Structural Analysis
of an Area near
Middlebury, Vermont

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

College of Arts and Sciences
Department of Geological Sciences

Paul A. Washington
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Abstract

Detailed mapping of an area near Middlebury, Vermont, reveals a multiple deformational scheme quite different from that previously proposed. The published stratigraphy of the middle Ordovician limestones, on which earlier structural theories are based, was found to be inaccurate, so a new system has been defined. An unreported early generation of cleavage has been discovered which indicates the existence of a decollement zone in the upper Bascom formation. The second generation of cleavage and its associated folding were well defined by earlier workers, but this study shows that it is also a thin-skinned event.

The last deformation, as exhibited by crenulation cleavage development, was restricted to narrow zones. These zones are shown to be related to thrusting. The thrusts are probably rooted in the decollement in the upper Bascom formation. Thus the deformation is found to be totally thin-skinned, which is contrary to the prior theory of the Middlebury synclinorium.

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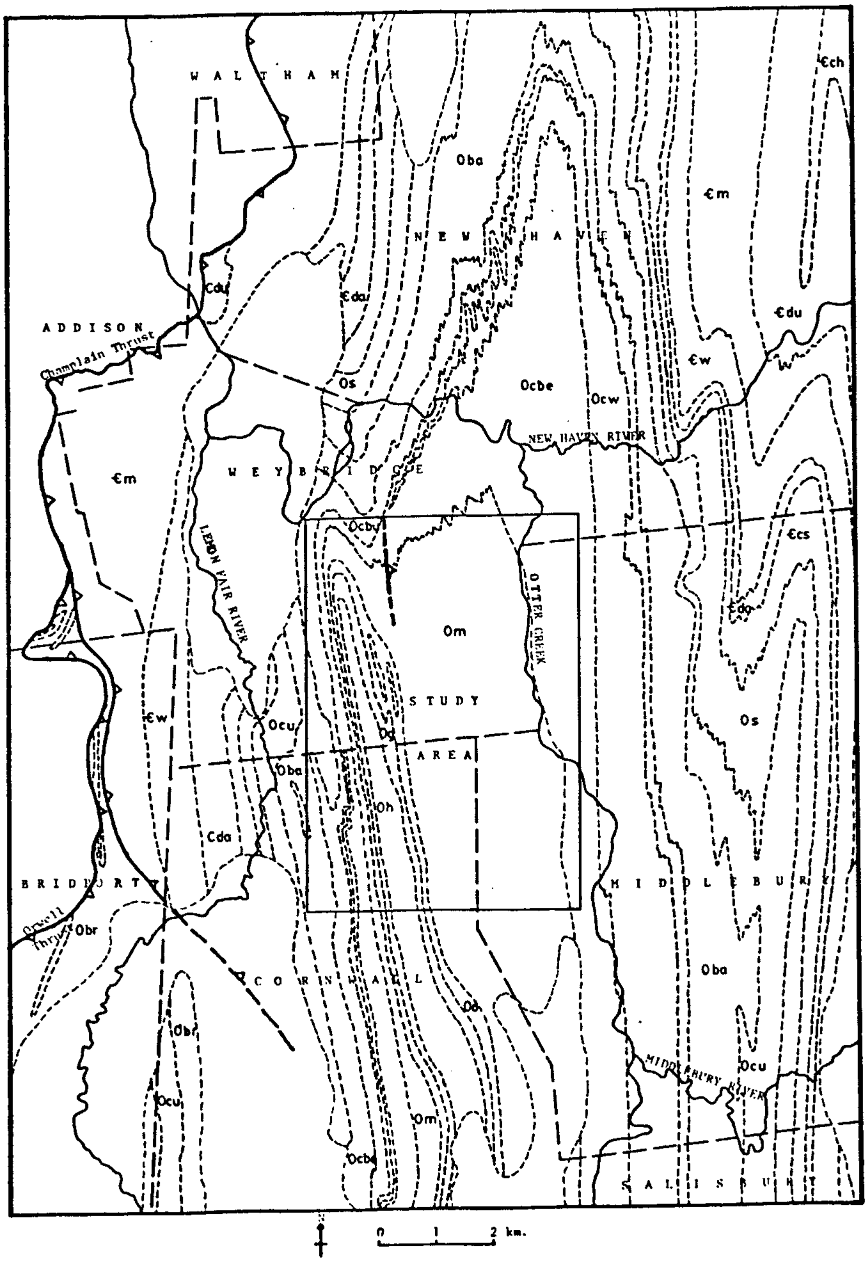
Introduction

The Middlebury synclinorium has long been considered a major structural feature of the northern Appalachians. It represents the western edge of the Taconian orogen and the rocks have undergone folding and faulting accompanied by low-grade regional metamorphism. The rocks are a Cambro-Ordovician quartzite and carbonate sequence capped by late middle Ordovician slate.

The synclinorium is bounded on the west by the Champlain and Orwell thrusts and on the east by the Green Mountain anticlinorium. The general structure, first defined by Wing (Dana, 1877a, b), is that of a large syncline overturned to the west and plunging gently southward. The north end of the slate belt, which marks the core of the synclinorium (figure 1), is in Weybridge, Vermont.

Although the theory of the synclinorium has existed for over 100 years (Dana, 1877a, b), there has never been any serious attempt to test its validity. All subsequent work has concentrated either on refining the mapping of the stratigraphic units previously defined or defining the exact structure in a small area. The purpose of this study, therefore, is to provide a test of the theory by means of structural analysis of an area critical to its validity.

The area selected for this study is an area of rela-



Oh-Hortonville Slate
Og-Glens Falls Limestone
Oo-Orwell Limestone
Om-Middlebury Limestone
  Chipman Formation
  Ocbe-Beldens Member
  Ocw-Weybridge Member
  Ocbu-Burchards Member
  Obr-Bridport Member

Oba-Bascom Formation
Ocu-Cutting Formation
Os-Shelburne Marble
Ccs-Clarendon Springs Dolomite
Cd-Danby Quartzite
Cw-Winooski Dolomite
Cm-Monkton Quartzite
Cdu-Dunham Dolomite
Cch-Cheshire Quartzite

Figure 1 - The geology of the north end of the Middlebury synclinorium (Cady, 1945).

tively high outcrop density at the northern end of the core of the synclinorium where the synclinorium fold pattern is supposedly most evident. It is located in the Middlebury, Vermont, and Cornwall, Vermont, 7½ minute quadrangles (figure 2) and includes portions of Cornwall, Middlebury, New Haven, and Weybridge townships. Mapping was carried out at a scale of 1:6300 over an area of about 27 square kilometers. Localities previously mapped in detail by Crosby (1963), Hickcox (1964), and Soule (1967) lie within the area and these studies contributed to the understanding of the structue (figure 3).

This study has found that much of the detailed geology is inconsistent with the existence of a major synclinorium. A more consistent interpretation for the gross structure of the region is thin-skinned deformation above shallow detachment surfaces. Listric thrusting off of these decollements caused reversal of the stratigraphy east of the central slate belt resulting in the present map pattern which has been interpreted as a synclinorium.

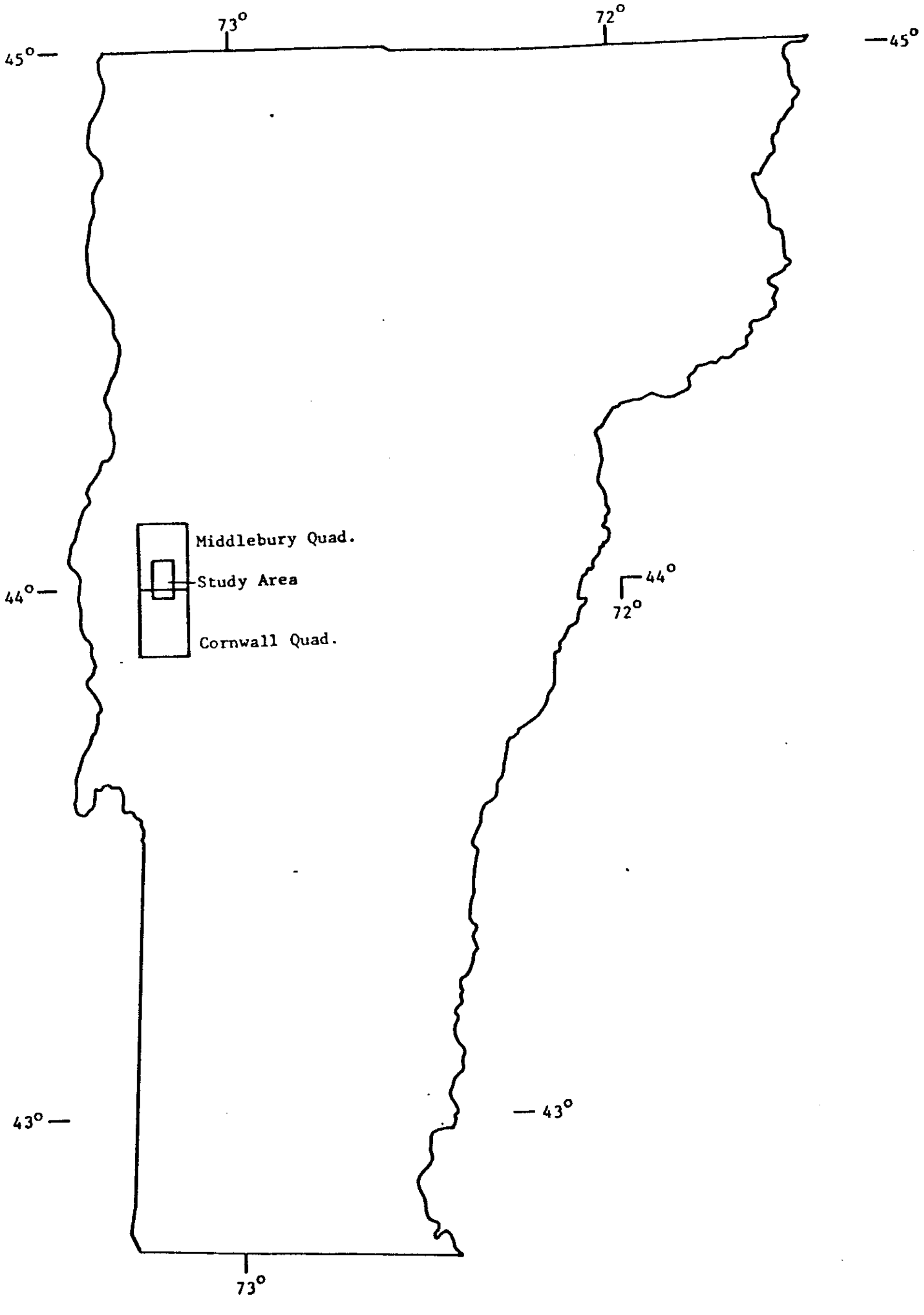


Figure 2 - The location of the study area in west-central Vermont.

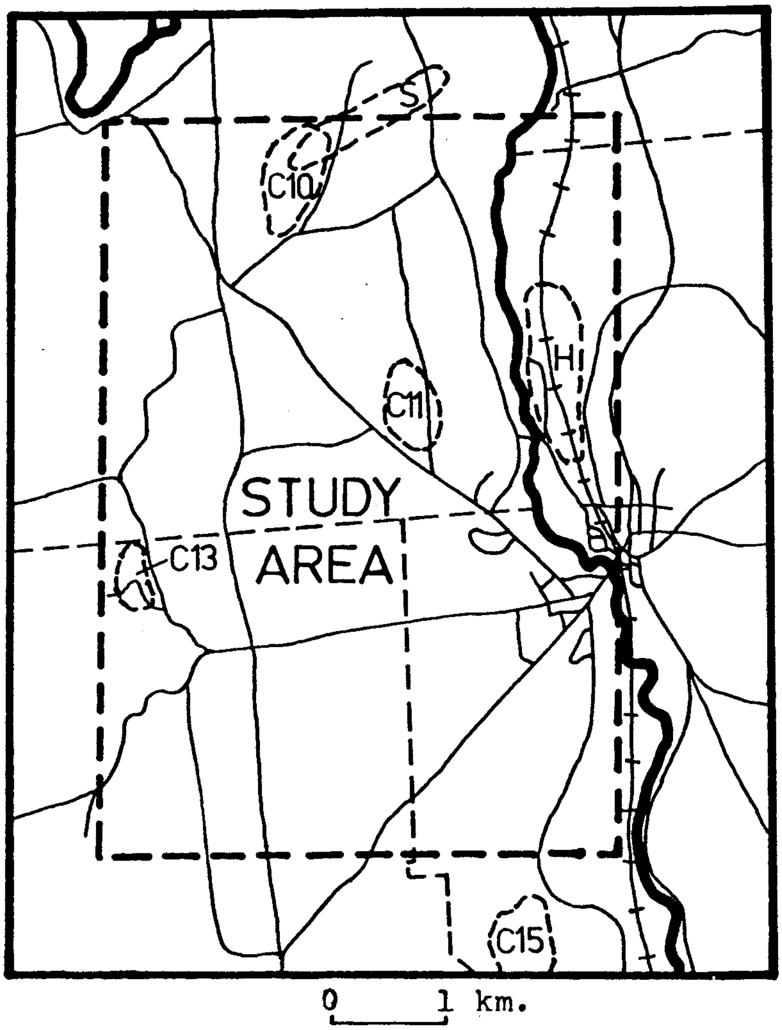


Figure 3 - Locations of areas mapped in detail by Crosby (1963), Hickcox (1964), and Soule (1967) relative to the study area. C10, C11, C13, and C15 are Crosby's stations 10, 11, 13, and 15 respectively, H is Hickcox's area, and S is Soule's area.

Previous Work

The first geologic investigations in west-central Vermont were prompted by the publication of the first geologic survey of Vermont which included a geologic map (Hitchcock and others, 1861). The map, which was necessarily vague and generalized, lumped all of the carbonates in western Vermont together into one formation (the Eolian limestone) with no age given. It was the very vagueness of this work that stimulated the first serious investigations in the Middlebury area.

The first investigator to start serious mapping near Middlebury was Rev. Augustus Wing, who unfortunately died before he could publish the results of his fifteen years of investigations. We are, however, fortunate enough to have his noteboks and correspondence from that period (Wing, 1858-1876), as well as a published summary of his work (Dana, 1877a, b). The present theories of the stratigraphy and structure of the Middlebury synclinorium are derived with only minor changes from Wing's work. He was the first to recognize different formations and successfully define their ages. He then used this stratigraphy to define the major folds of the synclinorium. Many of the problems which bothered him during the course of his investigation, such as the age of the eastern edge of the Sparry limestone and the lack of conclusive evidence for the main fold under the central slate belt, have never been resolved.

The next major investigation in the area was conducted by the faculty of Middlebury College, especially professors Brainard and Seely. This project was undertaken very soon after Wing began his work and, although they were very much aware of his work, they worked quite independently. Actually, Brainard and Seely were primarily concerned with paleontology (Brainard and Seely, 1890; Brainard, 1891), but the first reasonably detailed published map of the area was by Seely (1910) (figure 4).

After this, very little new work was done in the Middlebury area until that by Cady (1945). During this interval there were two review articles which dealt partially with the Middlebury area (Perkins, 1916; Gordon, 1923) as well as some new mapping of peripheral areas (Perkins, 1908; 1910; Dale, 1912; Dale, 1921; Bain, 1927; Swinnerton, 1932; Quinn, 1933; Rodgers, 1937). Although the mapping of Cady (1945) (figure 1) is now considered the classic work on the Middlebury synclinorium, his main contribution to our understanding of the area was the compilation and correlation of all previous work and the redefinition of the stratigraphy, making it consistent with that already in use in the Champlain lowlands west of the Champlain thrust. What new mapping he did served mainly to relocate the positions of the stratigraphic boundaries more accurately.

Since 1945, most of the work in the area has been

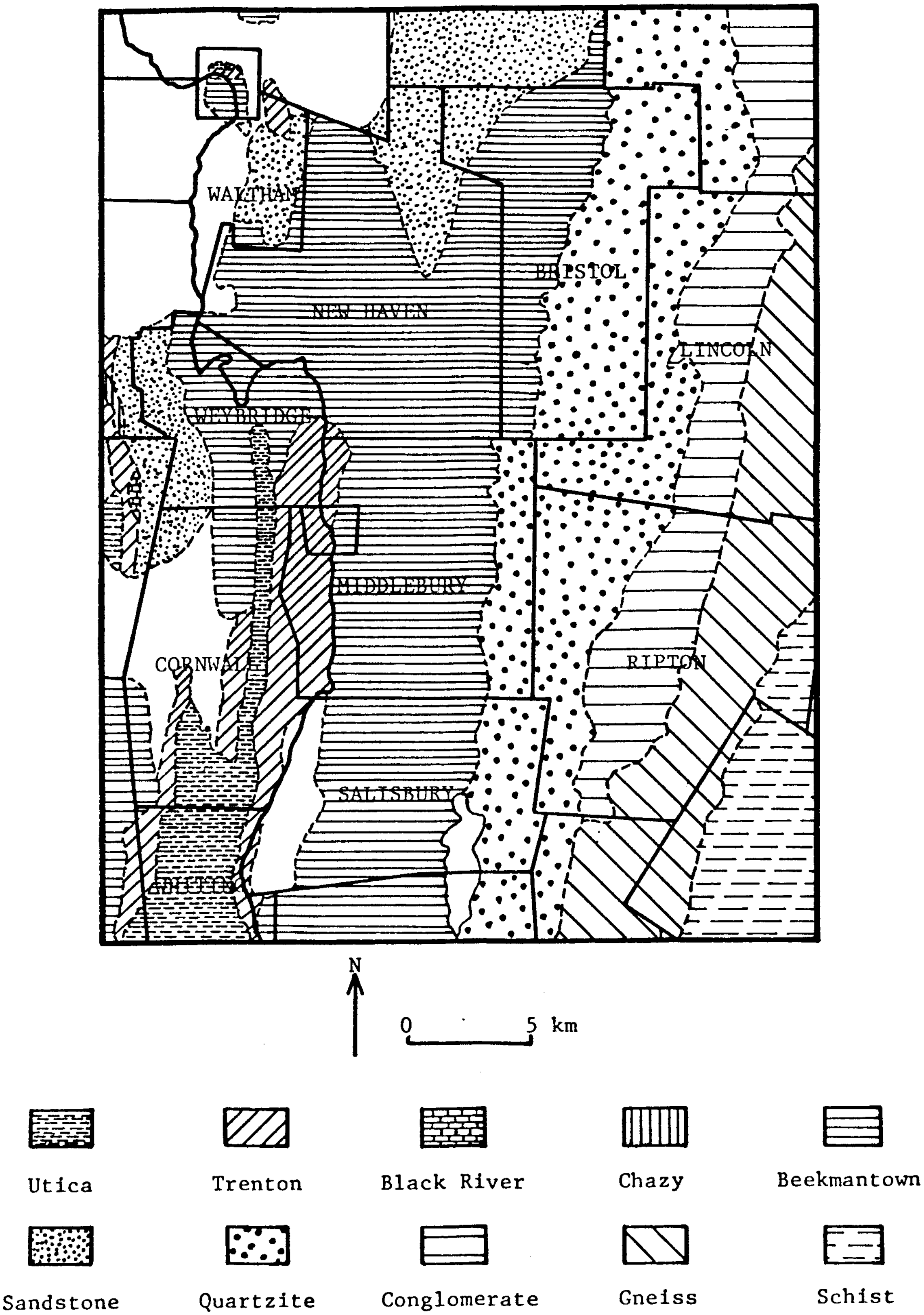


Figure 4 - The first published map of the Middlebury area from Seely (1910).

concerned with redefining the stratigraphic boundaries in small areas (see Coney and others, 1972), defining the structure exactly in a small area (Crosby, 1963; Hickcox, 1964; Voight, 1965; Soule, 1967), or redefining certain stratigraphic relationships (Kay and Cady, 1947; Cady and Zen, 1960). There has also been some remapping of adjacent areas (Osberg, 1952; Brace, 1953; Welby, 1961a; Stone and Dennis, 1964), but all of these studies have used Cady (1945) as the basis for that edge of the area mapped. There have also been some geophysical studies by Middlebury College students (see Coney and others, 1972), but these have not really contributed much to a detailed geologic understanding of the area.

Unfortunately, all of these studies were based on the underlying structural and stratigraphic theories presented by Cady (1945) which incorpoate the problems that Wing recognized over a century ago. Thus there has never been a valid evaluation of these theories using modern analytical methods. This study attempts to fill that gap.

Stratigraphy

The stratigraphy of the area covered by this study has long been considered fairly simple. The rocks, which represent the upper part of a Cambro-Ordovician carbonate shelf sequence (figure 5), are divided by Cady (1945) into: Bascom formation, Chipman formation, Middlebury limestone, Orwell limestone, Glens Falls limestone, and Hortonville slate (figure 1). For reasons discussed below, the Middlebury, Orwell, and Glens Falls limestones will be grouped together in this study into the Sparry limestone after Wing (Dana, 1877a, b). There are also two lamprophyre dikes.

Hortonville Slate

The Hortonville slate is a low-grade black slate. Although Cady (1945) and all prior investigators mapped it only as a narrow band in the center of the synclinorium, it can be found in a number of other places within the study area (plate 1). Microscopic examination shows that the slate consists mainly of clay minerals and chlorite, along with significant amounts of quartz, calcite, and carbonaceous matter. Minor amounts of microcrystalline pyrite are found in most samples, and sericite occurs in significant abundances near Otter Creek.

Most of the Hortonville slate is very dark colored, but light or sandy layers make it possible to identify bedding in many outcrops. In a few places in the eastern

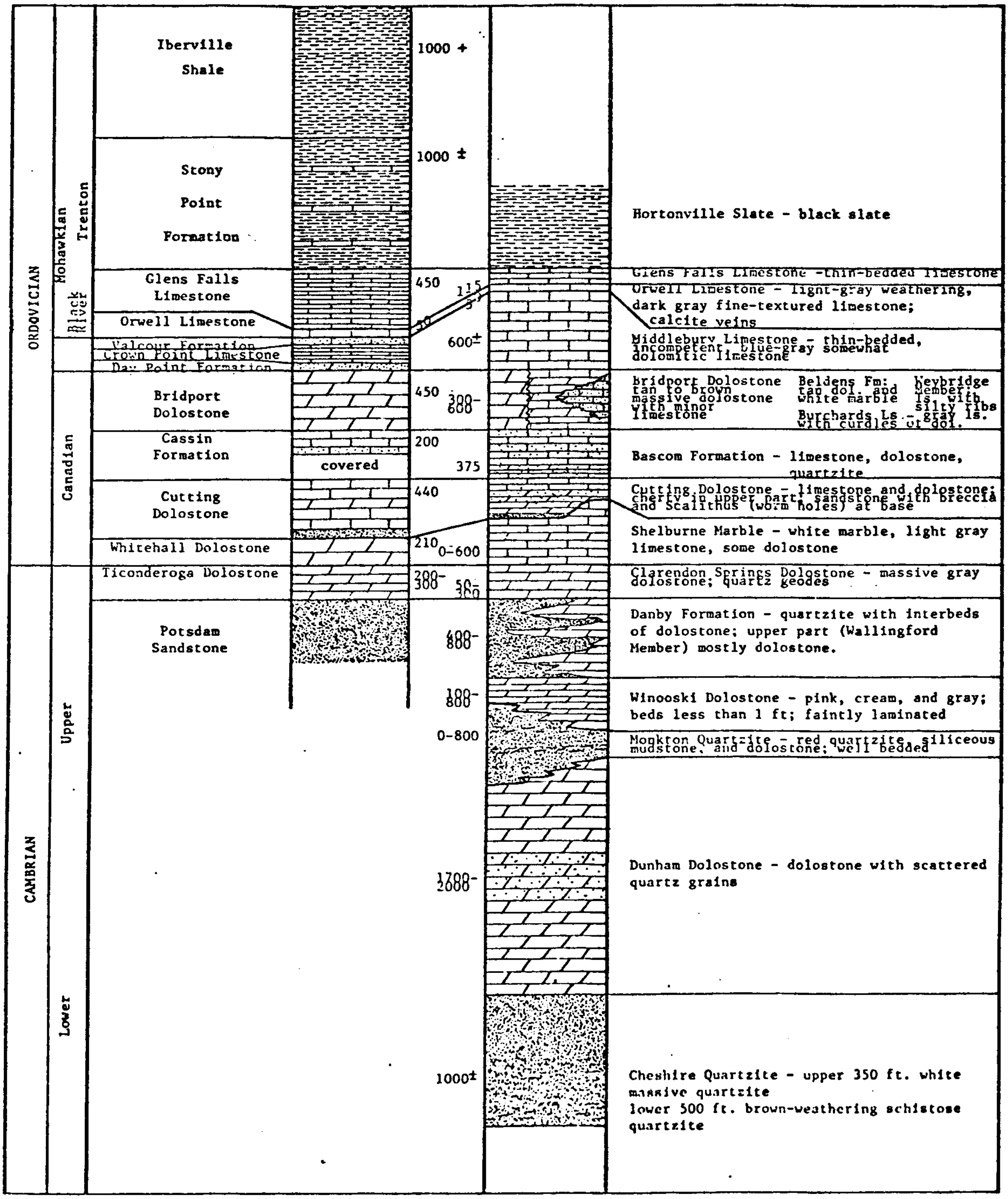


Figure 5 - Stratigraphy of the Middlebury synclinorium and the Champlain lowlands (after Coney and others, 1972).

edge of the main belt and in the slice by Otter Creek, there are large angular fragments of limestone, dolomite, and quartzite (figure 6), which resemble the older formations of western Vermont.

The correlation of the slate by Otter Creek with the Hortonville, rather than with the thin (less than 2 meters) slate layer at the base of the Sparry limestone (Cady, 1945), is based on the presence of these fragments, the thickness of the unit, and also on the occurrence of upper rather than lower facies of the Sparry limestone adjacent to the western edge of the slate. The other two small slate belts, which were previously unnoticed, are also correlated with the Hortonville because they have upper facies Sparry limestone along their western boundaries, and no lower Sparry or Chipman nearby.

Age - Although no fossils have ever been reported from the Hortonville slate, most workers have followed Wing (Dana, 1877a, b) and Cady (1945) in assigning it to Trenton time. This age designation is based on the age of the underlying limestone (which yields Trenton fossils) and correlation with the shales west of the Champlain thrust (figure 5). Because the existence of olistoliths indicates syntectonic deposition, additional support for this age is supplied by correlation with recent age determinations of the Taconian deformation in the northern Appalachian system, all of which fall during Black River and Trenton time (Baldwin,

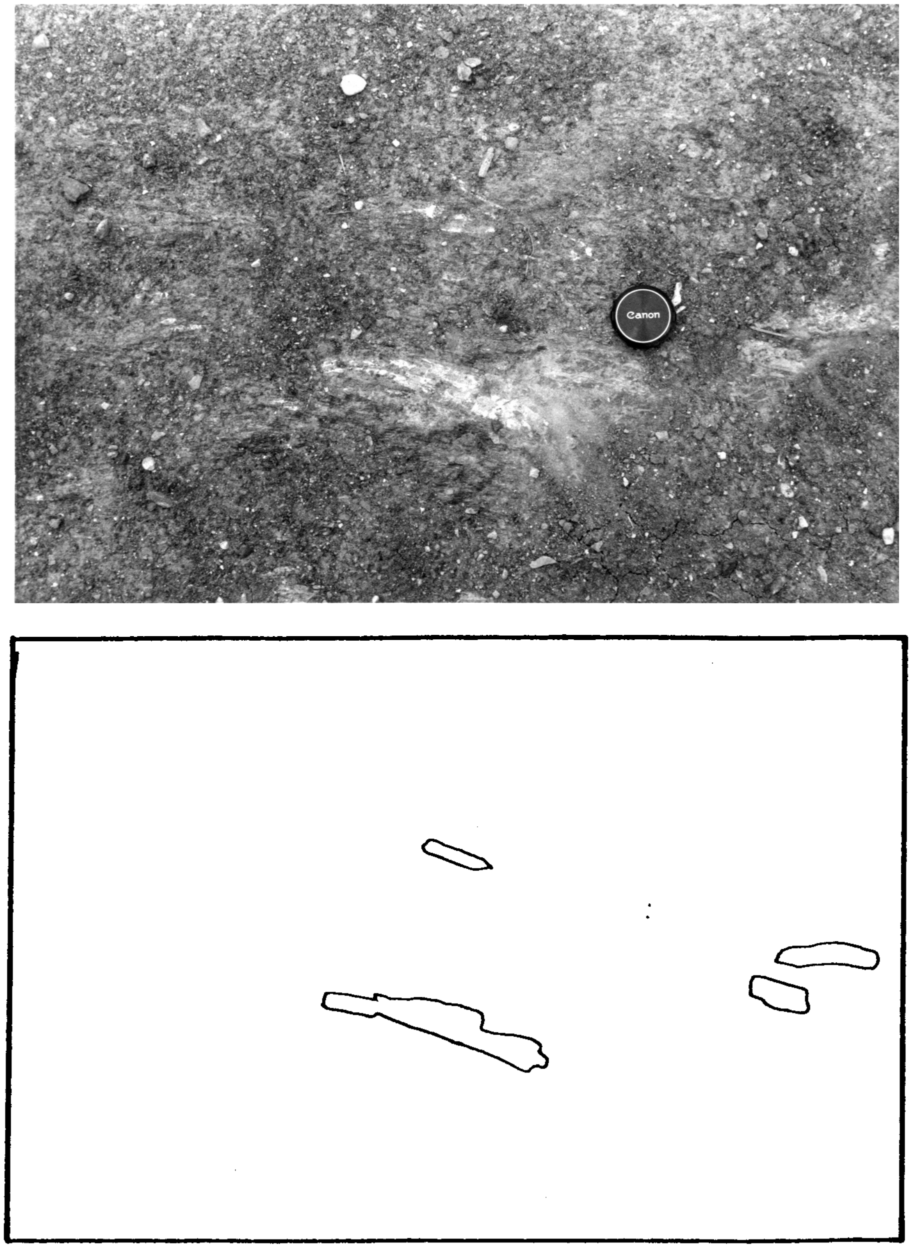


Figure 6 – Angular blocks of quartzite within the Hortonville slate on the edge of a new farm pond one kilometer north of the southern edge of the study area and fifty meters east of Cider Mill Road. Outcrop is now under water, but 50 meters north is another outcrop with similar blocks.

1977).

Sparry Limestone

The Sparry limestone (Wing, 1858-1876) is an impure blue-gray limestone. Cady (1945) divided this formation, following the stratigraphy of the Champlain lowlands west of the Champlain thrust, into the Middlebury, Orwell, and Glens Falls limestones (figure 5). According to him, the Glens Falls limestone is a very shaly limestone about 100 feet thick in this area, the Orwell limestone, 50 feet thick, is a very pure massive limestone with many calcite veins, and the Middlebury limestone, which is correlated with the Crown Point limestone of the Champlain lowlands (Kay and Cady, 1947), is composed of up to 600 feet of somewhat impure dolomitic limestone. The Sparry limestone of the study area, however, contains an internal stratigraphy quite different from that defined by Cady (1945).

Within the Sparry limestone there are three mappable stratigraphic horizons (figure 7). The lowest of these is a thin slate bed, one to two meters thick, directly overlain by color-banded limestone, five to ten meters thick, with thin dolomitic layers. The slate layer occurs about two meters above the base of the Sparry limestone and is only exposed along the northern edge of the study area, especially at Crosby's (1963) station 10. The color-banded limestone is also found only along the northern edge of the study area, with its best exposures at Crosby's

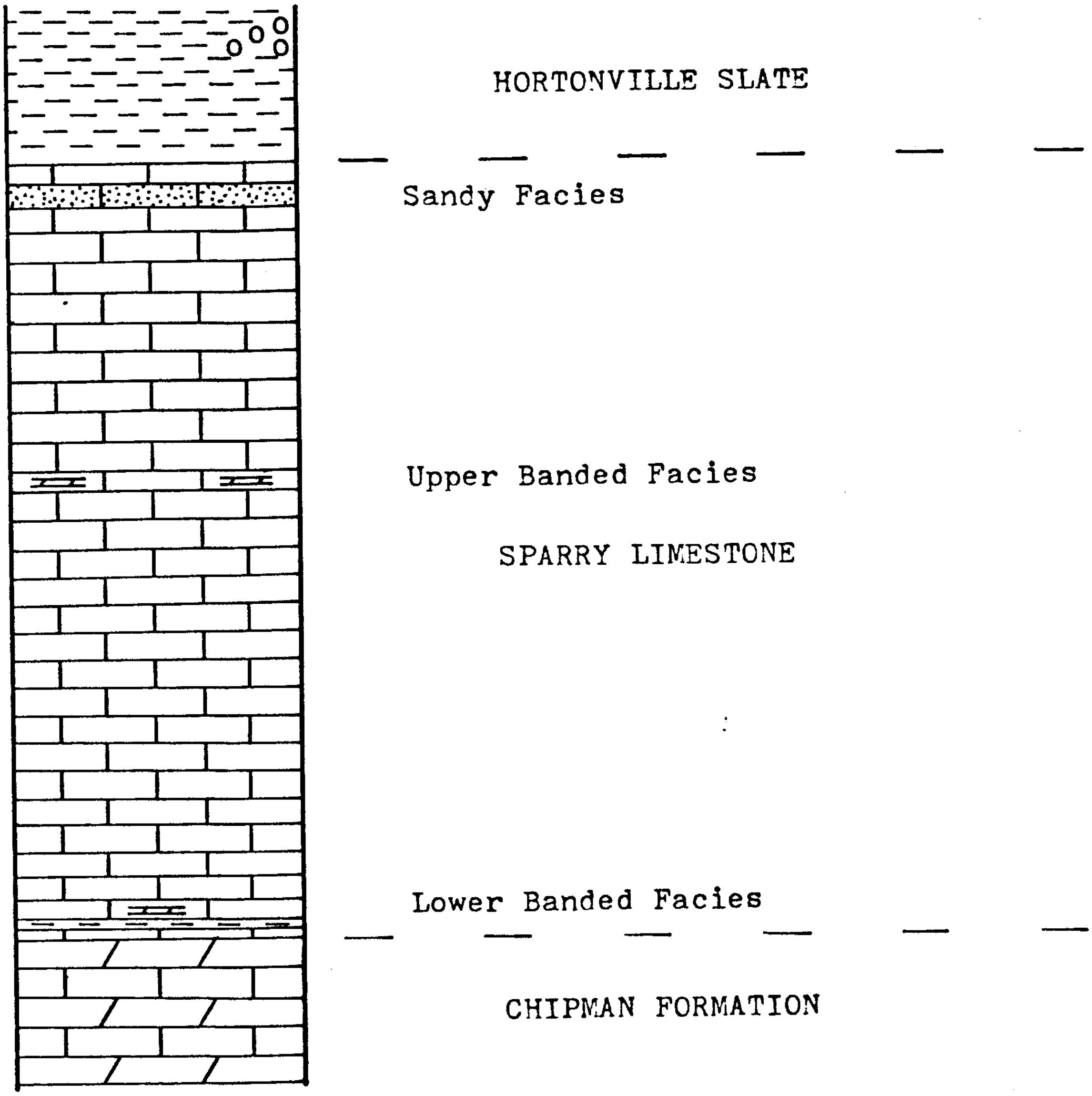


Figure 7 - Internal stratigraphy of the Sparry limestone.

(1963) station 10 and just to the east and west. The slate normally contains about 50% clay and chlorite, 25% quartz, and 25% calcite. The bands in the limestone are usually about five centimeters thick, apparently the result of differential weathering of limestone containing slight variations in dolomite and non-carbonate concentrations.

The second mappable horizon is another zone of color-banded limestone containing dolomite beds. The overall map pattern indicates that it occurs slightly above the middle of the Sparry limestone and is about five meters thick. The bands are generally wider in this horizon, but seldom exceed ten centimeters. Dolomite beds are slightly more common, although they occur infrequently. The outcrops that best locate this horizon stratigraphically lie in a northeast trending zone 500 to 1500 meters south of Crosby's (1963) station 10. The best exposures of this horizon occur at the southeastern end of this zone and adjacent to the eastern edge of the main belt of slate one kilometer north of the southern limit of the study area.

The upper mappable horizon of the Sparry limestone is a shaly limestone underlain by a sandy limestone. The shaly limestone, one to three meters thick, represents a gradational contact with the Hortonville slate. It thus contains increasing clay concentrations toward the contact, never reaching more than 25 to 30%, however. The sandy limestone contains up to 50% quartz sand with minor clay.

Along the western edge of the study area, this lithofacies is less than one meter thick, but at Crosby's (1963) station 11 it is at least two meters thick. Thin layers containing quartz sand occur locally in the five to ten meters immediately underlying this horizon. The best exposure of the sandy horizon is found where Beaver Brook crosses the western Hortonville-Sparry contact near the western edge of the study area. A quarry 500 meters east of there provides the best exposures of the slightly sandy layers below this horizon, and Crosby's (1963) station 11 contains the best outcrops of the sandy limestone.

The total thickness of the Sparry limestone, as inferred from outcrop geometry is probably about 80 to 100 meters. The primary lithology is an unbanded, fairly homogeneous, impure limestone roughly corresponding to Cady's (1945) Middlebury limestone (which incidently has its type locality within the study area at the Middlebury College campus). In thin-section it is a very finegrained crystalline limestone with varying quantities of carbonaceous matter and clay minerals. Chlorite, rarely accompanied by sericite, occurs in the more deformed areas. Microcrystalline pyrite and recrystallized fossil fragments are also present in many samples.

<u>Age</u> - The age of the Sparry limestone has long been a matter of dispute, which, although most present workers follow Cady (1945; Kay and Cady, 1947), has not been resolved.

Wing found only Trenton and Black River fossils in the Sparry limestone and called it all Trenton, but thought it should be divided into Trenton and Chazy. He never presented any evidence for this latter view (it was probably based on his dislike of time gaps in a sedimentary sequence), but it was followed by Cady (1945) anyway. All the other workers in the area (Seely, 1910; Perkins, 1916; Gordon, 1923) followed the other course, calling the limestone Trenton.

The problem arises mainly because the only fossils reported in the Sparry limestone area were found very close to the slate, except for some of questionable age found by Wing (notebook 4, p. 16-17) and a coral reported by Cady (1945; p. 553) from the bed of Otter Creek on the Weybridge Middlebury boundary (figure 1). This fossil is identified by Bassler (1950, p. 262) as Nyctopora van tulyi and given the age of upper Chazyan. The basis for this age is poor because it rests solely on the stratigraphic correlations of Cady (1945). In fact, most of the paleontologic evidence points toward a younger age. First of all this would be the only member of the genus Nyctopora from pre-Black River time. Second, there is only one other reported occurrence of this type of coral (tabulate with short septa) from pre-Black River time (Welby, 1961b). Third, there were no other fossils found nearby which would have constrained the date. Thus the use of fossil data to indicate an age older than Black River is unwarranted.

That the Sparry limestone may indeed include some Chazyan parts is quite possible, but there are no data at present to support this.

Chipman Formation

The Chipman formation as described by Cady and Zen (1960) contains four members, two of which occur in the study area: the Beldens and Burchards members. The Burchards member is only found along the western boundary of the study area. It is a blue-gray limestone which appears mottled because of localized concentrations of dolomite. The mottled appearence described by Cady (1945; Cady and Zen, 1960) is due primarily to the partial transposition of the thin laminae of dolomite.

The Beldens member of the Chipman formation is of more immediate concern to this study, because it is immediately juxtaposed with the Sparry limestone. The Beldens member consists of interbedded limestones and dolomites. To the west of the main belt of Hortonville slate, the limestones are blue-gray on a fresh surface, weathering gray. In places they contain shaly laminae. The dolomites of the same area are brown to buff weathering, blue-black dolomites. To the east, the limestone is often recrystallized to a white marble though the weathered surface often appears the same as the corresponding limestone to the west. The dolomite of the same area is also sometimes recrystallized to white or light orange marble, and the shale laminae are metamorphosed to chlorite and sericite films. The marble is only found as far west as Crosby's (1963) station 10.

Age - The age of the Chipman formation is generally accepted as upper Canadian (Cady and Zen, 1960; Coney and others, 1972). This age has been proposed because it seems to be the correlative of the Canadian of the Champlain lowlands and is directly below the Middlebury limestone, which has been correlated with the middle Chazyan Crown Point limestone of the Champlain lowlands. In his various discussions of the Chipman formation and its members, Cady (1945; Kay and Cady, 1947; Cady and Zen, 1960) has cited fossil data to support age assignments of both Chazyan and Canadian. It therefore seems proper to assign the Chipman formation to early Chazyan and late Canadian time.

Bascom Formation

Only the top part of the Bascom formation is found in the study area. This part can be divided into a shaly limestone and a quartzite-dolomite sequence. The shaly limestone, which is stratigraphically above the quartzite-dolomite facies (Cady, 1945), consists mainly of blue-gray microcrystalline limestone with thin layers and laminae of shale. In many exposures, the bedding relationships between the two are obscure because of the transposition of the layers during deformation. The quartzite-dolomite sequence is found only on the extreme western edge of the study area. It consists of blue to white quartzite and calcareous sandstone interbedded with blue-black and orange dolomite. The dolomite beds are increasingly replaced by limestone beds toward the upper edge of this sequence.

Age - The age of the Bascom formation is farly well established as Canadian. This formation has yielded many fossils (Brainard, 1891) which, though originally assigned to the lower Cahzy, are now assigned to the upper Canadian (Cady, 1945; Kay and Cady, 1947).

Igneous Rocks

The only igneous rocks found in the study area are two lamprophyre dikes in a quarry on the east side of James Road 500 meters north of the intersection with Perkins Road. These dikes are both less than ½ meter wide. They have typical lamprophyric textures and mineralogy, containing plagioclase, hornblende, carbonate, epidote, iron oxide, pyroxene (highly altered), and minor questionable orthoclase. The alteration of the minerals other than pyroxene is not very pronounced.

Age - The age of these dikes is probably early Mesozoic (Cady, 1969; McHone, 1978), but they have never been dated. The few basic dikes that have been dated in western Vermont yield early Mesozoic dates and have similar orientations.

Structural Elements

Most of the structural elements in this area have been previously descibed by Crosby (1963). Recognition of additional elements as well as variations on old elements necessitates the following redefinitions and expanded descriptions of the elements.

Bedding, S_0

Bedding is easily recognized in the Bascom and Chipman formations due to lithologic contrasts and is frequently seen in the Hortonville slate because of color contrasts (figure 8), but within the Sparry limestone it is rarely visible. Only where there are slight variations in clay, sand, or dolomite content can bedding be recognized, and even in those locations it is usually difficult because of the development of cleavages (S_1 and S_2). It is impossible, therefore, to map the folds within the Sparry limestone except within very limited areas such as Crosby's (1963) station 10.

The problem of identifying bedding in thin-sections of the Sparry limestone is magnified many times. Those contrasts which are visible in outcrop are not usually sharp or well defined and the layers have a thickness that exceeds the length of the average thin-section. Also, bedding in outcrop is usually more visible when observed from a short distance than when inspected closely,

Figure 8 – Color banding on cleavage surface defining bedding in the Hortonville slate. Roadcut on Cider Mill Road near the south edge of the study area.

indicating that the slight color variations are due to differential weathering of even slighter compositional differences. Fresh surfaces almost never show bedding.

Thus the identification of bedding within the Sparry limestone has proven to be one of the most difficult problems encountered during the course of this study. It is the key to positively identifying the early cleavage and the ability to recognize it has defined two distinctive horizons incorporated in the stratigraphy.

Early Cleavage, S_1

A previously unrecognized cleavage has been discovered during this investigation. It has been identified in only a very limited number of outcrops, however, so its areal and stratigraphic extent cannot be conclusively established at this time. S_1 has been found primarily in the Sparry limestone, but it is also found in the Hortonville slate and the limestones of the Chipman formation. Prior workers did not recognize this as a distinct surface because of the obscurity of bedding in the Sparry limestone and the very limited occurrences of S_1 elsewhere. Even in the Sparry limestone, S_1 occurs only sporadically.

S_1 was found in conjunction with both bedding and the later axial plane cleavage in only five outcrops, although it was recognized in several more on the basis of morphology. Where bedding is identifiable, the S_1 planes intersect bedding at a high angle. In the limestones, there are often two levels of S_1 development: widely spaced primary planes and clsely spaced secondary planes (figure 9). The primary planes are spaced up to several centimeters apart whereas the secondary planes are only a few millimeters or less apart. The primary planes contain significant selvages of insoluble residues and commonly cause small offsets in the marker horizons where the two surfaces are not quite perpendicular. The secondary planes are defined by very thin selvages and veins of coarse-grained calcite. Unfortunately, the secondary planes closely resemble S_2 and the primary planes have a spacing similar to bedding, making recognition of S_1 very difficult. In all cases S_1 is cut by S_2 and the material in the S_1 planes is concentrated into the S_2 planes giving the appearance of transposition. Even where it is possible to identify S_1, the stronger development of S_2 makes measurement of the orientation of S_1 almost impossible.

In the Hortonville slate there are too few examples (one definite, three possible) to arrive at a general description. In all cases S_1 closely resembles S_2.

Axial Plane Cleavage, S_2

The most obvious surface in the rocks of the study area is S_2. Although initially thought to be bedding in the Sparry limestone, it was quickly discovered by early workers that it is actually a cleavage. S_2 is well developed throughout the area, adding to the obscurity of

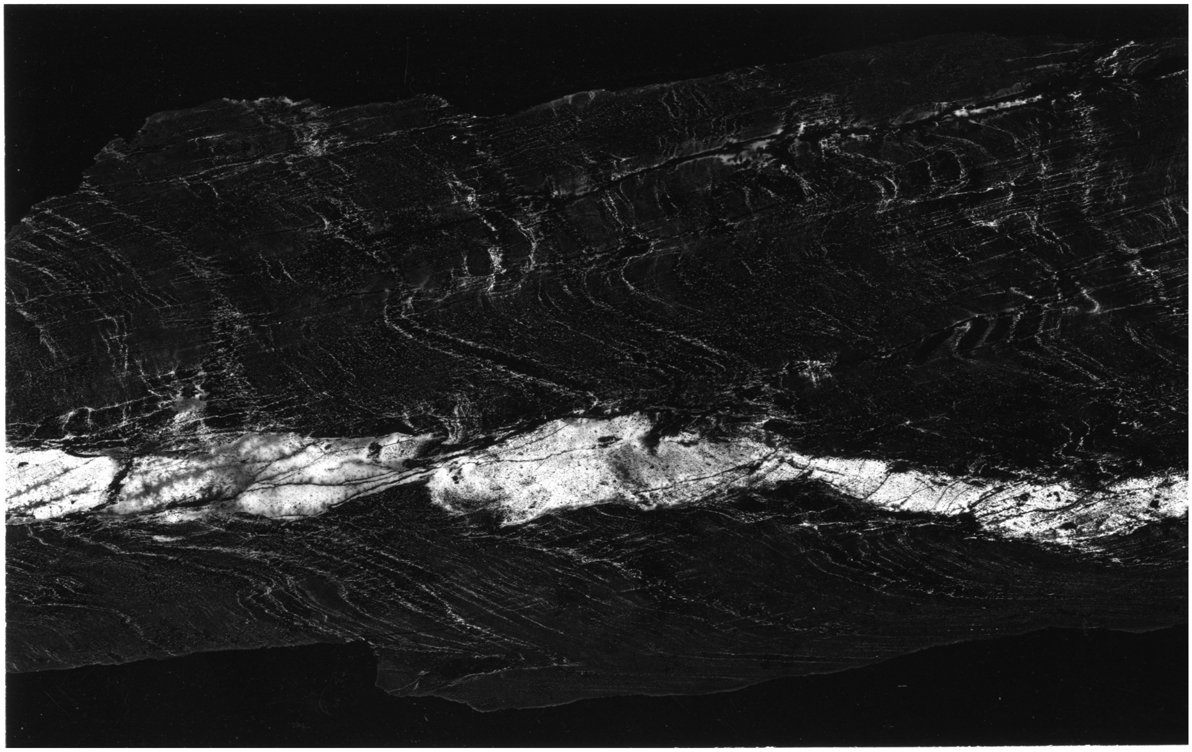


Figure 9 – Bedding, S_1, and S_2 in sawed section. Print from acetate peel.

S_0 and S_1, and has a strong preferred orientation (figure 10).

S_2 planes are closely spaced (0.5 to 5 mm.) in the limestones, with the closer spacings limited to the less pure limestones. The presence of quartz sand tends to increase the spacing. The dolomites do not commonly contain cleavage planes except where very thin. The quartzites of the Bascom formation have a cleavage only within the hinges of the folds. Spacing of cleavage planes in the Hortonville slate varies from virtually continuous in quartz-poor horizons to almost 5 millimeters in sandy horizons.

In thin-section S_2 planes in the limestones are seen to be defined by either selvages of clay and carbonaceous matter or veins of recrystallized calcite. Most rocks contain both types of cleavage, but the vein-type predominates in relatively pure limestones and selvage-type in impure limestones. The planes, although quite flat at outcrop and hand specimen scale, are often quite irregular in thin-section, selvages being generally more irregular than calcite veins.

Selvage thicknesses vary widely, depending on the purity of the limestone, reaching as much as one millimeter. Clay particles within the cleavage planes appear to be aligned parallel to the plane, although the minute grain size often makes determination of the orientation difficult. Where the clay has been metamorphosed to chlorite and seri-

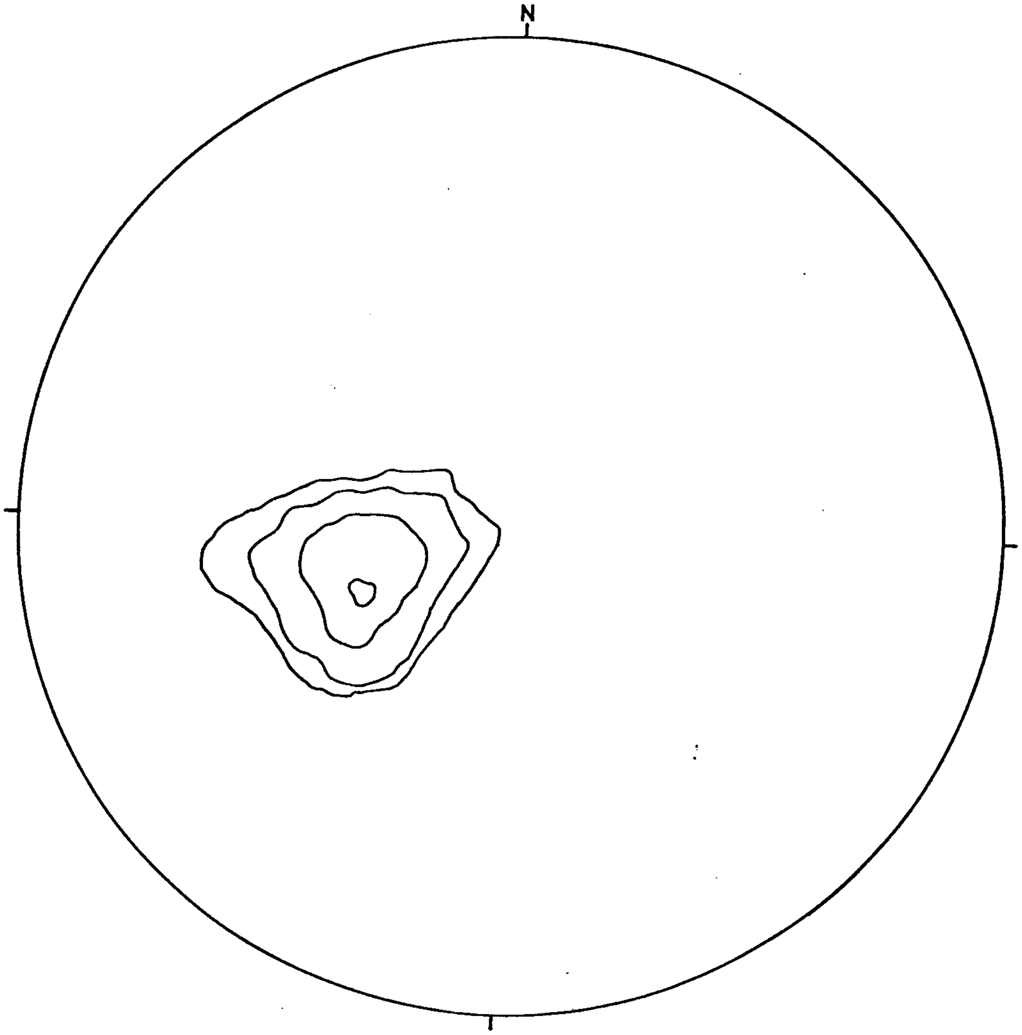


Figure 10 - Poles to S_2, lower hemisphere projection. 336 points contoured at 5%, 10%, 20%, and 30% per 1% area.

cite, the grains are definitely parallel to the cleavage planes.

The calcite grains within the vein-type cleavage planes are relatively large and subequant (figure 11). Grain size ranges from 0.1 to 1.0 millimeter whereas the groundmass grains are 3 to 10 microns. The veins are usually only one grain thick, but two and three grain thicknesses are not uncommon.

Crenulation Cleavage, S_3

The third generation of cleavage found in the Sparry limestone is a crenulation cleavage (Rickard, 1961). It occurs in conjunction with a small scale asymmetric folding of preexisting layering. This folding is most apparent where it occurs in the more impure limestones because the earlier cleavage is more pronounced, but it also is found in the more pure limestones. The fold morphology is very similar to that predicted by Cosgrove (1976) for the folding of weakly to moderately anisotropic material with layering inclined to the maximum principal stress.

One of the first characteristics which become evident when comparing the crenulation cleavage of this area to published examples is the coarseness of this element in outcrop. The spacing of the cleavage planes in this area ranges from 0.5 to 3 centimeters compared with spacings of less than 3 down to 0.1 millimeters reported by Talbot and Hobbs (1968), Williams (1972), Roy (1973), and Gray (1979)

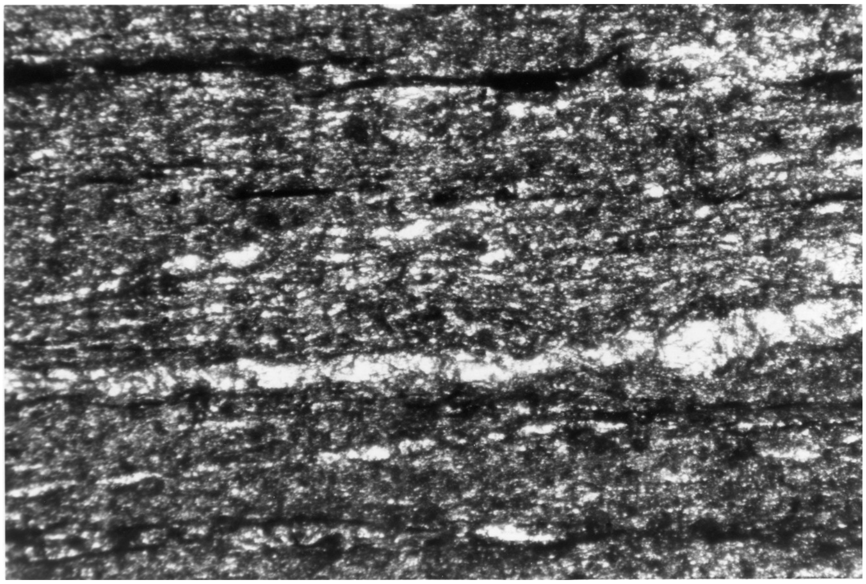


Figure 11 – S_2 planes in thin-section of intermediate limestone. Note the larger grain size in the calcite vein.

among others. The greater spacing is probably due to differences in material properties and layer thicknesses between the impure limestones of this area and the psammitic schists and slates in those other areas. Within the non-carbonate layers there is a much finer spacing in places similar to the normal spacing of other areas.

There is also a quite noticeable variation in the morphology of the crenulations. Fold shapes vary from rounded to quite angular. This variation corresponds to that which Cosgrove (1976) obtained by subjecting materials with different anisotropies to a compressive stress oriented 45° to the layering. When the folds are quite rounded, they have nearly equal wavelengths and amplitudes (1:1 to 2:1) (figure 12). In the most angular examples, however, the ratio of the wavelength to amplitude reaches more than 10:1. At least one of the limbs of these latter folds is quite straight and the crenulations occur in narrow zones which resemble kink bands (figure 13).

The S_3 planes occur in two basic positions relative to the crenulations. The classic position on the short overturned limbs of the asymmetric folds occurs commonly in this area. More common, however, is a cleavage cutting the longer limbs very near the fold hinges.

The cleavage planes found on the short limbs of the folds are similar to those dealt with by Williams (1972, PS_2) and Gray (1979), being directly related to the degree of folding (figure 14). As the folds develop (amplitude

Figure 12 – Rounded crenulation folds in roadcut on Vt. Rte. 23 about one kilometer north of Perkins Road.

Figure 13 – Angular crenulations which resemble kink bands. Width of photo is about 15 centimeters. Quarry face just south of Perkins Road.

Figure 14 – Crenulation fold developing to the point that a cleavage plane forms on the short limb. Scale 1:2. Quarry next to Vt. Rte. 23 just north of Perkins Road.

increases), the S_2 planes become more closely spaced on the short limb. When this spacing becomes small enough (the necessary distance varies with the type of fold, original spacing, and purity of the rock) and the S_2 planes are basically aligned, the cleavage planes begin to form. The S_3 surface is thus defined by the alignment of a series of S_2 segments. Usually the S_2 microlithon is totally lost along this plane so that the S_2 segments combine to form a continuous surface. The cleavage surface may consist of either non-carbonate selvage material or calcite veins, depending on rock type, but the former is much more common since this type of S_3 is developed primarily in less pure limestones.

The best developed S_3 planes are usually found in the long limbs very close to the fold hinges (figure 15). In the more angular crenulations, these planes occur almost on the hinges, while in the more rounded folds the planes are more distant. There is a continuous gradation, corresponding to the variation in folding style, between these two end members. The cleavage planes may develop at either or both ends of the long limbs. In the more angular folds no pattern is apparent, but normally in the more rounded folds either both ends of a limb contain S_3 or neither does.

The cleavage planes of this second variety are totally new surfaces. There is no extra thinning of S_2 layering associated with these planes. They do, however, occur at the point of thickness change between the thin layering of

Figure 15 – S_3 planes on the long limbs of a crenulation fold near the fold hinges. Scale about 3:2. Same quarry as in figure 14.

the long limbs and the thicker layering of the hinge zones. Both the vein-type and selvage-type cleavage planes occur commonly, the only apparent control being the purity of the limestone.

Where the S_3 planes are developed on both sides of an angular crenulation, they look very much like the boundaries of kink bands, except that they never quite occur on the hinges, always being just onto the longer limbs. In many instances where the longer limbs are relatively short, as in the most rounded folds, cleavage planes cross from near one hinge to near the other. This occurs only where there has been significant concentration of the carbonate in the hinges, leaving the limbs enriched in non-carbonate material similar to the zonation described by Marlow and Etheridge (1977).

In the more competent layers cut by the crenulation cleavage, there is much less folding than in the surrounding limestone. The cleavage planes are more widely spaced and appear more like faults offsetting the layer than cleavage planes (figure 16). Gray (1979) has explained similar relations as dissolution of fold limbs during folding.

In the more impure limestone, the crenulation cleavage seen in outcrop is not always the only crenulation cleavage present. A smaller set of crenulations sometimes occurs within the non-carbonate laminae (figure 17). These have a sense of asymmetry that is consistent with their posi-

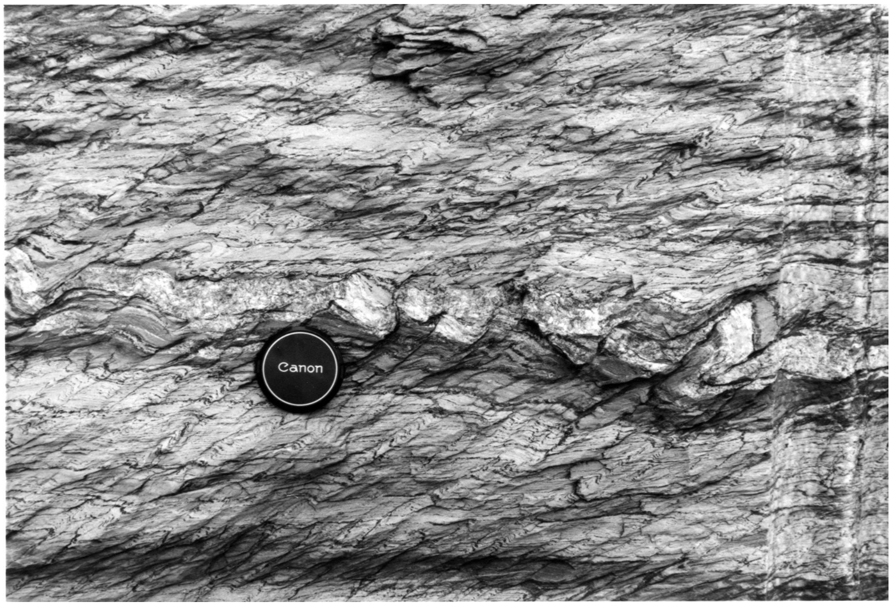


Figure 16 – Crenulation cleavage cutting more competent layer: note the reaction of the calcite vein running across the picture just above the lens cap. Quarry face containing old drill hole (right edge of picture) in same quarry as figure 14.

Figure 17 – Closely spaced crenulation cleavage within non-carbonate layers in the Sparry limestone. Scale about 3:2. From same quarry as figure 14.

tions on the folds of the crenulations. The spacing of these cleavage planes is less than one millimeter.

Lineations

There are only two commonly observed lineations in this area which result from the intersection of two generations of layering. A third such lineation, although rarely observed, is geologically important. Following the notation of Turner and Weiss (1963, p. 495) for fold generations, these lineations will be designated L_x^y where S_x is the earlier layering which intersects with S_y to cause the lineation. There is also one mineral lineation, designated L_m.

L_0^2 - The lack of observable bedding in the Sparry limestone has made the recognition of the lineation formed by the intersection of bedding and the axial plane cleavage, S_2, very difficult to recognize. The low angle between bedding and S_2 compounds this problem, and bedding is usually impossible to recognize in the hinges. In the few outcrops where bedding intersects S_2 at a relatively high angle and is recognizable, L_0^2 is a broad low-amplitude undulation (2 to 4 centimeter wavelength, less than 5 millimeter amplitude) on the S_2 surface. Measurement of this morphological element throughout the study area, however, produced an essentially random pattern. This could be due to the inclusion of genetically different elements which have the same morphology, such as ripples and L_1^2 where bedding and S_2 are nearly parallel.

In the slate, this lineation is marked by color stripes on the S_2 surface (figure 8) and sandy layers cause ridging on the cleavage surfaces because of the different spacing within these layers. In the uppermost Bascom formation, the S_2 partially transposes the limestone laminae creating pencilling, where the pencils are defined by the S_2 planes and shale laminae. In the quartzite-dolomite sequence, the cleavage crosses the lithologic boundaries creating a ridging parallel to the fold hinges.

L_1^2 - The intersection of the first two generations of cleavage in the limestones creates a lineation very similar to the L_0^2. The broad ridging on the S_2 surfaces in this case is caused by the intersection of the primary S_1 planes, and is usually indistinguishable from L_0^2 in outcrop except where S_1 can be positively identified. Often there is an irregular band (up to 5 millimeters wide) of clay on the S_2 surface along the actual trace of the primary S_1 plane. In a few places there is a fine streaking, parallel to the larger ridging, due to the intersection of the secondary S_1 planes with the S_2 planes. This streaking also is not totally distinctive, however, being similar to L_m, which is more common.

The few places where L_1^2 can be positively identified, it is oriented north-south. There are too few occurrences, however, to make statistical treatment meaningful.

L_2^3 - The intersection of S_3 and S_2 is often expressed on weathered surfaces by the development of pencils (figure 18). Since S_3 and S_2 are seldom orthogonal, slight variations in the orientation of the surfaces cause large variations in the orientation of the intersection line. The orientation of the pencils is not significantly affected by these variations, however, so the pencils are the most consistent expression of the lineation. The pencils are usually one to two centimeters wide (S_3 spacing) and about one centimeter thick (S_2 parting). Cross-sectional shapes of these pencils vary depending on the folding style of the crenulations. The top and bottom mimic the folding of the S_2 planes and the sides are planar since they are defined by S_3. Since S_3 and S_2 are very seldom perpendicular, the pencils are basically diamond shaped in cross-section (figure 19). L_2^3 has a very strong north-south orientation reflecting the orientation of the crenulation folding (figure 20).

L_m - Throughout the study area, most S_2 planes contain a fine ridging or striation. This lineation is caused by strings of large calcite grains (similar to the grains in vein-type cleavage planes) separated by grooves in which the large grains are missing. Although Crosby (1963) claims that the calcite grains that form the lineation are

Figure 18 – Pencils weathering out of outcrop in northeastern corner of Sparry limestone outcrop area. S_2 (horizontal) is folded and cut by S_3 (vertical). Pencils about two centimeters wide.

Figure 19 – Low power thin-section view of potential pencil from outcrop of figure 18. Pencil is formed by the intersection of S_2 and S_3. Scale about 5:1.

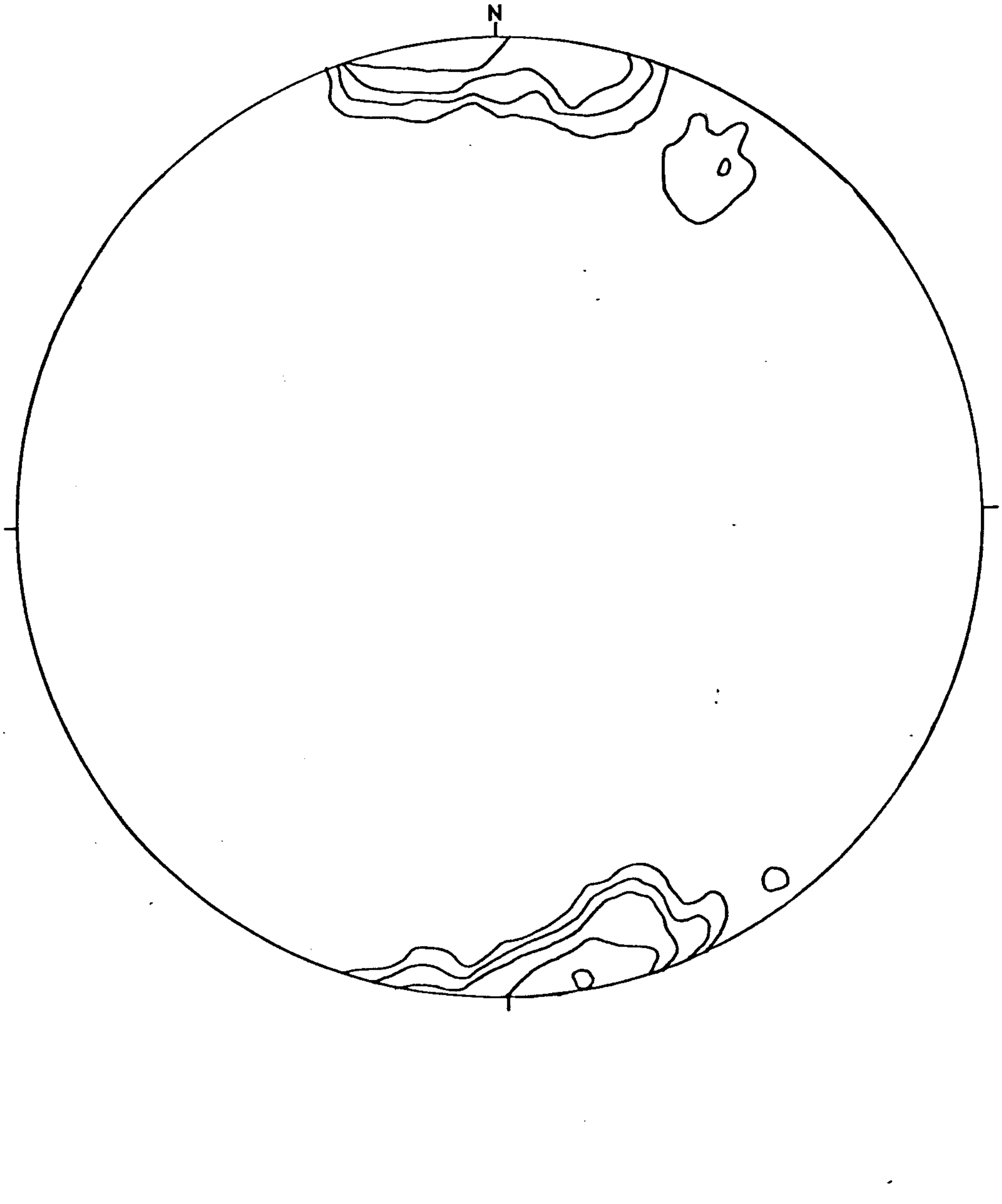


Figure 20 - L_2^3 (80 points) contoured at 3%, 5%, 10%, 20%, and 30% per 1% area. Lower hemisphere projection.

elongate, no evidence to support such an assertion has been found in this study. There is also a tendency for this striation to be present on chlorite cleavage surfaces, with thicker portions of the chlorite lining up in similar fashion. This lineation has a very pronounced orientation (figure 21) lying within the S_2 plane.

The origins of this lineation are unclear, since it does not bear any standard relationship to the folds associated with the formation of S_2. It is folded and cut by S_3, however, so it is reasonable to assume that it is genetically related to S_2 formation.

The lineation is a fine streaking with about one millimeter between the streaks (figure 22). The streaks often run for most of the length of an outcrop. The height of the linear textures varies from about one millimeter down to almost imperceptible. The lineation is much more visible in the pure limestones than in the impure.

Folds

Crosby (1963) defined two major generations of folds in the Middlebury area. The first of these is developed throughout the study area, whereas the second is developed primarily to the east of Otter Creek. It was the earlier generation which he studied in detail at station 10.

The earlier folds (associated with S_2) can be observed in isolated outcrops throughout the study area. They trend northwest (usually 300° to 330°) and are overturned toward

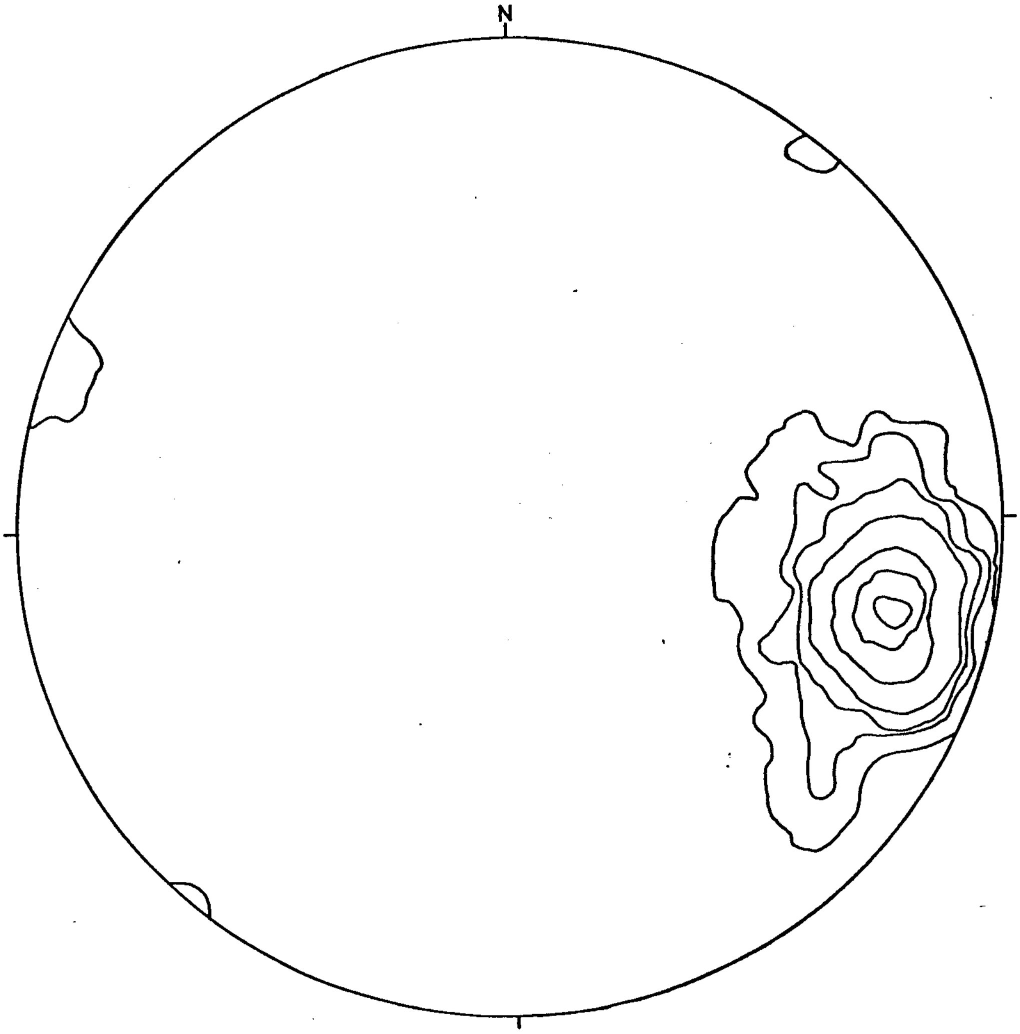


Figure 21 - L_m (114 points) contoured at 1%, 3%, 5%, 10%, 20%, 30%, and 40% per 1% area. Lower hemisphere projection.

Figure 22 – L_m on S_2: lineation is parallel to pen. Outcrop is just east of Vt. Rte. 23 near figure 12.

the southwest. Crosby (1963) described them as "passive flow folds" with hinge to limb ratios always in excess of three. His mapping indicates wavelengths of about 50 meters and amplitudes of about ten to twenty meters. The fold patterns suggest, however, that these may be second order folds with the first order folds having wavelengths of about 500 meters. There are also some indications from the outcrop patterns in the other parts of the study area, such as directly west of station 10, that this is indeed the case.

The later folds are apparently correlative with the crenulations described under S_3. To the east of Otter Creek, this set of folds is of similar size to the early folds mapped by Crosby (1963). Minor flexures expressing this tendency toward larger folds are often found in the Sparry limestone just above and below zones with the crenulation cleavage. All of the folds of this generation trend north-south. The fold type is closer to asymmetrical flexural slip with little thickening on the hinges.

Metamorphism

Regional Metamorphism

The rocks of the study area have been only slightly metamorphosed, with the grade generally increasing from west to east (figure 23). The western edge of the area shows little evidence of metamorphism, but along the eastern edge chlorite and sericite are almost universally present. There is also an increase in the recrystallization of the carbonate minerals from east to west. As well as the expected compositional controls, the development of these metamorphic minerals can be linked quite closely to the development of certain structural elements (figure 24).

In the slate, chlorite is present within much of the main slate belt and sericite occurs in a few places. This does not mean that chlorite is ubiquitous in either the eastern edge of the main belt or in the belt by Otter Creek. Chlorite and sericite developed during the later stages of deformation, being found only within S_2 and S_3 planes. The degree of this replacement is fairly complete in some areas, sericite occurring only where the replacement is complete. As the degree of cleavage development increases, the degree of replacement increases, and so it is only within the most intensely deformed areas of the main slate belt that sericite is common. Except in these intensely deformed areas, the chlorite is restricted to the last generation of cleavage.

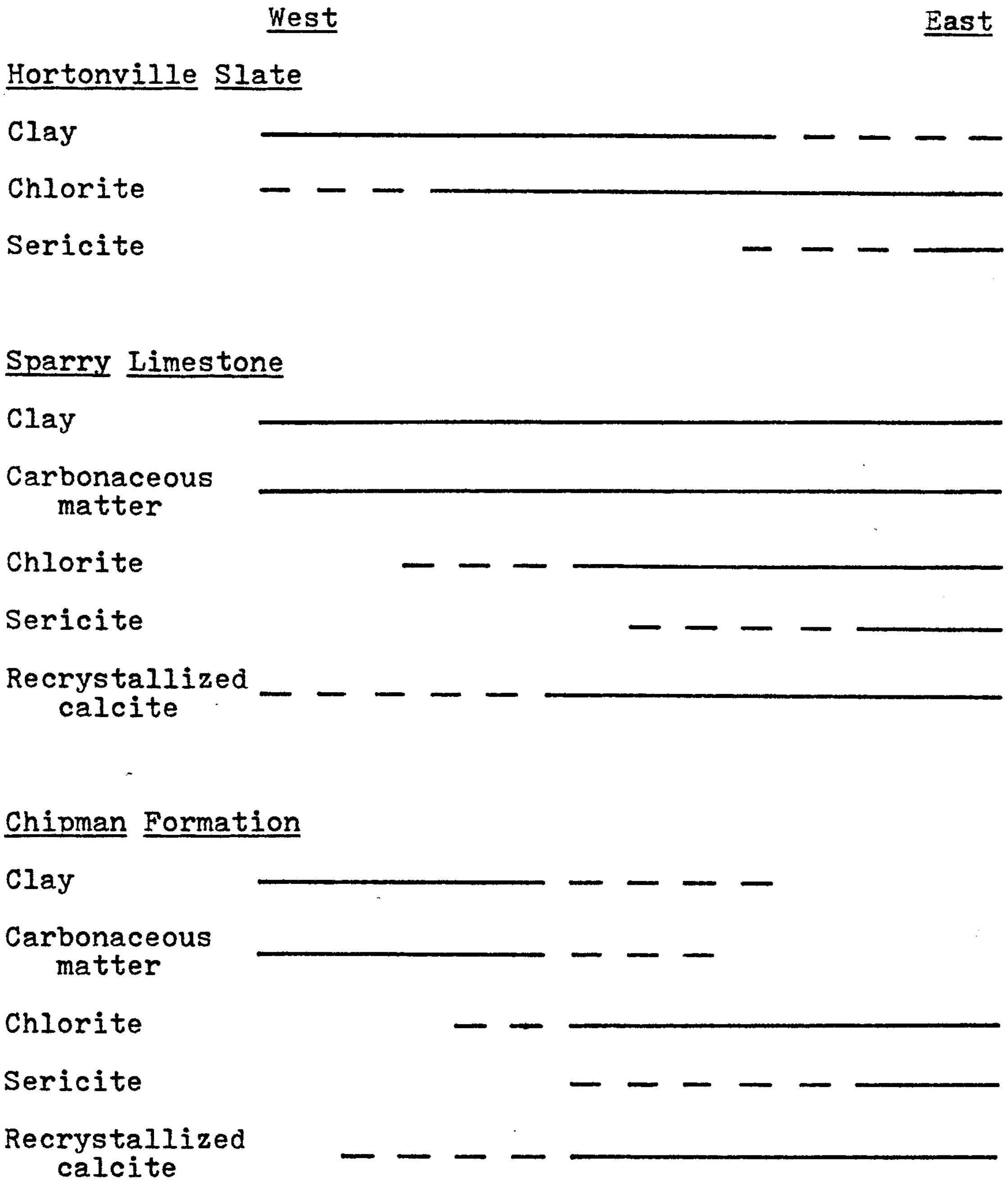


Figure 23 - Spatial distribution of minerals of interest in the study area. Solid lines indicate common occurrence, dashed lines indicate rare occurrence.

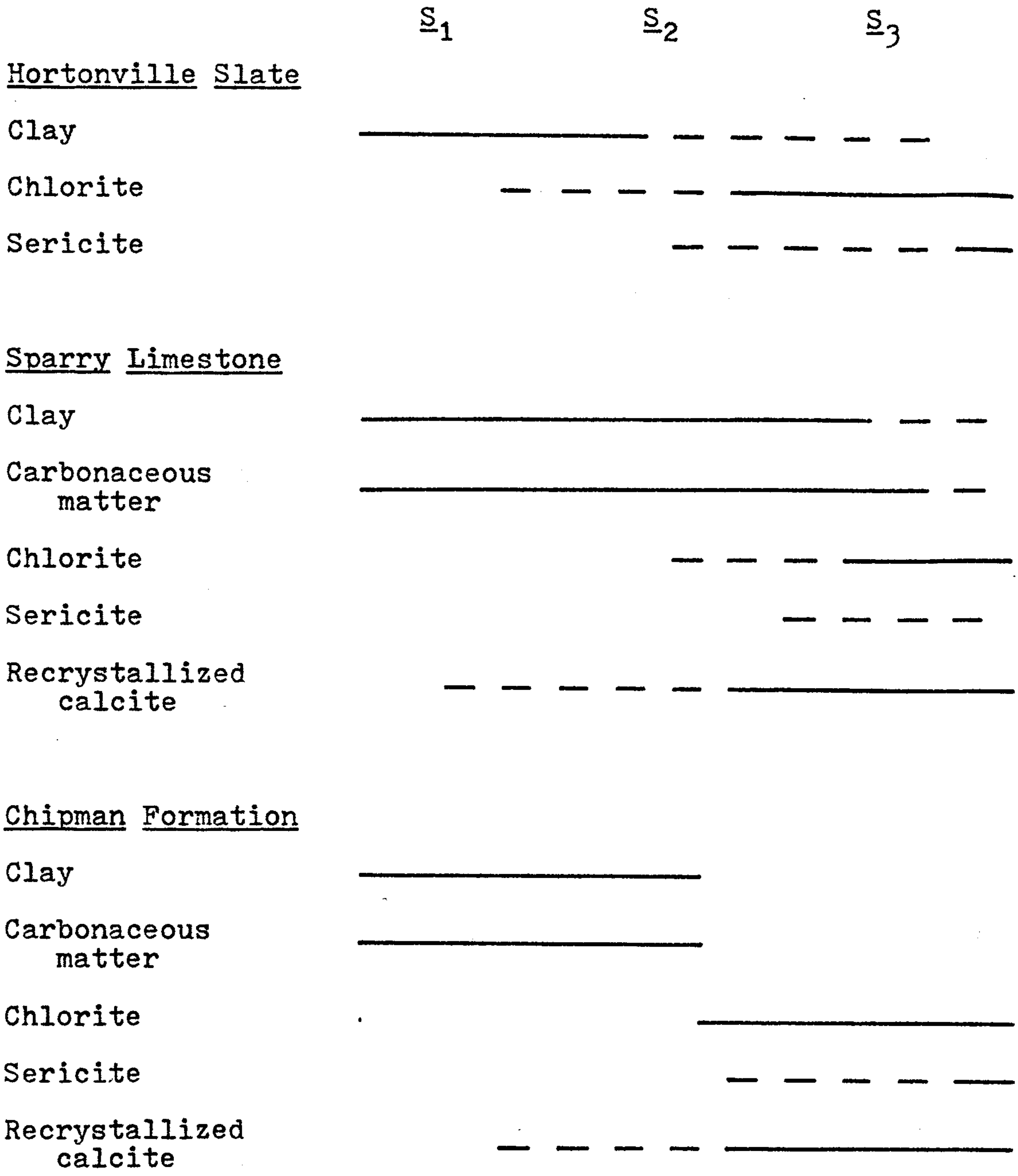


Figure 24 - Metamorphic and primary minerals vs. structural elements. Left to right within each category can represent either increasing development of the structural element or position west to east since metamorphic grade increases eastward for each deformational event. Symbols have same meaning as in figure 23.

In the belt of slate by Otter Creek, the same general relationships seem to exist. Thus, in the multiply deformed zone directly below the Chipman formation, sericite is ubiquitous, but near the base of the slate, chlorite does not always occur. That the metamorphic grade does generally increase from west to east is indicated by the occurrence of chlorite in most of the less deformed parts and the occurrence of sericite outside of the cleavage planes proper in the more highly deformed parts by Otter Creek, whereas the occurrences of these minerals are more limited in the main belt to the west.

In the Sparry limestone the metamorphic grade is apparently lower, the occurrence of chlorite and sericite being more limited. This is probably mainly due to the differences in the availability of necessary elements for their formation and the resulting compositional differences of the minerals. As in the Hortonville slate, the metamorphic minerals occur in association with certain structural elements. In the Sparry limestone they only occur in S_3 planes except for the eastern edge where they are found in a few S_2 planes. There is a gradation within the Sparry limestone from the west to the east showing an increasing metamorphic gradient. Along the western edge of the Sparry limestone, very little of the clay and carbonaceous matter has been replaced by chlorite, and sericite is unknown. Passing east across the Sparry limestone, chlorite increasingly replaces the clay and carbonaceous matter within the S_3 planes. Near the eastern edge of the area, the replacement is complete and some sericite is present. The exact limits of the sericite are difficult to define, some appearing in places before all of the clay and carbonaceous matter is totally replced.

The metamorphism of the Chipman formation varies the most of all the formations of the study area. On the eastern side of the area it is mainly marble, chlorite being ubiquitous. This marble shows a very strong flattening of grains similar to that produced experimentally in the Solenhofen limestone by Kern (1977) with relatively high temperatures and strain rates. These characteristics are found along the northern edge of the area from Crosby's (1963) station 10 eastwards. At that point, there is a sudden change from high recrystallized marble on the east to basically unrecrystallized limestone and dolomite to the west. At the same point there is a sudden disappearance of all chlorite and sericite. West of the main slate belt, there is no sign of any chlorite or sericite in any of the formations and the recrystallization of the calcite is not as pronounced as it is to the east.

Contact Metamorphism

There are only two small igneous bodies within the study area, so there is very little possibility for extensive contact metamorphism. Microscopic examination of the limestone along the contact with the two lamprophyre dikes shows virtually no metamorphic effects. There is no apparent change in grain size of either the calcite or the clay. The only noticeable effect is traces of prehnite(?) within 0.1 millimeter of the contact.

Structural Relations

The structural elements in the Middlebury area can be grouped into three separate deformational events. These events correspond to the three generations of cleavage, and each has its own structural and stratigraphic associations. The relative ages of these events is established by the relative ages of their associated cleavages.

First Deformation

The early cleavage does not appear to be related to any other major structural element. Neither this study nor earlier investigations have found any evidence for an episode of folding predating the main folding event, which folds S_1. The consistently high angle between this cleavage and bedding, although not based on sufficient data, is consistent with a lack of folding.

Recent mapping in the central Appalachians (Engelder and Engelder, 1977; Engelder, 1979; Engelder and Geiser, 1979; Washington, 1980) has discovered cleavages developed in unfolded rocks. Those cleavages occur primarily in the limestones with minor development in the shales. It has been demonstrated that the cleavages are stratigraphically bound, each occurring only above a specific horizon. Since these cleavages are the result of shortening of the strata (Slaughter, 1980), the bounding stratigraphic horizons, which always are less competent than the overlying strata, must contain decollements (figure 25).

In the study area, there is presently insufficient data to determine the stratigraphic bounds of S_1 development. The lack of development in the sandstones and dolomites of the middle Bascom formation may simply represent a lower susceptibility to cleavage formation. Since S_1 has never been reported from the formations below the Bascom formation, which below the Cutting dolomite do not contain cleavage, although some are favorable for cleavage formation, it is quite probable that the detachment surface is quite shallow. The interbedded limestone and shale facies of the Bascom formation is a likely horizon. Kehle (1970) has shown that such lithologies are favorable sites for decollement development in sequences. Therefore, although the position of the decollement cannot be established with certainty, it seems likely that the first deformation was a thinskinned event, happening above a decollement that possibly lay in the uppermost Bascom formation.

Second Deformation

The second deformational event in the study area produced isoclinal folds with an axial plane cleavage, S_2. The mineral lineation was also formed at that time. These elements are developed throughout the area and are associated with chlorite metamorphism on the eastern edge of the study area.

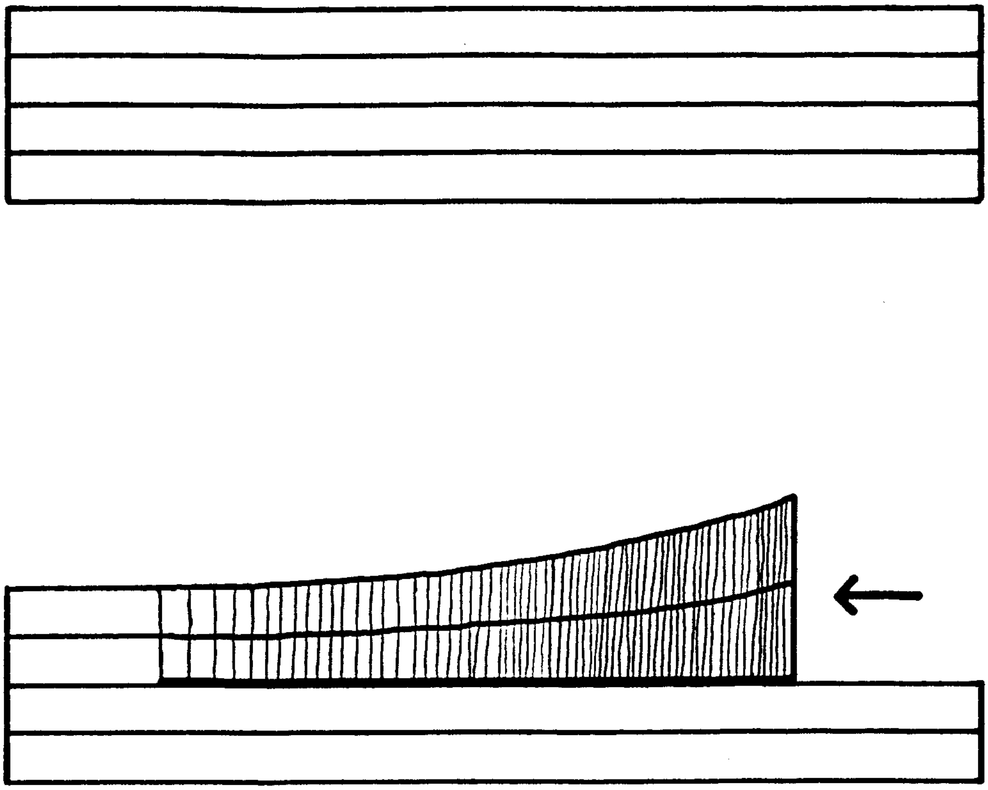


Figure 25 - Relative movement on a decollement where the upper plate moves due to shortening by cleavage formation without folding.

Although this was the dominant deformation within the Middlebury synclinorium, neither Cady (1945) nor Crosby (1963) considered it to have formed the main fold structure of the synclinorium. The consistent northwest fold orientation does not match the north-south synclinorium trend, and there is no evidence of major folds with sufficient magnitude.

Although no stratigraphic control can be shown for this deformation within the study area because the whole area is affected, reconnaissance work and Crosby's (1963) data indicate that the deformation is not found below the Cutting dolomite. The exact horizon where the cleavage and folding dies out has not been determined, but the change must be quite sharp since these elements are strongly developed in the upper Cutting dolomite but are totally absent below that formation.

The folds and cleavage represents a large amount of strain in the rocks above this structural discontinuity that the rocks below did not experience. Thus there must have been movement along that zone making it a decollement (figure 26). Welby's (1961a) map also shows that this generation of folds and cleavage is developed across a large portion of the Champlain lowlands west of the Champlain and Orwell thrusts which supposedly mark the western edge of the Middlebury synclinorium.

The genetic relationship between the mineral lineation and any of the fold generations or cleavages is

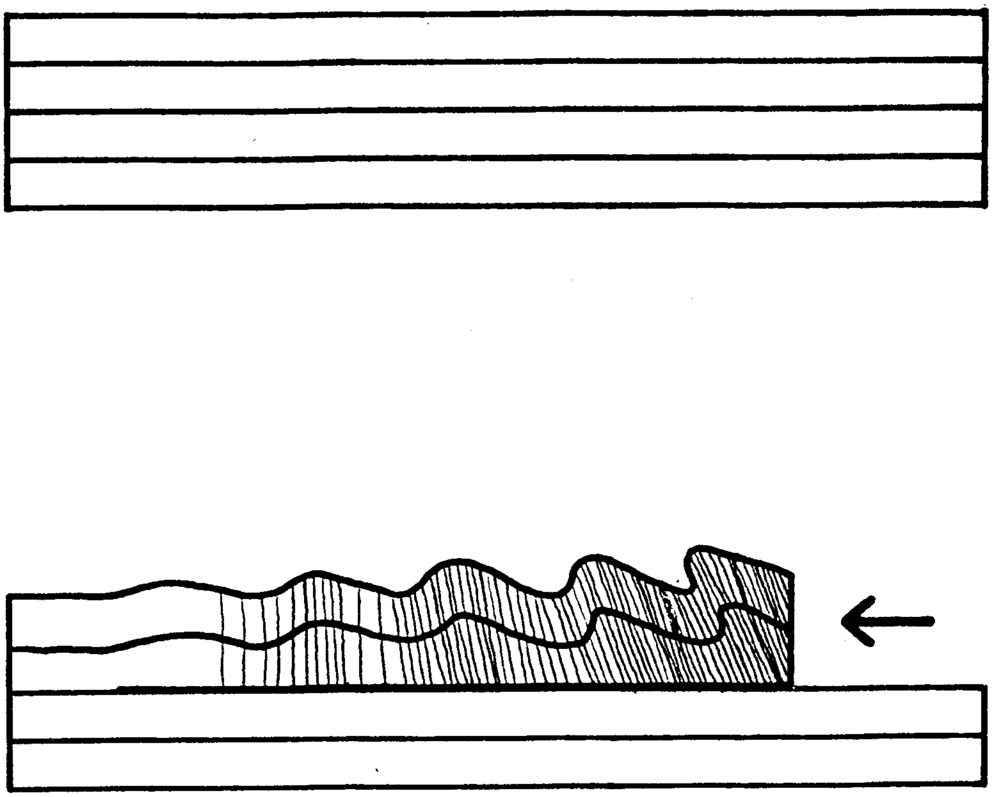


Figure 26 - Movement on a decollement due to shortening of the upper plate by folding and cleavage formation.

unclear. It was apparently formed at the same time as S_2 since it lies within the S_2 plane, but it is neither parallel nor perpendicular to the fold hinges.

Third Deformation

The third phase of deformation in the Middlebury area is represented by the crenulation cleavage and the second generation of folds. It was accompanied by chlorite metamorphism throughout much of the area and sericite development along the eastern edge of the study area.

The crenulation cleavage only occurs in relatively narrow zones in the Sparry limestone and adjacent Hortonville slate. In the limestone these zones generally range from two to fifteen meters thick and dip eastward at 15° to 35° (figure 27). The boundaries of these zones are quite sharp, with the crenulation cleavage planes and associated folds dying out in less than two centimeters in the narrowest zones and less than 30 centimeters in the widest zones.

The crenulation folds are all asymmetric in the same sense throughout the study area: the west limbs of the anticlines are shorter than the eastern limbs. If the crenulation cleavage were the result of the folding of a layer similar to that found in most areas where crenulation cleavage exists, the sense of asymmetry would be opposite on opposite limbs of the folds. The edges of the zones also do not follow bedding. Thus it appears

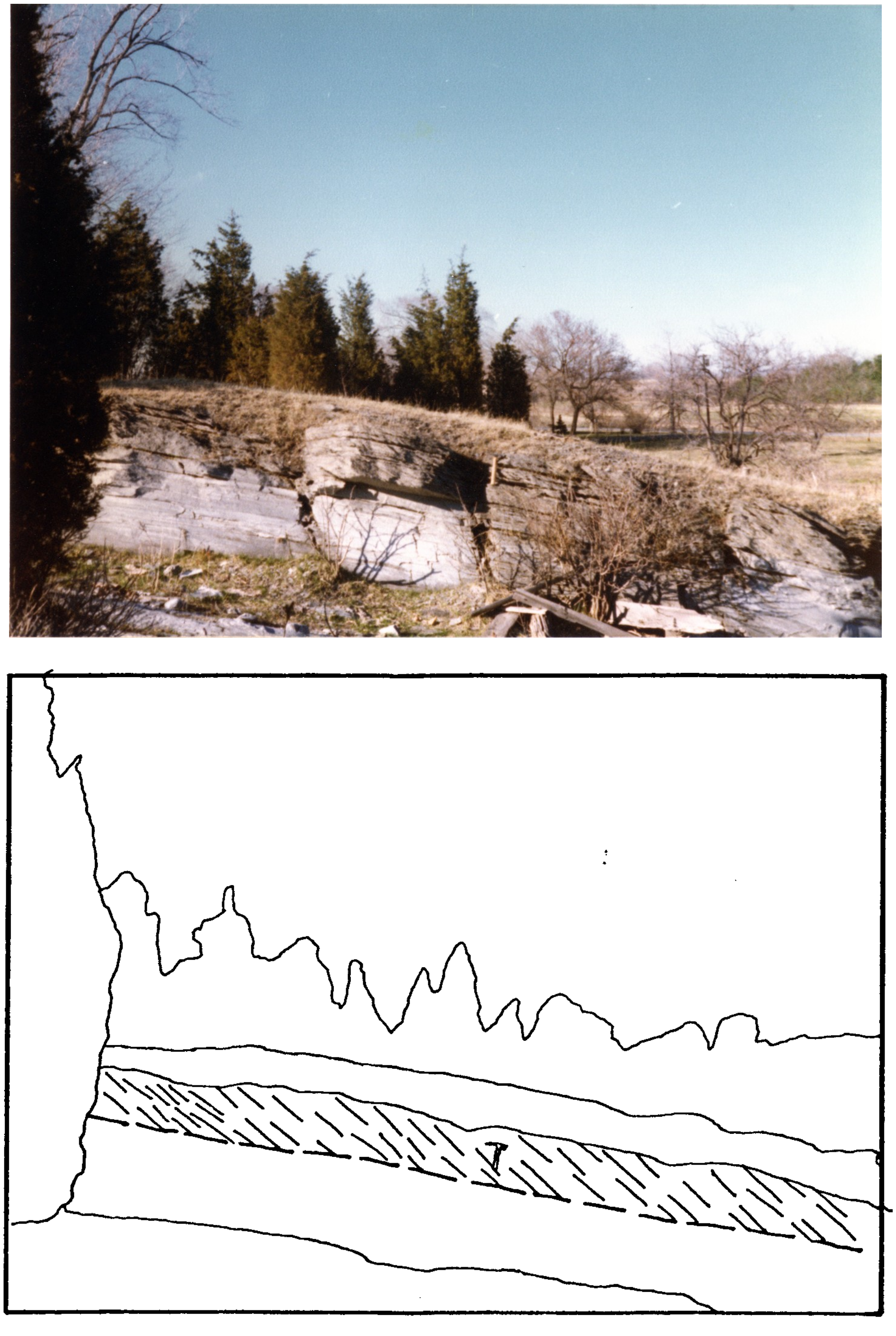


Figure 27 – Base of a crenulation cleavage zone dipping eastward. Outcrop located just west of Vt. Rte. 23 north of Perkins Road.

unlikely that they formed during the development of a major fold such as that of the Middlebury syclinorium.

Although the dip of these zones can rarely be determined in outcrop, there is subsurface control provided by water wells (table 1). Although accurate lithologic descriptions of the wells are totally lacking, they are still useful. Wherever there are closely spaced wells, the depths to water-bearing veins always defines planes which intersect the surface along the outcrop of S_3 zones (figure 28). Outside of the subsurface extrapolations of the S_3 zones, insufficient water is found for even household use. All bedrock springs in the area also occur along the outcrop of these zones.

The zonal nature of the S_3 occurrences suggests a shear zone mechanism, and the dip of the zones and the sense of asymmetry of the crenulations suggest that the movement was thrusting from east over west. The termination and offset of strata by these zones strongly supports this view, and the repetition of the sequence is consistent. Even the metamorphic continuity is disturbed by these zones, with the marble ending abruptly at the western edge of Crosby's (1963) station 10 along a major zone. The consistent occurrence of these zones along the eastern but not the western boundaries of the slate belts indicates that these belts are caught under such thrusts.

The lower limits of this deformation can be placed with reasonable assurance within the uppermost Bascom for-

TABLE 1

Well	Depth	Yield
A	382 feet	6 gal/min.
B	260	5
C	535	25
D	90	15
E	200	10
F	150	10
G	180	30
H	80	20
I	185	1½
J	215	2
K	150	4
L	335	5
M	280	7
N	400	4
O	245	20
P	100	15
Q	425	6

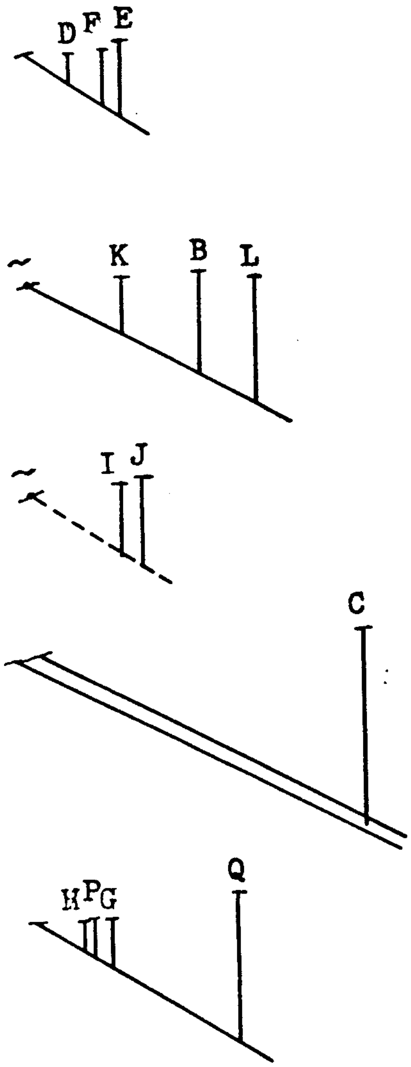


Figure 28 - Cross-sectional view of water wells defining dips of S_3 zones and thrusts. Same scale as plate 1.

mation. The lack of discernible deformation in the Bascom formation would tend to indicate this, but it is not conclusive. The additional evidence is provided by the eastern contact between the Sparry limestone and associated Hortonville slate and the Chipman formation. This contact is a thrust (figure 29) which is continuous from the Middlebury area south to the Sudbury nappe (Voight, 1965; 1972), which is just an extension of the thrust sheet westward over the Sparry limestone and part of the Hortonville slate. Along this whole line, the Chipman formation is the lowest unit involved, even though it is a thrust at least five kilometers westard within the Sudbury nappe. Therefore, this is not the deep-seated event which formed the main fold of the Middlebury synclinorium.

Figure 29 – Thrust contact between the Chipman formation (above) and the Hortonville slate (below) by Otter Creek in Middlebury.

Conclusion

The structure of the Middlebury area has traditionally been considered a synclinorium (figure 30). The theory has existed for over a century without being rigorously tested. It has been based primarily on stratigraphic correlations and outcrop patterns.

This investigation has discovered that the Middlebury area has experienced three deformations. The first of these has been almost totally obscured by the the later two and has therefore gone unnoticed by previous investigators. All three deformations apparently affected only the upper formations and were bounded below by decollements. This study has found no evidence of a deep-seated fold under the core of the "synclinorium" and the orientations of the foliations is constant across the area, so no major folds formed after the deformations discussed. The later movement on the Champlain and Orwell thrusts did no more than to warp the section toward the west, not being associated with any penetrative deformation.

The metamorphic history of the area may hold the key to the age of the deformations. The grade of the metamorphism shows a steady increase with each deformational event, indicating that they may be part of a single progressive deformational and metamorphic event. Age dates in Vermont indicate that the major progressive metamorphic event in western Vermont was during the late Ordovician,

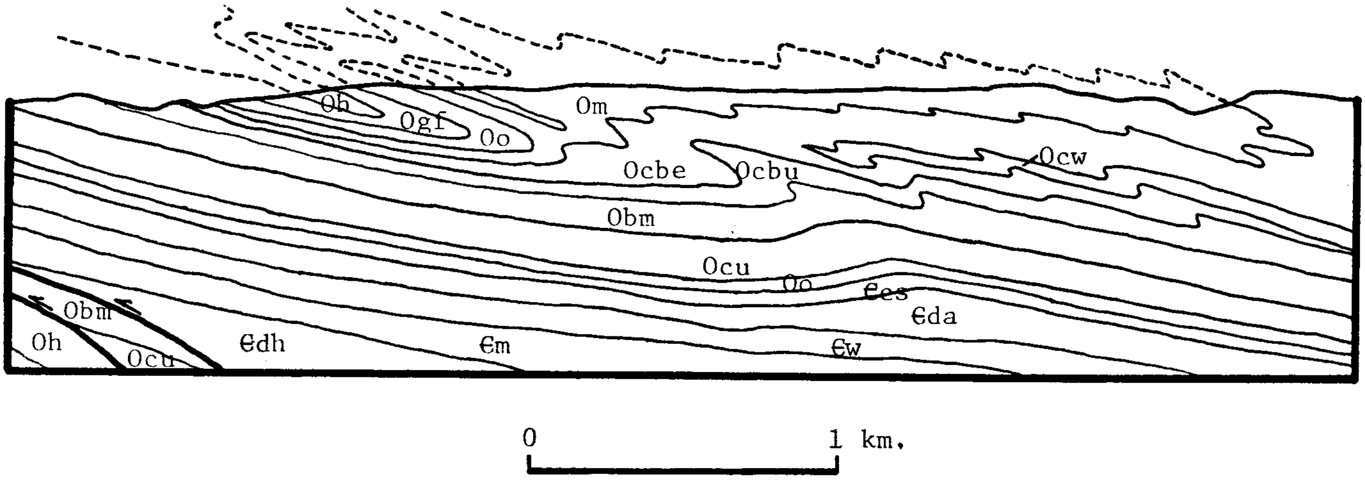


Figure 30 - Cross-section showing Cady's (1945) interpretation of the structure of the study area. Section is between the cross-sections in plate 2.

i.e. the Taconic orogeny. The olistoliths in the Hortonville slate mean that there was deformation going on in western Vermont at the time that it was deposited. Thus all of the deformations in the Middlebury area can be inferred to have occurred during the Taconic orogeny in the middle to late Ordovician.

References Cited

Bain, G. W., 1927, Geologic history of the Green Mountain front: Vt. State Geologist, 15th report, 1925-26, p. 222-241.

Baldwin, Brewster, 1977, Tectonic implications of the Crown Point section, New York: Geol. Soc. America abstracts with programs, v. 9, p. 240.

Bassler, R. S., 1950, Faunal lists and descriptions of Paleozoic corals: Geol. Soc. America memoir 44, 315p.

Brace, W. F., 1953, The geology of the Rutland area, Vermont: Vt. Geol. Survey Bull. 6, 120p.

Brainard, Ezra, 1891, The Chazy formation in the Champlain valley: Geol. Soc. America Bull., v. 2, p. 293-300.

Brainard, Ezra, and Seely, H. M., 1890, The Calciferous formation in the Champlain valley: Geol. Soc. America Bull., v. 1, p. 501-516.

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

Cady, W. M., 1969, Regional tectonic synthesis of north-western New England and adjacent Quebec: Geol. Soc. America memoir 120, 181p.

Cady, W. M., and Zen, E-an, 1960, Stratigraphic relationships of the lower Ordovician Chipman formation in west-central Vermont: Amer. Jour. Science, v. 258, p. 728-739.

Coney, P. J., Powell, R. E., Tennyson, M. E., and Baldwin, Brewster, 1972, The Champlain thrust and related features near Middlebury, Vermont: New England Intercoll. Geol. Conf., 64th ann. mtg., p. 97-115.

Cosgrove, J. W., 1976, The formation of crenulation cleavage: Jour. geol. Soc. London, v. 132, p. 155-178.

Crosby, G. W., 1963, Structural evolution of the Middlebury synclinorium, west-central Vermont: Ph. D. dissert., Columbia University, 136p.

Dale, N. C., 1921, Notes on the areal and structural geology of a portion of the western flank of the Green Mountain range: Vt. State Geologist, 12th report, 1919-20, p. 43-56.

Dale, T.N., 1912, The commercial marbles of western Vermont: U. S. Geol. Survey Bull. 521, 170p.

Dana, J. D., 1877a, An account of the discoveries in Vermont geology of the Rev. Augustus Wing: Amer. Jour. Science, 3rd series, v. 13, p. 332-347, 405-419.

Dana, J. D., 1877b, Supplement to an account of the discoveries in Vermont geology of the Rev. Augustus Wing: Amer. Jour. Science, 3rd series, v. 14, p. 36-37.

Engelder, T., 1979, The nature of deformation within the outer limits of the central Appalachian foreland fold and thrust belt in New York State: Tectonophys., v. 55, p. 289-310.

Engelder, T., and Engelder, R., 1977, Fossil distortion and decollement tectonics of the Allegheny plateau:

Geology, v. 5, p. 457-460.

Engelder, T., and Geiser, P. A., 1979, The relationship between pencil cleavage and lateral shortening within the Devonian section of the Allegheny plateau, New York: Geology, v. 7, p. 460-464.

Gordon, C. E., 1923, Studies in the geology of western Vermont: Vt. State Geologist, 13th report, 1921-22, p. 143-285.

Gray, D. R., 1979, Microstructure of crenulation cleavages: an indication of cleavage origin: Amer. Jour. Science, v. 279, p. 97-128.

Hickcox, C. W., 1964, Geology field project, Middlebury College.

Hitchcock, Edward, Hitchcock, Edward, Jr., Hager, A. D., and Hitchcock, Charles, 1861, Report on the Geology of Vermont, published for the legislature in Claremont, N. H., 2 vols.

Kay, Marshall, and Cady, W. M., 1947, Ordovician Chazyan classification in Vermont: Science, v.105, p. 601.

Kehle, R. O., 1970, Analysis of gravity sliding and orogenic translation: Geol. Soc. America Bull., v. 81, p. 1641-1664.

Kern, J. C., 1977, Preferred orientation of experimentally deformed limestone marble, quartzite, and rock salt at different temperatures and states of stress: Tectonophys., v. 39, p. 103-120.

Marlow, P. C., and Etheridge, M. A., 1977, The development of a layered crenulation cleavage in mica schists of the Kanmantoo group near Macclesfield, South Australia: Geol. Soc. America Bull., v. 88, p. 873-882.

McHone, J. G., 1978, Distribution, orientations, and ages of mafic dikes in central New England: Geol. Soc. America Bull., v. 89, p. 1645-1655.

Osberg, P. H., 1952, The Green Mountain anticlinorium in the vicinity of Rochester and East Middlebury, Vermont: Vt. Geol. Survey Bull. 5, 127p.

Perkins, G. H., 1908, Preliminary report on the geology of Chittenden County: Vt. State Geologist, 6th report, 1907-08, p. 221-264.

Perkins, G. H., 1910, Geology of the Burlington quadrangle: Vt. State Geologist, 7th report, 1909-10, p. 249-256.

Perkins, G. H., 1916, The geology of western Vermont: Vt. State Geologist, 10th report, 1915-16, p. 200-231.

Quinn, A. W., 1933, Normal faults of the Lake Champlain region: Jour. Geology, v. 41, p. 113-143.

Rickard, M. J., 1961, A note on cleavages in crenulated rocks: Geol. Mag., v. 98, p. 324-332.

Rodgers, John, 1937, Stratigraphy and structure in the upper Champlain valley: Geol. Soc. America Bull., v. 48, p. 1573-1588.

Roy, A. B., 1973, Nature and evolution of subhorizontal crenulation cleavage in the type Aranalli rocks around Udaipur, Rajastan: Proc. Indian Natl. Sci. Acad., v. 39, p. 119-131.

Seely, H. M., 1910, Preliminary report on the geology of Addison County: Vt. State Geologist, 7th report, 1909-1910, p. 257-313.

Slaughter, James, 1980, Strain and strain partitioning in middle Devonian rocks of the eastern New York plateau: Geol. Soc. America abstracts with programs, v. 12, p. 83.

Soule, J. M., 1967, Structural geology of a portion of the north end of the Middlebury synclinorium, Weybridge, Addison County, Vermont: Senior Thesis, Middlebury College.

Stone, S. W. and Dennis, J. G., 1964, The geology of the Milton quadrangle, Vermont: Vt. Geol. Survey Bull. 26, 79p.

Swinnerton, A. C., 1932, Structural geology in the vicinity of Ticonderoga, New York: Jour. Geol., v. 40, p. 402-416.

Talbot, J. L., and Hobbs, B. E., 1968, The relationship of metamorphic differentiation to other structural features at three localities: Jour. Geology, v. 76, p. 581-587.

Turner, F. J., and Weiss, L. E., 1963, Structural Analysis of Metamorphic Tectonites, McGraw-Hill, New York, 545p.

Voight, Barry, 1965, Structural studies in west-central Vermont: Ph. D. dissert., Columbia University.

Voight, Barry, 1972, Excursions at the north end of the Taconic allochthon and the Middlebury synclinorium, west-central Vermont, with emphasis on the structure of the Sudbury nappe and associated parautochthonous elements: New England Intercoll. Geol. Conf., 64th ann. mtg., p. 49-96.

Washington, Paul, 1980, Evidence for multiple generations of cleavage in the Lackawanna syncline and the Pocono plateau; their possible tectonic significance: Geol. Soc. America abstracts with programs, v. 12, p. 88.

Welby, C. W., 1961a, Bedrock geology of the central Champlain valley of Vermont: Vt. Geol. Survey Bull. 14, 296p.

Welby, C. W., 1961b, Occurrence of Foerstephyllum in Chazyan rocks of Vermont: Jour. Paleontology, v. 35, p. 391-394.

Williams, P. F., 1972, Development of metamorphic layering and cleavage in low grade metamorphic rocks at Bermagui, Australia: Amer. Jour. Science, v. 272, p. 1-47.

Wing, Augustus, 1858-1876, 5 notebooks and assorted letters in the library of Middlebury College.