequently, and lies interbedded with black and dark-gray slates. Confusion arises when the slates become more siliceous and the Mudd Pond becomes darker and more coarse-grained. It is one of the dominant lithologies cropping out within the study area, especially in the Ganson Hill area and eastward.

BLACK PATCH GRIT MEMBER OF BROWNS POND FORMATION

Another characteristic lensing lithology within the Browns Pond is the Black Patch Grit, an intermittently calcareous sub-graywacke lying interbedded with grayish-black slates just above the Mudd Pond Quartzite. Occurring within the graywacke are black rip-up clasts of slate from which the name "Black Patch Grit" is derived.

Figure 2.9
Finely-laminated carbonate horizon (Beebe Limestone) visible next to compass, within the Browns Pond Formation, lying interbedded with black slate.
Outcrop lies in SW corner of study area. (521-2).

Figure 2.10
Thin, lensing carbonate breccia (Beebe Limestone) interbedded with black slate of Browns Pond Formation, in same outcrop as previous photo of Fig 2.9. (521-2)

This lithology is only rarely seen within the study area, generally lying closely associated with the Mudd Pond Quartzite and often slightly above it.

CARBONATE HORIZONS WITHIN THE BROWNS POND FORMATION

The most distinctive horizon within the Browns Pond are thin (generally less than 30 cm) limestone lenses or breccias dominated by thinly laminated micrites or calcisiltites. Locally, the limestone can be shown to be substantially thicker, up to 3 meters, at the southwest corner of the study area. The carbonates are generally restricted to the uppermost layers of the formation. The breccias and layered sequences, are often found to grade into each other laterally. The carbonate is typically black when fresh and weathers to a light gray in color. This lithology is the equivalent of the Beebe limestone of Zen (1961). The carbonate is generally uncleaved though transected by fractures filled with vein carbonate. Some of the limestone outcrops within the study area also show locally abundant stylolite development. The slaty cleavage within the interbedded slate often wraps around the limestone lenses and breccia blocks. The limestone is locally fossiliferous and contains numerous small black phosphatic grains representing a phosphatic horizon on the slope which has been dismembered during sedimentation. (E. Landing 1987, personal communication).

The Browns Pond crops out poorly within the study area and is best exposed in the complexly thrusted sequence at the southwest corner of the study area where it is protected by the overlying Mudd Pond Quartzite. Following this lithology to the north of these outcrops is difficult, as the Mudd Pond is no longer present and the carbonate horizon is hidden by the abundant vegetation and soil cover.

Thicknesses for the Browns Pond are determined by Jacobi (1977) to be approximately 130 meters thick at the type section.

MIDDLE GRANVILLE FORMATION

The lower boundary of the Middle Granville marks the transition from the black carbonate-rich lithologies of the Browns Pond back to the more siliceous green and purple horizons of the Middle Granville. It is equivalent to the uppermost part of the Bull Formation as used by Zen (1961). In the western part of the Taconic outcrop (Rowley et al., 1979), it can be shown to be enclosed by the black slates of the Browns Pond Formation lying stratigraphically below and the black slates of the Hatch Hill Formation lying stratigraphically above.

At the lowest levels, the Middle Granville contains thin micritic limestones and gray slates. The gray slates are slightly calcareous and grade into the interbedded green and purple slates that dominate the formation. These colors can be shown to grade into each other both vertically and laterally and are probably due to diagenetic fluids as evidenced by bedding parallel "green streaks" within purple slate. Such streaks and other diagenetic features are best exposed in the slate quarries that expose this lithology, such as those at Cedar Point and near Granville, NY. Bedding within this lithology is defined by green streaks within the purple slate and thin darker purple seams within the purple lithology. In some places, these color streaks can be shown to lie subparallel to bedding defined by micritic layers, so such color banding must be used with caution as a bedding indicator. Rowley (1983) has suggested a thickness of about 53 meters for this lithology.

In the study area, the exposure of this lithology is restricted to the southwest subregion just east of the large pastures along Ganson Hill road.

No other Taconic lithologies are thought to be present in the study area. It should be realized, however, that outcrops of the Hatch Hill formation and the Poultney formation are both exposed to the west in the core of the Ganson Hill structure as reported by Aparisi (1984). Those readers interested in a more thorough description of Taconic stratigraphy are referred to Rowley et al. (1979), Rowley (1979; 1983), Jacobi (1977) and Rowley and Kidd (1981).

BLACK POND LITHOFACIES

Although the Black Pond Lithofacies is not thought to be exposed within the study area, it has significant regional importance and has some bearing on the nature of the controversial black slate at the north end of the Allochthon.

Rowley (1983) used this stratigraphic term to describe a complexly-deformed sequence composed of interlayered medium to coarse-grained quartzites and gray to dark gray, silty to fine-grained slate. The most significant structural feature of these strata are lithic fragments of foliated slate and/or phyllite, felsic volcanic clasts and occasional polycrystalline quartz.

These slates are very similar to the Hortonville Slates of the Parautochthon which generally contain an abundance of detrital lithic fragments in a black matrix. At the same time, quartzites within these Black Pond strata appear very similar to the Zion Hill Quartzite within the Bomoseen Member of the Allochthon. Rowley suggests that these strata are perhaps the result of stratigraphic and/or structural commingling during emplacement of the Allochthon onto the Shelf Sequence.

REGIONAL LITHOLOGIC VARIATIONS WITHIN THE ALLOCHTHON

Rowley (1983) describes several significant variations within the Allochthon stratigraphy. The Bomoseen Member of the Bull Formation shows the most profound variation moving laterally within the Allochthon. The lithology becomes thinner, areally less prominent and more fine-grained. In the Lake Bomoseen area, the easternmost region studied by Rowley, the Bomoseen Member becomes more of a siltstone or a silty wacke and the purple and green Mettawee slate facies becomes much more dominant within the sequence. Similarly, and also within the Bull Formation, the Truthville facies become much less silty and are more desirable as roofing slates. Overall, Rowley suggests that the Truthville fines to the east.

The Browns Pond becomes much thinner moving eastward and carbonate is thought to become virtually absent, according to Rowley. The lithology also becomes more siliceous and more of a dark gray color in contrast to the black slate seen further to the west.

Interestingly, the present study does not fully support these trends. While there are a large number of gray to gray-green slates in the study area that are extremely difficult to classify, there are significant horizons of black slate and thinly-laminated carbonate, in addition to carbonate breccias, within the southwestern corner of the study area. In the gently south-dipping plateau-like area between High Pond to the north and Mudd Pond to the south, there are abundant coarse-grained arenites interbedded with arenaceous slates of the Bomoseen member. These results suggest that many of the stratigraphic variations that Rowley (1983) reports across strike of the Allochthon are made more complex by along-strike variations as well. Further work could confirm this in a more substantive manner.

PARAUTOCHTHON STRATIGRAPHY:

The stratigraphy of the Parautochthon is based on the work of Zen (1961). The present discussion is based only upon the observed lithologies found at the northeast end of the Allochthon. Those readers desiring more complete discussions of the stratigraphic sequence of the Autochthon/Parautochthon are referred to Zen (1961) and Washington (1981).

CHIPMAN FORMATION

The Chipman Formation of Zen (1961) is composed of three members described further below. The Weybridge Member is confined to the lower stratigraphic levels and the Burchard Member is found near the upper levels of the formation. These members appear quite similar in outcrop and it is very difficult to fully identify the individual lithologies, the nature of the contacts that separate them, and the large-scale structural features that they define.

In the study area, Zen (1961) suggests that the sequence is right-side-up and indicative of a normal sequence. These relationships are suggested by apparent cross-bedding found within the Weybridge Member. This feature is probably the famous "Vermont Cross-bedding" produced by structural slicing or fault truncation of the overturned limbs of small-scale isoclinal folds. The present study has indicated the widespread presence of transposition fabrics within these rocks and structural slicing within these strata. An excellent example of this slicing can be seen along the Willow Brook School road. In addition to these pseudo-sedimentary structures, most lithologic layering is defined by laminae of dark insoluble residues interlayered with carbonate and dolomitic layers.

These boundaries are usually stylolitic, suggesting that finely-laminated "bedding" is actually a metamorphically differentiated layering.

WEYBRIDGE MEMBER OF CHIPMAN FORMATION

A fine-grained gray marble interbedded with brown-weathering, slightly dolomitic layers spaced approx. 2 cm. These locally show cross-bedding (?).

BURCHARDS MEMBER OF CHIPMAN FORMATION

This lithology is similar to the Beldens Member but is characterized by buff-weathering dolomite in the fine-grained gray limestone or marble beds.

BELDENS MEMBER OF CHIPMAN FORMATION

The dominant lithology within the formation. A gray, massive marble with interbedded white dolostone, also a white massive marble with red hematite streaks which often causes an attractive pinkish-white weathering. In a few places this lithology is nearly a blood red color when fresh.

IRA-HORTONVILLE FORMATION

This formation is composed of several distinct members. The exact relationships between the Ira and Hortonville Formations is unknown, since it is impossible to trace each of the lithologies around the Allochthon. Zen (1961) designated those black slates along the eastern Taconic margin the Ira Formation, and those along the western

Figure 2.11
Photo illustrates “Vermont cross-bedding” caused by structural slicing of mesoscopic folds within the Weybridge member of the Chipman Formation.
Along the Willow Brook School Road. (69-14A)

Figure 2.12
This photo from the same outcrop confirms the origin of the “bedding” within the Weybridge member. An isoclinally folded calcite vein has been transposed into parallelism with the dominant layering. (69-14B)

Figure 2.13
Photo illustrates the typical appearance of the Burchards member showing a spaced cleavage and a second weaker fabric lying parallel to pen. This is one of the few outcrops of the crenulation morphology. (614-5).

Figure 2.14
Outcrop of Beldens member of Chipman Formation showing the pronounced transposition fabrics prominent throughout the study area. Isolated fold closures and limbs of a black chert layer form the more resistant protrusions on this outcrop. Outcrop is found at NE corner of study area in NE cow pasture. No obvious secondary foliations or related structures are present here. (610-10).

boundary the Hortonville Formation. These two units appear nearly identical and are composed of dark-gray slates with variable bedding thicknesses and intermittent outcrop continuity. In addition to this lithology is a black dolomitic quartzite facies identical to that described by Rowley (1983) from within the Black Pond lithofacies. The bulk of the formations are composed of a coarse, massive dark gray to black, slate/phyllite. Albite porphyroblasts are strongly developed on the eastern margin of the Allochthon where the metamorphic grade is higher. Such porphyroblast development was not widely observed within the study area.

These black slates and related lithologies represent a significant problem in our understanding of the nature of the Allochthon/Parautochthon boundary. This will be further discussed at the end of this chapter.

FORBES HILL CONGLOMERATE MEMBER OF IRA-HORTONVILLE FM.

The Forbes Hill is probably the most distinctive lithology of the Parautochthon. This lithology contains elongate and flattened pebbles of green slate, buff-weathering limestone, dolomitic sandstone and brown-weathering dark dolostone, according to Zen (1961). Zen reports that these pebbles contain a foliation lying parallel to that of the enclosing matrix. He further indicates that these pebbles can all be derived from within the Taconic lithologies to the south.

Figure 2.15
Forbes Hill Conglomerate showing elongate calcareous clasts in black slate matrix.
Outcrop lies within eastern imbricate zone of Forbes Hill in study area.

Figure 2.16
Forbes Hill lithology showing a small-scale folded arenite lithic fragment which pre-dates the slaty cleavage development in this outcrop. Same outcrop as previous photo.

The present study area contains two of the finest exposures of the Forbes Hill outcrops. The first of these is along the Willow Brook (described by Zen, 1961) and the second, due east approximately 0.75 kilometers. In the present study, small scale, thinly-bedded, isoclinally folded arenite/quartzite layers can be found that have axial surfaces that do not lie parallel to the dominant outcrop slaty cleavage. (See Figure 2.16) These folds predate the development of this cleavage and the fold is enclosed as a clast in the conglomerate. The size of these pebbles range from thin centimetric-long, paper-thin clasts flattened in the cleavage, to clasts a centimeter thick measured parallel to cleavage and several centimeters long. The longer clasts are generally the dominant pebble lithology and are composed of a buff-weathering calcareous micrite. The lensing nature of these outcrops described by Zen (1961) is reinterpreted in the present study as small imbricate thrust zones similar to those seen along the Taconic Frontal Thrust.

THE BLACK SLATE ENIGMA ALONG THE ALLOCHTHON BOUNDARY

The problem of differentiating the different (?) black slate units at the north end of the Allochton has caused considerable confusion as to the exact nature of the Allochthon/Parautochthon boundary and the continuity of structural and stratigraphic relationships across the Taconic Basal, or Giddings Brook, Thrust. Zen (1961) mapped considerable regions of black slate at the north end as Allochthon, the so-called "Signal Hill Slice" of Voight

(1965), which lies to the north of the Keeler Pond fault and extends to the northern Allochthon boundary. Zen indicated, however, that "In the field, the Hortonville and Ira formations are indistinguishable from the lower Cambrian West Castleton formation [now mapped as either the Browns Pond or Hatch Hill fm.]." (p. 310)

Voight, mapping an area along the northwest boundary of the Signal Hill Slice, suggests structural continuity between alleged "Taconic" and Parautochthonous rocks. This is problematic in light of Zen (1972) who suggested that this same area is actually a large wildflysch sequence which has more Parautochthonous affinities. This new interpretation casts considerable doubt on the nature of Voight's conclusions from his work along the Allochthon boundary. Zen (1972) has suggested that these slates are actually the Hortonville Slate of the Parautochthon, and their confusing appearance is the result of complex intermingling with exotic "Taconic" blocks in a wildflysch-type sequence. This melange origin is similar to that proposed by Rowley (1983) for the Black Pond lithofacies.

In the present study, further confusion exists due to the lack of any key marker horizons within the black slates along the boundary. While Forbes Hill strata are locally present, probably in imbricate thrust slices, no overly distinctive stratigraphic evidence is present which conclusively indicates the provenance of these black slates. If indeed the slates are those of the Allochthon, black slate is only found within the Browns Pond, Hatch Hill and Poultney lithologies. No evidence was found of the carbonate breccias, Mudd Pond quartzites (both of BP), dolomitic arenites (HH) and related key marker horizons of these Formations, respectively. Structural evidence indicates several highly sheared horizons, one adjacent to the Forbes Hill outcrops along Willow Brook and along the carbonate/black slate contact to the north. Such highly sheared carbonate/slate contacts seem to be universally present although only one outcrop exposes the actual contact. The approximate position of the thrust zone is usually delineated by a zone of complexly cleaved rocks whose phacoidal cleavage weathers to what could be called a "fibrous pencil" structure. The individual cleavage "pencils" display shredded ends and the outcrops consist of steep hillsides of very small "shards" of complexly deformed phacoidally-cleaved slate. Similar cleavage morphologies are well-known from imbricate thrust zones along the Taconic Frontal Thrust (Rowley, 1983; Bosworth and Rowley, 1984) The field evidence supports the idea that both the Forbes Hill imbricate faults and the Giddings Brook Fault should be mapped where these zones of phacoidal cleavage are found. The presence of Forbes Hill lithologies within the black slate in an imbricate thrust position, argues for an allochthonous nature for the black slate in the study area. Supporting this interpretation is the widespread development of scaly or phacoidal cleavage near the shelf carbonate/black slate contact where it is exposed along the Willow Brook. Above this contact, the black slate is highly deformed, but no obvious zones of phacoidally cleaved slate are present and the black slates appear to show some degree of structural and stratigraphic continuity.

Full knowledge of the exact provenance of the black slates might be possible through rigorous sedimentary petrographic analyses not utilized in the present study. The rocks do appear to be in structural continuity and appear quite similar on a gross lithologic basis. Early structural features appear nearly identical throughout the black slate in the study area. The relative scarcity of these early deformational features, however, does not allow unequivocal assignment of these strata to the Allochthon or Parautochthon.

CHAPTER 3 PREVIOUS STRUCTURAL ANALYSES IN THE REGION

INTRODUCTION

The structural geology and tectonics of the Taconic Allochthon have been the source of controversy since the pioneering work of T.N. Dale (1899) in the late 19th Century. The presently-accepted allochthonous interpretation of the region finally emerged after years of intense debate during the 1950's. Following this agreement, a theory involving a soft-sediment, gravity-sliding tectonic emplacement came into vogue and has been repudiated only within the last few years. Although the allochthonous nature of the region is now firmly established, the tectonics of emplacement remain controversial. In this section, I will discuss the findings of recent workers in the Taconics by dividing the discussion into two parts: 1) structures of the Allochthon and 2), structures of the Autochthon/Parautochthon.

REGIONAL STRUCTURES OF THE ALLOCHTHON

The impetus towards our present understanding of the Taconic region was provided by the landmark efforts of Zen (1961). His detailed stratigraphic work and clarification of existing nomenclature helped foster a renaissance of geologic investigation in the region. He recognized that the Taconic sequence consisted of interleaved tectonic slices, each possessing distinctive stratigraphic and structural features. One of the most important elements of

Zen's work is his description of mesoscopic structural features that had only been previously described by Dale (1899). Although both texts contain structural inaccuracies, the latter work particularly utilized confusing terminology and structural mechanisms that are now known to be invalid.

Zen finds that two or more cleavages generally occur in an outcrop. The best developed is a slaty cleavage which generally parallels bedding. This relationship is probably due to the prominence of isoclinal folding in the Taconics. Several locales can be found where the slaty cleavage is at right angles to bedding (i.e. the hinge regions of isoclinal folds), notably the Cedar Point quarry and the Scotch Hill syncline on the southeastern shore of Glen Lake, which suggest that isoclinal folds are responsible for the widely-observed, parallel cleavage/bedding relationships.

Zen finds that the later set of "slip cleavage" is more coarsely spaced, crosscuts the earlier slaty cleavage and commonly indicates a secondary axial plane around which the slaty cleavage is folded. He suggests that this slip cleavage is genetically-related to fractures in more competent layers, and that the formation of the slip cleavage is penecontemporaneous with metamorphism since "new" mica growth defines the plane of cleavage. Zen also describes a feature he terms "cleavage banding" which "consists of subparallel layers of hard, dense argillite, locally quartzite-like in appearance, about 1 inch thick, interspersed with fine slates with parallel orientation of the cleavage." He suggests that these are the result of intense shearing.

Zen's text also describes linear structures such as elongate pebbles and pencil structure which tend to lie parallel to local fold axes.

Zen suggests that minor folds are only of limited importance but seem to indicate closure orientations of larger features. Zen found no minor folds related to his first-generation folding and proposed that all such generation folds (F_1) must be cut by and/or folded by the later slaty cleavage (D_2). He suggests that thrusting occurred as submarine gravity slides, as evidenced by the alleged "numerous" soft-sediment slump structures. The Taconic sequence was thought to have been deposited in the area of the present-day Green Mountains, since there appears to be a litho-stratigraphic correlation between the Taconic sequence and similar lithologies in eastern Vermont although metamorphic grade is much higher in the eastern regions. Regional structure is thought to be dominantly large-scale recumbent folds. Zen suggests that intense deformation took place <u>after</u> the "Taconic" (gravity-sliding) event, perhaps related to formation of the Middlebury Synclinorium and the deformational features of late Ordovician age to which it is correlated.

A later paper by Zen (1964) reported his work in the southern and southeastern corner of the Castleton

Quadrangle. In this text, he suggests the same two-phase deformation sequence but a different age for the second event: 1) Emplacement of the Giddings Brook and Sunset Lake slices as submarine gravity slides of soft sediments with large-scale recumbent folding during the late middle Ordovician, and 2) a later event of refolding and regional metamorphism during the Acadian orogeny.

In 1972, Zen revised a number of his earlier statements. He suggested a three-phase deformation sequence consisting of:

1) large-scale submarine gravity sliding (Trenton age)

2) Late Ordovician to early Silurian; isoclinal recumbent folding, low grade regional metamorphism and the formation of slaty cleavage; thrust emplacement of the Sudbury slice and the Florence nappe.

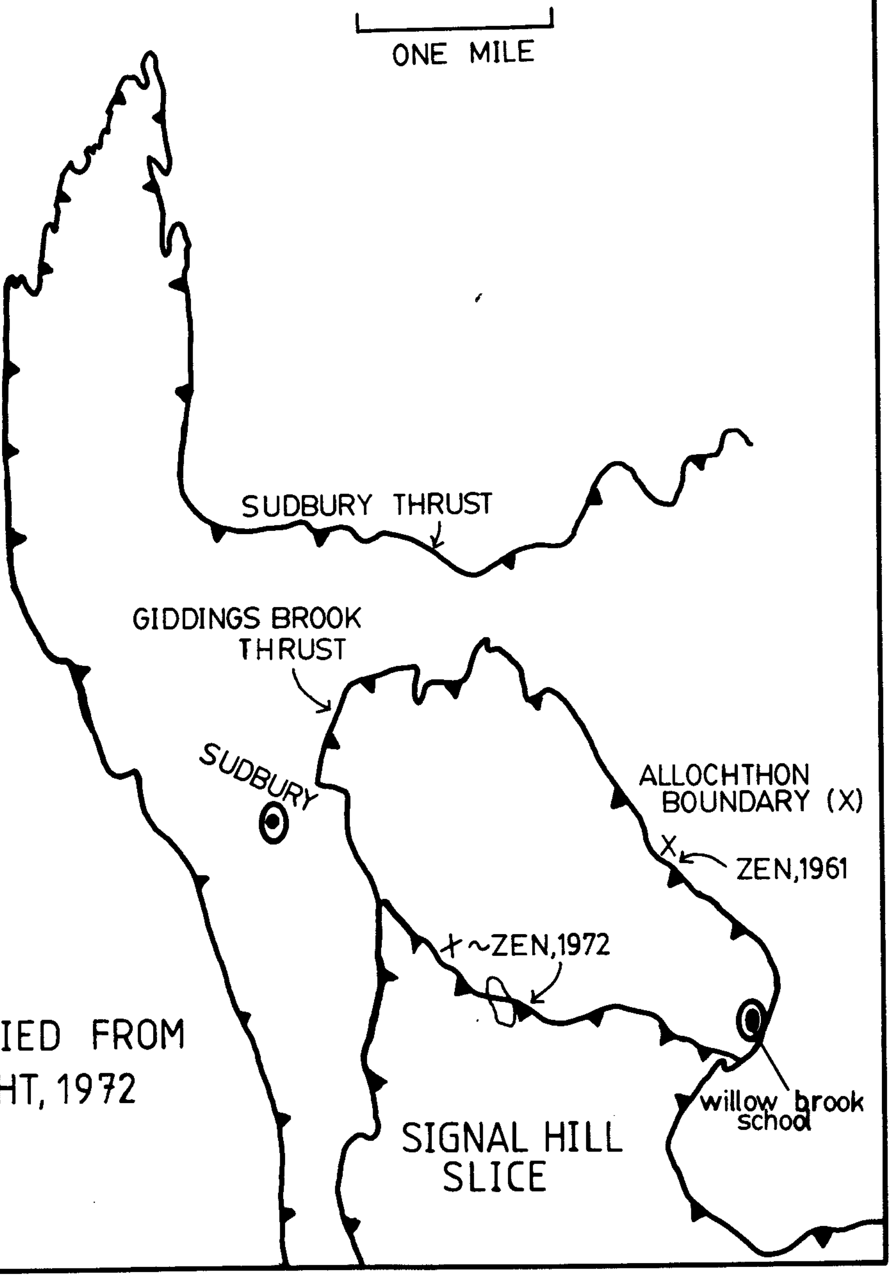
3) Acadian (?), small-scale upright to overturned folds with shallow-plunging, North-trending axes. These later folds refolded the event II slaty cleavage and developed slip cleavage across the earlier foliation. A second metamorphic event was perhaps imposed in the higher grade localities.

This text also redefines the nature of the Signal Hill Slice of Voight (1965) and suggests that the actual boundary of the Allochthon is found along the NW/SE trending dirt road leading away from the town of Sudbury. Zen (1972) maps the extensive region of black slate, previously mapped as part of the Allochthon, as a region of wildflysch with affinities towards the Forbes Hill lithology. This relationship is problematic in light of Voight's (1965)

FIGURE 3.1 LOCATION MAP SHOWING SHIFT OF GIDDINGS BROOK FAULT LOCATION BY ZEN (1972) AFTER REMAPPING AT NORTH END OF ALLOCHTHON. VOIGHT'S STUDY AREA IN THE "ALLOCHTHON" IS OUTLINED FOR REFERENCE.

FIGURE 3.1

MAP OF NORTHERNMOST END OF ALLOCHTHON AND SUDBURY NAPPE



MODIFIED FROM VOIGHT, 1972

efforts that indicated the black slate, thought to be allochthonous, lies in structural continuity with the parautochthonous black slate and carbonate sequence to the north. Zen's remapping suggests that the reported structural continuity between the Allochthon and Parautochthon reported by Voight (1965; 1972) might not actually be the case, and that Voight was merely confirming the structural orientation and sequence within the Parautochthon. It must be recognized, however, that the exact nature of these black slates remains controversial. The region does contain a considerable amount of green slate and related Taconic lithologies ,although the dominant lithology is that of black slate which may have affinities to either the Parautochthon and Allochthon or some complex intermingling of the two environments.

Perhaps, most importantly, this paper attempted to constrain the time of cleavage development. Earlier papers assumed that early cleavage was contemporaneous with emplacement of the Taconic sequence. Although in this text (1972), Zen brings up the mechanism of tectonic dewatering, popular during the late 1970's, but rejects it, since feldspar and quartz porphyroblasts do not contain inclusions of a pre-existing fabric. Such inclusions might be present if the cleavage formed during, or perhaps before, the same metamorphism in which the plagioclase and quartz grains grew. In "thin silty seams" at the Cedar Point quarry on Lake Bomoseen,, Zen finds that quartz and feldspar are not shape-oriented but exhibit incipient fracturing parallel to the slaty cleavage. These observations led him to speculate that the cleavage formation occurred after emplacement and synchronous with metamorphism, to allow the development of a preferred orientation of micas.

Zen (1972) also suggests that the Giddings Brook-Ganson Hill fold system did not form as a result of Event I, but was due to recumbent folding and cleavage forming processes of Event II. The Ganson Hill complex and that of the Great Ledge-Porcupine Ridge complex to the west were thought by Zen to be linked, but are now separated by an Event III oblique fold that brought autochthonous black shales to the surface and destroyed the continuity of the earlier fold relationships. This relationship was disproved by Rowley (1983) who showed that the west limb of the Porcupine Ridge fold is not overturned and hence cannot be related to the Ganson Hill structure. Within the Ganson Hill fold, Zen indicates that a cleavage lies axial-planar to this structure. He states (Zen, 1972) that within the Ganson Hill structure, best displayed on the 1,330 ft. (960m) hilltop N/NW of Parsons School, "the early, slaty cleavage, generally parallel to bedding here, is folded by the late cleavage" (p. 2577). Zen (1961) shows that the inverted southern limb of this structure has been refolded into a series of west-facing folds whose axial surfaces are north-trending and dip to the east. The crenulation cleavage lies parallel to these axial surfaces.

Rowley et al. (1979) marks a significant advance in our present understanding of structural and stratigraphic relationships of the Taconic Allochthon. These authors placed the Taconics in a regional framework in which the "Taconic" continental rise facies were thrust over the carbonate sequence of the continental shelf during an arc-continent collision following the sedimentologic/tectonic model first suggested by Bird and Dewey (1970). The structural features are interpreted to show that the low Taconics were thrust as coherent structural sheets and were not unlithified as previous interpretations have suggested.

These workers recognize a four-fold structural sequence from detailed studies in the Fairhaven-Middle Granville section of the Giddings Brook Slice. The earliest (D_o) involves soft-sediment, syn-depositional slumping and is manifested as local dismemberment or tight folding of bedding. These features are generally restricted to a few beds and never influence large-scale relationships. This folding is designated F_o as it involves distortion (non-tectonic) of bedding (S_o).

The first generation features (D_1) of Rowley et al. (1979) are characterized by large coherent, west-verging, overturned, tight-to-isoclinal, gently-plunging folds (F_1). Associated with this is an axial planar (to F_1) slaty cleavage. In more arenaceous lithologies, S_1 manifests itself as a spaced axial planar cleavage although it is often absent in these lithologies.

Mesoscopic features of the second generation (D_2) include local, open to angular, upright to asymmetric folds (F_2). Associated with these is an upright to steeply east-dipping axial planar crenulation cleavage S_2. To the east, a second, often conjugate, crenulation cleavage is sometimes found. Structure is demonstrably more intensely deformed in the eastern regions in comparison to the west, as manifested by greater fold tightness and thrust truncation of F_1-related features. Some thrusts to the east are also folded by F_1, indicating a pre-to-syn F_1 age for their formation.

Rowley et al. reject the archaic "fracture or slip cleavage" terminology of Zen and, replace it with "spaced crenulation cleavage", a term which separates deformation mechanics from the geometric structure. It is emphasized by Rowley et al. (1979), that the "presence of a second, crenulation cleavage is not necessarily associated with or indicative of a second, wholly separate and later, in this case, Acadian deformation." It is further suggested that coaxial flattening of the early cleavage possibly led to the conjugate formation of the crenulation morphologies. This assertion is largely an attempt to suggest alternative explanations and to emphasize the non-Acadian timing of the cleavages which adds support for an accretionary prism deformation continuum for the Allochthon.

Rowley and Kidd (1981) reiterated many of the structural ideas of Rowley et al. (1979) for a wider audience, and used provenance data of the medial Ordovician flysch to investigate evolutionary trends in the structure and stratigraphy of the rocks affected by the Taconic orogeny. Rowley and Kidd (1981) also suggest an east-to-west stacking sequence where the structurally highest and oldest slices lie to the east. This is perhaps better described as a foreland-propagating imbricate thrust system. The oldest slices ride piggyback on the younger as the thrust system moves toward the foreland, or in the case of the Taconics, onto the carbonate shelf sequence. It should be emphasized that this stacking order is the opposite of what had been suggested by earlier workers but is much more common in well-understood fold, and thrust sequences in Taiwan and the Canadian Rockies. This point remains controversial to some but is well-documented by westward-younging of the Taconic flysch sequence which contains lithified and cleaved rock fragments from the overriding Allochthon as it approached from the east.

One important observation within this analysis is the recognition of red slate clasts (resembling the Indian River red lithology) in the flysch. This suggests that slaty cleavage developed within the low Taconic slices prior to, or contemporaneous with, the medial Ordovician, not later, so that the clasts containing slaty cleavage could be found in flysch of that age. As thrust sheets were carried piggyback and most recent thrusting occurred toward the continental margin or the foreland, flysch progressively becomes younger to the foreland and contains fragments of the thrust slices that are eroding to the east.

This is perhaps the strongest evidence for a pre-slaty cleavage age emplacement of the Allochthon onto the Shelf. Cleaved detrital fragments indicate that the Allochthon possessed some structural fabric that developed prior to or synchronous with emplacement. Other evidence of this timing includes slaty cleavage-age folding of the Basal Thrust reported by Rowley (1983). This relationship is controversial, however, since later crenulation-age folding could appear very similar in outcrops where exposure is inadequate. Even relatively well-developed examples of Basal Thrust folding, such as that which produces the fold culmination and fenster at the William Miller Chapel, cannot be unequivocally demonstrated as a slaty cleavage age fold, since post-slaty cleavage folding is present there and could have produced similar results. In the case of the William Miller Chapel, related localities do not show the crenulation folds and cleavage to be strongly developed, suggesting that only a slaty cleavage age fold could produce the observed geometry.

In response to a critique by Rodgers (1982) of this paper, Rowley and Kidd (1982) renamed the D_1 of Rowley et al. (1979) D_2, in recognition of the fact that an earlier generation of folds (described by Rodgers) exist locally in the Allochthon which do not contain an axial planar cleavage. Rodgers' discussion most clearly summarizes the present controversy regarding the structural continuity between the allochthon and parauthochthonous elements. Rodgers describes three periods of folding. The earliest of these is that which caused the redesignation of Rowley and Kidd's deformation sequence. The second phase is that associated with the regional slaty cleavage and the final phase that related to local crenulation development, at least in the western Taconics. Rodgers states that "the Taconic rocks were already in place on top of the carbonate sequence...[and now] the principal cleavage (the regional slaty cleavage) in all the rocks, both in and out of the klippe, is axial plane to the synclinorium and the folds that form it." A further observation is made that "older" folds are transected by the "later" slaty cleavage. In the Sunset Lake slice, axes of the older folds lie nearly E/W in sharp contrast to those found by Zen, (1961) which trend to the northeast. Rodgers indicates that the later folds (F_2? of Rowley, 1983) and related slaty cleavage are parallel in the northeast and northwest areas of the allochthon and can be traced out into the carbonate shelf sequence without any perturbations. The lack of parallelism of the earlier fold axes (e.g. between Ganson Hill and Sunset Lake area) is thought to be due to a clockwise rotation of the Sunset Lake slice relative to the Giddings Brook slice. The early folds are suggested to have formed during emplacement of the klippe over the carbonate shelf. Confusing the situation is that Rodgers states that an axial planar cleavage is also present in early folds (pre-regional slaty cleavage) in the eastern Taconics. Whether Rodgers still believes that Zen considers the E/W axes of Ganson Hill to be the result of erosion and not a real shift in the axes (as he suggests in his 1961 paper) is unknown. If this is true, this could help to resolve the confusion produced by his statements. E/W trending folds are present in both the Sunset Lake area and also in the Northeast Taconics, and in the northeast are transected by both the "regional" slaty cleavage and the crenulation cleavages. As originally indicated by Zen (1972, p. 2577) these E/W trending early folds contain an axial planar cleavage and are transected by all generations of cleavage as Rodgers cryptically states.

Rodgers reports that his mapping, supported by the work of Zen (1961), shows that at many locales in the northern Taconics, the regional structure is complicated by the fact that early folding places non-overturned allochthonous Cambro-Ordovician black shale on top of right-side-up Ordovician black shale of the parautochthon. The structural observations made by Rowley et al. (1979) near Granville, New York, are explained as the result of a near-parallelism of early and later folding, perhaps even coaxial, such that differentiation of various structural generations is difficult. Thus, the "principal" slaty cleavage could be axial planar to both sets of folds.

Problems with these statements by Rodgers include a widespread lack of overturned strata and most importantly, the apparent lack of multiply cleavage-transected, cleaved early folds at the north end of the Allochthon. The possible existence of such relationships in the northeast Taconics, though not reported by other workers since Zen (1972), could be of great importance to our understanding of the structural sequence of the region.

The revised deformational sequence initiated by the discussion by Rodgers (1982) is reflected in Rowley (1983) which in turn is partly based on Rowley (1980). This most recent saga (1983), indicates a five-phase deformation sequence.

D_o is a syn-depositional phase involving slump folding and bed disruption. Some syn-depositional faults are locally important and may have had an initial normal fault displacement.

D_1 is typified by meso- and macroscopic folds and faults that pre-date regional D_2 folds and related slaty cleavage. F_1 folds are difficult to recognize, largely being recognized on the basis of F_2 superposition patterns and F_2-related slaty cleavage transection of the earlier folds. Discrimination between F_1 and F_o folds appears to be difficult as both F_o and F_1 folds lack an axial planar folation and are generally west-facing, tight-to-isoclinal. T_1 thrusting is widespread but displacement is very limited, often unobservable. An important exception to this, is the basal thrust of the Allochthon which is exposed along its northern edge and around the structural window behind the

Wm. Miller chapel just inside New York State. Thrusts (T_1) also enclose the lower structural surfaces of carbonate thrust slices exposed at the northern end of the Allochthon.

D_2 is the main regional deformation, involving large scale, west-verging, asymmetric folds (F_2) and an associated axial planar slaty cleavage (S_2). Regional low-grade metamorphism appears to be of D_2-age as evidenced by parallelism of phyllosilicates in the S_2 slaty cleavage.

D_3 structures involve folding (F_3) and crenulation cleavage development (S_3). Two generations of crenulations exist, but due to their restricted local occurrence they are lumped together as S_3. F_3 folds F_2 geometries and S_2 slaty cleavage causing a steepening of these earlier structures at the north end of the Allochthon. This relationship is not observed to the south.

D_4 elements include very rare, steeply dipping kink bands of variable orientation but generally striking east/west. Some late, small-scale normal faulting is also attributed to this generation.

Rowley (1983) also showed that Zen's (1972) postulated structural continuity between the Great Ledge-Porcupine Ridge and the Giddings Brook-Ganson Hill sequence is incorrect, and that the fold oblique to the regional trend that is used to separate the two, in Zen's scenario, does not exist. This is supported by the lack of large-scale overturned strata that pre-date or are syntectonic with the formation of the slaty cleavage. These relationships can be seen in Figure 3.3 which shows a section through the alleged overturned strata. The importance of this discovery is based on the recognition that the absence of a large scale recumbent, isoclinal geometry negates earlier workers' ideas of a large-scale stratigraphic inversion for the Giddings Brook slice.

The important feature to be seen is that the large-scale structure is that of a recumbent antiform which has been refolded into a synformal shape by later deformation. The recumbent antiform is interpreted as the general shape of the Giddings Brook slice and the synform that of the Great Ledge/Porcupine Ridge fold.

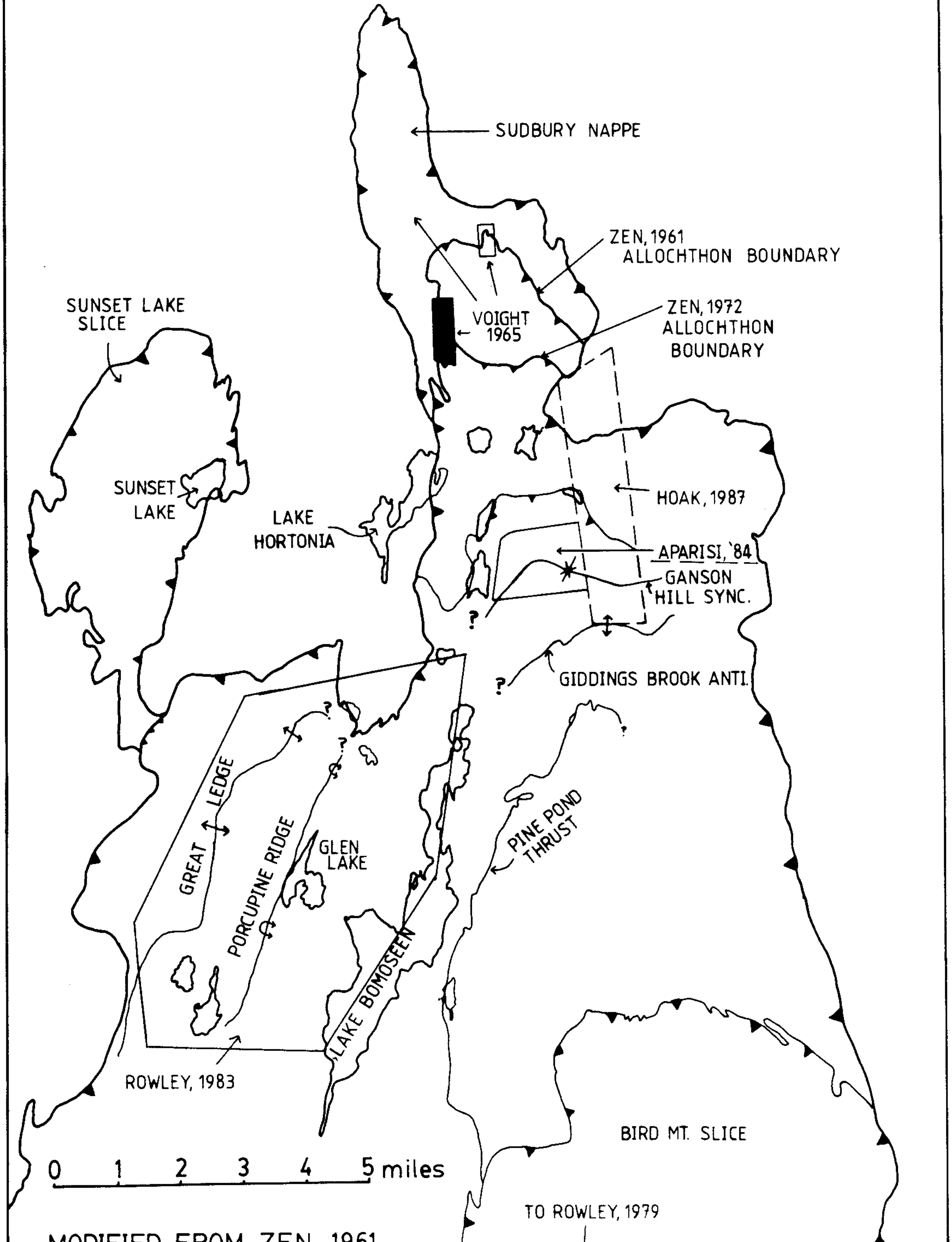
This five-phase (D_o-D_4) sequence of Rowley (1983) comprises our present understanding of deformation and deformation-induced structures in the northern and western regions of the Allochthon.

Bosworth and Rowley (1984) described in detail the D_o to D_1 early generation of folds and faults that either predate, or are contemporaneous with, tectonic emplacement of the Allochthon onto the carbonate shelf sequence of the Vermont Valley (the "synclinorium sequence"). Field data suggests the presence of <u>local</u> stratigraphic inversion via F_1 folding to produce complex F_2 folds and S_2 slaty cleavage with stratigraphic complications. This appears <u>only locally</u> and regional stratigraphic inversion is nowhere recognized, indicating the implausibility of the large-scale recumbent folds illustrated in the structural sections of Zen (1961;

LOCATION MAP SHOWING FIELD AREAS OF ALLOCHTHON WORKERS:

FIGURE 3.2–

LOCATION MAP OF ALLOCHTHON SHOWING STUDY AREAS OF THE VARIOUS AUTHORS



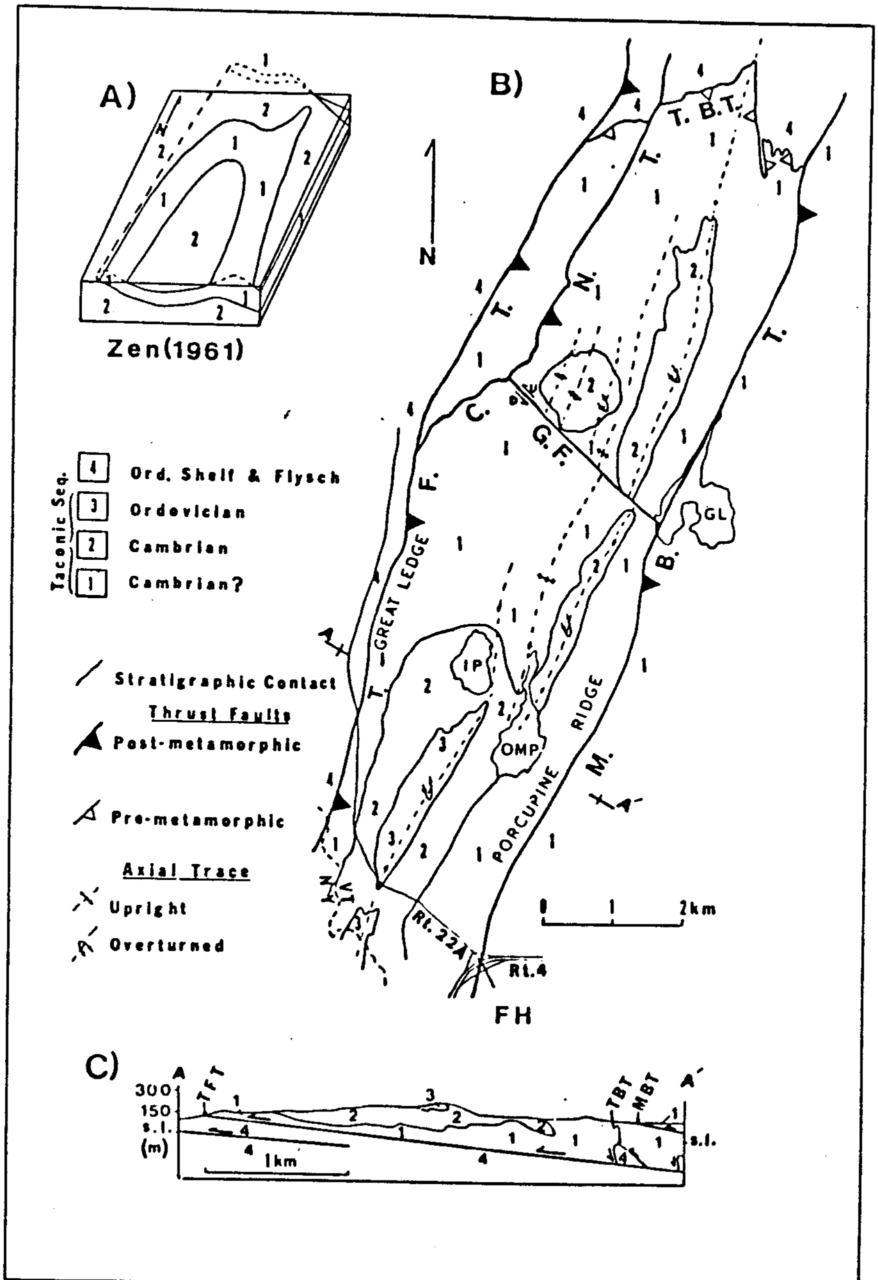
MODIFIED FROM ZEN, 1961

FIGURE 3.3- MAP AND STRUCTURAL SECTION OF ROWLEY (1983) SHOWING THE IMPLAUSIBLILITY OF ZEN'S (1961) RECUMBENT FOLD GEOMETRY FOR THE ALLOCHTHON.

FIGURE 3.3 —

——— Great Ledge–Porcupine Ridge fold complex at north end of Taconic Allochthon. A. Schematic diagram showing the geometry of the Great Ledge–Porcupine Ridge "bottoming fold" redrawn from Zen (1961). The surface shown is the top of the Bomoseen wacke (1), with topographic effects ignored. Heavy lines = intersection of the stratigraphic surface with the faces of the block diagram. Dashed lines = continuation of the heavy lines beyond the confines of the block diagram, and the hinge line of the recumbent fold. The effect of boudinage is shown at the north end of the diagram.

B and C. Geologic sketch map and cross section of the Great Ledge–Porcupine Ridge fold complex based on recent mapping of Rowley (1983). Note the complete absence of evidence of an earlier phase of folds. Location is shown in Figure 1. Stratigraphy: 1 = Bull Formation, including Bomoseen Wacke, Truthville Slate, and undivided purple and green slates all of Cambrian? age; 2 = Cambrian formations including the Browns Pond, Mettawee, and Hatch Hill Formations; 3 = Ordovician Poultney Formation. T.B.T. = Taconic Basal thrust, T.F.T. = Taconic Frontal thrust, C.N.T. = Cobble Knoll thrust, M.B.T. = Mud Brook thrust, G. F. = Gulch Fault. FH = Fair Haven, Vermont; GL = Glen Lake; IP = Inman Pond; OMP = Old Marsh Pond.



FROM BOSWORTH AND ROWLEY, 1984

1964). This paper attempts to further illustrate the lithified nature of the Taconic sediments during deformation, by citing the widespread abundance of pre-slaty cleavage fibrous veining and slickensiding which indicate that the rocks were lithified enough to brittly fracture before the formation of cleavage and early tectonic deformation. In addition, Bosworth and Rowley indicate that substantial deformation occurred before, or during, the time when the Allochthon emplacement occurred, but before the sequence was thrust into its present position. Support for this scenario is the pre-slaty cleavage timing of the structures discussed in the text and their transection by the Taconic Frontal Thrust, which demonstrates the post-to-syn-slaty cleavage final movement of the Allochthon.

STRUCTURE IN THE NORTHEAST ALLOCHTHON (STUDY AREA REGION)

Aparisi (1984) investigated the geometry of the Ganson Hill fold complex, which is of great interest since the Ganson Hill area marks a change in the regional fold strike from northeast/southwest to nearly east/west. She describes two cleavages (S_1 and S_2) present in the region and refers to them as the early and late cleavages, respectively. The early cleavage is a slaty cleavage and the second, a crenulation cleavage. Some confusion arises when comparing this study to the D_0-D_4 deformation sequence of other recent workers. Though data on crenulation orientations is limited (total of 14 measured), Aparisi suggests that the strike of the two cleavages are parallel with each other and that the crenulation is generally more steeply-dipping. The crenulation is thought to lie axial planar to folds of the slaty cleavage which in turn lies parallel to the axial planes of major regional folds. However, a cleavage lying axial planar to the east/west trending Ganson Hill fold is not described. The two later cleavages should both cut this early cleavage but no evidence of this was found by Aparisi (1984). The possibility of this early cleavage and the slaty cleavage and crenulation cleavages that should transect it, are important relationships that prompted the present investigation.

Aparisi defines three periods of folding, an early pre-cleavage set, and two later sets related to the "early" and "late" cleavages. The earliest folds possess an axial planar slaty cleavage and the late, an axial planar crenulation cleavage. Fold axes show three general trends, the earliest, an east-west trend is reflected by the cleavage-transected Ganson Hill fold, a later shallow to moderately north-plunging which trends more northerly, and the latest, a shallow southeasterly orientation. Aparisi suggests that early folds containing cleavage are those expressed in the map pattern and suggests that late folds with their axial planar crenulation, cause a slight flexure of that pattern. The early cleavage-containing folds are of varying tightness and overturned to the west, whereas the later folds display similar profiles to the earlier, plunge gently south and appear to be upright. The pre-slaty cleavage folds are restricted to the Ganson Hill area and have axes trending approximately east-west.

A major thrust (Hubbardton Gulf Thrust) was also found by Aparisi which crops out on the south side of Ganson Hill. This thrust is interpreted to truncate the westward continuation of the Ganson Hill fold system and indicates that linkage of the Ganson Hill system to the Porcupine Ridge-Great Ledge structure or others to the SW, as suggested by Zen (1961; 1972), is impossible due to the presence of this thrust.

Minor structures found by Aparisi in the Ganson Hill area include vertical, north/south-striking kink bands and small-scale interbed deformation manifested in fracturing and related veining.

The results of Aparisi, reassessed using the deformation sequence of Rowley and others (1979), are important in two primary contexts. First, the study attempted to clarify the relationship of the Ganson Hill fold complex to regional structural geology. Secondly, the study defines the nature of structural relationships at the northern end of the Taconics--relationships that have relevance for emplacement histories of the allochthon and the parautochthonous carbonates that lie beneath it. Aparisi explains the change in regional fold geometry as being due to either shear along the allochthon base or as a

FIGURE 3.4--SUMMARY OF ALLOCHTHON DEFORMATION SEQUENCES AS PROPOSED BY THE VARIOUS AUTHORS

FIGURE 3.4-

AUTHOR	DEFORMATION SEQUENCE	FOLD GENERATIONS	CLEAVAGES	THRUSTING
Zen, 1961	two	early and late	slaty cleavage slip or fracture cleavage	gravity sliding
Zen, 1972	3 (D_1-D_3)	Event II-isoclinal recumbent large-scale folding Event III-small-scale upright to overturned folding	Event I- no cleavage event Event II-slaty cleavage Event III- slip cleavage	Event I- submarine gravity sliding Event II- emplacement of Sudbury and Florence Nappe
Rowley et al. 1979	4 (D_0-D_3)	D_0- soft sed., syn-dep. folding & def. D_1- large-scale isoclinal folds with axial-planar slaty cleavage. D_2- small-scale folding with axial planar cren. cleav. D_3- late brittle kink folds	S_1- slaty cleavage S_2- crenulation cleavage	T_1 thrusting- emplacement of Allochthon onto Shelf T_2 thrusting- imbrication of sequence and final Allochthon & Sudbury Nappe movement
Rowley (1979)	same as Rowley et al. (1979)			
Rowley and Kidd 1982	5 (D_0-D_4)	D_0- soft sed., syn-dep. folding & def. D_1- meso-folding w/o an ax. planar cleav. D_2- large-scale isoclinal folds with an axial planar slaty cleavage. D_3- small-scale folding w/ ax. planar cren. cleavage D_4- vert. kink bands and normal faults	S_2- slaty cleavage S_3- crenulation cleavage	T_1 thrusting- same as above T_3 thrusting- same as T_2 above
Rowley, 1983	same scenario as Rowley and Kidd, 1982			
Aparisi, 1984	2 (early/late)	uncleaved macroscopic, isoclinal early fold early- macroscopic isoclinal folds with an axial planar slaty cleavage late- late open folds with an axial planar crenulation cleavage.	early- slaty cleavage late- crenulation cleavage	???

result of irregularities in the thrust surface during emplacement, and prior to the formation of later folds with their related cleavages.

The first of these two mechanisms for the reorientation of the Ganson Hill fold axes appears unlikely. Basal shear seems unlikely to have caused penetrative deformation extending through an accretionary prism of any great thickness. The basal emplacement surface for the Ganson Hill slice probably contains some form of lateral ramps or other E/W trending structure features which caused the realignment of structural elements in the region. From the work of Zen (1961) and Aparisi, it is plain that both fold axes and thrusts are deflected from their NE/SW orientation to a near E/W trend in map view. The answer to this enigmatic pattern in this area lies in better constraining the temporal relationships of thrusts and folds within the region and across the Allochthon/Parautochthon boundary.

A summary of the various workers deformation sequences for the Allochthon can be seen in Figure 3.4.

STRUCTURE OF THE PARAUTOCHTHONOUS SHELF SEQUENCE

The interpretation of structural elements in the shelf carbonates of the Middlebury Synclinorium or Valley sequence has changed dramatically since Cady's (1945) suggestion that the entire region (Allochthon and Autochthon) was folded together in the Mid-Ordovician to form the Middlebury Synclinorium. The field areas of the various workers can be seen in Figure 3.5.

Zen (1961) demonstrates that the Sudbury nappe does not root in the east limb of the synclinorium but is a thrust slice which partially underlies the Allochthon on its southeast edge. This interpretation was quite contrary to the prevailing opinion of these relationships. This analysis also discussed the complex stratigraphic relationships at the northeast end of the Allochthon, where black slate of unknown affinities rests on shelf carbonate in an apparent conformable relationship. This black slate also displays strong affinities with the allochthonous black slates, so accurate determination of the Allochthon/shelf boundary is difficult. The presence of the Forbes Hill conglomerate lithology within these black slates is cited as by Zen as evidence that the black slates are the Hortonville of the shelf sequence. These relationships remain confusing.

Zen (1964) indicates an early period of folding and thrusting in the Allochthon followed by refolding during the formation of the Middlebury Synclinorium. The structure of the carbonates to the north and east of the Allochthon is portrayed as fairly simple. The structure is that of the west-younging eastern limb of the south-plunging synclinorium. Zen (1967) further suggests a structural continuity exists between the carbonate sequence and the Taconic rocks but does not explicate these relationships in any detail.

Crosby (1963) examined structural elements in the parautochthon shortly after the work of Zen. Following the popular emplacement mechanism of the period, he sought to explain observed structural elements in the context of a gravity sliding model.

Crosby utilizes stereographic projection techniques applied to regional "domains" to better comprehend the complex relationships between the various structural elements. He apparently utilized <u>over 13,000</u> structural orientation measurements during his statistical analysis of deformational relationships.

The earliest structures described by Crosby are a set of "passive flow" folds, named B-folds, which are generally isoclinal, recumbent and possess a near-axial planar "flow cleavage". These folds are greatly thickened in the hinge area and thinned substantially on the limbs. In areas thought to be unaffected by later deformation, their hinge lines plunge gently to the southwest. There appears to be little change in their structural style across the synclinorium from east to west.

Continued deformation (thought by Crosby to be due to uplift in the Green Mountains or subsidence in the synclinorium, or both) resulted in the formation of B' folds which developed around axes nearly north/south in orientation. These structures are interpreted by Crosby as flexural slip folds which are gradational into flexural flow folds. A fracture or crenulation cleavage, gradational into a "strain-slip" cleavage, is subparallel to the axial planes of these B' folds.

These earlier generations of structures were deformed again during the formation of B'' folds. These are very shallow undulations that are thought to have developed perpendicular to B' folds and are suggested by Crosby to have been penecontemporaneous. These folds are interpreted as developing during the final stages of east-west-directed movement which produced the B' folds. Crosby utilizes stereographic techniques to demonstrate the relative rotational movements of these various structural elements during progressive later deformation by assuming various models of folding as discussed by Weiss (1963).

The early cleavage (S_2, S_1=bedding) is described by Crosby as strongly resembling a slaty cleavage, especially where interbedded pelitic material is present. This cleavage is approximately parallel to the axial surfaces of folds that correspond to this generation. Late cleavage (S_3) is a solution cleavage in modern terminology, but is described as resembling fractures through the rock. Between pairs of S_3 slip surfaces, bedding and the early cleavage are puckered into sigmoidal folds with the ends of each limb lying near parallel to the late cleavage. The late cleavage is spaced and lies near axial planar to folds of the earlier cleavage. These latter two features permit its easy recognition.

Crosby asserts that "all structural elements described in this report are definitely common to the synclinorium and the Klippe; moreover, the preliminary work done in the Taconic rocks during this investigation indicates that similar geometries are found in both sequences." (p. 82) He further suggests that the Taconic rocks arrived early in the deformation scheme and were likely deformed <u>during</u> but primarily <u>after</u> emplacement onto the synclinorium carbonate sequence. Crosby did not map extensive regions in great detail, but performed a more reconaissance-type survey of structural elements of the synclinorium.

Another highly detailed analysis of the parautochthonous carbonate sequence is that of Voight (1965; 1972). Voight examined structural elements in the Sudbury nappe and along the perimeter of the adjacent Signal Hill Slice in the Allochthon. His 1965 thesis is very confusing, especially with regard to relationships within the black shale or slate along the Allochthon/Parautochthon boundary. The nature of these slates is extremely important, as it is unknown whether they are part of the Allochthon or the Parautochthon. If these slates are Parautochthonous, the alleged structural continuity between the two terranes is still undocumented. Similar problems exist at the northeast end of the Allochthon where black slate of the Allochthon apparently has been thrust onto black slate of the Parautochthon.

Voight found that structural orientations within the Sudbury Napppe are nearly identical to those of the Synclinorium or Autochthon. Two generations of structures are found, the fist involving isoclinal folding of bedding (S1) and the development of an axial planar cleavage (S2). At several sites, this foliation is transected by a cleavage possessing features nearly identical to that which preceded it. As a consequence of this relationship, and the widespread occurrence of only one "slaty cleavage" or dominant axial planar cleavage, both possessing similar orientations, Voight has classified these features under the broad category "secondary foliations." The nature of this foliation appears to be mostly dependent on lithologic control and deformation processes related to rock type. Apparently in hinges of folds demonstrating lithologic contrasts, a later axial planar cleavage will transect a layer-parallel foliation in the hinge. This is thought to be the effect of early folia refraction complicated by further flattening and continued cleavage development in these isoclinal folds. Orientation of this foliation is a N/S striking, intermediate east-dipping plane. This strikes parallel with the trend of the fold axes.

Boudinage is apparently of the same generation as the early folding and cleavage development and boudin axes lie parallel to fold axes of this generation. At several stations this apparently preceded cleavage development as the early cleavage transects the boudins.

A strong penetrative lineation (L_m) is associated with the early generation folding, boudinage and cleavage. It plunges shallowly to the east, and lies approximately orthogonal to boudin axes. Voight suggests that these are not slickensides formed during flexural slip (i.e. not related to thrusting) but represent the tectonic stretching lineation. Supporting this contention is the observation that deformed brachiopods show their maximum extension parallel to this lineation. These same fossils also show preferential strain partitioning as a function of the lithology, in that slates and the fossils they contain are preferentially deformed over limestone which in turn is favored over dolomite. This no doubt reflects the contrasting deformation mechanisms in the three rock types.

This early phase of deformation is followed by late folding of all previous structural elements about shallow north-trending axes. This second deformation folds the earlier axial planar foliation and the early folds, producing a Type III interference pattern. [This is best seen at the "bluffs" along the Lemon Fair River northwest of Sudbury.] The foliation (S_3) produces an intersection lineation on the "slaty cleavage" resembling "crinkles or pseudo-ripplemarks." Boudinage in a few places is associated with S_3 but is unspectacular compared to the earlier generation. The orientations of the cleavage is north-striking an dominantly steeply east-dipping, though often of variable dip.

Voight states that locally in the Taconic rocks, several sets of S_3 are developed but that their orientations indicate development after the arrival of the Allochton into its present position. This is a confusing statement. Perhaps Voight means that east-dipping orientations are dominant and that passive rotation of these cleavage planes due to final thrusting is not observed.

Voight also describes brittle kink band structures, steeply-dipping, north-striking that he suggests developed synchronously with late folding. No evidence of this relationship is described.

On a regional scale, Voight suggests that the Synclinorium consists of a series of genetically-related nappes, and that lower tectonic levels are progressively exposed to the north. The Synclinorium then, "cannot be regarded as a late, relatively open (B') structure." In other words, the concept of a Synclinorium structure with a cleavage lying axial planar to it is incorrect and should be replaced by a model consisting of numerous nappe structures showing a fairly consistent alignment of structural elements (including cleavage) within each slice.

As Voight's thesis is one of the few highly detailed studies across the Allochthon boundary, especially at the Northeast end, his observations are important for our understanding of sequence across the contact.

Voight shows considerable variation in structural attitudes within the Sudbury Nappe parautochthonous rocks, but fairly consistent foliation/lineation patterns in the northwest rim of the Taconic rocks. Voight suggests that the general structural trend of the parautochthonous rocks appears to continue across the boundary to the Keeler Pond thrust identified by Zen (1961). It should be emphasized that the studied boundary area is quite small. The region of Taconic rocks to the northwest of the Keeler Pond thrust are named the Signal Hill Slice by Voight.

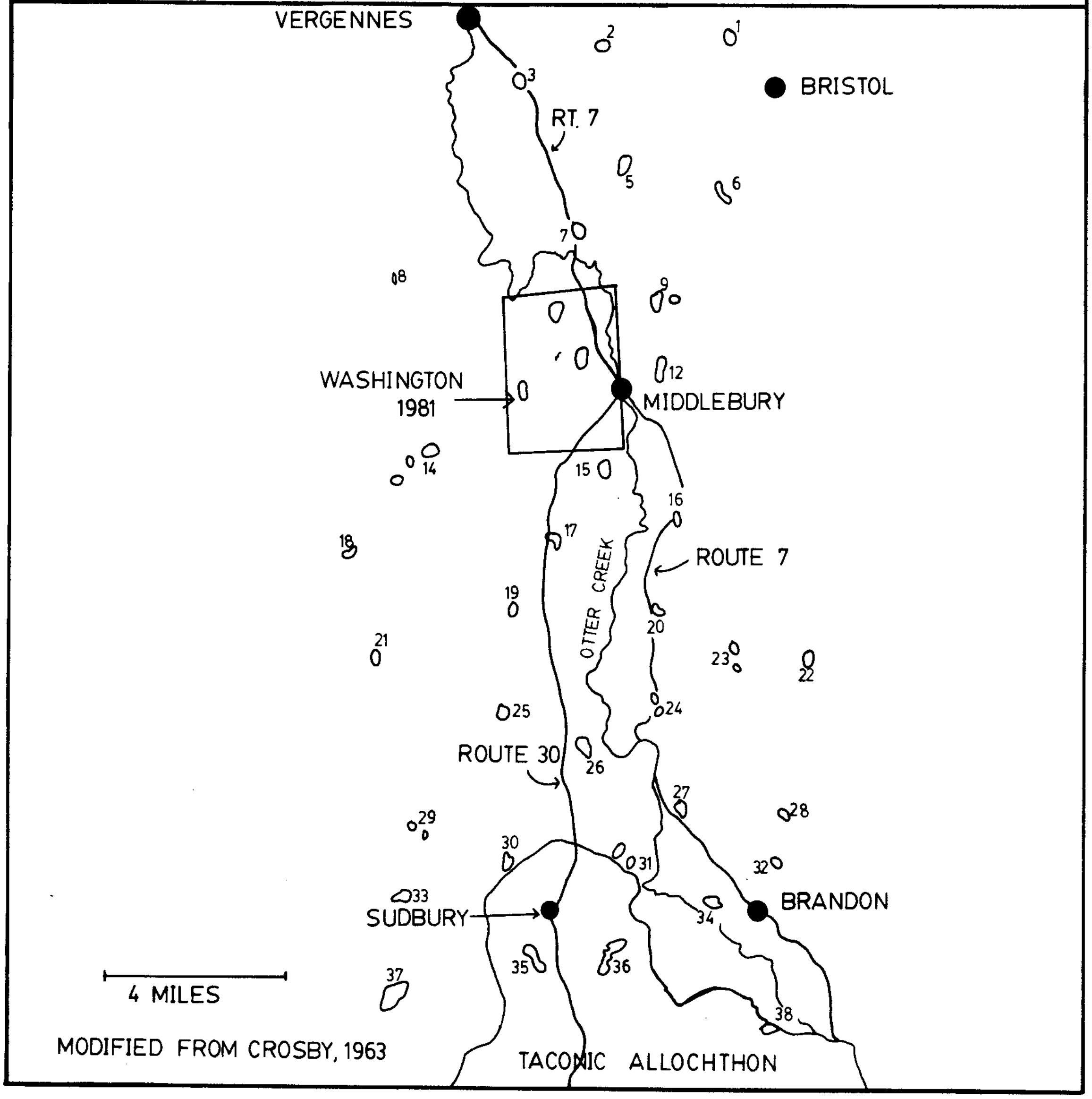
His thesis states that similarities in structure between the Taconic rocks and the underlying Sudbury Nappe indicate that Allochthon emplacement occurred during the earliest phase of deformation. He further suggests that the "entire nappe may be considerd as a type of movement horizon separating Allochthon from Synclinorium autochthon" (p.144). Voight concludes by stating that the deformation sequence is common to both Allochthon, Parautochthon (Sudbury Nappe) and Autochthon, as a result of early gravity sliding.

Washington (1981) examined structural relationships within the parautochthonous carbonates near Middlebury, Vermont. His work attempted to assess the validity of the "synclinorium" structure proposed by Cady (1945). Washington finds an early generation of cleavage, previously undescribed, which is interpreted as evidence of a decollement within the Bascom Formation. Second generation cleavage and associated elements were well-described by previous authors. Washington suggests that the carbonate strata of the area have experienced thin-skinned shortening

FIGURE 3.5- MAP SHOWING LOCATIONS OF CROSBY (1963) AND THE STUDY AREA OF WASHINGTON (1981) WITHIN THE PARAUTOCHTHON.

FIGURE 3.5

STATION LOCALITIES OF CROSBY, 1963 AND LOCATION MAP OF PARAUTOCHTHON



above the shallow decollement without experiencing folding (?). This produced the early cleavage. This initial phase of deformation was followed by isoclinal folding with an axial-planar spaced cleavage. This cleavage contains selvages of insoluble residues and some small offsets of marker horizons due perhaps to dissolution pheonomena. These early folds (F_1) trend toward the northwest and are overturned to the west. They have amplitudes of around .5 km. This folding was followed by a second phase (F_2) which is more open showing wavelengths of approximately 50 meters and amplitudes of 10-20 meters. A crenulation cleavage lies axial planar to these late folds. The crenulation cleavage truncates the earlier cleavage and appears to have transposed it in several places. Washington suggests that the crenulation deformation is related to thrusting.

This work further documents the presence of four lineations. The first is an intersection lineation between bedding and the initial, very faint cleavage (S_1). The second lineation is much more pronounced as a strong cleavage (S_2)/bedding intersection lineation that curiously manifests itself as color striping in slaty lithologies and pencilling in the more calcareous lithologies. This shows a scattered north-trending orientation due to later crenulation development and related folding. These two early lineations are indistinguishable except where both are present, except that the latter cleavage appears to be more strongly developed. Both appear to trend roughly north/south, especially the cleavage intersection (S_2-S_1) lineation.

The intersection of the primary cleavage (S_2) with the crenulation cleavage (S_3) produces 1-2 cm wide pencils that are around 1 cm thick. These thicknesses correspond to the spacing of the S_3 and S_2 cleavages respectively. A mineral lineation is present on the S_2 cleavage and is defined by strings of calcite grains. This is thought to be related to S_2 generation structures since the crenulation generation struature folds and cleaves it.

Washington concludes by suggesting that the "Synclinorium" is not a tenable structure and that the studied region is better interpreted as the result of thin-skinned deformation and imbricate thrusting. This idea was first proposed by Voight (1965) as quoted earlier.

Following the previous thinking of Voight's deformation sequence (1965), Rowley (1983) attempts to demonstrate that the parautochthonous shelf sequence and the allochthonous Taconic rocks have shared at least D_2 and younger deformations in his structural sequence discussed earlier for the Allochthon. Evidence for earlier deformation (D_1 thrusting) in the parautochthonous sequence is found primarily at the bases of carbonate slivers attached to the basal thrust of the Allochthon. No F_1 folding appears to be present but could be locally represented by intrafolial isolated fold remnants within the primary S_2 slaty cleavage found in more pelitic shelf horizons. T_1 thrusting within the shelf is suggested by the observation that thrusts of the shelf are folded along with the basal thrust of the Allochton during later D_2 deformation.

D_2 features closely resemble those of the Allochthon. The "regional" slaty cleavage is quite evident, especially on a microscopic scale, and extensive fracturing is common within the more dolomitic carbonates. "Ductile flow structures" are also present but are not pictured nor described in detail in the thesis. No T_2 thrusts were reported by Rowley from the shelf sequence. Aside from minor details usually poorly developed in pelites compared to carbonates, the deformation sequence in the shelf sequence is thought by Rowley to be nearly identical to that within the Allochthon. Perhaps the most important concept is the statement that the Allochthon/Parautochthon strata are in structural continuity due to D_1-age juxtapostion of the two sequences. **It should be emphasized that Rowley did not map extensive areas of the Parautochthon and that his efforts in the Parautochthon were largely of a reconaissance nature.** To the west of the Allochthon, the shelf displays complex late imbricate relationships as evidenced by numerous carbonate slivers or meso-duplexes found within the black shales near the frontal thrust of the Allochthon, as described by Rowley (1983) and Bosworth and Kidd (1985).

A summary of the various deformation sequences proposed for the Parautochthon by the various workers can be seen in Figure 3.6.

STRUCTURAL SEQUENCE WITHIN THE PARAUTOCHTHON

AUTHOR	FOLD GENERATIONS	CLEAVAGES
Crosby 1963	B-folds- isoclinal, recumbent with an axial planar cleav.	S_2 "slaty cleavage"
	B'-folds- isoclinal with ax. planar cren. cleav.	S_3 crenulation cleavage
	B''-folds- open folds w/o and axial planar cleav.	
Voight 1965	F_1- nearly isoclinal folds w/ axial planar cleav.	S_1 slaty cleav.
	F_2- gentle flexuring with ax. planar cren. cleav.	S_2 crenulation cleavage
Washington 1981		S_1-early cleavage due to shortening without folding
	F_1- isoclinal folding with S_2 cleav. axial planar	S_2-"slaty cleavage"
	F_2- more open folding with axial planar cren.	S_3-crenulation cleav.

Rowley (1983) Structure of Shelf and Allochthon are same due to T_1-age juxtaposition of the two sequences.

FIGURE 3.6 DEFORMATION SEQUENCES FOR THE PARAUTOCHTHON AS PROPOSED BY THE VARIOUS WORKERS

CHAPTER 4 STRUCTURE OF STUDY AREA:

INTRODUCTION TO THE CHAPTER

This chapter discusses the structural results of the field and laboratory analysis of the study area. The present study allows the construction of a new deformation sequence for the eastern Allochthon which incorporates and expands the earlier five-phase sequence of Rowley (1983) developed in the western Taconics. The chapter discusses the outcrop-scale structural features associated with each of these deformational phases. In addition, the outcrop-scale structure of the Parautochthon is discussed. The chapter concludes with a summary of the structural orientation data obtained from the Allochthon and Parautochthon and a discussion of emplacement timing constraints for the sequence.

THE DEFORMATION SEQUENCE

The present deformation sequence is a seven-phase sequence that has been determined using observed outcrop and macroscopic relationships. Since style and orientation criteria have been long recognized to be fraught with difficulties for the discrimination of structural sequence (Means, 1963; Williams, 1970; Williams, 1985), this present study attempts to define the sequence of deformation using refolded-fold criteria and cross-cutting cleavage relationships. These results do, however, support the use of orientation analysis. The consistency of structural orientations for specific generations of structures within the study area, indicates that they can be used to confirm structural sequence. Care must be taken to insure that such orientation criteria are supported by more rigorous criteria such as transected cleavages and refolded folds.

It should be further emphasized that the concept of generation is merely an artifact of our methodology of structural analysis, which in no way denies the fact that structures of different generations undoubtedly overlap temporally in an orogenic system. For example, in accretionary prisms, deformation at the front of the wedge and upper levels are generally deforming by soft-sediment processes. At deeper levels, the deformation is occurring by more brittle processes in more lithified sediments and at the deepest levels we should expect to see more ductile processes occurring where pressure and temperature conditions favor them. So, at any time, there exists a continuum of mechanisms and structural development within an accretionary wedge or orogenic system. This need not always be the case, however, especially for regions which have been multiply affected by several orogenies. In this context, only the final generation of structural features (D_6) in the study area are thought to be of post-Taconic age and that all preceding "generations" of structural features within the Allochthon represent a continuum of deformational processes associated with its emplacement.

D0 PHASE OF DEFORMATION WITHIN THE ALLOCHTHON

The earliest phase of deformation is also the most difficult to unequivocally differentiate within the study area. The structural features ascribed to this phase include soft-sediment slump folding and faulting. Such activity is limited in scale and demonstrated unequivocally only where exposure is adequate to show undisrupted strata above the convoluted zone.

In general, such deformation appears as small-scale, often micro-scale, boudinage and slicing or truncation of lithologic layering. On a mesoscopic scale within the Allochthon, the most spectacular exposure of this early deformational structure can be seen in the roadcut along U.S. Rt. #4 near the eastbound entrance ramp from Scotch Hill road. In this locality, slump folds within the Browns Pond slates can be observed that are conformably overlain by undisturbed (at least during D_0) strata. An equivocal example of possible sedimentary deformation in a hand specimen from the study area can be seen in Figure 4.1. This deformation is extremely similar to that seen in Figure 4.27 and this similarity emphasizes the problem of identifying the early deformation in rocks with such a complex deformational history. In the present study area, most of this earliest deformation is seen on a hand specimen scale although this evidence is equivocal since it could have also been caused by later tectonic processes. In these

Figure 4.1
Soft-sediment deformation (?) on a mesoscopic scale from within Bomoseen member, demonstrating the ambiguous nature of such deformation. This deformation is very similar to that seen in Figure 4.26 which shows small-scale slicing of the same lithology.

rocks, assignment to the D_0 phase is nearly impossible for most examples because similar-appearing structures can form through boudinage and small-scale slicing in rocks which possess a significant litho-rheologic contrast such as finely laminated graywacke/slate units.

An excellent discussion of deformation in partly dewatered and consolidated sediments of accretionary terranes is found in Cowan (1982). The mesoscopic structures found by Cowan within the Franciscan melange are remarkably similar to those found within the study area. The deformation within these Franciscan strata was enhanced by the abundant pore fluids which were thought to have been present during deformation. Interestingly, strain data from these rocks suggest a biaxial (true) flattening which will be important to our discussion of volume loss and strain in Chapter 5, that chapter discussing strain analysis of the Allochthon.

D1 DEFORMATION WITHIN THE ALLOCHTHON

The deformational characteristics of D_1 have not been identified within the present study area but have been included to make the deformation sequence complete and applicable for the entire Allochthon. Younging indicators are not sufficiently abundant within the present study area to be able to clearly define any of these early folds. The observed stratigraphic/structural relationships do not require the presence of any large scale stratigraphic inversion, and where younging indicators have been found in the study area, they indicate a normal (noninverted) stratigraphic sequence.

Bosworth and Rowley (1984) have suggested that these folds may have formed in a manner analogous to sheath folds in ductile shear zones (c.f. Cobbold and Quinquis, 1980; Hudleston, 1986) as the morphology of the pre-slaty cleavage fibrous veining suggests extensive shearing. The folds are considered "rootless" and should have axes parallel to the ~E/W transport direction, as first discussed by Hansen (1971). Unfortunately, the orientation of the early fold axes is unknown and the exact nature of these local early pre-slaty cleavage folds is thus unknown. There is no reason to suggest extensive development of Allochthon deformation in a dominantly simple shear environment on the basis on scattered observations of bedding parallel fibrous veining which could also have formed during the early phases of flexural slip folding, an inference supported by their orientation relative to later folds.

Bosworth and Rowley (1984) assign these early bedding-parallel fibrous veins to the pre-to-syn emplacement phase. Similar and much better-defined examples were found in the course of the strain analysis within the Cedar Point quarry (for location, see Figure 5.1). These veins have been folded during the slaty cleavage (D_3) event. They are composed of alternating domains of calcite and chloritic material which has been folded on a microscopic scale, the limbs sliced and the sequence transected by the slaty

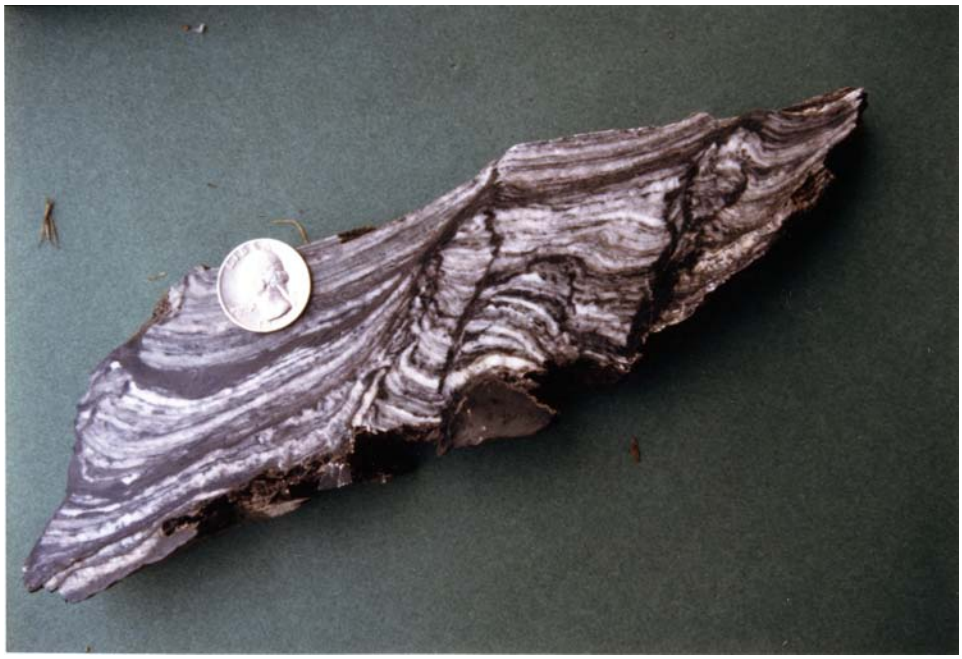


Figure 4.2
Hand specimen showing fibrous bedding-parallel veining from Cedar Point Quarry. Deformation is pre-slaty cleavage which transects the folded calcite and chlorite layers forming oblique chlorite-rich zones.

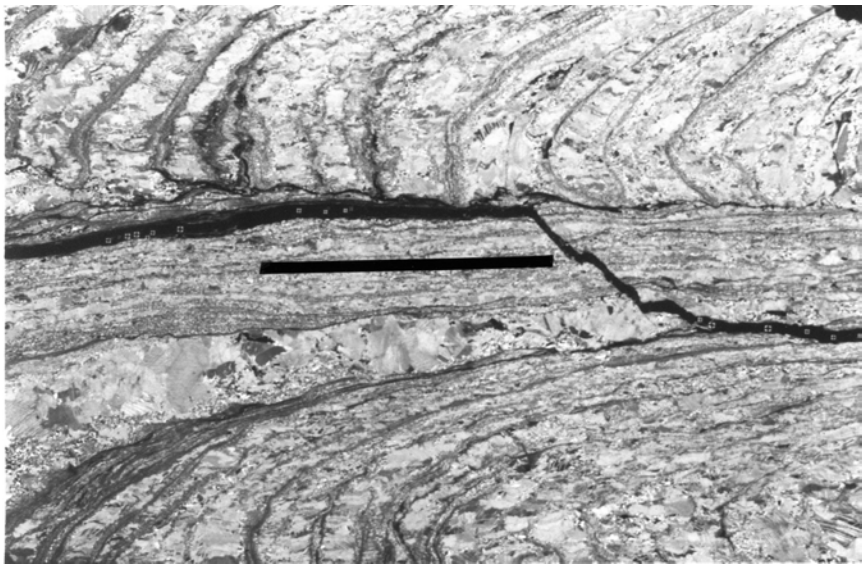


Figure 4.3
Thin section of fibrous pre-slaty cleavage veins in Cedar Point Quarry showing slaty cleavage transection and truncation/slicing of earlier folding. Note twinning in calcite grains and stylolitic appearance of chlorite-calcite zone boundaries. Black line lies parallel to slaty cleavage.

cleavage. These relationships can be seen in the hand specimen and thin-section photos of Figures 4.2 and 4.3.

The emplacement of the Allochthon onto the shelf sequence likely occurred during this initial deformational phase, as the Basal Thrust of the Allochthon (Rowley, 1983) has been folded during the later deformational phases. This point remains controversial as the observed continuity has not been demonstrated for an extensive region along the boundary. Furthermore, there are few exposed examples of the Basal Thrust being folded.

D2 DEFORMATION WITHIN THE ALLOCHTHON

The recognition of this generation of structural features represents a significant finding of the present investigation. On a megascopic scale within the study area, these structures consist of the East/West trending Ganson Hill Syncline, an isoclinally folded, west-plunging, recumbent syncline containing an axial planar fabric.

The present study has found a previously undocumented axial plane foliation within the core of this structure. The outcrops displaying this fabric are of the Bomoseen wacke lithology and the foliation resembles a slaty cleavage in outcrop but microstructurally it is a strongly differentiated layering, in comparision to the more anastamosing fabrics seen elsewhere in the Allochthon. This foliation dips moderately to the south, parallel to the bedding attitudes within the Ganson Hill structure, suggesting that the foliation lies axial planar to the fold.

This "early" slaty cleavage/foliation (S_2) can be shown to be transected by at least two later cleavages, both north/northeast trending structures. These relationships can be seen in Figures 4.4 and 4.6. The latest of these corresponds to the steeply east-dipping crenulation cleavage (S_5), while the other foliation is a less steeply-dipping "slaty" cleavage and probably the equivalent of the "regional" slaty cleavage (S_3) that is most strongly expressed in the western Taconics. This contention is supported by the observation that the late "slaty" cleavage feature has the same approximate orientation as the "regional" slaty cleavage (S_3) and the later cleavage has the same orientation as the crenulation cleavage (S_5) orientations reported from the western Taconics and the Lake Bomoseen area. Unfortunately, the orientations of these two transecting cleavages are quite similar. It is possible to distinguish the sequence, however, since most outcrops in the Ganson Hill region and further to the north, show a dominant NE-striking slaty cleavage (S_3) and a weaker crenulation fabric (S_5). Only in several outcrops at the easternmost closure of the Ganson Hill structure was the "early" slaty cleavage (S_2) clearly distinguishable. In the study area, the "regional" slaty cleavage (S_3) is the dominant cleavage in outcrop and is generally crenulated by the S_5 cleavage which strikes northeasterly and dips more steeply to the east.

It is possible, though unlikely, that the few outcrops containing a **clear** "early" (D_2) cleavage are actually just south-plunging crenulation (D_5) folds of the slaty cleavage (S_3). In other words, the outcrops found during this study that illustrate a south-dipping cleavage element are actually found in the hinge zones of F_5 synforms or antiforms of the S_3 cleavage. Several observations suggest that this is not the case.

First, the outcrops containing the early cleavage do not appear to be folded on the meter-scale fold wavelength typical of the F_5 structures. The folds to which this early cleavage belongs appear to be more kilometric in scale and cannot be identified except from map pattern, unlike the slaty cleavage and crenulation cleavage folds (F_3 and F_5).

Second, thin sections from samples collected from these outcrops, (for location, see Figure 4.5) show three cleavages in the absence of any fault zones, suggesting that they should be assigned to S_2, S_3 and S_5 respectively. The highly variable appearance of these cleavages throughout the multitude of thin sections made from samples collected throughout the study area makes simple assignment of these generations difficult in terms of morphologic appearance alone. Only where clear cross-cutting relationships can be found in oriented sections can the sequence be well constrained.

Third, the hand specimen and outcrop appearance of the early S_2 cleavage does not appear similar to the slaty

Figure 4.4
Early cleavage relationships within the core of Ganson Hill syncline. Earliest foliation lies parallel to lithologic layering/differentiated layering which has been gently folded (dips from upper left to lower right). Two other cleavages are present (S_3 & S_5). These cleavages produce the planar front (S_3) and side (S_5) of the outcrop.

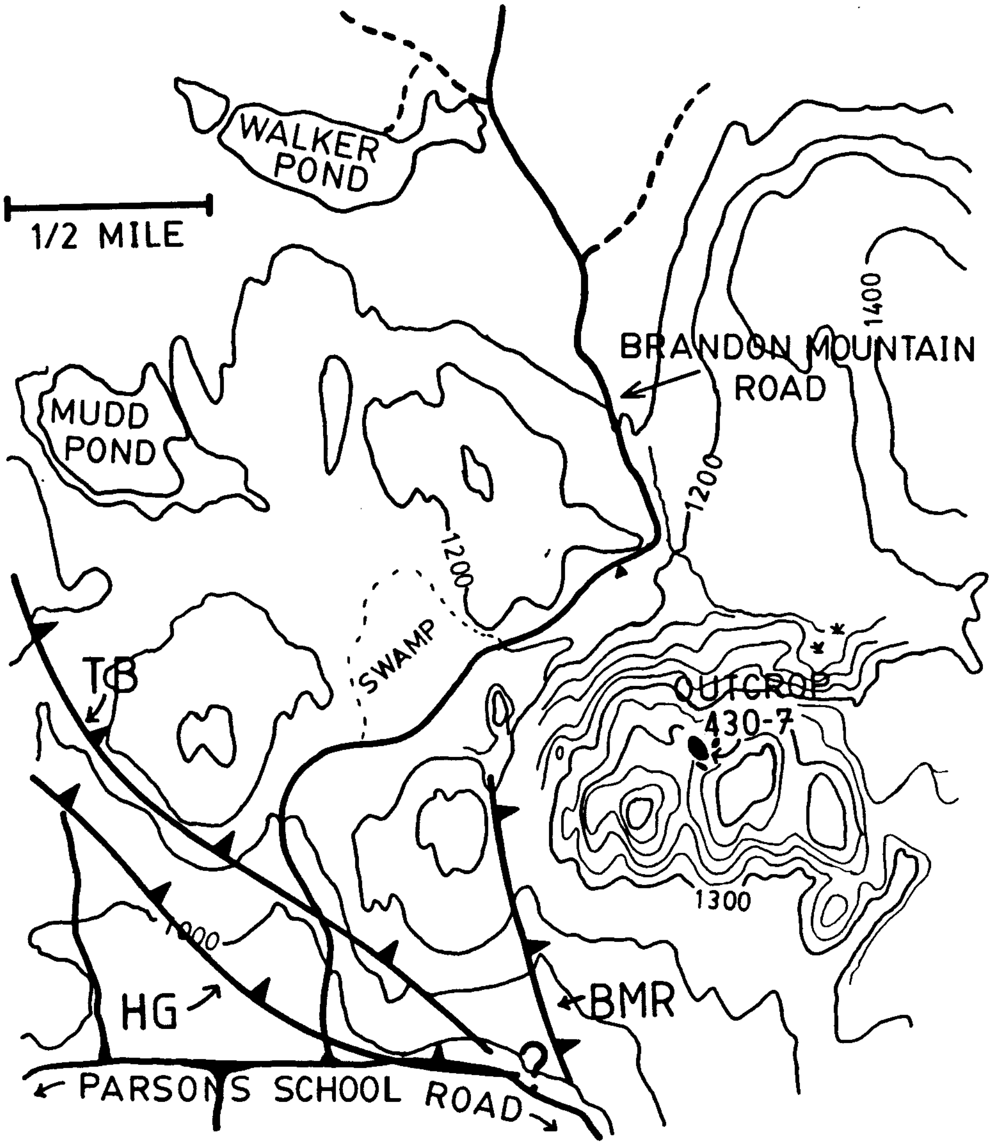


FIGURE 4.5- LOCATION MAP OF OUTCROPS SHOWING THE EARLY S2 CLEAVAGE FROM WITHIN THE CORE OF THE GANSON HILL STRUCTURE.

Figure 4.6
Same location showing buckled quartz veining lying perpendicular to the early S_2 foliation. Crenulation cleavage (S_5) lies parallel to pen. A third cleavage (S_3) is visible in this outcrop and produces an oblique fabric from upper right to lower left lying at a high angle to the S_2 cleavage.

cleavage both with respect to morphology and orientation. Outcrops of the Bomoseen Member adjacent to the locality where the S_2 fabric was first discovered show a weak spaced cleavage striking to the NE and moderately to the east. At places, this fabric is crenulated on a metric scale and a spaced crenulation cleavage lies axial planar. Nowhere do either of these cleavages appear similar to the S_2 fabric. In addition, although it is difficult to identify the generation of cleavage(s) that transect the early S_2 fabric, every outcrop within the locality where the S_2 fabric is found shows this cleavage to be transected by at least one and generally two, later fabrics.

On the limbs of the Ganson Hill structure, it is nearly impossible to fully differentiate the various generations of structure on the basis of orientation, since later refolding has caused rotation of previous cleavage elements towards the new poles to the new cleavages, an amount dependent on the magnitude of the strain associated with the new cleavage (Ramsay and Huber, 1985). Without full knowledge of these strain parameters, it is difficult to reconstruct the movement of cleavage poles and discriminate the older fabric elements, particularly in the study area where the cleavages appear very similar and can only be clearly distinguished on the basis of cross-cutting relationships which are only well-developed in the more pelitic lithologies. This also explains why this S_2 cleavage is obscure in the western exposures on Ganson Hill and on the limbs of the structure.

D3 DEFORMATION WITHIN THE ALLOCHTHON

Deformational structures of this generation are the dominant northeast-trending structures of the Allochthon. In the Lake Bomoseen area and further to the west, the D_3 deformation is identified as the dominant regional folding and its associated axial-planar "regional" slaty cleavage. In the western Taconics, these folds produce the regional map pattern. Well-exposed examples of this generation include the Scotch Hill Syncline and Cedar Mt. Synclines, near Glen Lake and on the shore of Lake Bomoseen, respectively. These structures can be seen in Figure 4.7. They are typically drawn in profile as isoclinal structures and show slight thickening in the hinges.

In the study area, this generation consists of the dominant cleavage identifiable in outcrop which lies axial planar to the isoclinal folds which are overturned to the west. These features produce the large-scale digitations on the dominant east/west trending Ganson Hill structure.

An alternative theory was examined in which the slaty cleavage (S_3) widely developed within the western Taconics would be the equivalent of the Ganson Hill "early" slaty cleavage (S_2). Such a relationship would suggest a large scale warping of this fabric and tightening of this generation of folds in the Ganson Hill area. This alternative can be ruled out, since in the study area a slaty cleavage and the "early" cleavage are present. The dominant slaty cleavage (S_3) strikes to the NE, transects the "early" fabric (S_2), and is crenulated by the S_5 cleavage in the study area. Also, several locations were found during the present investigation where F_3 folds could be seen which possessed an S_3 slaty cleavage lying axial planar. The best exposures of these features are along the steep NE-trending bluff leading from High Pond to the south and in large outcrop scale folds NNW of Mudd Pond, in addition to a third exposure found just south of Brandon Mt. Road within the Zion Hill lithology. These folds display structural geometries similar to F_3 folds seen at Cedar Point along Lake Bomoseen and at Scotch Hill along Glen Lake and have wavelengths on a metric to half-kilometric scale as opposed to the kilometric scale of the Ganson Hill Syncline. In light of these relationships, the Ganson Hill axial planar "early" slaty cleavage (S_2) is considered as separate from the "late" or "regional" slaty cleavage (S_3).

No thrusts appear to be associated with this generation, although most of these would be assigned to later deformation phases in light of their cleavage-transecting nature. Reactivation of these thrust surfaces during later deformation further confuses the recognition of sequence. A clear example of such reactivation is found along the east shore of High Pond where the Keeler Pond thrust shows crenulation cleavage well-developed within and adjacent to the thrust zone but has been macroscopically folded in map view. The apparent absence of early thrusts is largely an artifact of the methods of determining structural sequence by cross-cutting relationships.

For example, if the fold lies above a thrust ramp, it is possible that it formed as a consequence of the ramp as shown in the fault-bend-fold models of Suppe (1983) and as first described by Rich (1934). If the fold is formed by thrusting over a ramp, it is possible for the fold to be transected if a later imbricate fault off the earlier fault ramps up through the fold along the short or overturned limb as a consequence of further shortening. Most importantly, the thrust plane can transect and/or lie subparallel to the cleavage if the tip of the thrust propagates up through the fold along its axial plane (see Figure 4.8). In the study area, only through recognition of folded vs. unfolded thrust zones can the true relative ages of faulting be determined. Such geometric relationships complicate the structural analysis and determination of sequence in the Allochthon, where bedding is often indistinguishable and where the "age" of fault transection relationships and cleavages are often ambiguous.

D3 DEFORMATION WITHIN THE PARAUTOCHTHON

This generation of structures is poorly exposed within the Parautochthon of the study area though it is the dominant generation of structure that can be seen in outcrops of the Parautochthon. The dominant structural fabric that can be found is a NE-striking, intermediate east-dipping spaced solution cleavage. Bedding is highly

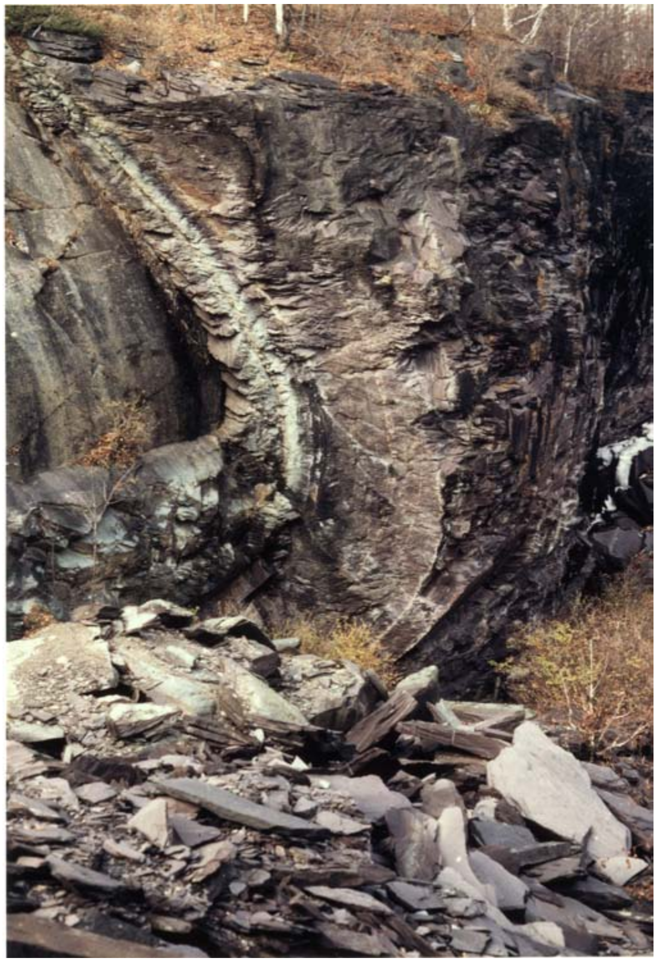


Figure 4.7
Cedar Mountain syncline in Cedar Point Quarry, a D_3 generation structure within the Middle Granville slates, showing the regional slaty cleavage (S_3). This is also a location used for strain analysis of this cleavage.

FIGURE 4.8

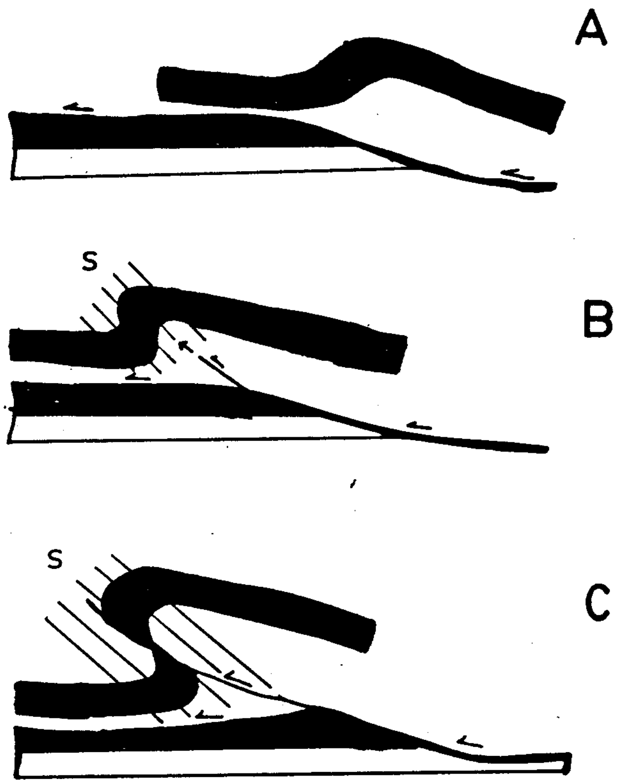


FIGURE 4.8- DIAGRAM ILLUSTRATES A STRUCTURAL SEQUENCE IN WHICH AN IMBRICATE THRUST, DEVELOPING SYNCHRONOUSLY WITH THE CLEAVAGE, TRANSECTS THE CLEAVAGE. A) INITIAL SHORTENING ABOVE A SMALL RAMP IN THE BASAL DETACHMENT PRODUCES GENTLY FOLDED STRATA. B) FURTHER MOVEMENT OVER THE BASAL RAMP PRODUCES ADDITIONAL TIGHTENING OF FOLD AND THE DEVELOPMENT OF CLEAVAGE. SYNCHRONOUS WITH THIS DEVELOPMENT, THE SMALL IMBRICATE BRANCHING OFF THE BASAL FAULT IS PROPAGATING ALONG THE AXIAL PLANE OF THE FOLD. C) FURTHER DISPLACEMENT ALONG THE IMBRICATE THRUST, PRODUCES A GEOMETRY WHERE THE CLEAVAGE IS TRANSECTED AS IS THE FOLD AXIAL PLANE, ALTHOUGH THE IMBRICATE AND CLEAVAGE DEVELOPED SYNCHRONOUSLY.

THIS SEQUENCE ILLUSTRATES THE POTENTIAL COMPLEXITY OF STRUCTURAL DEVELOPMENT AND THE DIFFICULTY OF UNEQUIVOCALLY DETERMINING STRUCTURAL SEQUENCE BASED ON TRANSECTING RELATIONSHIPS.

transposed and isolated fold closures lie detached and enclosed within the cleavage (see Fig 2.12). Unfortunately, the timing of this transposition cannot always be unequivocally demonstrated to be of the same age as the cleavage (See Fig. 2.14). The best exposures of this phenomenon can be seen in the cow pastures in the northeast corner of the study area (as shown in Chapter 2, Figures 2.12 and 2.14). Both creamy white dolomitic layers and a single thin black chert layer have been isoclinally folded and transposed on a mesoscale into parallelism with the dominant cleavage in the outcrop.

Most of the apparent sedimentary structures in the carbonates are actually tectonic structures. Only where dolomitic layers lie interbedded within the gray limestone/marble can the bedding orientation be firmly established.

Cleavage in the limestones/marbles is a well-developed spaced cleavage and appears to be of a solution origin, since insoluble residues are often found concentrated along "bedding" planes. In the dolomites, the cleavage varies from this weak spaced cleavage in the more calcareous lithologies, to a more Mg-rich rock displaying a complex intersecting set of fractures. These fractures do not show any obvious preferred orientation with regard to the cleavage in the nearby calcareous lithologies or with respect to geographic orientation. The appearance of this fracturing can be seen in Figure 4.9.

Schweitzer and Simpson (1986) have discussed the origin of cleavage in dolomite. They indicate that the different deformational behavior of dolomite versus calcite reflects the different deformation mechanisms operative under the pressure and temperature conditions that prevailed during deformation. According to these authors, the most important mechanisms of deformation in carbonates are pressure solution and mechanical rotation. Significant deformation occurring by twinning in dolomite is not recognized in their analysis. They suggest that dolomite generally deforms by brittle processes up to approx. 400° C while calcite deforms by mechanical twinning and pressure solution. These results are based on work by Turner and Weiss (1959) and Wenk and Shore (1975).

The temperature of deformation within the Giddings Brook Slice was thought to be greater than 300^{0} C, based on conodont coloration indices (E. Landing, 1987, personal communication). These conodonts show a dark black color of index 5. Interestingly, all rocks he has examined from the Giddings Brook Slice reflect this same minimum temperature, so that deformation was occurring under brittle conditions for the dolomites while the calcite was able to behave in a more ductile fashion. This explains why the more dolomitic lithologies show irregular fracturing while the calcitic lithologies show a spaced solution cleavage.

Marshak and Engelder (1985) emphasized the importance of clay minerals and silica in the formation of cleavage in

Figure 4.9
Photo illustrates the nature of the cleavage in the dolomitic lithologies dominant within the parautochthon study area. Note that the deformation in this lithology occurs by brittle fracturing and veining filled by pressure-solved calcite instead of twinning and other processes that would lead to a planar cleavage fabric.

carbonates of the Acadian-age, Hudson Valley thrust belt. Their results indicate that a strain mechanism partitioning between the processes of twin gliding and pressure solution, is dependent on the amount of clay-quartz matrix present in the rock. At quartz-clay contents of >10%, cleavage can develop via an interconnected network which allows sites of dissolution to be linked to free-fluid movement within the rock body. At lesser amounts of clay-quartz contents, twinning strain dominates. Thus, strain in carbonate rocks is partitioned between these two mechanisms; intracrystalline twinning strain, and dissolution mechanisms such as pressure solution. In the study area, abundant stylolitic seams parallel to cleavage and twinned grains indicate that such mechanisms were also responsible for the observed structural features.

D4 DEFORMATION WITHIN THE ALLOCHTHON

Crenulation cleavage and mesoscopic folds possessing a more easterly orientation than similar-appearing elements comprise the structural features of this generation. This deformation is restricted to thrust zones and is defined by hand-specimen-scale folds containing an axial planar crenulation cleavage that have E/W trending fold axes and a steeply-dipping, E/W striking crenulation cleavage. In most thrust zones, the folding is locally defined by folded quartz veins, many of which show fibrous slickensided surfaces. Within these thrust zones, these folded veins are transected by a N/S striking crenulation cleavage (designated D_5) which folds the quartz veins about these axes. In other words, the S4 cleavage has a strike approximately parallel to the direction of tectonic transport and has a dip approximately perpendicular to the fault plane. The intersection lineation of the S4 cleavage and the fault plane then, lies parallel to the slickenside lineation on the fault plane.

This cleavage is problematic, in that it does not lie approximately perpendicular to the direction of greatest flattening as has been suggested by many workers for the origin of cleavage, assuming that the maximum plane of shortening is oriented with a strike parallel to the strike of the fault plane. Wojtal (1986) has determined that the line of maximum material shortening in the plane of section is oriented at a high angle (>60^{o}) to the thrust surface. In three dimensions, this would be a plane striking parallel to the fault plane strike and dipping down the dip of the fault plane at a high angle. A hand specimen illustrating this S_4 fabric is shown in Figure 4.10. A thin section of this fabric can be seen in Figure 4.11.

Several explanations can be advanced to explain the observed orientation of this foliation:

1) rotation of earlier fold elements into parallelism with the thrust transport direction and passive rotation of

Figure 4.10
Hand specimen showing anomalous cleavage fabric lying normal to shear plane. Photo is taken of block looking east into the thrust plane. The shear plane lies approximately horizontal in the photograph. Folded fibrous slickenside can be seen on left lower corner dispelling support for the solution-modified fracture model.

Figure 4.11
Thin section of S_4 discrete crenulation cleavage showing small-scale folding of quartz veining and earlier slaty cleavage fabric. Section plane is N-S oriented and transport is top of photo OUT of the page, bottom INTO the page.

cleavage elements within the core of these folds. Bryant and Reed (1969) have suggested that many of these small scale structures near major thrusts within the southern Appalachians and the Caledonides have been passively rotated into parallelism with the thrust movement direction after developing normal to the transport and experiencing large shear strains. Similar observations and interpretation were made by Peach and Horne (1907) for fault zones of the Moine thrust in NW Scotland. Johnson (1960) and Christie (1963) have recognized similar relationships throughout the Moine Thrust zone. Christie suggested that transport followed the orientation of the realigned folds. Coward and Kim (1981) have shown considerable variation in such relationships due to variable magnitudes of shear strain and shortening in the Assynt region of the Moine Thrust.

In both of these models involving rotation of earlier fabric elements, however, the foliations strike approximately parallel to the fault plane. This mechanism of rotation has no doubt occurred in the study area to a limited extent, as evidenced by quartzite and granular quartz boudins whose long axes lie parallel to the transport direction. Unfortunately, this explanation suffers from the widespread occurrence of the anomalous cleavage element where no evidence of rotation of material such as fault blocks of material into parallelism with the transport direction exists and on small imbricate slices from within the fault zone which have not behaved as cohesive (and hence rotatable) units with the rest of the fault zone.

2) the folds have rotated into parallelism with the transport direction and the apparent cleavage is actually a solution modified morphology of brittle compressional fracturing related to emplacement of the hangingwall onto the footwall of the thrust sheet. Later solution activity along these fractures could enhance the cleavage-like appearance. A problem with this model is widespread observation of folded quartz veining within these thrust zones to which the anomalous cleavage lies axial planar. The fracturing should not be capable of folding these veins and the veins themselves appear unfractured. Also, this "fracturing" is not restricted to the footwall as might be expected in the model where the hangingwall acts as a "load" on the footwall strata causing fracturing. Gretener (1981) has demonstrated the importance of this "load" for the expulsion of tectonic pore fluids and the initiation and propagation of new thrusts. The anomalous cleavage is restricted to the immediate area of the thrust zone, including the immediate hangingwall and footwall, so that the operative mechanics are thought to be limited in extent. The strongest evidence against this scenario is the microstructure of the S_4 cleavage. This fabric is a true discrete crenulation cleavage showing a local anastamosing character. It does not resemble fracturing in any fashion as no transected grains are fractured in a brittle manner

but instead show stylolitic boundaries under high magnification. It is of course possible that the present microstructure evolved through a complex sequence of fracturing and solution activity along these micro-channelways. Such relationships have been described by Foster and Hudleston (1986) in troctolitic rocks from the Duluth Complex of NE Minnesota. These rocks show a "fracture cleavage" morphology caused by extensional fracturing, combined with fluid migration. The microstructure of the rocks from the study area, however, do not show evidence of any extensional dilation during or related to the formation of the anomalous cleavage fabric.

3) The most plausible explanation involves the formation of the anomalous cleavage in a situation involving a complex strain state due to intersecting thrust faults. The dominant crenulation cleavage (S_5) in the outcrop would form perpendicular to the principal plane of the strain ellipsoid (XY or S_1-S_2 plane) as is conventional behavior (c.f. Gray and Durney, 1979). The plane containing the greatest and least strain axes (S_1/S_3 plane) would also be compressional and the anomalous cleavage would form parallel to this plane and to the intermediate strain axis (S_2). This would be a case of uniaxial extension and biaxial flattening. This latter orientation would also lie axial planar to the folded quartz veining to which the S_4 cleavage lies axial planar. The anomalous cleavage then, would be an S_2 normal fabric. Such a strain state would

also facilitate the rotation of boudin axes and similar structural elements into parallelism with the transport direction, since their axes would attempt to align themselves with the direction of greatest extension (S_1).

Support for this orientation is the presence of unfolded extensional veining which forms fibrous growth both **normal** to the fault plane and also **parallel** to the direction of thrust transport. In the outcrop, the slickenside fibers can be shown to have grown parallel to the transport direction (their characteristic orientation) but also grow perpendicular to the fault plane. Fibers have grown parallel to the direction of greatest extension (i.e. parallel to S_1) and at the same time parallel to S_3, the direction of greatest shortening. This model is best supported by the outcrop evidence and is the one favored here. These fiber growth relationships can be seen in Figures 4.12, in the hand specimen photo of 4.13 and the outcrop photo of 4.14. A characteristic of this model is the hetereogeneity of strain on a local scale, especially on the thin section scale. These relationships can be seen in Figure 4.12. In the context of the complex hetereogeneity of deformation described on a thin section scale by Means et al. (1984), Lister and Snoke (1984) and Simpson and Passchier (1986), such a model does not seem implausible.

The complex strain state supporting the above model could be produced by two converging thrust systems and/or a lateral ramp structure, causing the formation of a flattening deformation parallel to the transport direction. A strong flattening component would be produced by the intersecting thrust systems as they converged. Complex strain relationships in the lateral tip regions of thrust sheets have been described by Coward and Potts (1983), and also from the Moine thrust in the Loch Eriboll region in the work of Fisher and Coward (1982). A lateral ramp would produce a similar steep compressional regime in an E/W orientation as the hangingwall overrides the lateral ramp (Knipe and Needham, 1986). In the Pine Mountain thrust block, first studied by Rich (1934), folds can be demonstrated to lie with their axes parallel to the lateral ramps (Russell Fork and Jacksboro faults) of the thrust block. As suggested by Hossack (1983), where two of these ramps lie together, possible transport directions are highly constrained. The lateral ramps required in the present model are not identified in most places where this S_4 cleavage is exposed. The best exposure of such a situation is found along the Brandon Mt. Road where the S_4 cleavage is probably enhanced by the effect of the late T_{4-5} imbricate thrust intersecting with the lateral ramp of the older Hubbardton Gulf Thrust surface immediately to the South. This intersection would allow the development of a compex strain regime where the Hubbardton Gulf Thrust acts as a lateral ramp to the more recent structure.

A problem with this model is the infrequent observation of lateral ramps and related convergence of thrust systems

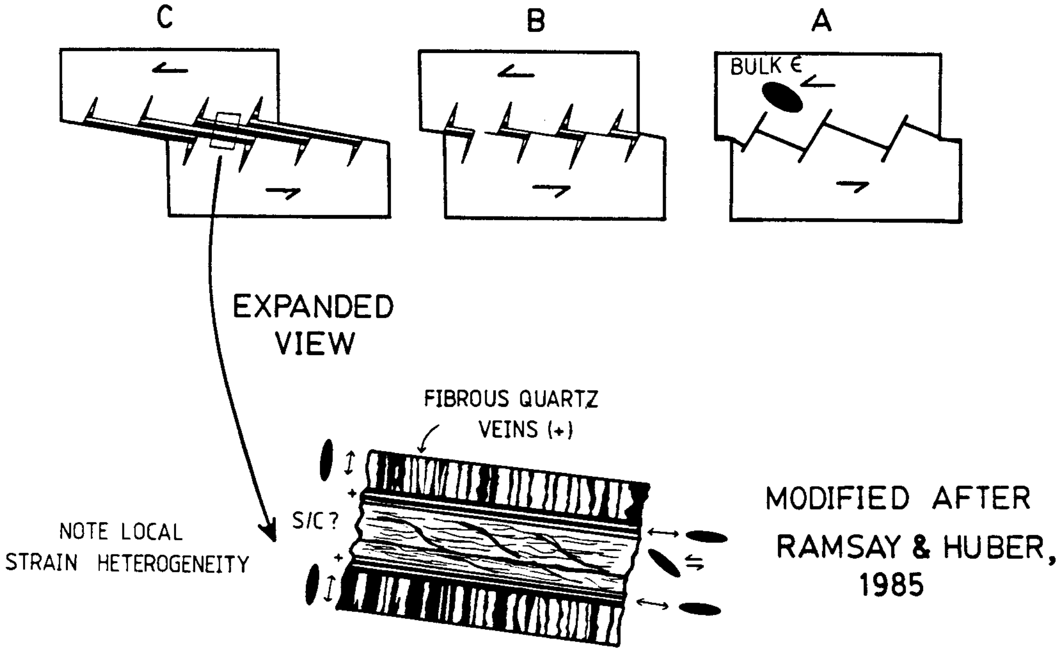


FIGURE 4.12- FIBER GROWTH PATTERN IN FAULT ZONES. NOTE FIBER GROWTH IN DIAGRAMS A, B, C SEQUENCE LIE PARALLEL TO THE BULK EXTENSION DIRECTION (oriented at 45 degrees from the shear plane and parallel to the long axis of the strain ellipse) BUT ON A FINER SCALE (BELOW) THE FIBERS LIE **BOTH** PARALLEL TO THE LOCAL EXTENSION DIRECTION (inner fibers that flank chloritic material in center of diagram) AND NORMAL TO THE BULK EXTENSION ORIENTATION (the outside fibers of the diagram) WHILE THE CHLORITIC MATERIAL (in center) SHOWS COMPLEX S/C RELATIONSHIPS MORE SIMILAR TO THE BULK SHEAR GEOMETRY OF THE THRUST ZONE.

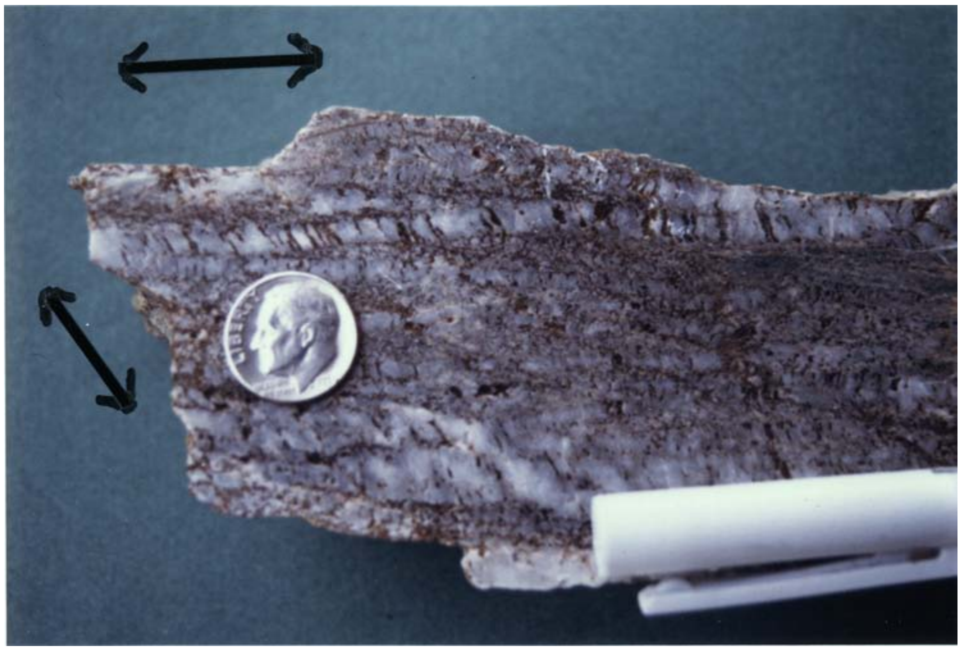


Figure 4.13
Fiber growth pattern in hand sample from fault zone, cut parallel to movement lineation and normal to shear plane foliation. Note fibrous growth both normal to shear plane and parallel to slickenside lineation and long dimension of the photo (or transport direction). It would be interesting to examine whether the fibers growing normal to the fault plane, now oblique in a sinistral sense, have been rotated into this orientation or grew in this geometry.

Figure 4.14
Typical appearance of fibrous quartz slickensides from within a fault zone. Note S_4 cleavage in lower right hand corner of photo.

within the study area compared to the prevalence of the S_4 cleavage fabric. Such relationships are unlikely due to the poor outcrop in many of the critical areas, although the Two Bears Thrust zone does show complex slicing suggesting the plausibility of complex thrust intersection relationships.

Several outcrops in the study region illustrate thrust ramp structures with associated fold geometries. These folds are of crenulation age and contain an axial planar crenulation cleavage (S_5). The best-exposed ramp sequence in thrust zones is that found as part of the Brandon Mt. Road thrust. In this thrust zone, Zion Hill quartzite and the Bomoseen siltstone have been thrust over green slate and quartzite of similar affinities. These relationships can be seen in Figures 4.15, 4.16 and 4.17.

The thrust zone itself is defined by an extensively brecciated and veined region containing the S_4 cleavage and folding. The strike of strata in the thrust ramp footwall is oblique to that in the hangingwall and the dip of the footwall strata is slightly steeper than that in the hangingwall. The strike of the thrust ramp is slightly oblique to the movement direction as defined by slickenside lineations. This suggests either movement out of section (i.e. non-plane strain along the section line and a violation of balancing criteria) or a non-parallelism between slickenside lineations and fault movement. Both ideas are probably valid, since several authors have reported thrust movement out-of-section (McClay and Insley, 1986, Spang et al., 1979) and many fibrous slickensides are folded and lie non-parallel to the unfolded, more recent slickensides, suggesting a continuum of slickenside development with only the latest thrust movements parallel to the slickenside lineation.

In the thrust zones, several different sub-generations of veins exist. Some lie parallel to the thrust plane and are unfolded while others in this orientation have been folded about both F_4 and F_5. This indicates a transfer of displacement to the active slip horizons within the thrust zone and folding of older shear surfaces. These observations strongly argue for synchronous development of the D_4 and D_5 phases of deformation. On the basis of widely-observed folding of D_4 veining by the D_5 folds within the thrust zones, and the transection of S_4 by S_5, the sequence will be defined using these criteria.

D5 DEFORMATION WITHIN THE ALLOCHTHON

The D_5 structures are those which form the outcrop-scale folds that are common throughout the study area. These structures are expressed as the abundant, variably open to tight F_5 folds containing the axial planar S_5 crenulation cleavage. The structural style of these crenulation-age folds can be seen in Figure 4.18 (A-E). The crenulation cleavage widely observed, though best developed in more pelitic lithologies, folds the slaty cleavage and lithologic layering about N/NE-trending fold axes. This S_5

Figure 4.15
Photo of Brandon Mt. Road thrust showing ramp structure at base of quartzite layer continuing up slope to west beneath arenites of the Bomoseen member, near tree at upper right of photo.

FIGURE 4.16

SCHEMATIC INTERPRETIVE SECTION OF BRANDON MT. ROAD THRUST RAMP AND FLAT GEOMETRY

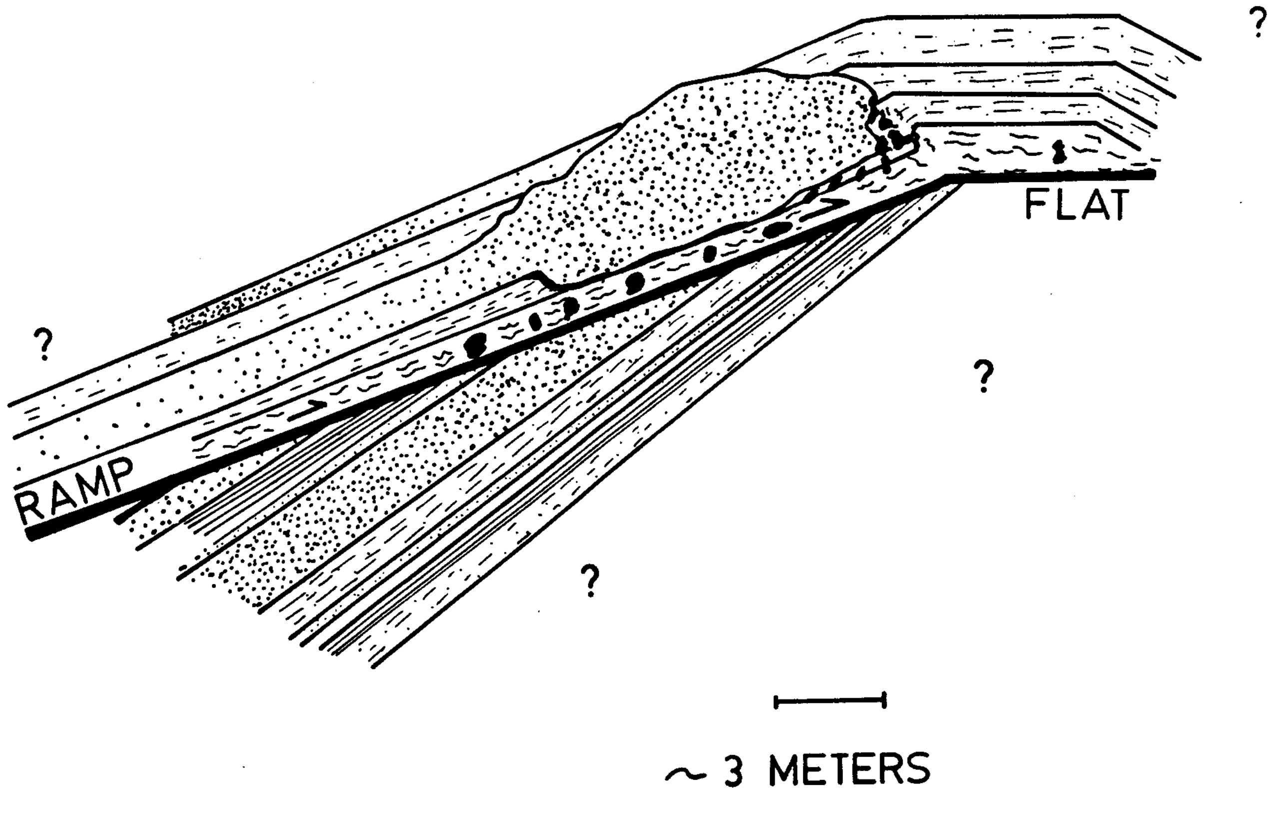


FIGURE 4.16- SCHEMATIC SECTION OF BRANDON MT. ROAD THRUST SHOWING RAMP STRUCTURE AND LITHOLOGIES PRESENT IN THRUST ZONE.

Figure 4.17
Brandon Mt. Road thrust zone on east side of ravine, showing dip of quartzite strata in hanging wall which are overlain by the dead tree trunk. Thrust ramp continues from other side of ravine to base of large oak tree in top center of photo. Dips of bedding in quartzite masses in foreground and those upslope of tree are distinctly different, allowing recognition of the thrust geometry. Another thrust slice is present to the east on the top of this hillside, best exposed further to the south.

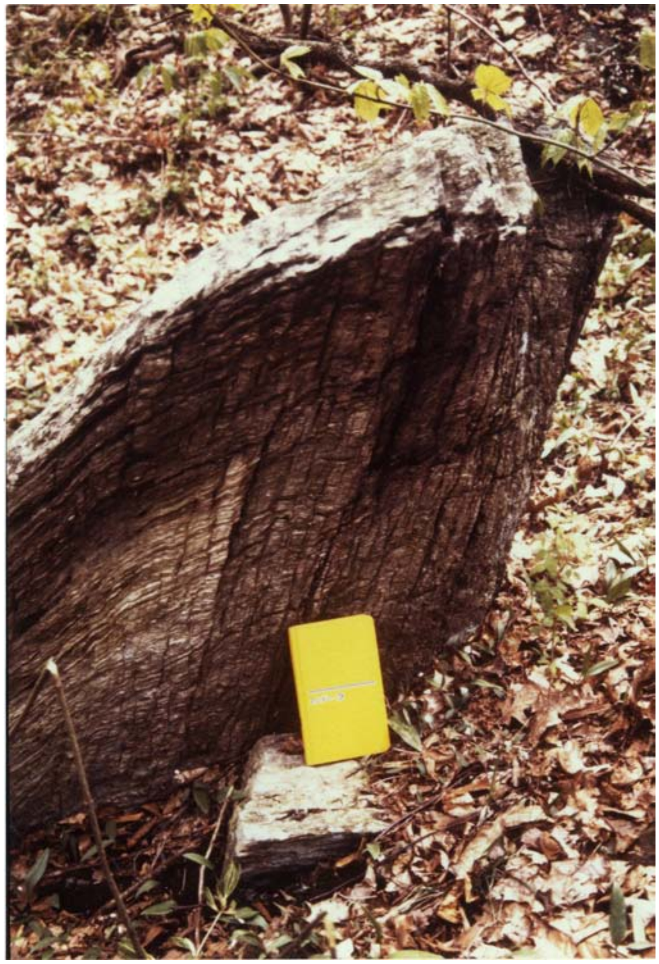


Figure 4.18A
F_5 fold showing a well-developed crenulation cleavage lying axial planar.

Figure 4.18B
F_5 fold showing variation in crenulation fold geometry. Note axial planar quartz veining in this outcrop.

Figure 4.18C
F_5 crenulation fold showing variable geometry of these structures.

Figure 4.18D
F_5 fold showing variable geometry within the Allochthon.

Figure 4.18E
F_5 fold showing variable geometry of these structures within the Allochthon.

cleavage is morphologically indistinguishable from the S_4 crenulation cleavage except that the two cleavages can be distinguished from each other on the basis of orientation and the transecting relationships within thrust zones. The S_5 crenulation lies axial planar to F_5 folds within the study area. In slates, it is an easily recognized, well-developed planar crenulation cleavage whose nature in outcrop varies from a discrete to zonal morphology. The intersection of S_3 and S_5 produces a strong pencil structure which lies parallel to F_5 fold axes. These structures can be seen in Figure 4.19. In the more siliceous lithologies it is expressed as either a weak crenulation lineation, or as commonly seen in arenites of the Bomoseen Member, the S_5 foliation is defined by a number of quartz veins which show a convergent fan geometry. These quartz veins, ranging in thickness from 1 mm to 1 cm, are not fibrous and it is likely that they represent either a volume replacement of dissolved material within the hinge region, or indicate some component of extension in the outer layers of the fold. The latter explanation is most likely. In this scenario, the veins formed as a result of quartz infilling along fractures produced by tangential longitudinal strain during folding. The veins thin towards the inner arc of the fold as the influence of the longitudinal strain diminishes, as would be expected from the discussion by Ramsay, (1967, p. 348). This field geometry is illustrated in Figure 4.20. The presence of fibrous veins near these outcrops supports the idea that these veins have not experienced extensive recrystallization and the loss of their fibrous habit, but instead are the result of infilling along the extensional fractures generated by the fold.

In the study area, the crenulation age N/NE trending folds produce minor digitations of the E/W trending Ganson Hill structure and the slaty cleavage age (D_3) folds but of a much lesser scale than the latter structures.

In large thrust zones such as near the Brandon Mt. Thrust, the intensity of S_5 crenulation cleavage development increases substantially toward the thrust zone. Similar relationships were suggested by Rowley (1979, 1983). Away from these thrust zones, the D_5 structures are more open, often only visible as a crenulation lineation on earlier cleavage planes. As the thrust zone is approached, the tightness of these folds becomes quite pronounced, often near-isoclinal, and the planarity of the crenulation cleavage is best developed. An example of such folds can be seen in Figures 4.21 and 4.22.

Mitra and Yonkee (1984) described similar relationships from the Canadian Rockies. They were able to define the pre-erosional extent of thrust sheets by mapping the zones of crenulation development at the front of thrust sheets. They observed similar relationships to those in the present study with regard to increased intensity of crenulation development within the thrust zone as compared to the hangingwall and footwall strata.

Figure 4.19
Pencil structure near Keeler Pond Thrust outcrop along the eastern shore of High Pond. Pencilling generally lies parallel to F_5 fold axes and is caused by the intersection of the S_3 and S_5 cleavages.

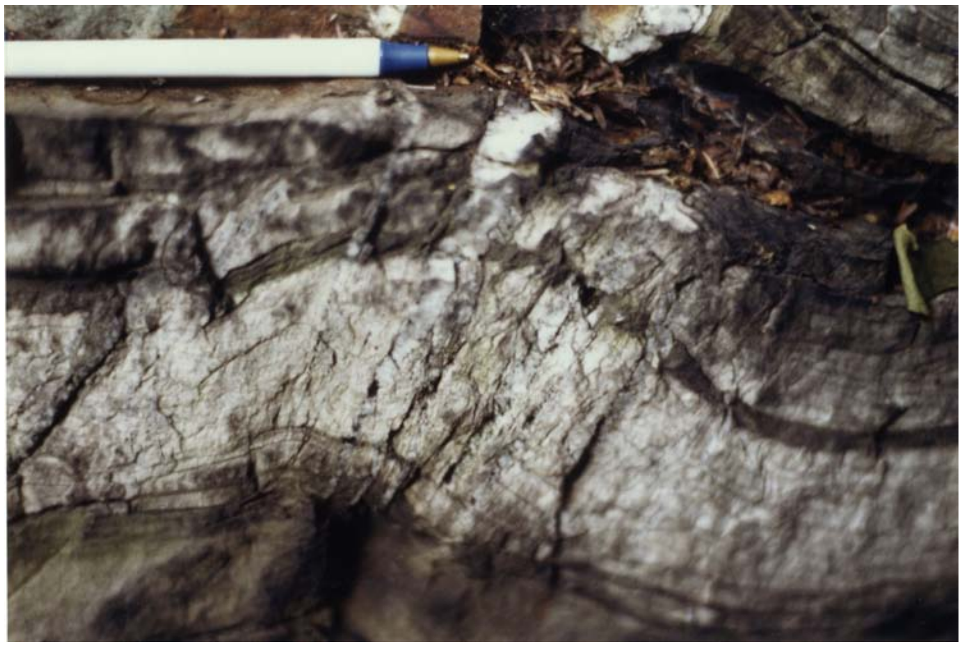


Figure 4.20
Fold within Bomoseen member showing axial planar quartz veining. Note that many of the veins decrease in thickness as the inner arc of the fold is approached.

The study area is extensively imbricated by late T_5 thrusts. These thrusts are probably those late thrusts that imbricate the entire Allochthon and Parautochthon, and sole to the Champlain Thrust as the regional basal detachment or decollement. Such a relationship has been confirmed by Rowley (1987, personal communication) who obtained access to several unpublished E/W seismic sections along strike of the Champlain valley. In outcrop, these thrusts show abundant fibrous quartz and chlorite veining although the more arenaceous lithologies do not show the chlorite veining as frequently as the slates. The quartz veining is generally slickensided and this lineation is assumed to parallel the most recent direction of transport on the thrust zone. The length of the fibrous quartz vein fibers is perhaps related to the amount of displacement, since those thrust zones of greatest regional importance (frequently those which also can be traced the greatest map distance) display the longest fibrous growth. Interestingly, these same zones also show the greatest width of the thrust zone, suggesting that the thrust zone has perhaps experienced strain hardening which resulted in lateral expansion of the zone. A continuum of deformation involving these veins is the most likely scenario, in which fibrous veins are constantly being deposited by solution processes and progressively deformed as movement continues on the thrust.

The complexity of these thrust zones can be seen in Figures 4.23 and 4.24 which show the mesoscopic imbricate system associated with the Two Bears Thrust within the Browns Pond formation at the southwest corner of the study area. The reorientation of the earlier foliation into parallelism is similar to that described by Ramsay and Graham (1970), Berthe' et al. (1979) and Simpson (1981), for foliation behavior and development in ductile shear zones.

Near the Brandon Mt. Road thrust, bedding in the Bomoseen Member can be demonstrated to be highly transected by late structural slicing. Although these features closely resemble soft sediment deformation, their spatial relationship to late faulting suggests their D_5 age. This suggests that even on a very small scale, deformation is occurring by a mechanism similar to that suggested by Wojtal and Mitra (1986) and Wojtal (1986). These authors suggest that such deformation in fault zones is comparable to a large-scale form of "grain-boundary-sliding" in which fragments of rock slide past each other assisted by high fluid pressures. The rocks become progressively finer-grained due to a complex combination of brittle and ductile deformation mechanisms. This small scale slicing can be seen in Figure 4.25 and 4.26.

These D_{4-5} thrust zones are nearly ubiquitous at the base of all steep bluffs within the study area. Nearly every steep bluff can be shown to shown to contain some degree of slickensided fault surfaces. This perhaps results from preferential erosion by ice and water along the more highly brecciated fault zones. While the age of these zones

Figure 4.21
Crenulation fold near thrust zone showing slickensided shear surface beneath fold. Note planarity of crenulation development and tightness of fold. The E-W trending (S_4) crenulation fabric can also be seen in this photo lying parallel to the profile plane.

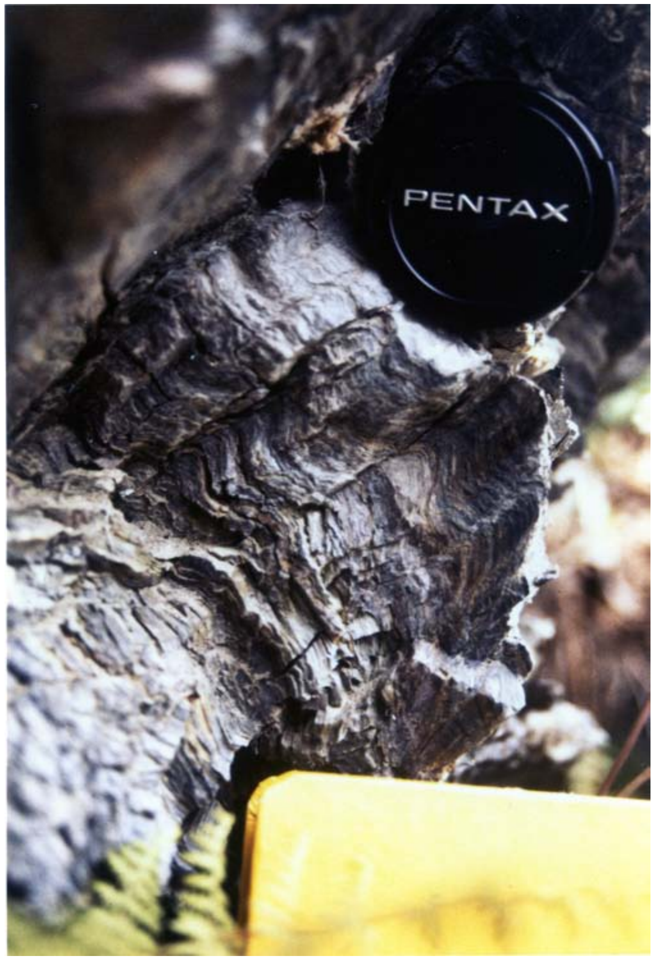


Figure 4.22
Closeup of same fold showing dominance of buckling behavior within hinge zone of the early slaty cleavage and a more "zonal" appearance of the crenulation on the limb regions.

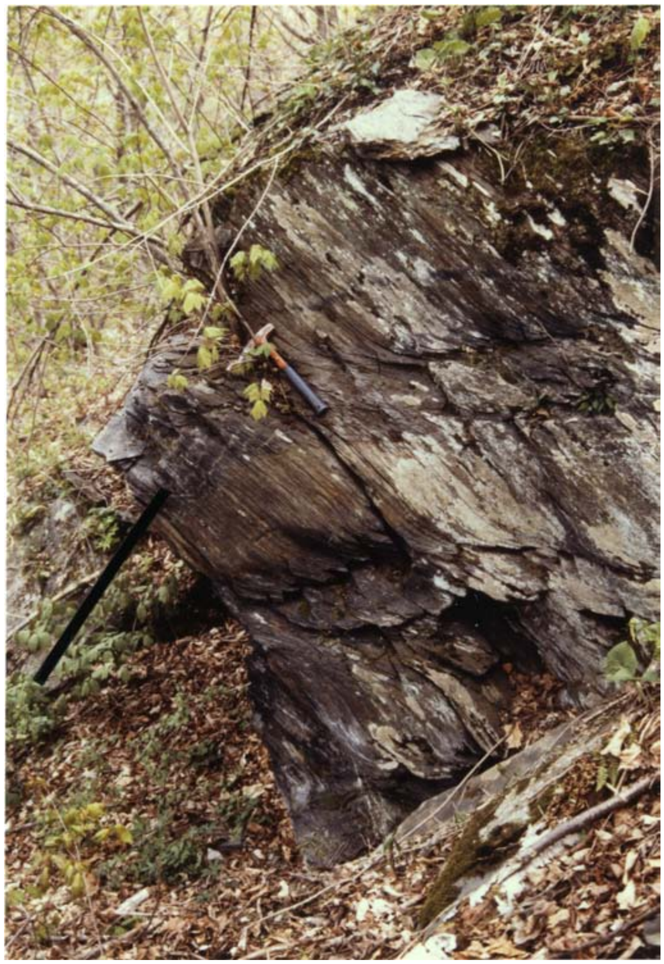


Figure 4.23
Outcrop-scale structural slicing within the Browns Pond Formation. This thrust truncates the hinge region of a recumbent F3 fold as steeply dipping bedding can be seen within the imbricate zone. Outcrop of the Two Bears Thrust.

Figure 4.24
Closeup of previous photo of meso-structural slicing showing S/C relationships where cleavage is rotated into parallelism with the shear foliation which lies near horizontal in the photo. Note the bedding which has been folded in the mid-left area of the photo about a cleavage of likely S_5 generation (?).

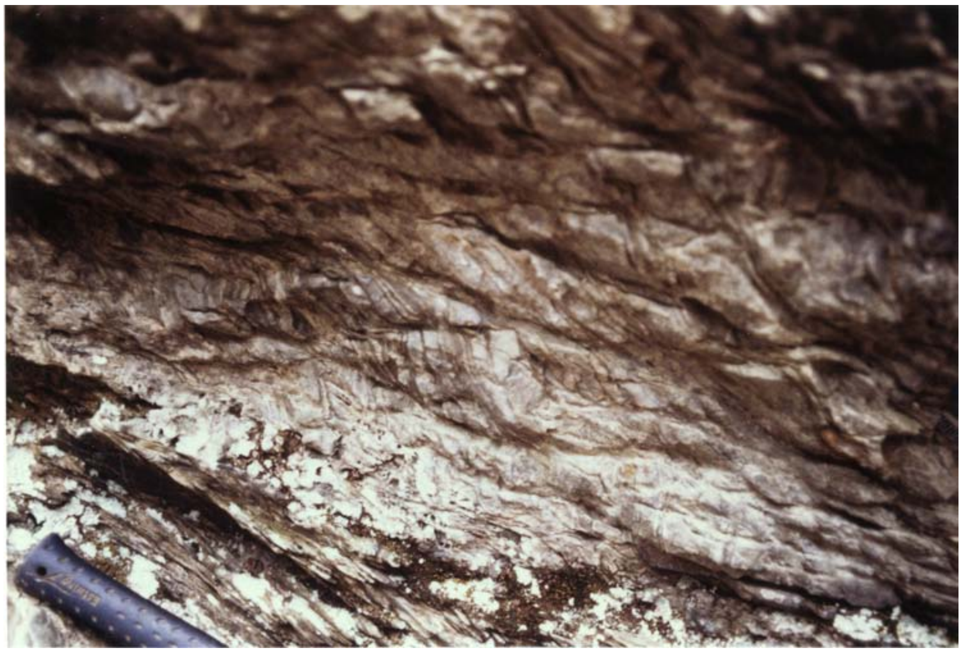


Figure 4.25
Photo of Brandon Mt. Road Thrust zone and small-scale slicing of lithologic layering.

Figure 4.26
Hand specimen showing structural slicing in the Brandon Mt. Road Thrust zone, from same outcrop as in previous photo.

is sometimes ambiguous, they generally appear to be fairly late as they transect the slaty cleavage and show a well-developed crenulation cleavage in the thrust zone. In the Parautochthonous carbonates, these thrusts are nowhere well-exposed, but some degree of continuity of these faults is assumed across the Allochthon boundary. Washington (1981) has suggested that thrusts within the carbonate sequence are delineated by restricted zones of crenulation cleavage development. In Washington's study area, only in the thrust zones is the crenulation cleavage present. Similar relationships were found in the carbonates during the present study, although the number of crenulation age structures is small. The crenulation cleavage is very poorly-developed and only one outcrop is thought to be a thrust zone. Full understanding of the deformation within the Shelf Sequence is made more complex by the poor outcrop and poor development of cleavage in the dolomitic lithologies which dominate the exposure due to their resistant nature.

This phase of deformation is also responsible for the final movement of the Allochthon into its present position, as evidenced by crenulation age (D_5) movement on the Taconic Frontal Thrust, as described by Rowley (1983).

D6 DEFORMATION WITHIN THE ALLOCHTHON

The final deformation structures within the region are very localized brittle kink folds/kink bands and normal faults related to the development of the Champlain Valley. The orientations of these brittle structures reported by other workers accords with their relationship to N/NE-trending brittle structures throughout the Champlain Valley. On synthetic aperture radar image maps of the eastern New York/western Vermont region, these brittle structures can be seen to transect all structures and continue eastward into the Green Mountains of Vermont, indicating their post-Taconic development (R.H. Fakundiny, 1987, personal communication). For this reason, and the host relationship of these fractures to well-known late alkaline intrusives throughout the Champlain Valley (Dale, 1899; Kemp and Marsters 1893), these structures are assumed to be of post-Taconic age. Zen (1972) reports that the age of some of this faulting is post-late Cretaceous, since an augite-camptonite dike of late Cretaceous (K/Ar, hornblende) age is offset by one of the faults associated with the development of the Synclinorium. The majority of these dikes, however, are older than those discussed by Zen (W.S.F. Kidd, 1987, personal communication).

DISCUSSION OF STEREOGRAPHIC DATA

The stereographic analysis of the study area supports the previous structural sequence and is one of the most useful techniques to distinguish the later crenulation phases of deformation.

Poles to bedding (S_0) were not plotted due to the paucity of bedding measurements from many parts of the study area and the complexity of structural development. Little essential information could be gained by analysis of bedding orientations, other than a poorly-defined complex sequence of fold development during the five phases of tectonic deformation involving folding. Where suitable, bedding measurements and the stereographic projection were used to determine the orientation of macroscopic fold axes where the structural age of the fold could be constrained using the type of axial planar cleavage present in the structure.

The plots of poles to slaty cleavage (S_3) for both the Allochthon and Parautochthon show a maxima defining the dominant intermediate east-dipping cleavage striking between north and northeast (see Figure 4.27). The slaty cleavage has been folded about the north-to-northeast trending crenulation folds to produce a dispersed girdle with a strong maxima oriented approximately 023 42E. These plots indicate that regionally, the slaty cleavage lies parallel to the prominent east-dipping orientation of bedding and supports the observed dominance of isoclinal folding in the Allochthon. Some of the scatter in this plot might be an artifact of the similar morphology of the S_2 and S_3 slaty cleavage. The scatter could result from the crenulation (F_5) refolding of the earlier slaty cleavage fabric elements, the majority of which strike N/S (S_3) and the minority of which strike E/W (S_2). Refolding of these orientations would account for the observed scatter of data.

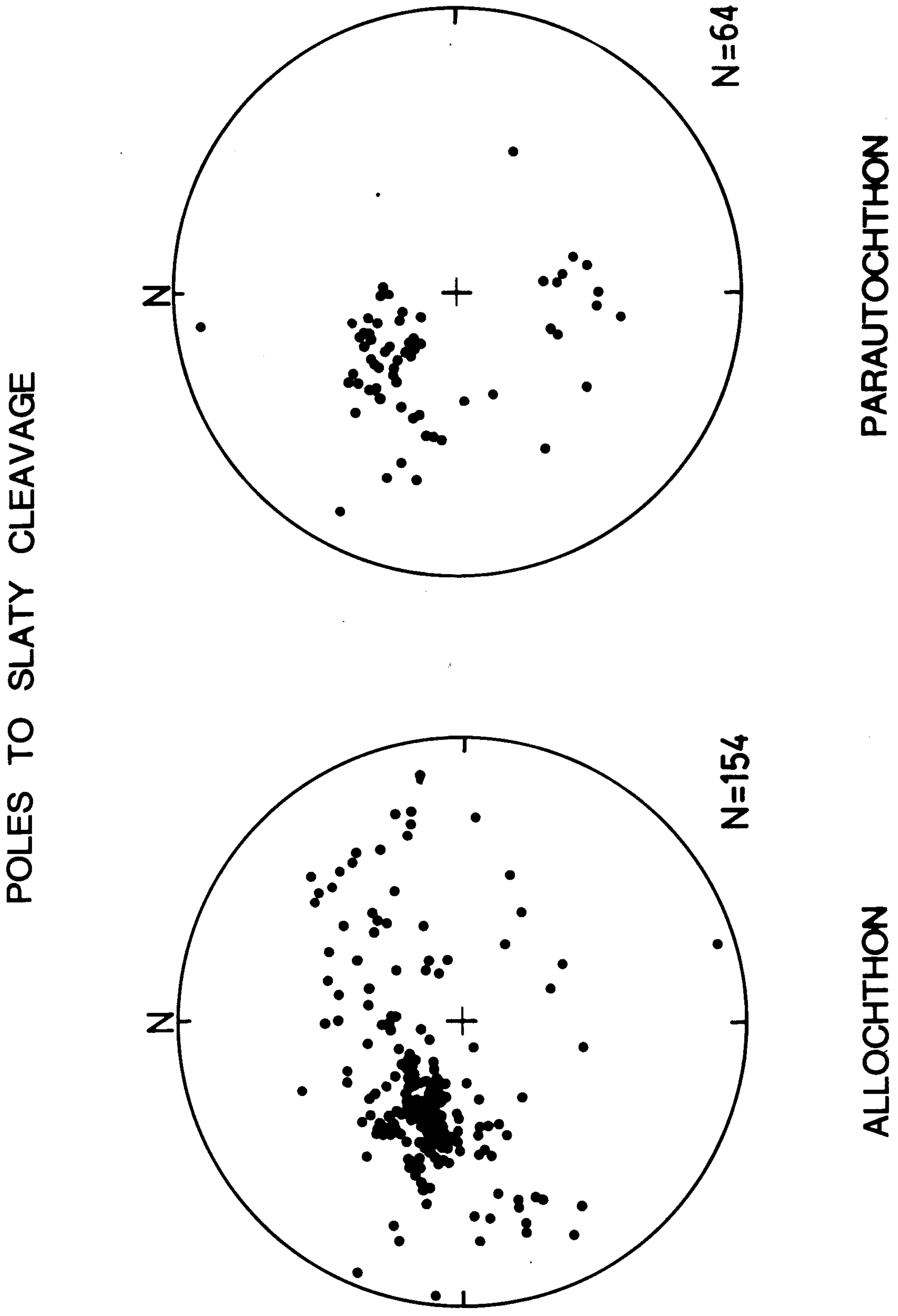


FIGURE 4.27-STEREOPLOT OF POLES TO CLEAVAGE

The "slaty cleavage" in the Parautochthon shows a dominant maxima in an orientation nearly identical to that of the Allochthon, but also shows a weaker maxima defining a E/W-striking cleavage element, probably lying axial planar to macroscopic folds of this orientation reported by other authors in the Parautochthon (Crosby, 1963; Voight, 1965) but not observed in the present study. The data from the Parautochthon show a much stronger cluster of points supporting the N/NE striking fabric but do not indicate any substantial refolding during later tectonic deformation. This could be due to: 1) the widespread transposition fabrics seen thoughout the Shelf sequence, or 2) the flattening of crenulation age (D_4) thrusts to the Giddings Brook (or Basal Thrust) of the Allochthon without substantial imbrication through the Shelf sequence in the study area and the production of crenulation-age deformation widely associated with these zones.

The poles to crenulation cleavage (S_5) of the Allochthon, lying axial planar to folds of this generation, show two clusters of points, both reflecting planes that strike N/S and dip steeply to either the east or west (see Figure 4.28). The points are poorly clustered reflecting an approximately 25 degree variation in strike of the planes. Several points plot in the orientation of the S_4 crenulation cleavage restricted to fault zones. Overall, however, the crenulation fabric data show a dominance of N/S striking orientations with varying steep dip probably reflecting the degree of overturning of these folds. The data plot shows a weak girdle suggesting folding about a N/S axis. This relationship is nowhere observed except perhaps where the early slaty cleavage (S_2) has been folded about the crenulation cleavage (S_5). Alternatively, due to the similarity of cleavage elements in the study area, it is considered more likely that some of the observed crenulation cleavage measurements are perhaps the "slaty cleavage" (S_3) crenulating the earlier slaty cleavage (S_2) within the Ganson Hill structure. The observed relationships probably reflect the interacting effects of complex cleavage relationships and local variation of the crenulation cleavage orientations within the study area.

Data from the Parautochton are sparse, reflecting a poor development of this structural element within the study area. Curiously, such features are widely developed within the Sudbury Nappe, especially along the front of the Sudbury Thrust, as reported by Voight (1965; 1972). Washington's work (1981) in the Middlebury area demonstrates a total absence of crenulation cleavage development in equivalent lithologies to the north of the study area. As he indicates, the crenulation is best-developed in the thrust zones. The absence of such zones in both his area and in the present study area suggest that thrusting preferentially followed different horizons in the study area causing the restricted development of crenulation development.

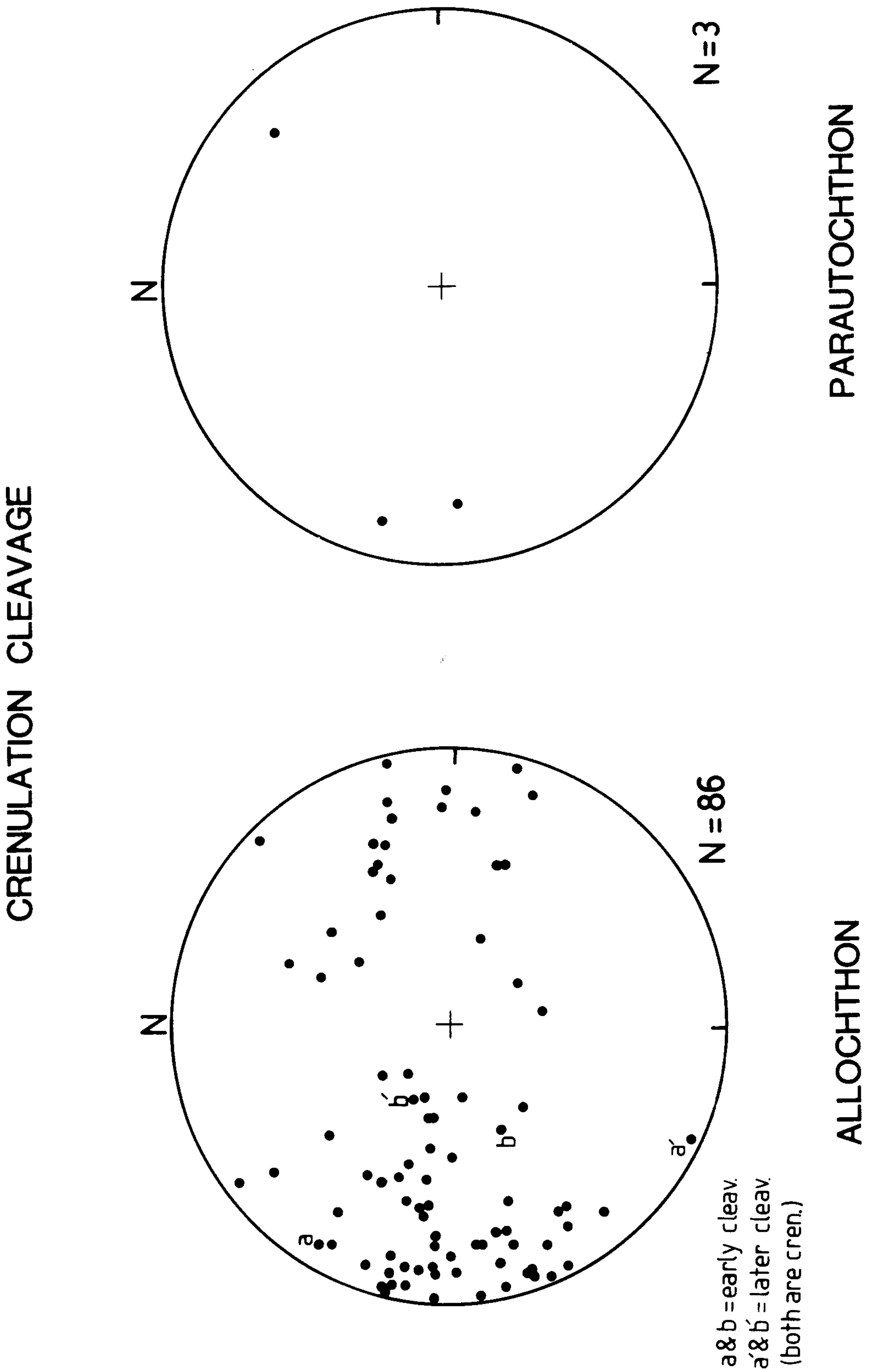


FIGURE 4.28- STEREOPLOT OF POLES TO CRENULATION CLEAVAGE

Crenulation lineation data from the Allochthon show that F_5 folds of the earlier cleavage elements containing an axial planar S_5 cleavage, almost exclusively, plunge shallowly south (See Figure 4.29). Several orientations plunging shallowly E/SE are those folds of F_4 generation from within fault zones.

Crenulation lineation data from the Parautochthon are again sparse, but suggest a dominance of south-plunging orientations within the study area.

Small-scale folds were plotted separately from crenulation lineations to assess the extent of transection within the study area, and because the generation of many mesoscopic folds is unclear. (see Figure 4.30). Borradaile (1978) has developed several criteria to assess the extent of transection and the possibility of refolding about pre-existing axes. The most effective method is to plot intersection lineation data separately from fold axes, in order to assess the mismatch of the two parameters. If the maxima of the two features do not coincide, it is a good indicator that transected folds are present in the region. Data collected from the Allochthon show a dominance of shallow, south-plunging orientations with lesser abundances of shallow north-plunging features. Generally these structures trend N/S although significant variation is present. This variation could be the result of passive rotation of such folds in thrust zones, where such small folds are best developed, or small-scale refolding. The

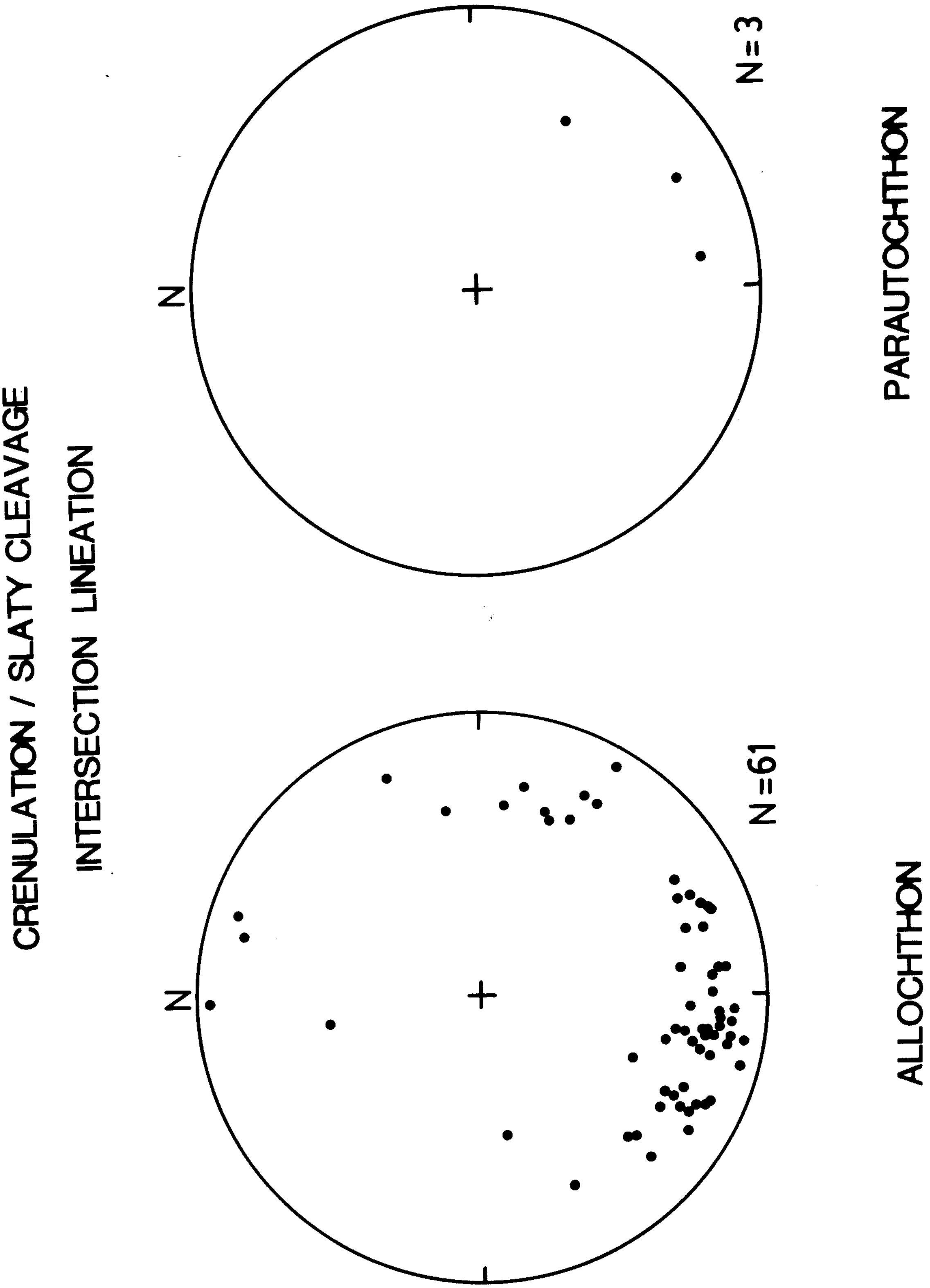


FIGURE 4.29- STEREOPLOT OF CRENULATION LINEATION DATA.

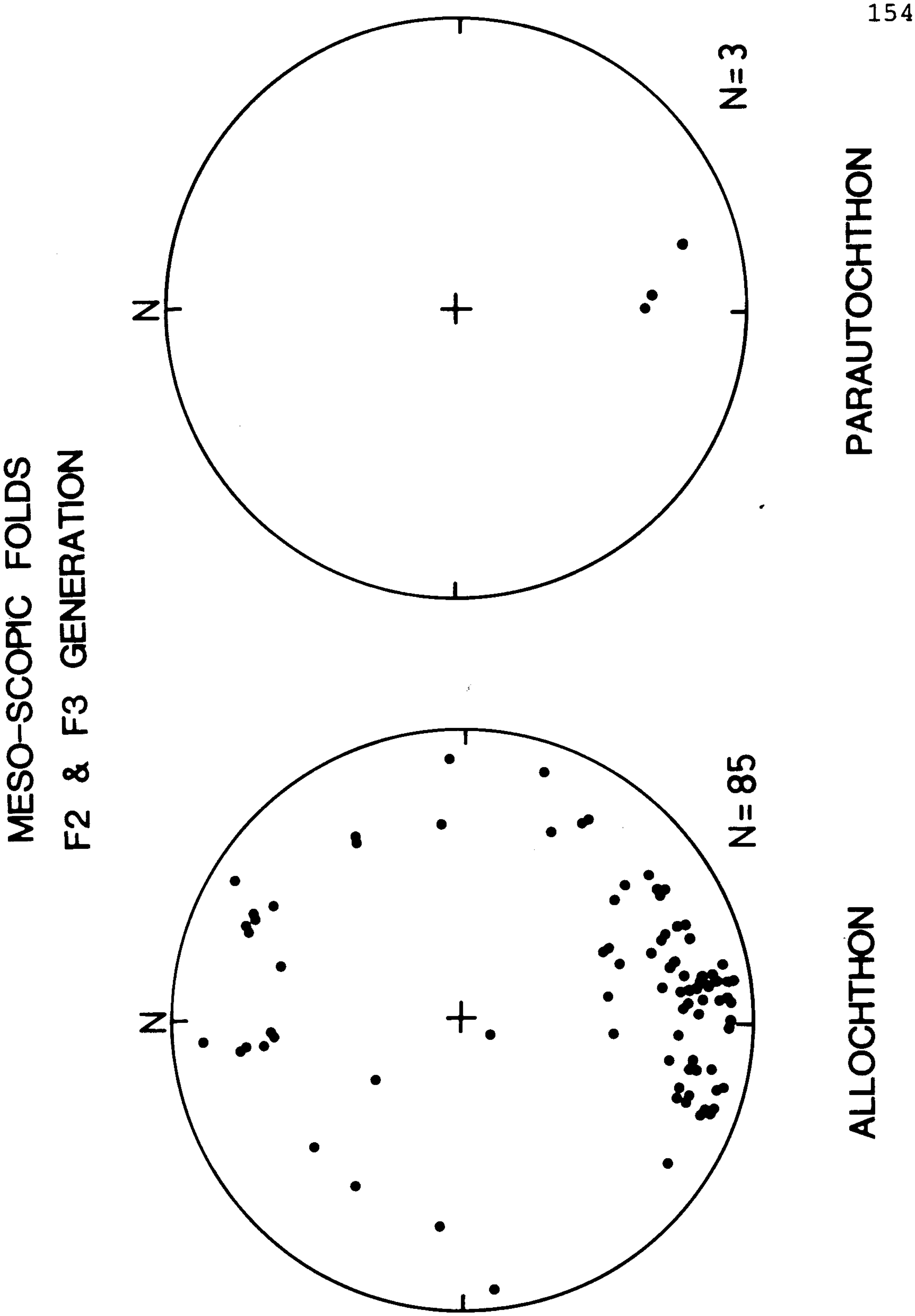


FIGURE 4.30- STEREOPLOT OF SMALL SCALE FOLDS

SLICKENSIDE LINEATIONS FROM

WITHIN ALLOCHTHON

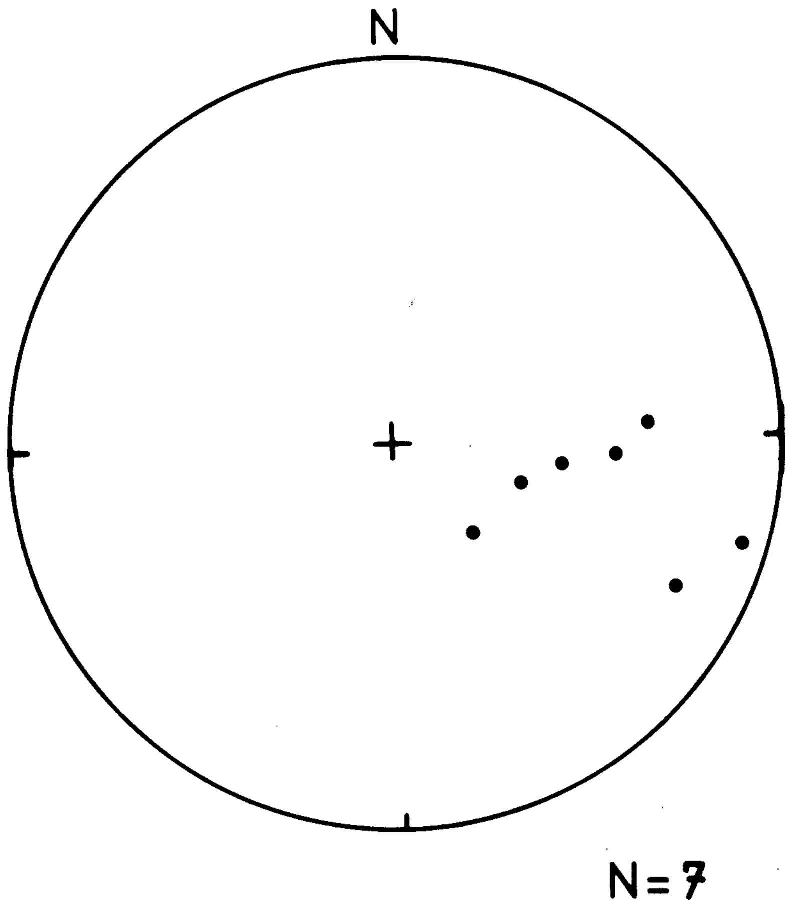


FIGURE 4.31- STEREOPLOT OF SLICKENSIDE LINEATIONS

former interpretation is favored in light of such relationships having been observed in many thrust zones in the study area.

Small scale folds from the Parautochthon are poorly developed as are most of the crenulation age (D_5) structure. Slickenside lineations indicate that the dominant direction of late (T_{4-5}) thrust transport was from the east/slightly southeast direction, and that the thrust planes dip a variable amount in that direction, probably reflecting the relative dips of thrust ramps and flats (see Figure 4.31).

CONSTRAINTS ON EMPLACEMENT AND STRUCTURAL SEQUENCE

The poor development of the late structural elements within the Parautochthon is problematic in light of the alleged early (D_1) juxtaposition of the Parautochthon and Allochthon and the shared slaty cleavage age (D_3) structural elements (c.f. Rowley, 1983). It might be expected that the study area would demonstrate better development of the later elements.

Since the basis of this early juxtaposition is equivocal and has not been conclusively demonstrated, a well-exposed example of Basal Thrust folding that could be undeniably placed in the D3 generation of structure would be helpful. It remains possible that the observed structural relationships along the boundary developed during the D5 generation. The present study did not manage to constrain these relationships other than to describe a virtual absence of crenulation age (D_5) age deformation in the Shelf Sequence. Further work to the east and northwest of the present study would be required to confirm these relationships.

A scenario involving late thrust imbrication within the Allochthon flattening out at shallow depths to the Basal Thrust (or Giddings Brook fault) of the Allochthon is considered likely and the strongest support is found for this model. Shortening within the Shelf Sequence would be accomodated by thin-skinned shortening within the Bascom Formation as reported by Washington (1981), and emplacement of the Sudbury Nappe. The final movement of the Allochthon intos its present position could have occurred when the Allochthon and the Sudbury Nappe were thrust westward. In such a model, the Parautochthon mapped in the present study area would lie beneath these strata and would be unlikely to show the effects of this deformation. In front of the Sudbury Nappe, extensive crenulation development is present as are outcrop scale thrust systems. The movement horizons for the final transport would be the Sudbury Fault and a reactivation of the Basal Thrust. It is possible that the Basal Thrust ramped downward into the Forbes Hill/Hortonville-Ira black slates on top of the carbonates during the final movement, a geometry favored by the observed deformation along the Basal Thrust/Giddings Brook Fault. The significant exposure of Taconic lithologies along the Allochthon/Parautochthon boundary does not show any such large-scale thrust zones to be present which can be unequivocally traced out into the underlying carbonates except into topographic depressions. If present, however, the poor exposure of carbonate lithologies within the study area would preclude the recognition of such late imbricate zones through the Shelf. The appearance of the slaty units near the Basal Thrust suggests that they have been much more strongly deformed in comparision to the underlying carbonates, lending support to the model involving imbrication of the Allochthon to a sole thrust at the base of the Allochthon and parautochthonous slates above the Parautochton carbonate sequence during the final thrust emplacement.

No unequivocal evidence was found during the present study which constrained the timing of Allochthon emplacement. As discussed previously, the Wm. Miller fenster/culmination is one of the few examples where the Basal Thrust of the Allochthon can be inferred to be folded by later deformation. Unfortunately, the generation of deformation which produced this geometry cannot be clearly ascribed to either the D_3 or D_5 generation.

Similarly, the relative timing of movement on the Taconic Frontal Thrust is also equivocal. Clearly exposed examples of Basal Thrust folding are unknown along the northern Allochthon boundary.

In the present study, the age of late imbrication through the Allochthon is difficult to constrain since these thrusts do not crop out in the Parautochthon. In the Allochthon, however, the age of these features are syn-to-post slaty cleavage (D_3-slaty cleavage or crenulation age-D_5) features. Nowhere is the Basal Thrust exposed so that folding of this structure is visible. It is considered highly likely, however, that this fault is transected by the crenulation-age imbricate thrusts that were found throughout the study area although it is more likely that it serves as the sole thrust for these smaller imbricates. The crenulation fabric is well developed in the slates along the Allochthon boundary and several faults were found which could be extrapolated across the boundary. Further mapping to the northwest of the study area where the Basal Thrust and the Sudbury Nappe carbonate sequence along the boundary are better exposed would be useful to more fully understand the timing of faulting relative to emplacement of the sequence. Such relationships are present to the northwest of the study area near Spooner Hill.

SUMMARY OF DEFORMATION SEQUENCE IN THE NORTHEAST ALLOCHTHON STUDY AREA:

D0- Syn-depositonal soft sediment slump folding and faulting.

D1- Early, pre-emplacement (??) folding reported only from within western Allochthon. Orientation of axes unknown. Recognized by downwards facing indicators on later upright structures. Emplacement of Allochthon onto Shelf (??).

D2- Differentiated layering/foliation lying axial planar to the kilometric scale Ganson Hill Syncline. Fold axes and cleavage are oriented nearly east/west. (first reported in this thesis)

D3- Dominant metric-kilometric scale, northeast-oriented folding in Allochthon with the "regional" slaty cleavage lying axial planar. Responsible for the regional map pattern/distribution of lithologies.

D4- East/west striking Cleavage found only in late (S3-transecting) thrust zones and showing a discrete crenulation morphology. The fabric is oriented normal to the fault plane and the intersection lineation of the fabric with the fault plane lies parallel to the transport direction as defined by quartz and chlorite slickensides. Quartz veining is locally found folded about this cleavage which in turn is transected by the S5 fabric.

D5- Small-scale, meter-scale folding with an S5 crenulation cleavage lying axial planar. Best developed near thrust zones and in eastern Allochthon. Structures are oriented to northeast, similar to D3 structures.

D6- Rare, brittle kink bands that post-date all other structures and are thought related to normal faulting common throughout the Champlain Valley.

CHAPTER 5 STRAIN AND CLEAVAGE ANALYSES

In the past three decades, a renaissance has taken place in the field of structural geology. Pioneering work by such workers as E. Cloos (1947) and D. Flinn (1962; 1965) has been followed by that of Ramsay (1967) which helped demonstrate the importance of strain analysis as a tool for modern structural analyses of complexly deformed regions.

A more complete knowledge of the strain associated with cleavage development is important for our understanding of how cleavage forms, the calculation of orogenic shortening Hossack (1978;1979), and for the accurate restoration of balanced structural cross sections (Reks and Gray, 1981; Woodward et al. 1986a; and Woodward et al. 1986b)

This chapter will be divided into several parts, the first dealing with slaty cleavage and the problem of volume loss during deformation, and the second being concerned with the strain magnitudes associated with the development of the various cleavages in the Allochthon. The chapter will conclude with a discussion of the microstructure of the study area.

STRAIN, SLATY CLEAVAGE AND VOLUME LOSS

The origin of slaty cleavage has proven to be one of the most controversial topics in the history of structural geology. Sharpe (1847) first noticed that fossils were flattened in the plane of cleavage and he suggested a compressive origin for the observed fabric. Sorby (1853) prepared thin sections of several slates and advanced the idea that slates have undergone a slight elongation in the cleavage plane and a strong compression perpendicular to cleavage. In addition to recognizing the idea of "cleavage refraction", Sorby attempted to use reduction spots from the Welsh slate belt to determine the orientation and magnitude of deformation. He found that ellipsoids are elongated on the cleavage plane in the direction of cleavage dip and most strongly compressed normal to cleavage. Sorby speculated that a 50% volume reduction had taken place during cleavage development. Sorby differed from Sharpe in that he felt that the micas had only been mechanically rotated, and had not experienced shape changes due to physical compression while assuming their final preferred orientations. Harker (1885) concurred with Sorby that cleavage was produced by compression, yet suggested that cleavage developed later, well after folding was initiated. He further demonstrated that cleavage formation by simple shear was impossible in light of observed strain states in these rocks. Sorby (1908) carefully measured the X and Z dimensions (using the convention of Ramsay that $X \geq Y \geq Z$) of a large number of reduction ellipsoids from the Welsh fold belt and found strong evidence in support of his previous assertions.

Interestingly, such mechanisms as rotation of phyllosilicates and recrystallization, and the relationship between strain and cleavage have remained valid today, though controversial at times, although we have directed much more powerful analytical techniques to the problem.

Numerous authors have recently subscribed to these ideas such as: Ramsay (1967), Oertel (1970), Ramsay and Wood (1973), Wood (1973; 1974), Tullis and Wood (1975), Siddans (1976), Tullis (1975), Wood et al. (1976), Wood and Oertel (1980), Beutner (1978), Beutner and Diegel (1985). The results of these studies conclude that slaty cleavage (and the strongest rock fabric) forms perpendicular to the direction of maximum shortening (Z). At the same time, a much weaker preferred orientation develops parallel to the direction of greatest elongation (X).

More recently, the importance of volume loss during deformation has become an important issue. Early work by Ramsay and Wood (1973) based on their observations of the density changes accompanying lithification and subsequent deformation, that volume loss during deformation must on the order of 20% or less. This is supported by their obervations on the average strain values known from slate belts and the effect of a volume loss on this stability field. Volume losses greater than about 20% will cause a shift of the data plotted from the field of flattening into the field of constriction (see figure 5.2 for a schematic illustration of this point). The lack of well-defined constrictional deformation in most slate belts argues against volume changes of any magnitude although it should be mentioned that significant volume losses can occur during deformation **without** constriction. Small volume losses during deformation will not cause profound errors with regard to the shape of the total strain ellipsoid (c.f. Means, 1976 for a discussion of this term) in most situations. For example, an isotropic volume loss of 20% during deformation will cause an error in the magnitude of the stretches of less than 12%. Ramsay and Wood's study also demonstrated the importance of strain state to the mechanics operative in orogenic belts. Most of the data from this study was that collected by D.S. Wood from the slate belts of the Appalachian/Caledonide orogenic belt. The majority of these slates show well-developed stretching lineations on the cleavage surfaces.

In one of the most profound analyses of the volume loss problem, Wright and Platt (1982) suggested that volume loss by pressure solution is the dominant cleavage-producing mechanism for their study area. Using deformed graptolites and the known theca spacing of undeformed organisms, Wright and Platt were able to demonstrate approximately 50% shortening occurred normal to bedding and resulted in the slaty cleavage. Interestingly, these rocks do not show any stretching lineation as the deformation is that of volume loss without any related extension. The evidence of volume loss deformation on such a large scale has profound significance for studies of deformation in slate belts.

Milton and Chapman (1979) examined the strain variation in a sequence of sandstones and conglomerates in northern Norway. Their data suggested an initial volume loss sedimentary (perhaps tectonic) deformation producing an oblate strain fabric (1.5:1.5:1.0) followed by a plane strain prolate deformation of magnitude R_s=1.27.

Similar observations were made by Cowan (1986) who found an initial oblate ellipsoid shape in melange sediments of the Franciscan formation. These sediments have only experienced soft-sediment deformation in a partly dewatered and consolidated state.

These three authors (Cowan, Milton and Chapman) indicate the likelihood of an initial oblate strain ellipsoid in most deformation regimes where sediments are undergoing dewatering and lithification prior to deformation. As the Taconic Allochthon developed in a tectonic context analogous to the accretionary prism characteristics of the Franciscan, these results suggest the applicability of these observations to the observed study area and the strain values determined for the Allochthon.

Bell (1985) suggested from his analyses of accretionary lapilli in the Borrowdale Volcanics of the English Lake District, that the tectonic strain path best supported by the data is one involving initial pure volume loss followed by progressively more constant-volume deformation. This would suggest that in slate belts that the initial strain is that of volume loss "deformation" such as that recorded by Wright and Platt (1982) and that with increasing deformation, that deformation occurs by methods involving constant or slight volume loss effects such as suggested by Ramsay and Wood (1973). However, Boulter (1986), has indicated that accretionary lapilli sequences show widespread compaction values within specific horizons so that Bell's assumed compaction value (Y/Z=1.86) is in error. Boulter indicates that variation in this ratio can range from 1.5 to 1.95, and thus the determined total volume loss should also reflect this variation. Boulter concludes with the observation that Bell's results are also in accord with moderate incremental volume loss during plane strain deformation. Such incremental volume loss throughout deformation is also supported by studies linking deformation mechanisms to mass transfer and fluid flow behavior through tectonites. Boulter suggests that the magnitude of the moderate progressive volume loss during deformation is on the order of 20%.

SLATY CLEAVAGE STRAIN IN THE TACONIC SLATE BELT (LAKE BOMOSEEN TO FAIRHAVEN, VT)

As part of an undergraduate thesis (Hoak, 1985), the strain associated with slaty cleavage in the Taconic Allochthon was determined using reduction spots collected from several sites along the regional strike of the Slate Belt from the Cedar Point Quarry on the shore of Lake Bomoseen to the Vermont Structural Slate Co. quarry near Fairhaven. Four sites were examined with the intent of documenting the relationship between total strain values and the variations in along-strike fold plunge within the Allochthon. The location of these sites can be seen in Figure 5.1. A reinterpretation of these results was performed during the course of this investigation, especially with regard to volume losses during deformation, and the results presented in Table 5-1. In addition, the slaty cleavage age strain data are compared to strain data from earlier and later cleavages determined during the present analysis.

Cleavage planes containing the reduction ellipsoids' X-Y dimensions were serially ground and measured to determine the maximum dimensions of the X and Y axes of the strain ellipsoid. At the same time, the thickness of the slate block was measured so that the material removed <u>after</u> the maximum XY values were obtained could be added to the measured Z/2 value. The Z/2 value was determined by cutting the block parallel to the long dimension of the ellipsoid and measuring the thickness (Z/2) of the ellipsoid in the plane of shortening (X-Z). Error resulting from this technique is less than 10%.

A significant number of collected samples were discarded due to the non-ellipticity of the samples, especially in the critical X-Z plane of the reduction ellipsoid. As can be commonly observed in many of the quarries, non-ellipsoidal strain markers are the norm. From the minority of ellipsoidal examples, flattening or shortening values range from 65-73% and extension ranges from 120-140%. Determined values from the four quarries showed mean strain values as shown in Table 5-1. Note the minimal effect of a 20% isotropic volume loss on the observed strain magnitudes. A 20% volume loss normal to the Z-direction or parallel to the XY-plane reduces the total shortening by 10%.

Wood (1974) suggested that there is an extremely close relationship between strain state and fold position. In the Welsh slate belt, maximum values of flattening strain (Z) are found in fold plunge culminations andd minimum values in fold plunge depressions. Variations in plunge and the extent of tectonic thickening appear dependent on variation in the flattening component of strain. Ramsay and Wood (1973) have emphasized the role of differential transport and fold axis extension and its dependence on strain state. In the present study, no obvious relationships between transport and strain could be determined. We find that the greatest flattening occurs at the Green Dump locale followed by the Cedar Point site. Between these locales, Zen (1961) shows a plunge reversal from north to south respectively.

These quarries of course do not lie on the same fold, but this plunge reversal appears to be present in all folds in the immediate region. Unfortunately, the paucity of data and suitable markers from the Green Dump does not provide total support for the observed relationship between fold hinge plunge variation and total strain values. The other two quarries used for analysis both lie on south-plunging folds.

One important observation that emerges from this analysis is the idea that strain values associated with

FIGURE 5.1
LOCATION OF QUARRIES USED FOR STRAIN ANALYSIS

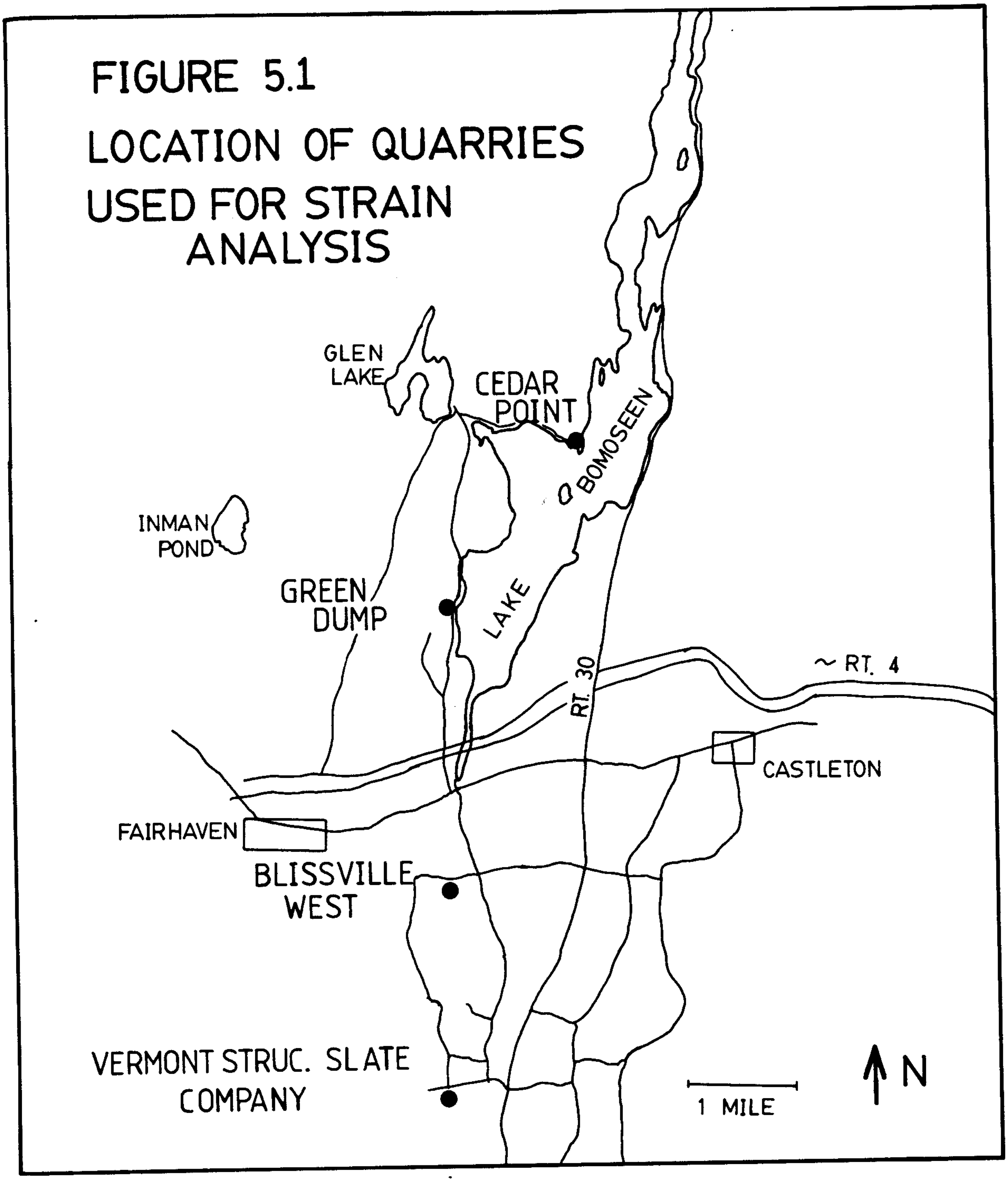


TABLE 5-1

MEAN TOTAL STRAIN VALUES FROM THE FOUR STUDY SITES

	S1 : S2 : S3		
Cedar Point Quarry (1.60 : 1.00 : 0.21)++	2.3 : 1.4 : 0.30	*	
	2.4 : 1.5 : 0.32	**	n=19
	2.3 : 1.4 : 0.38	***	
Green Dump Quarry (1.50 : 1.00 : 0.21)++	2.2 : 1.5 : 0.31		
	2.3 : 1.6 : 0.33		n=5
	2.2 : 1.5 : 0.38		
Blissville West Quarry (1.85 : 1.00 : 0.21)++	2.5 : 1.4 : 0.28		
	2.4 : 1.3 : 0.27		n=21
	2.5 : 1.4 : 0.35		
VT Struc. Slate Co. Quarry (1.70 : 1.00 : 0.24)++	2.3 : 1.4 : 0.32		
	2.2 : 1.3 : 0.31		n=15
	2.3 : 1.4 : 0.40		

KEY:

++ mean shape of ellipsoid determined by direct measure

* principal stretches calculated assuming no volume loss

** principal stretches calculated assuming 20% isotropic volume loss during deformation

*** principal stretches calculated assuming 20% volume loss from the XY-plane of ellipsoid (normal to Z-direction)

n= 12 refers to the number of data points measured per locale

recalculated from Hoak, 1985

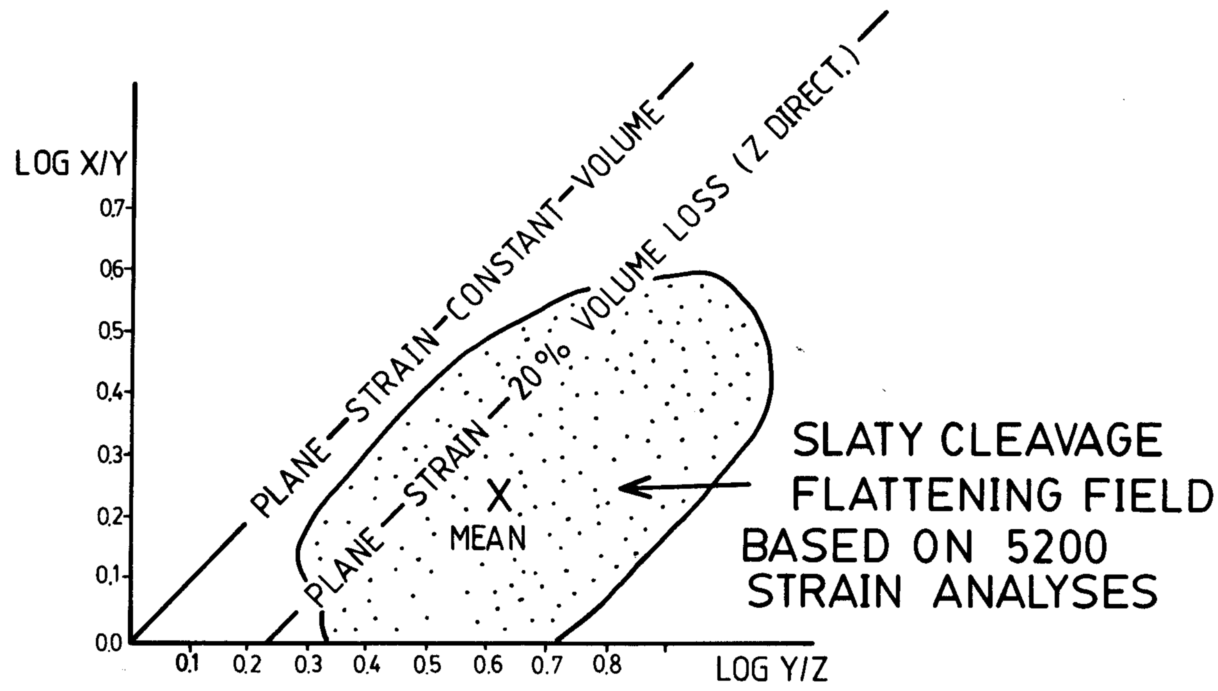
slaty cleavage are fairly constant along-strike throughout the Allochthon. These strain values are also similar to those determined by Wood (1973; 1974) for the Welsh and Taconic slate belts in his study of strain states and tectonic environments, and slaty cleavage, respectively.

There are several problematic observations of cleavage in the quarries chosen for analysis. One of the most important is the widespread occurrence of a weakly developed crenulation cleavage. This cleavage can be shown to transect the reduction ellipsoids in a discontinuous fashion. The weakness of this cleavage development in the specimens chosen for analysis suggests that its importance and effect on the slaty cleavage strain values is minimal.

Another problem within the study area is the amount of volume loss during slaty cleavage formation. In this study, variable amounts of volume loss have been assumed during the calculation of the total strain values. Volume losses on the order of 10-20% have probably occurred by comparision with other rocks from slate belts. This is based on theoretical grounds as first explained by Ramsay and Wood (1973). This argument is expressed in Figure 5.2. This result does not indicate, however, whether the volume loss was of a progressive nature or occurred during one finite strain increment of the deformation.

It must be emphasized, however, that the magnitude of strains occurring entirely by volume loss (50%) of Wright and Platt have not occurred in the study area. The slates

SHIFT IN STABILITY FIELD OF
CLEAVED ROCKS BY A 20% VOLUME
LOSS IN THE Z-DIRECTION



MODIFIED FROM WOOD, 1974

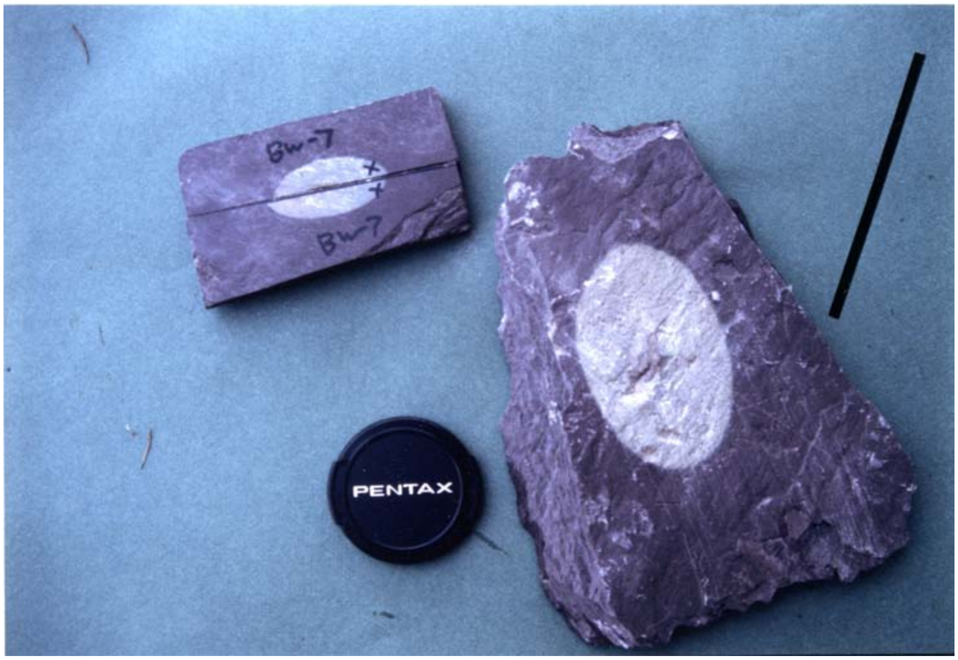


Figure 5.3
XY plane of slaty cleavage showing this plane of the reduction spot. Note the weak crenulation lineation that can be seen cutting the right block from upper right to lower left.

Figure 5.4
XZ plane of reduction spots showing several ellipsoidal spots and several irregular spheres unsuitable for analysis. Note bedding perpendicular to cleavage as defined by red layer in purple slate. Also note bedding plane reduction streak caused by diffusion both along and normal to the bedding plane. The timing of this diffusion could be synchronous with deformation so that diffusion occurred normal to bedding and along the dominant anisotropy in the strata (the incipient to well-developed cleavage). Note, however, how the reduction bodies are concentrated in one "bed" (from edge of glove to camera lens cap) and are unlikely to have attained their present shape via tectonic or post-tectonic fluid movement paths. In addition, similar reduction shapes are found along bedding and as isolated spheres in the Chinle Formation, an undeformed redbed sequence in north-central New Mexico.

examined in this study show relatively strong stretching lineations on the cleavage surfaces in sharp contrast to those studied by Wright and Platt which are lacking such lineations. This lineation implies that the Taconic slates have experienced marked flattening and related extension during deformation, as opposed to rocks of the Great Valley which show only volume loss. In microstructural analysis, no specimens displayed apparent offsets of lithologic layering or veining that would suggest the presence of widespread pressure solution. Such structures were only found where related to crenulation cleavage development, especially in the eastern study area.

The most problematic observation with regard to the use of reduction spot data, results from the pre-slaty cleavage deformation reported within the Allochthon (Rowley, 1983; Bosworth and Rowley, 1984). In the Allochthon, diagenesis and lithification of sediments in an accretionary prism should produce an oblate (true flattening) ellipsoid (Cowan, 1986) as sediments are symetrically flattened during lithification. This is analogous to "gravity spreading" of thrust nappes as discussed by Elliot (1976). The magnitudes of these early strains combined with volume loss and other pre-slaty cleavage deformation should result in an extremely complex ellipsoid shape history (and an unlikely circular shape!) prior to the imposition of the slaty cleavage flattening strain.

Plane strain deformation is assumed in most orogenic belts (Price, 1970; Wood, 1973, 1974; Woodward et al., 1986) due to the apparent absence of along-strike extension of the orogen and/or the assumption that any small unit of rock is effectively constrained by adjacent rock units. In our present scenario, such an assumption will be made for a deformation ellipsoid which has already experienced extension in the intermediate direction due to the early pre-slaty cleavage oblate flattening produced by sedimentary compaction. The shape of our initially circular marker will show not only the slaty cleavage strain, but also the previous strain. This suggests that our determined strain value is a true minimum estimate.

The earliest oblate strain will show a bedding parallel fabric coplanar with the principal plane. Later, slaty cleavage will be imposed at a high angle to this ellipsoid in hinge zones, while on the fold limbs, the slaty cleavage ellipsoid will lie coplanar to the sedimentary fabric and related oblate strain shape. This is, of course, assuming isoclinal folding with an axial planar slaty cleavage as is the case in the Allochthon.

As a consequence of this superimposition of strain ellipsoids from the two deformations, strain markers will show lesser total strains in the hinge zones, and greater total strains in the limbs. We should then, expect strain markers from the limbs to reflect the true total strain while those in the hinge reflect a lesser magnitude of total strain. This should be only the case, of course, for the situation where a pre-existing tectonic or sedimentary fabric is present prior to the imposition of a later tectonic strain.

Support for this interpretation is found in analyses of fossils in slate belts which show similar flattening relationships to those determined by reduction spot analysis (Haughton, 1856; Sharpe, 1847; Tan, 1973)

In the Taconic Allochthon, strain data from hinge zones (Cedar Point locality) is not markedly different from that for fold limbs (Blissville West, VT Struc. Slate Co.). These data indicate the implausibility of significant pre-slaty cleavage deformation due to either sedimentary lithification or tectonic influences.

Only if the reduction spots formed during 1) late diagenesis, or 2) during the early stage of cleavage development, can the presence of such an initial fabric be suggested. Neither of these alternative explanations for the observed strain states seems acceptable in light of the presence of spherical reduction spots in undeformed sediments, and the only locally observed (Bosworth and Rowley, 1984) early tectonic (?) deformation in the Allochthon.

Wood (1974) in his analysis of the Taconic Slate Belt suggests that the variable shortening (65-85%) and related variable extension (55-84%), while little variation occurs in the intermediate strain direction, can only be explained in terms of differential volume loss during cleavage formation. It is possible that this variation is due to variable hinge/limb relationships and the presence of an early tectonic fabric in the quarries that Wood analyzed. Wood's explanation seems quite plausible, though, in light of the previously described results from limbs and hinges and the widespread variability of cleavage development reported within the Allochthon (e.g. Rowley et al., 1979).

STRAIN AND SLATY CLEAVAGE IN THE EASTERN ALLOCHTHON (GANSON HILL AREA)

The shortening associated with the development of the "early" slaty cleavage (S_2) in the eastern study area was determined using a buckled quartz vein which lies nearly perpendicular to the slaty cleavage (S_2) and whose profile plane lies nearly parallel to the crenulation cleavage plane (S_5) as observed in outcrop. In this orientation, the buckled vein can be analyzed for the "early" slaty cleavage strain without the problems of determining the magnitude of crenulation strain and subtracting this value from the previous determination, since the buckled vein is not affected by the later deformation. Similarly, the slaty cleavage (S_3) lies at a high angle to both the profile plane and the S_2 "early" slaty cleavage plane so that its effect is also minimal on our analysis.

Hudleston (1986) has developed several criteria for the discrimination of buckling behavior during fold development.

Figure 5.5A
Outcrop photo showing appearance of buckled quartz vein found normal to the early slaty cleavage (S_2) within the core of the Ganson Hill syncline. Crenulation cleavage lies parallel to profile plane (S_5). Oblique fabric from upper right to lower left is the S_3 fabric which lies at a high angle to both the profile plane and the early S_2 cleavage. Outcrop locality 430-7 can be seen on Plate 1.

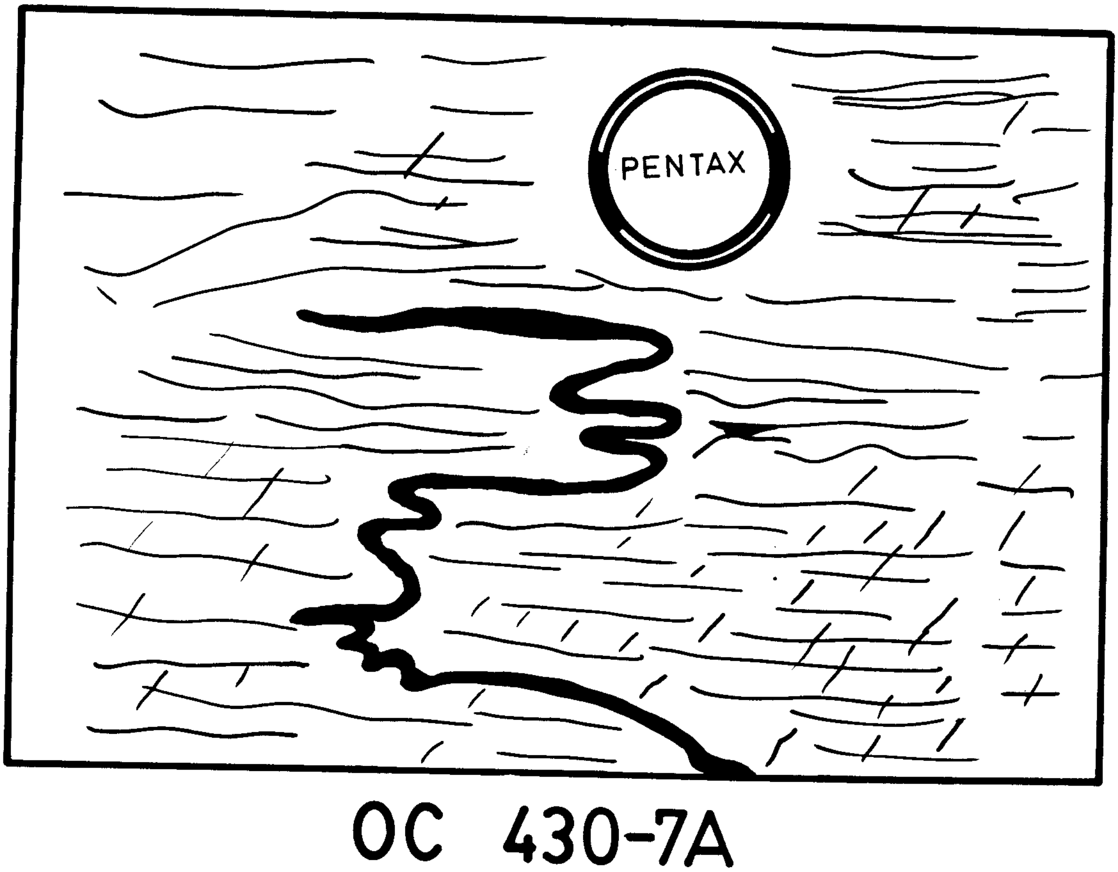


FIGURE 5.5B- SKETCH OF BUCKLED FOLD USED FOR ANALYSIS OF "EARLY" SLATY CLEAVAGE STRAIN (S_2) IN GANSON HILL CORE.

Characteristic features of buckle folds include: 1) a preferred arclength/thickness ratio; 2) a tendency for the competent layer to maintain a constant thickness; 3) rapid decay of folds away from the most competent layer; and 4) cuspate interfaces between layers in which the cusps point toward the more rigid layering. Hudleston indicates that with knowledge of the arclength/thickness ratio and the magnitude of the strain affecting the layering, the extent of non-linear flow law behavior can be assessed for the competent layer. In the outcrop studied, all mesostructural indicators indicate that this is a true buckle fold and the minimum shortening strain magnitude can be determined by merely determining the ratio of deformed to undeformed line lengths, as suggested by Hudleston (1986, p. 239). The folds maintain a constant thickness, there appears to be a preferred arclength/thickness ratio and the folds die out quickly as we approach less competent layers.

The outcrop displaying this buckled vein is found within the core of the Ganson Hill Syncline, approximately 300 meters due south of the easternmost quartzite outcrop alongside Brandon Mountain Road just south of the High Pond Ski area. The outcrop relationships can be seen in Figures 5.5.

Straightening of the buckled vein shows that it has been shortened 74% normal to the slaty cleavage. A similar analysis was performed for a buckled quartz vein by Gray, in Borradaile et al. (1982, Plate 112 A, p. 276-7). There are several contrasts between the two analyses. In the vein from the core of the Ganson Hill syncline, the quartz vein, buckled in the quartzose layers, becomes planar and approximately parallel to the lithologic layering in more pelitic horizons, suggesting that the vein was rotated into parallelism with the foliation. In Gray's analysis, the veins are highly refracted through more quartzose siltstone layers and the buckling is best developed in the pelitic layers. In the Ganson Hill vein, however, the buckling is best expressed in what are apparently very finely-laminated siltstone-slate layers. The bulk rheology of this layer is more quartzose than the adjacent layers. In those layers, where the vein has been more profoundly deformed and now lies parallel to lithologic layering, there appears to be a relatively greater abundance of pelitic material. It is likely that in these layers the vein has been passively rotated into parallelism with the layering or bedding whereas such passive behavior is retarded in the more quartzose layers in which buckling behavior dominates.

The determined strain value is quite similar to that determined for slaty cleavage in the reduction spot analyses in the slate quarries to the west. It is important to realize though, that the determined strain value is a minimum value, since some strain has probably occurred by longitudinal flattening strain as discussed by Ramsay (1967), Gray and Durney (1979), Hudleston and Holst (1984) and Hudleston (1986).

The bulk appearance of the outcrop deformation might suggest that strain had been unevenly partitioned between the competent and less competent layers. This assumption is incorrect, however, and the variable buckling development is a result of partitioning of deformation between homogeneous strain in the less competent layers and buckling behavior in the more rigid layering. Ramsay (1967) has discussed the idea that strain magnitudes provided by buckling data from more competent layers is identical to that experienced in less competent layering (p. 378). This observation, supported by abundant laboratory studies of buckling behavior, indicates that the observed heterogeneity of buckling behavior observed within the distinct lithologies seen in the study outcrop have not caused preferential accomodation of the imposed strain. The determined strain value is well-supported by strain data from other slate belts, utilizing different strain markers, which indicate similar magnitudes of minimum shortening during the formation of the early slaty cleavage. Further emphasizing the fact that our strain value is a minimum value (i.e. in addition to that due to longitudinal flattening strain), the lithologic layering at this outcrop is a differentiated layering, apparently transected by the buckled vein, which indicates that the strain associated with the formation of this foliation is not included within the calculated minimum value. This assumes that the layering is of tectonic origin as suggested by its orientation lying axial planar to the

Ganson Hill fold. It is not possible to fully determine the extent to which the strain has been partitioned between buckling and the formation of the differentiated layering as only the later buckling strain is determinable from the vein. The magnitude of the strain associated with the formation of the differentiated layering (unless synchronous with vein development and hence reflected partially by the buckling strain shown by the vein) cannot be determined from this outcrop since the vein transects the differentiated foliation.

STRAIN AND CRENULATION CLEAVAGE

The relationship between strain and crenulation cleavage has experienced a controversy similar to that of slaty cleavage. The controversy occurred as a result of the problem of whether the crenulation cleavage formed normal to the maximum compressive stress and/or the maximum shortening strain (Ramsay, 1967; Wood, 1974; Gray and Durney, 1979), or whether it lies at an angle to the maximum compressive stress and has experienced significant shear strain (Williams, 1972, 1976; Hanmer, 1979).

The most recent exhaustive study of these relationships is the work of Gray and Durney (1979). Using pressure shadow fibers, deformed porphyroblasts and flattened microfolds, these authors showed that the principal plane of the bulk crenulation strain coincides within four degrees of the crenulation cleavage trace. These data suggest that the importance of shear strain in the evolution of crenulation morphologies is minimal.

One of the primary reasons for the persistence of the shear strain hypothesis for the formation of the crenulation cleavage, is due to the frequent observation that lithologic layering and/or veining is apparently offset along the trace of the crenulation cleavage. This is particularly true for discrete crenulation cleavages. Gray (1977; 1979) demonstrated that these offsets are apparent offsets and due to the effects of dissolution on inclined layers. Close inspection of the offset vein terminations along the crenulation plane show stylolitic features consistent with the origin of the cleavage and offsets by pressure solution.

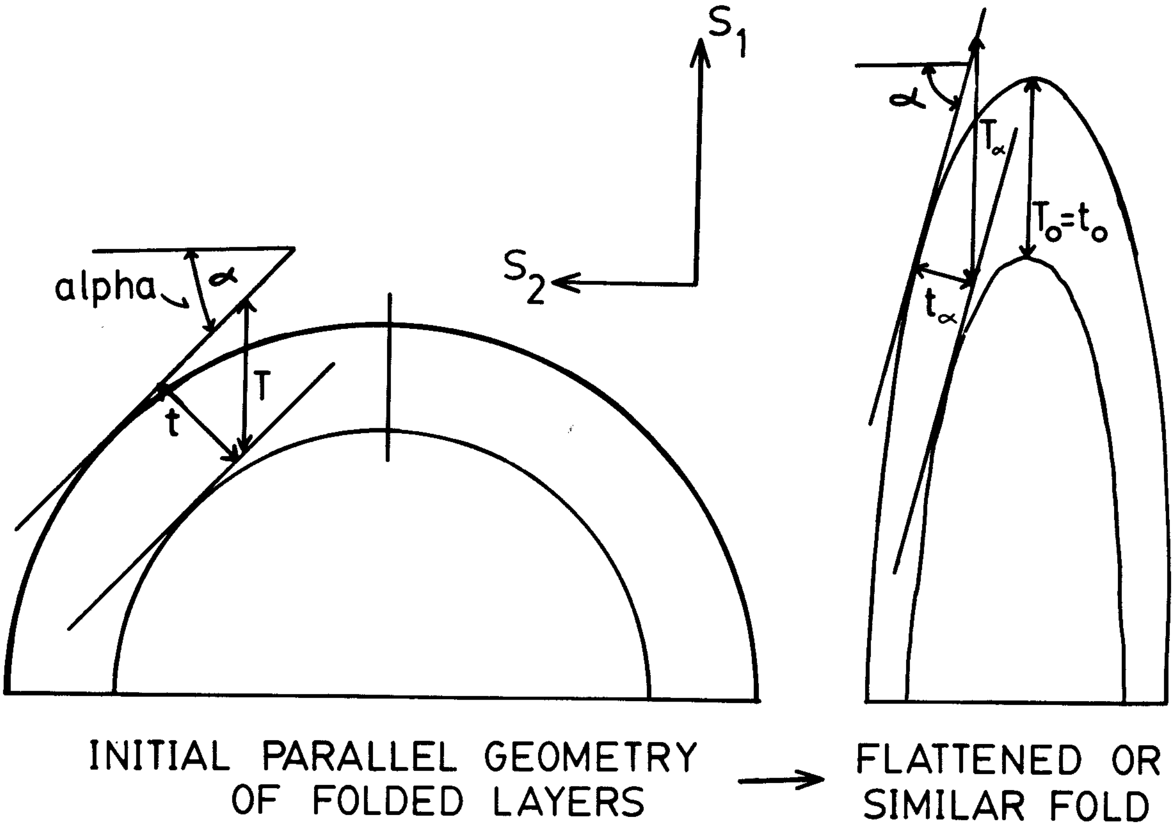
In the present study, the strain associated with crenulation cleavage development was determined by buckling analyses of centimetric-scale crenulation folds. The analytical techiques followed are similar to those used by Gray (1977 ;1979) in his studies on crenulation cleavage morphologies. In these folds, where only buckling behavior has occurred, strain determinations were made by merely measuring the length of the deformed and undeformed layers to calculate the magnitude of shortening. In folds where this simple method of shortening analysis cannot be determined, as a result of flattening strain modification of the original fold profile, the t'_{alpha} technique introduced by Ramsay (1967), modified by Gray and Durney (1979), and most recently discussed by Ramsay and Huber (1987), has been used to determine the extent of flattening in small-scale folds.

The t'_{alpha} technique is well-suited to measurement of flattening strain in small folds as discussed by Schwerdtner (1973). One of the most important requirement of strain studies is the scale of the analysis. According to Schwerdtner, the scale of analysis should be greater than the spacing of the structure being measured. For example, to determine the strain associated with crenulation cleavage, it is essential to measure a parameter that is greater than the spacing of the crenulation microlithons. The small folds used in this study are considerably larger than the spacing of their axial planar crenulation cleavage.

In its simplest description, the t'_{alpha} technique is based on the shape modification of parallel folds by longitudinal flattening strain into a more similar fold geometry. In other words, the imposition of a flattening strain in parallel folds causes thickening of the hinges and thinning of the limbs to produce a similar fold geometry.

The method is based on the changes in limb laminae thickness with the angle of dip. These thickness changes are expressed as a proportion of the maximum laminae thickness which is generally found at fold hinges. Similar folds can be mathematically described as a parallel fold which has experienced an infinite amount of flattening strain. These can be seen in Figure 5.6 which shows the

TRANSFORMATION FROM PARALLEL TO SIMILAR FOLD GEOMETRY BY THE IMPOSITION OF FLATTENING STRAIN



MODIFIED FROM RAMSAY, 1967

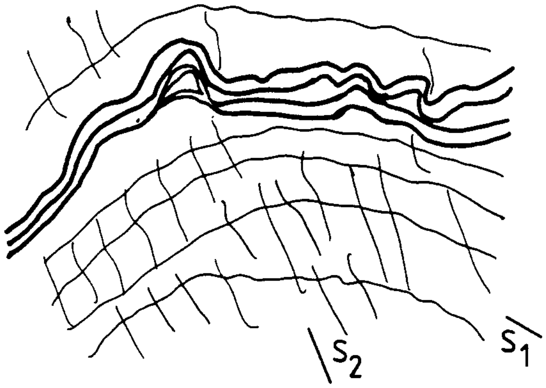
FIGURE 5.6- MODIFICATION OF A PARALLEL FOLD INTO A SIMILAR GEOMETRY BY IMPOSITION OF A HOMOGENEOUS FLATTENING STRAIN. T_0 IS THE MINIMUM REFERENCE THICKNESS MEASURED PARALLEL TO THE AXIAL PLANE. t_0 IS THE MAXIMUM REFERENCE DIRECTION THICKNESS MEASURED NORMAL TO THE DIP ISOGONS. t_{alpha} IS THE THICKNESS MEASURED NORMAL TO THE DIP ISOGON. T_{alpha} IS THE THICKNESS MEASURED PARALLEL TO THE AXIAL PLANE. NOTE THAT AT POINT OF MAX. CURVATURE, $T_0=t_0$.

transition from a parallel fold into a similar geometry by the imposition of a flattening strain.

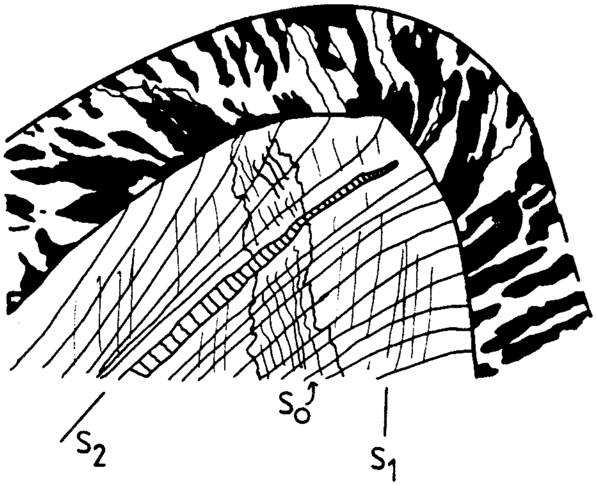
The method involves several critical assumptions. The most important of these is homogeneity of strain so that the observed thickness variations display consistent variations within the modified fold system. Another assumption involves the initial shape of the folded layering. In Ramsay's technique, the initial fold shape must be assumed parallel. This is a consequence of Ramsay's ideas that flattening follows buckling in most natural folds. Hudleston (1973) and Gray and Durney (1979) have modified Ramsay's ideas in light of their observations that buckling and flattening coincide throughout the development of the structure. Gray and Durney (1979) suggest that Ramsay's theoretical t'_{alpha} curves are valid for both models of fold development for limb dips of up to 60 degrees. Hudleston's (1973) values for the flattening strain are slightly higher than Ramsay's values. The present analysis used the values determined by Gray and Durney (1979) which are based on those of Hudleston (1973).

To verify the original parallel nature of the fold, Ramsay (1967) has suggested that all lithologic layers in a fold should display identical t'_{alpha} values for a given alpha angle. That is, all t'_{alpha} values should lie along the same theoretical curve of S1/S2 values. Departure from this ideal behavior indicates non-homogeneous flattening within the fold.

BUCKLED VEIN GEOMETRIES OF THE ALLOCHTHON



526-8



67-9

FIGURE 5.7- BUCKLED FOLDS USED FOR ANALYSIS FROM ALLOCHTHON. OUTCROP 526-8 LIES MIDWAY ALONG THE STEEP BLUFF TO THE WEST OF THE HIGH POND SKI AREA SUMMIT. OUTCROP 67-9 LIES ON SMALL EAST-FACING BLUFF ON WESTERNMOST EDGE OF STUDY AREA IN METTAWEE SLATES ON HANGINGWALL OF KEELER POND THRUST, 1 KM WEST OF HIGH POND.

The flattening strain associated with the crenulation folds was determined using this technique on one centimetric-scale fold from the Allochthon. Two other folds analyzed from within the Allochthon are buckled quartz veins and the shortening associated with their folding has been determined by merely unfolding the curved layering, as suggested by Ramsay (1967) and Gray and Durney (1979). This also provides a simpler, useful check on the t'_{alpha} results.

SIMPLE BUCKLING ANALYSIS RESULTS

The Allochthon crenulation strain determined by comparision of undeformed to deformed length of the buckled veins shows a shortening magnitude ranging from a minimum of 22% for one specimen to a maximum of 35% for the second. Assuming **plane strain and no volume loss** in any direction, these correspond to an extension of 28% and 54% respectively for the two folds. The veins used in the analysis are illustrated in Figure 5.7.

t` alpha STRAIN ANALYSIS RESULTS

The strain ratio (S_1/S_2) determined from the t'_{alpha} technique indicates a strain ratio with a magnitude of 1.8 for the left limb while the right limb shows a strain value of 2.0. Other layers within the fold show nearly identical values for both limbs of 1.6-1.8. Since each fold is composed of multilayers, the analysis technique was applied to each layer on each limb, to verify the accuracy of the technique and to gain a better understanding of strain hetereogeneity within the fold system. Performing the analysis for these individual layers also provides a check on the initial parallelism of the fold as suggested by Ramsay (1967). Some of the apparent hetereogeneity is an artifact of the measuring accuracy and the subjective manner in which the dip isogons were drawn. As much as was possible, subjectivity was minimized by multiple measurements and averaging of the results. To compare the plotted data with the theoretically derived curves of Gray and Durney (1979) the best-fit curve corresponding to the data was approximated. This is the source for the majority of the error in the final flattening strain determination, since many folds show distinct t' values for the different layers within the fold for a given alpha value. It became necessary to determine which lithologic layers were best suited for analysis. Generally, those chosen were those whose layers showed no surface irregularities and whose thickness appeared to change consistently along the limbs as expected for similar fold geometries.

The majority of the observed heterogeneity within the Allochthon fold is probably the result of differing flattening behavior of the folded layering due to varying amounts of quartz in each layer. We should expect to see that silty layers show less ideal homogeneous flattening behavior in contrast to the argillaceous interbeds. In the

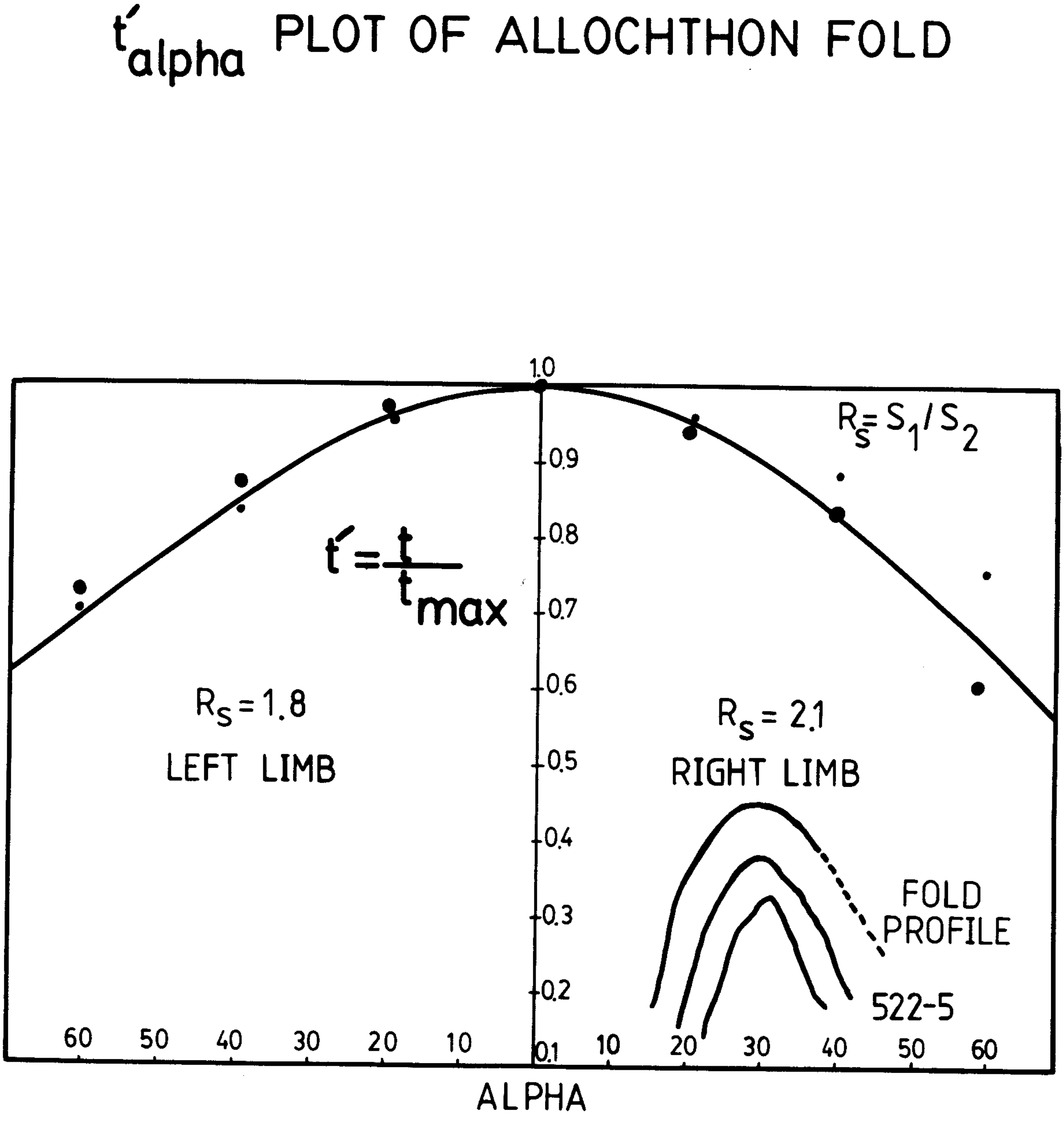


FIGURE 5.8- t`alpha PLOT OF ALLOCHTHON FOLD.
OUTCROP LOCATION IS ON SW END OF 1200' KNOB WHICH LIES TO SOUTH OF MUDD POND BETWEEN GANSON HILL AND BRANDON MT. ROADS. LITHOLOGY TO WHICH THIS SPECIMEN BELONGS IS THE BULL FORMATION.

TABLE 5-2:
CRENULATION STRAIN SHORTENING DATA USING BUCKLED VEINING AND THE t'ALPHA METHOD:

	S1	S3	FOLD #
SIMPLE BUCKLING ANALYSIS ASSUMING PLANE STRAIN W/O ANY VOLUME LOSS	1.28	0.78	526-8
	1.54	0.65	67-9
t'ALPHA, WITHOUT VOLUME LOSS OF 18% SHORTENING ADDED ON AND ASSUMING PLANE STRAIN.	1.17	0.69	right limb
	1.26	0.63	left limb
t`ALPHA, ASSUMING PLANE STRAIN AND -20% VOLUME LOSS WITH THE BUCKLING COMPONENT ADDED ON TO THE TOTAL SHORTENING STRAIN.	1.96	0.51	right limb
	1.80	0.55	left limb
SAME CONDITIONS AS ABOVE FOR PARAUTOCHTHON FOLD (920-6)	1.75	0.57	right limb
	2.33	0.43	left limb

** NOTE HOW VALUES FOR t'ALPHA AND THE SIMPLE BUCKLING ANALYSIS ARE SIMILAR UNTIL ADDITIONAL BUCKLING SHORTENING IS ADDED TO VALUES FOR t'ALPHA.

FROM THE FINAL DATA, AND ASSUMING PLANE STRAIN, WE CAN CALCULATE (USING FOLD 526-8) THAT A 54% VOLUME LOSS IS NECESSARY FOR THE BUCKLING STRAIN VALUES TO APPROACH THOSE OF THE T'ALPHA RESULTS VIA:

S1/S3 = 1.64, since S1 = 1.28 and S3 = 0.78. SO,

S1=1.64*S3. Assuming that S3 =.53 and S1 = 1.88, we can work backwards using the relationship S1 * S2 * S3 = V to determine the initial volume loss (1-V) required. By assuming plane strain, S2=1.

So, $(S3)^2 = .2809 = \mathbf{.46}/1.64$ since S3*(1.64*S3)=V using the relationship above that S1*S3=V.

<u>This implies that our required volume loss is -54%.</u>

(A lesser value of -44% volume loss would be required for fold # 67-9 to approach the strain values determined by the t'alpha approach.)

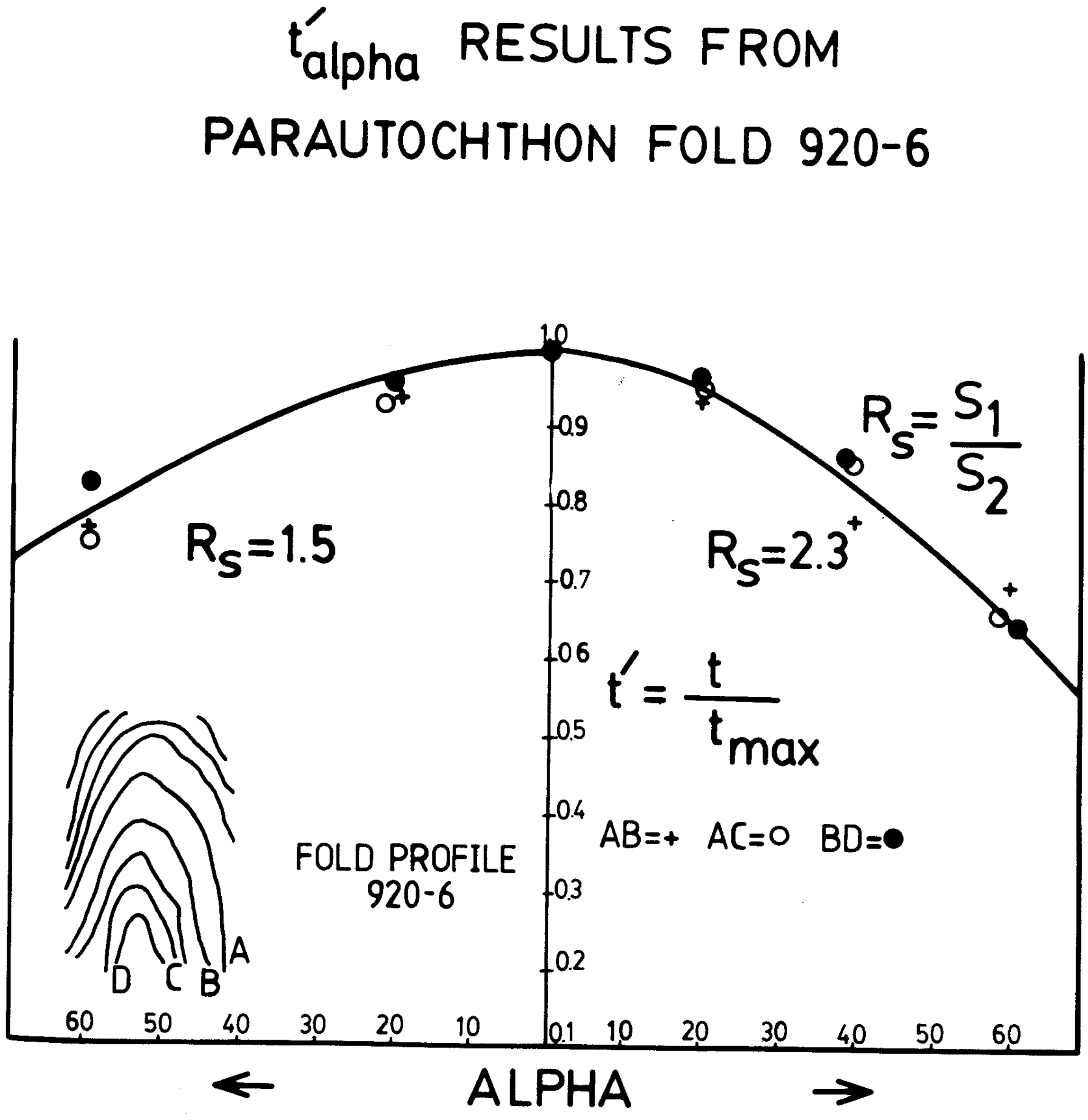


FIGURE 5.9- t' ALPHA PLOT OF PARAUTOCHTHON FOLD
(OUTCROP 920-6)

Parautochthon folds to be discussed shortly, the hetereogeneity could be caused by contrasting amounts of dolomitic and calcite in the various layers. This would affect the fold rheology similar to that produced by varying amounts of silica. As most of the folds analyzed have been affected by diffusional mass transfer, as evidenced by the crenulation cleavage in the slate and by the stylolitic layering in the carbonates, it is also possible that some departure from ideal flattening behavior of an initially parallel fold has occurred due to volume loss and transfer of this material during the deformation. The data does strongly suggest, as a result of these observations, that early fold relationships were not of a wholly parallel geometry. Lithologic dependence on t'_{alpha} behavior similar to that discovered in the present study has been very briefly discussed by Ramsay and Huber (1987).

Reassessing the values of the crenulation strain, if we assume plane strain and a volume loss of 20%, we can calculate the magnitude of the stretches and the amount of shortening. Such a value was chosed for two reasons. The first is the theoretical results of Ramsay and Wood (1973) and the results of Boulter (1986). Both of these papers indicate a volume loss of approximately 20% during deformation. Secondly, this value allows the results of the buckling analysis and the t'_{alpha} approach to be contrasted. This will allow us to more easily compare the strain results determined by buckling analyses with those determined by the t'_{alpha} approach.

To calculate the shortening from the ratio of the maximum and minimum stretches (S_1/S_2), we can use the relationship: S1 x S2 x S3 =1 for the volume of a cube of original dimensions 1:1:1. Assuming plane strain and 20% volume loss (probably a maximum value as suggested by Ramsay and Wood, 1973), our equation changes to:

S1 x S2 x S3 = 0.8. (since S2=1 assuming plane strain)

we have, **S1 x S3 = 0.8.**

From the strain ratio determined by the t'alpha approach, we can determine the magnitude of the principal stretches by simple substitution.

The flattened fold from the Allochthon, with a S_1/S_2 ratio of 1.8 (left limb) and 2.1 (right limb), demonstrates an extension of 17% (S_1=1.17, left limb) and a shortening of 31% (S_3=0.69) for this limb. The right limb shows an extension of 26% (S_1=1.26) and a shortening of 27% (S_3=.63).

These values are remarkably similar to the values obtained by simple buckling analysis. However, it must be emphasized that the t'_{alpha} results do not include the shortening due to buckling. **The t'_{alpha} technique only reflects the flattening imposed on an initially parallel fold geometry.** The apparent agreement of the t'_{alpha} results using 20% volume loss, with the buckling analysis is misleading since the total shortening must include the shortening determined by unrolling the folded layering and also the flattening strain imposed on the layering. To determine the total magnitude of the shortening strain, it it necessary to remove the flattening strain effect for any given limb dip; a procedure which will cause the limb dip to lessen. By performing this for a number of limb dips, it becomes possible to reconstruct the pre-flattening configuration of the fold. Unrolling this folded layering for the t'_{alpha} fold from the Allochthon shows an additional shortening of 36%. Each limb of this fold then, has been shortened 18% in addition to the t'_{alpha} flattening strain.

CRENULATION STRAIN IN THE PARAUTOCHTHON

The t'_{alpha} technique was applied to one thin-section scale crenulation fold from within the Parautochthon. This fold, unlike those of the Allochthon, does not display a pronounced axial planar crenulation cleavage. Instead, it shows a weak grain shape foliation in which the constituent grains are equant and entirely recrystallized. This fold was collected from one of the few localities where the crenulation cleavage is developed in the Parautochthon. Interestingly, it is located near a small bluff usually indicative of a thrust zone in the allochthonous rocks to the south. No such thrust zone could be clearly identified.

The layering in the microfolds is defined by very thin black laminae of insoluble residues within a white, fine-grained calcite and dolomitic matrix. The insoluble material appears stylolitic and the axial surfaces of microfolds, distinguishable within the stylolites, lies grossly parallel to the grain shape foliation within the larger scale structure.

These folds are less suitable for the t'_{alpha} approach since they lack significant rheologic contrast and probably did not develop as initial buckle or parallel folds. The analyses reflect much less heterogeneity between microfold layering but do indicate significant differences between strain magnitudes of the limbs. The buckling component determined by removing the flattening strain and unrolling the determined geometry, shows a 33% shortening by buckling. This has been applied uniformly on both limbs (i.e. 16.5% per limb).

Unfortunately, we have no buckled veining with which to contrast the magnitude of these strain values. The data show a fairly consistent amount of flattening, shortening and related extension for the various multilayers and the lesser strained limb shows great similarity to the strain values determined by the t'_{alpha} approach for the Allochthon folds. This suggests that the strain for the crenulation deformation in the Parautochthon and Allochthon are similar although it is much less well-developed in the Parautochthon.

CONCLUSIONS OF STRAIN ANALYSIS

The strain values determined by buckling analyses and the t'_{alpha} method show comparable results but require recalculation, using different amounts of volume loss during deformation, for the results to be similar. Interestingly, since the simple buckling analysis does not include any magnitude of volume loss, the results obtained in this manner are fairly close to those determined by the t'alpha approach if the volume loss in the former is assumed to be approximately 44-54%. By assuming a value of 54% volume loss during buckling, and a 20% volume loss for the t'alpha analyses, the determined strain values are very similar. These calculations are shown in the Table 5-2. Significant variation exists within this data to suggest the need for more rigorous statistical support, however the basic ideas discussed previously can be seen from this chart. The combined methods allow some idea of the volume losses that must have occurred during deformation to be approximated and roughly quantified. It must be emphasized, however, that these results have been quantified by making assumptions about the deformation regime (e.g. plane strain and variable volume losses) and that non-plane strain is to be expected in the study area due to the non-parallelism of slickenside lineations with the normal (horizontal line) to the fault plane strike. See Wojtal, 1986 (p. 354) and McClay and Insley (1986) for a discussion of non-plane strain deformation in thrust systems and its significance.

Further analysis of small crenulation folds should be performed using both the t'alpha and buckling analyses to verify these results and add greater statistical substance to the argument. This support for the t'_{alpha} technique should permit other workers to apply the approach to other regions of the Allochthon. This work could prove extremely fruitful as a means of assessing the strain variation associated with the various cleavages within the deformation sequence of the Allochthon. This information could permit the discrimination of distinct thrust sheets if an individual imbricate would display a consistent strain magnitude which distinguished it from other slices. Perhaps more importantly, further work along these lines could allow the variation in strain within the various subregions to be more accurately quantified for the purpose of calculating total shortening within the study area and across the Allochthon.

MICROSTRUCTURAL CHARACTERISTICS OF THE DEFORMATION SEQUENCE: CLEAVAGES AND FAULT ZONES

This section of the thesis is subdivided into microstructural elements of the Allochthon and those features of the Parautochthon. Emphasis is on the Allochthon since the microstructure is much better developed and pre-existing fabric elements are well-preserved. Each section discusses the general microstructural characteristics of the study area subregion and concludes with several representative examples of the various microstructural elements. The classification scheme used and descriptive terminology are those found in Borradaile et al. (1982) and Gray (1977). These morphologies are shown in Figure 5.10.

MICROSTRUCTURE OF THE ALLOCHTHON

The microstructure of the Allochthon is extremely complex as a result of the widespread development of transecting cleavage relationships from the various generations of structures. This section discusses the characteristics of the cleavages found within the deformation sequence determined for the Allochthon. The final section discusses the microstructure of fault rocks collected from the study area.

GANSON HILL AXIAL PLANAR FOLIATION/CLEAVAGE

The earliest tectonic microstructure in the study area is the differentiated layering and slaty cleavage associated with the Ganson Hill Syncline. In thin section, the early foliation is a well developed differentiated layering in which quartzoze and micaceous domains are strongly segregated. The section has been crenulated into a zonal crenulation morphology although locally this cleavage is more discrete and shows new mica growth along the cleavage domains. These features can be seen in Figure 5.11 and 5.12.

REGIONAL SLATY CLEAVAGE (S3)

The regional slaty cleavage (S_3) displays a variable morphology depending on the lithology. In the more arenaceous rocks, this cleavage manifests itself as a rough cleavage which forms anastamosing domains enclosing uncleaved material. In the cleavage domains, the cleavage is defined by thin layers of fine-grained opaque material and very fine-grained micaceous material. Often, this rough cleavage appears strongly lenticular as a result of the anastamosing network of cleavage domains. Large grains of quartz frequently show mica beards or overgrowths (c.f. Means, 1975) and several show quartz overgrowths as well.

The more pelitic rocks show a well-developed slaty cleavage that is generally parallel to lithologic layering as a result of axial planar development in isoclinal folds. This relationship is made more complex by the greater intensity of the crenulation development found within these rocks. The nature of the slaty cleavage is often difficult to perceive as the later crenulation cleavages have extensively modified the earlier fabrics. In most sections, the slaty cleavage resembles a differentiated layering as insoluble residues and mica are differentiated from those horizons with quartz present. This produces a marked layering in the thin section that is suggestive of bedding. In most samples, it is impossible to determine with certainty if these differentiated layers lie parallel to bedding. However, in nearby quartzite outcrops, bedding possesses an orientation similar to the dip of this foliation and does not display any evidence of folding.

CRENULATION CLEAVAGE IN THE STUDY AREA (S4 and S5)

Gray (1977a, 1977b, 1979) discussed the microstructure of crenulation cleavage and suggested a means of classifying the various morphologies of crenulation cleavage. Gray's work clearly demonstrated the importance of pressure solution mechanics in the formation of crenulation cleavages.

The crenulation cleavage (S_5) is the most interesting microstructural feature of the study area. It shows every possible configuration ranging from a discrete cleavage to a discrete zonal cleavage to a zonal cleavage. In many sections, three crenulation cleavages can be distinguished in addition to the slaty cleavage and lithologic layering. In these sections, two zonal crenulation cleavages are generally transected by a discrete crenulation cleavage.

In several sections, the transition between a zonal and discrete cleavage can be demonstrated. The discrete cleavage can always be shown to transect the zonal cleavage, suggesting a formation of the former from the latter. The zonal cleavage shows strong microkinking of micas of the slaty cleavage on a spacing equivalent to the later discrete cleavage's spacing. The discrete cleavage preferentially follows these zones of intense microkinking. At the termina of the incipient discrete crenulation laminae, the discrete cleavage branches out into a number of very thin laminae before dying out. Following these zones into the regions where the discrete cleavage is undeveloped, it can be clearly demonstrated that the discrete cleavage is concentrated in zones where the microkinking of the slaty cleavage is most intensely developed. This relationship does not appear to be dependent on lithology. In addition, some sections show that the discrete zonal crenulation does not appear to follow any specific pathway, favoring neither hinge zones or limbs of small microfolds. Conventional behavior that has been observed by other authors (e.g. Gray, 1977, 1979; and those in Borradaile et al. 1982) suggests that limbs are preferentially dissolved. This behavior has been observed in some sections although an equal number show no preferred route of discrete cleavage development.

Several sections show kink band crenulation cleavages defined by alignment of kinkbands of the slaty cleavage to produce a distinctive crenulation cleavage. These produce a crenulation cleavage which resembles a zonal crenulation but which is bounded by discrete surfaces which delineate the kinkband boundary. The kinkbands show a complex orientation as the stage is rotated and the cleavages are difficult to relate to observed mesoscopic relationships.

In the majority of the cases, however, the origin of the crenulation cleavage occurs dominantly by pressure solution. Lithologic laminae and quartz veining are buckled and then dissolved along the traces of the crenulation cleavage. This is particularly true for the discrete crenulation cleavage. The termina of the lithologic banding and veining along the cleavage laminae are zones of concentrated insoluble residues and under high magnification show stylolitic surfaces along which dissolution has occurred. Perhaps more conclusively, buckled quartz veins have had material removed from the limbs of the folds resulting in significant shortening of the buckled vein by dissolution. In several sections, small micas can be seen growing parallel to the new cleavage trace.

The zonal crenulation cleavages also show thinning of lithologic layering and quartz veining where they transect it, but the magnitude of the dissolution is much less. There appears to be a transition from zonal crenulation morphology to discrete crenulation cleavage as the magnitude of the crenulation strain increases. This observation is based on observed offsets and thinning of buckled quartz veins and lithologic layering.

The following sections illustrate representative microstructural features of slaty cleavage and crenulation cleavage as observed in the study area.

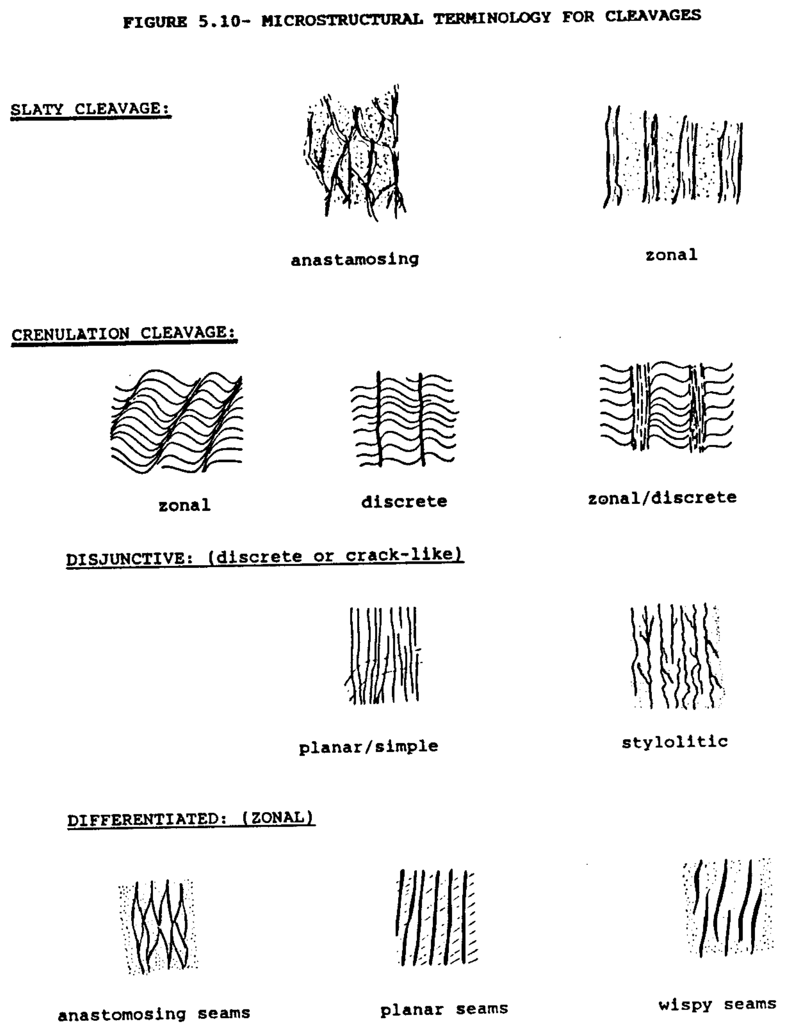


FIGURE 5.10- DIAGRAM SHOWING TERMINOLOGY USED IN MICROSTRUCTURAL ANALYSIS. MODIFIED AFTER BORRADAILE ET AL., 1982.

Figure 5.11
Differentiated layering and “early” slaty cleavage from the core of the Ganson Hill syncline. Early cleavage has been crenulated into a zonal morphology and locally a discrete cleavage with new mica growth is present.
Lithology is the Bomoseen member (?)/Bull Formation. Outcrop locality 430-7A.

Figure 5.12
Differentiated layering/S_2 cleavage, showing cleavage lamellae defined by both discrete, rusty colored laminae and also by differentiated layers of quartzose and chloritic material. Note apparent absence of any earlier fabric. A spaced crenulation is suggested by the fabric element trending from upper right to lower left.

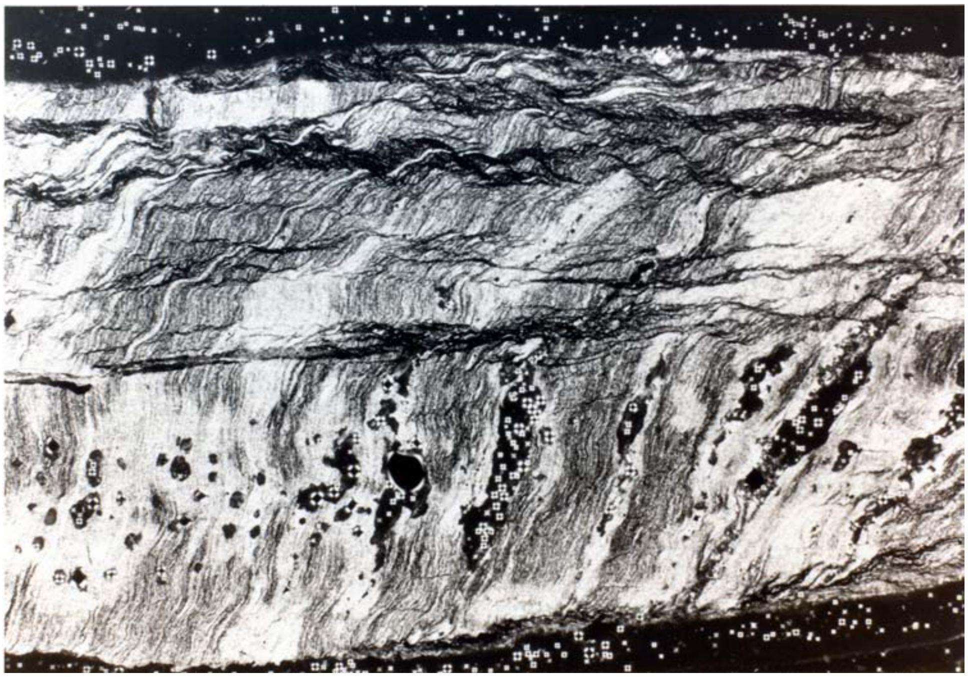


Figure 5.13
This section shows a strongly crenulated, slaty cleavage fabric. The crenulation varies from a zonal type in the lower area of the photo into an anastomosing discrete fabric towards the top. The top area shows a weaker zonal (locally discrete) crenulation (oriented top left to lower right) of the horizontal crenulation. Most interesting in this section are the sigmoidal calcareous layers (plucked out at the bottom of the section) suggesting dextral shear along the cleavage. This can also be seen in the lighter-colored zones in the center left area. The center left area indicates that the apparent shear is the result of dissolution along discrete cleavage following an initial buckling which produced gentle folding of the calcareous layering.
Outcrop lies 1.5 km WNW of High Pond Field Station in Bull formation.
(Outcrop 1021-3)

Figure 5.14
This section shows a strongly differentiated layering to which the slaty cleavage lies coplanar in the section. It is transected by a discrete crenulation cleavage, more zonal in the more pelitic layers, which is beautifully refracted as it enters the distinct layers. Outcrop is located on steep SE-trending bluff at NE end of study area, close to basal thrust of the Allochthon and 500 meters NNE of abandoned slate quarry. Outcrop is located 0.5 km N of large pasture/hay field which lies to NE of the Burden Estate main house. Lithology is the Browns Pond Formation.
(Outcrop 616-2)

Figure 5.15
This section shows a slaty cleavage lying parallel to a differentiated layering. This foliation is transected by a variably oriented discrete crenulation cleavage. Extensive refraction causes this variability. A subhorizontal crenulation cleavage fabric seems present but is extensively modified by the dominant discrete foliation. Note the stylolitic veins lying parallel to the lithologic layering in the photo center. Outcrop is located [*omitted*]
(Outcrop 66-3)

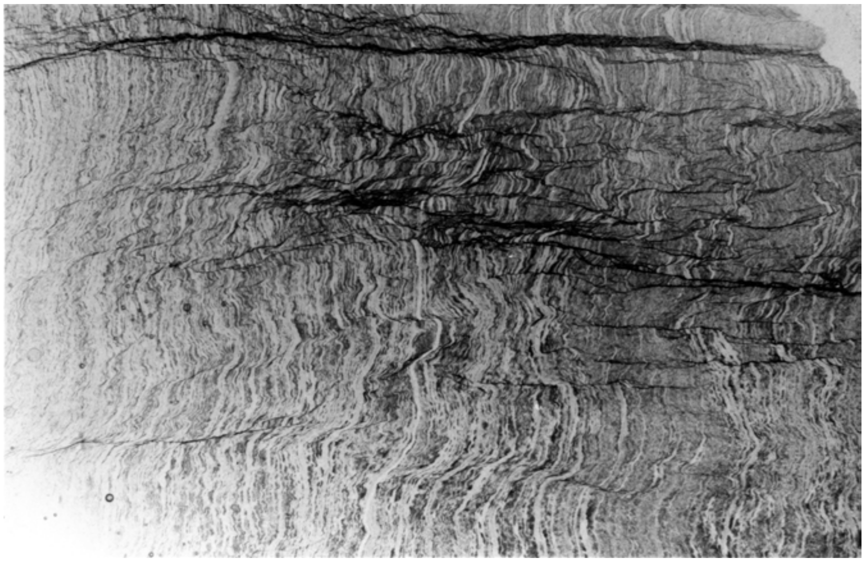


Figure 5.16
This section shows the differentiated appearance of the lithologic layering. Most important in this section, is the transition from a zonal crenulation cleavage to a discrete crenulation by dissolution along very small micro-kinks of the early layering. These can be seen by following a discrete crenulation plane out into the zonal fabric where an incipient discrete cleavage development can be seen. See Figure 5.15 for location of outcrop [*but there omitted*]
(Outcrop 66-3)

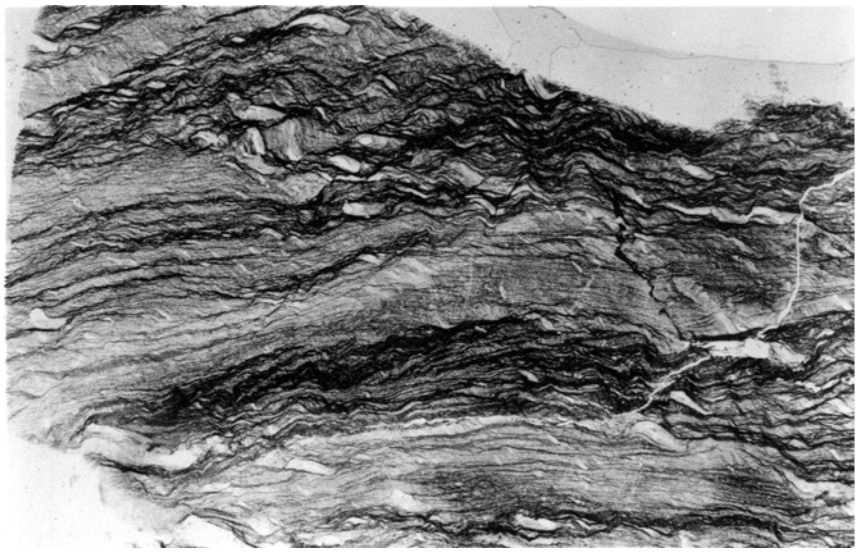


Figure 5.17
An early slaty cleavage, steeply dipping from upper left to lower right, can be seen in this section. This is transected by the dominant horizontal discrete crenulation fabric in the lower half of the photo. In the upper region, this is crenulated by a discrete fabric oriented from left center to upper right. Outcrop is located due east approximately 500 meters from small house with lake to south lying along Ganson Hill Road. Lithology is the Browns Pond Formation.
(Outcrop 528-3)

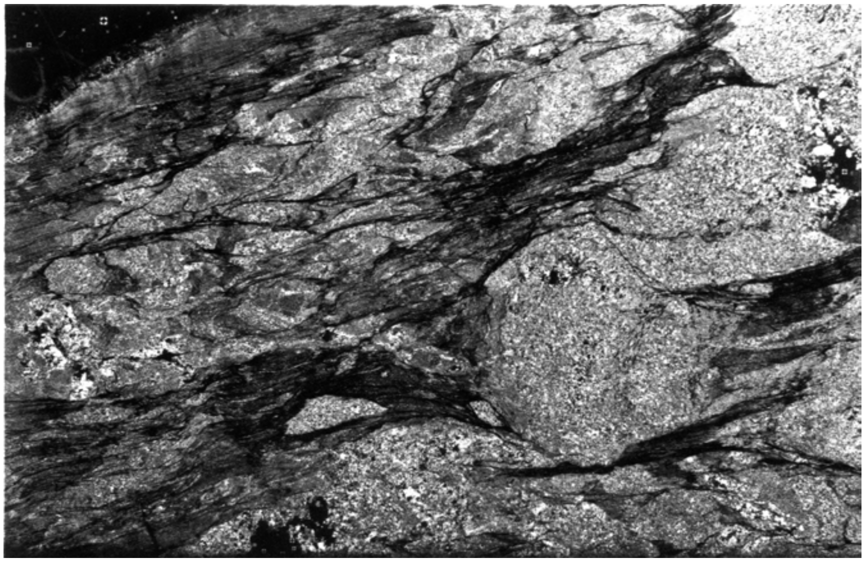


Figure 5.18
This section shows an interbedded arenite-slate with a slaty cleavage present in the slate and a discontinuous disjunctive cleavage in the arenite. The strong crenulation cleavage seen nearby is not well-developed in this lithology. The folded arenite layer has the cleavage axial planar. Outcrop is located at NE corner of High Pond just on the footwall of the thrust sheet. Lithology is the Browns Pond Formation.
(Outcrop 531-9)

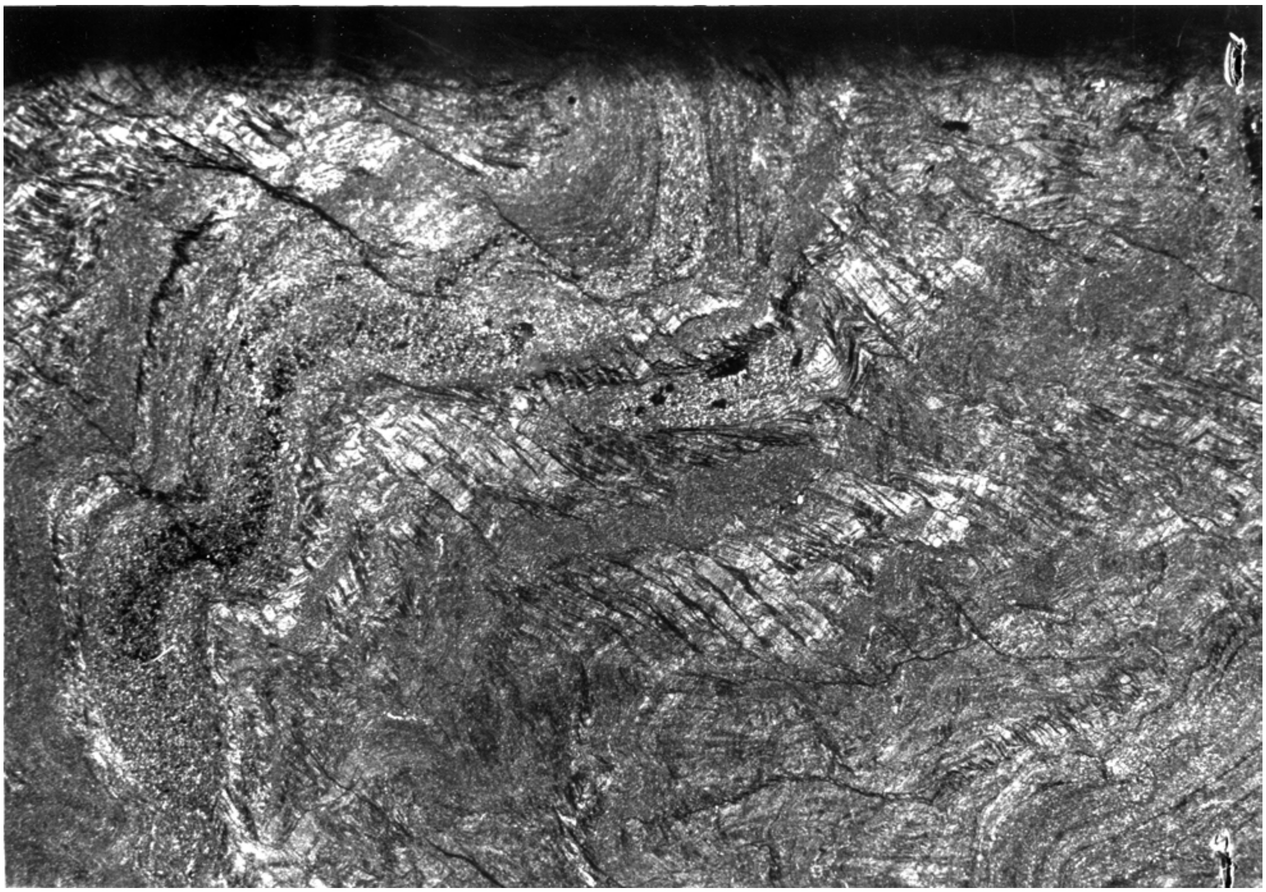


Figure 5.19
A differentiated layering and slaty cleavage fabric which has been folded around a variably developed discrete crenulation fabric which shows a strong refraction between layers. The siltstone (?), more quartzose layering shows a virtual absence of the crenulation fabric.
For location of outcrop, see Figure 5.16 [*which references 5.15, but there omitted*].
(Outcrop 66-3)

Figure 5.20
This section shows a buckled fibrous quartz vein showing a shortening of 35%. This section also shows some late axial planar dilation as evidenced by fibrous veining. This extension has been removed from shortening measurements. The slaty cleavage and bedding can be seen in this photo and are transected by a discrete crenulation which shows some new mica growth parallel to it. Interestingly, the fibrous veining shows a distinct asymmetry supported by the fact that folding has not occurred in the bedding. This suggests that the cleavage did not lie parallel to bedding during the deformation. Outcrop location described in Figure 5.7.
(Outcrop 67-9)

<u>Deformation sequence in this section:</u>
1) formation of slaty cleavage
2) formation of vein perpendicular to cleavage
3) buckling of vein and development of crenulation cleavage
4) axial planar dilation and formation of extensional veining parallel to the axial plane

Figure 5.21
This section shows a siltstone layer with euhedral pyrite folded around the discrete crenulation cleavage. The slaty cleavage lies parallel to the short dimension of the photo. The euhedral pyrite shows curved pressure shadow fibers suggesting complex deformation resulting from the multiple deformation history. Outcrop location described in Figure 5.8.
(Outcrop 522-5)

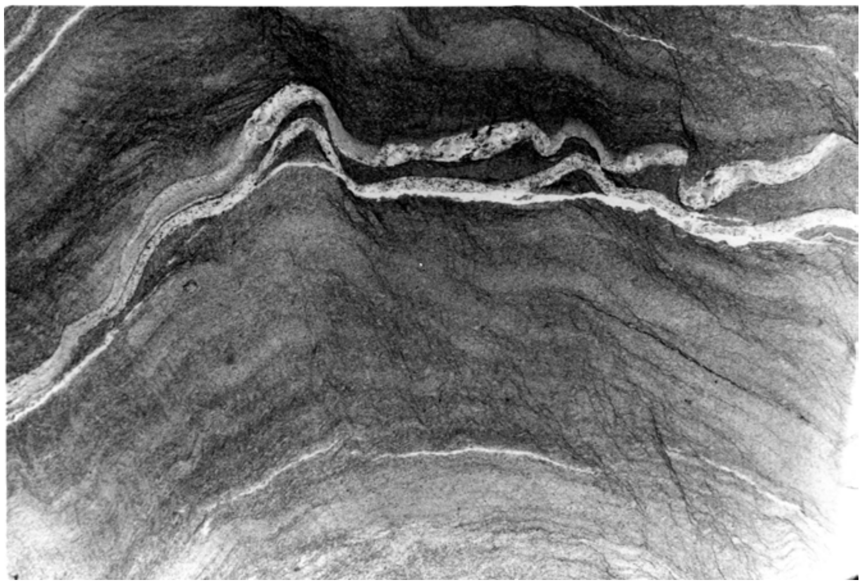


Figure 5.22
Buckled vein indicating 22% shortening. Measurement avoided those regions where pressure solution has obviously thinned the layering. Slaty cleavage lies parallel to the lithologic layering. The crenulation is of a discrete morphology and lies approximately axial planar to the folds in the quartz vein. Outcrop location is described in Figure 5.7. (Outcrop 526-8)

MICROSTRUCTURE OF ALLOCHTHON FAULT ZONE ROCKS

Specimens collected from the abundant fault zones exposed within the Allochthon study area display a fascinating diveristy of microstructure. Many of the features seen in these rocks are similar to those described from authors working in ductile shear zones. In addition, several specimens allow the shear sense to be determined by the relationships between inclusion trails in quartz veins and more commonly, by angular modifications as the crenulation cleavages are passively rotated into parallelism with the shear plane. By careful sampling, it would be possible to determine the local magnitude of shear strain in a thin section by observing the modification of the angular relationships.

The fault zone rocks are dominantly composed of fibrous quartz with lesser amounts of chloritic material and occasional lithic fragments of the surrounding strata. All sections were cut parallel to the movement direction as defined by mineral lineations on the fault surfaces, and normal to the shear plane.

Most sections show fibrous quartz growth parallel to the long dimension of the section or in the direction of thrust transport. Interestingly, these sections also illustrate fibrous growth normal to the fault plane between the domains of transport parallel growth. So, in any one section, we have two directions of fibrous growth, the one parallel to transport as sheetlike veining coplanar with the thrust plane, and the second growing normal to the thrust plane. These observations support the stress orientations suggested in Chapter 4. Commonly, these fibrous veins have been further deformed and the fibers no longer lie normal to the shear surfaces. This is potentially a shear sense indicator and could allow determination of local shear strain on a thin-section scale.

The chloritic material is extremely fine-grained and tends to form isolated lozenges within the quartz matrix. Often, the chlorite is found as thin laminae showing a strong lineation in hand sample which is intensely crenulated in thin section. In "lees" where the flowing fault material experiences less shearing, analogous to pressure shadows around rigid objects, the crenulation cleavage often lies at an angle around fifty degrees from the shear surfaces (Similar "lees" have been briefly described recently by Wojtal and Mitra, 1986, p. 682-3). Moving out of the pressure shadow or "lee" area, this crenulation fabric is rotated into parallelism with the shear plane. Excellent examples of this relationship can be seen by tracing along the quartz veining with the microscope and finding those zones where the vorticity is reduced due to sheltering effects of protruding quartz blebs or concave surfaces within the more rigid quartz veining.

These cleavage rotations allow the shear sense to be determined for any fault zone specimen. In zones where the nature of displacement is ambiguous, this is a powerful tool to determine the kinematic history of the fault zone.

In one specimen, inclusion trails indicating crack-seal behavior (Ramsay, 1980, Ramsay and Huber, 1985) can be found which have been rotated from their shear plane normal orientation into an orientation oblique to the shear plane. This example also could allow the reconstruction of micro-scale shear strain deformation in these fault zones.

Another sample shows a rootless fold within the chloritic fault zone material. This is a sheath fold structure similar to those investigated by Cobbold and Quinquis (1980) in ductile shear zones. Berthe' and Brun have investigated similar relationships within the South Armorican Shear Zone in Brittany. The presence of this sheath fold in chloritic fault zone material suggests that ductile deformation within these thrust zones is taking place in these zones after significant brittle fracturing and widening of the fault zone, as suggested by Wojtal and Mitra (1986).

Further research into these zones would be fruitful. Considerable insight into meso-and-microstructural processes of fault zones would be gained through such an analysis.

Examples of these structures can be seen in the following photos:

Figure 5.23
This section shows a rootless sheath fold developed within the chloritic material found with quartz veining in thrust zones. These chloritic surfaces are shear surfaces as are the slickensided quartz veining. This section shows only weakly developed fibrous veining in the upper right corner, while the majority of the quartz is highly granulated.
Outcrop location is 500 meters SW of house and barn built on hill to SW of Mudd Pond. Outcrop forms a west-facing bluff just to south of gravel driveway. Thust zone is that of the Two Bears Thrust. Lithology is the Browns Pond Formation.
(Outcrop 522-10)

*** <u>ALL fault rock thin sections have been cut parallel to the quartz slickenside and chlorite lineation, normal to shear foliation</u>.

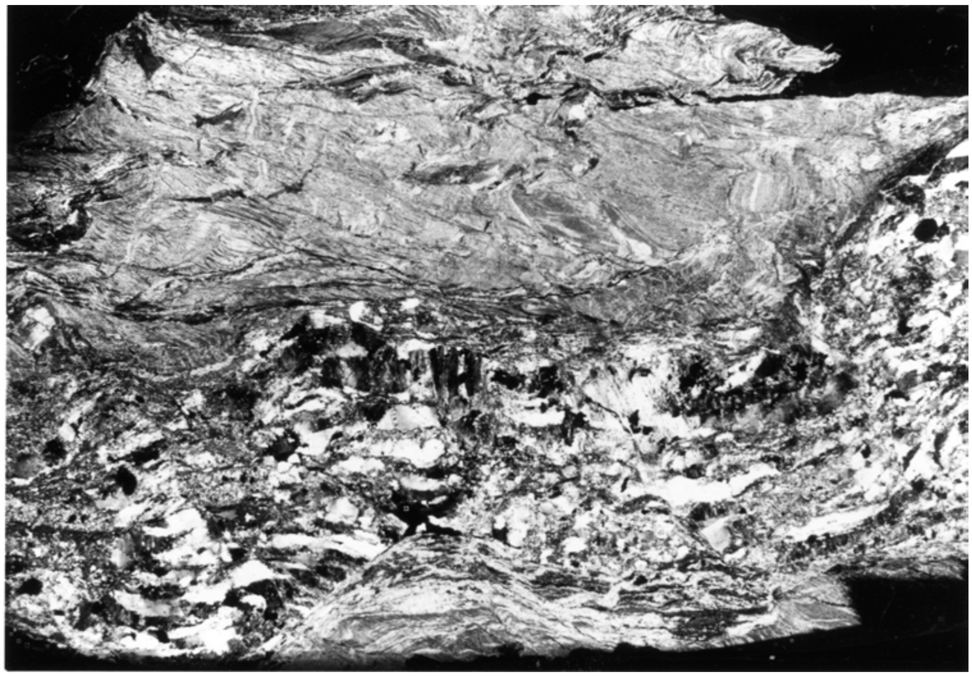


Figure 5.24
This section shows fibrous veining lying subparallel to the shear plane. In the concave areas along the quartz veining, the crenulation cleavage can be traced out into the more highly sheared material and the rotation of this crenulation can be used to determine the shear sense in fault zones. As shown, the shear sense is sinistral. Shear plane is horizontal in the photo. Outcrop location is 1.5 km north of High Pond and forms a NW-SE trending ravine and a break in a NE-trending bluff. Lithology is Bull Formation. (Outcrop 925-11)

Figure 5.25
This section shows a complex geometry of shear surfaces and quartz veining. The section shows a geometry similar to that classically described from within ductile shear zones. The dominant shear surfaces ("C" equivalents) are horizontal in the photo and the oblique foliation ("S" equivalents) trend from upper left to lower right. In this orientation, the shear sense is sinistral. Some brittle behavior is evident from the microcracking of quartz grains which also show extinction patterns and recrystallization morphologies indicative of more ductile conditions of deformation.
Outcrop location lies just west of Willow Brook approximately 2 km north of High Pond. Outcrop forms a NW-SE trending bluff which transects the NNE-trending bluff along Willow Brook. Lithology is Bull Formation.
(Outcrop 925-4)

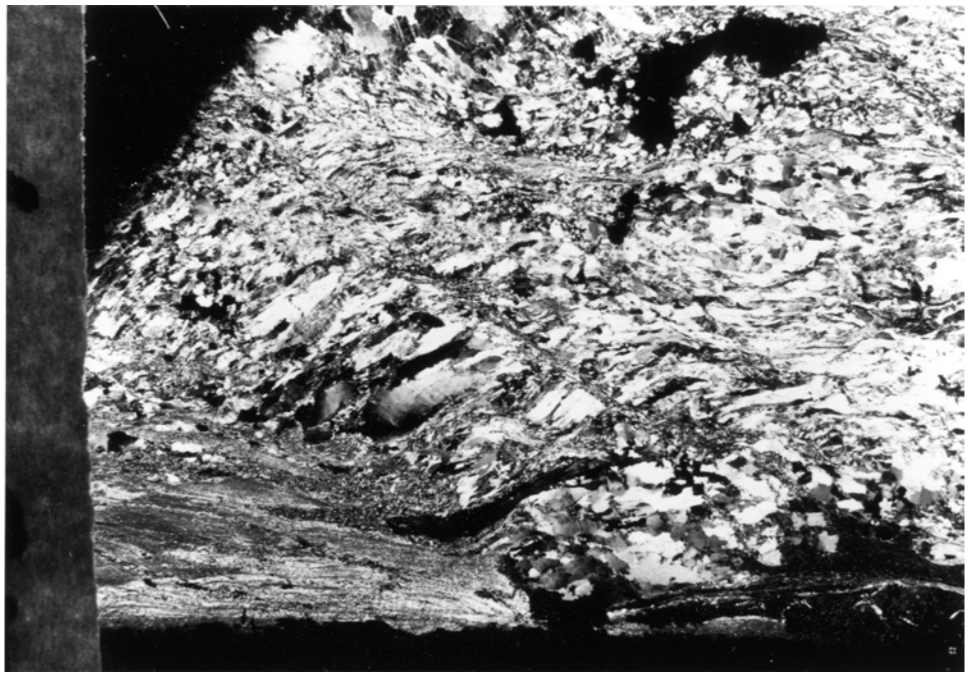


Figure 5.26
This section is enlarged from the lower right corner of the previous photograph. In this closeup of the shear surfaces, fibrous quartz veins can be seen growing normal to the "C" shear surfaces. Again the shear sense is sinistral and the dominant shear planes ("C") run from upper left to lower right. The "S" planes display a sigmoidal geometry from top right to lower left.
Same outcrop as previous figure.
(Outcrop 925-4)

MICROSTRUCTURE OF THE PARAUTOCHTHON

The microstructure in the exposed Parautochthon of the study area is poorly developed. Only the "slaty cleavage" is widely developed and the crenulation cleavage is found at only three places.

"SLATY CLEAVAGE" FABRIC IN THE PARAUTOCHTHON

In thin section, this fabric is highly diverse. The dominant morphology appears to be a grain shape foliation lying between micaceous seams which are usually stylolitic. This stylolite development is most prominent in closures of small meso-folds. The calcite grains are generally highly twinned and quartz shows a strong undulose extinction. In most sections, the majority of grains are twinned while the remainder are untwinned and show no apparent intracrystalline deformation. These grains are generally slightly elongate and lie parallel to the cleavage defined by mica seams. Twinning and dissolution processes appear to dominate deformation mechanisms within the Parautochthon. Overall, the microstructure of the Parautochthon study area is fairly monotonous and does not significantly contribute to our understanding of structural relationships in the region. An example of deformation in the Parautochthon can be seen in Figure 5.27.

Figure 5.27
This thin section shows the interbedded calcite and mica-opaque layering folded into a similar geometry and showing a weak grain shape foliation lying axial planar. Note the stylolitic nature of the mica-opaque layers. Outcrop lies 1.5 km due east of the hunters' cabin built along the dirt road leading south from Cemetery Road and Parsons School at north end of study area. Lithology is the Beldens (?) member.
(Outcrop 920-6).

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