GEOLOGY OF THE WESTERN BOUNDARY
OF THE TACONIC ALLOCHTHON NEAR TROY
AND THE ANASTOMOSING CLEAVAGE IN THE TACONIC MELANGE

Abstract of

a thesis presented to the Faculty

of the State University of New York

at Albany

in partial fulfillment of the requirements

for the degree of

Master of Science

College of Science and Mathematics

Department of Geological Sciences

Zong-Guo Xia

1983

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ABSTRACT

The Taconic Allochthon is located in eastern New York, western Vermont, western Massachusetts, and western Connecticut and extends about 200 kilometers north-south and east-west for about 25 kilometers. It contains rocks of Late Proterozoic, Cambrian and Ordovician age. The rocks are predominantly slates with lesser amounts of arenites, wackes, limestone, chert, and conglomerates. All rocks have been subjected to chlorite or biotite grade metamorphism and at least two generations of deformation. The emplacement of the Taconic Allochthon onto the coeval shelf took place during the Middle Ordovician Taconic Orogeny.

The study area lies at the western margin of the Taconic Allochthon. Field mapping indicates that in the present area the stratigraphy of the Taconic allochthonous sequence and the lithological characteristics of individual rock units match the descriptions of Jacobi (1977) and Rowley et al. (1979) in the Granville area and in central Washington County. The stratigraphic units observed include the Bomoseen Formation, the Truthville Formation, the Browns Pond Formation, the Indian River Formation, the Mount Merino Formation and the Snake Hill Formation. The well-known Diamond Rock Quartzite was found to lie near the base of the Browns Pond Formation and a correlation with the Mudd Pond Quartzite in the northern Taconics is suggested. It is also demonstrated that the "Troy Shale" of Ruedemann actually lies at the same stratigraphic level as his "Nassau Beds".

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The most remarkable structural features of the mapped area are the widespread distribution of commonly tight, westward-leaning or overturned folds, the presence of the basal thrust of the Taconic Allochthon and the development of peculiar anastomosing cleavages in the Taconic Melange beneath the Allochthon. Anastomosing cleavages were produced after the formation of slaty cleavages parallel to the axial plane of mesoscopic folds. Observations at the outcrop scale and under the microscope suggest that the anastomosing cleavage surfaces are possibly conjugate shears arranged in various orientations oblique to the normal to the axial plane cleavages.

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CHAPTER 1 INTRODUCTION

GEOGRAPHIC LOCATION

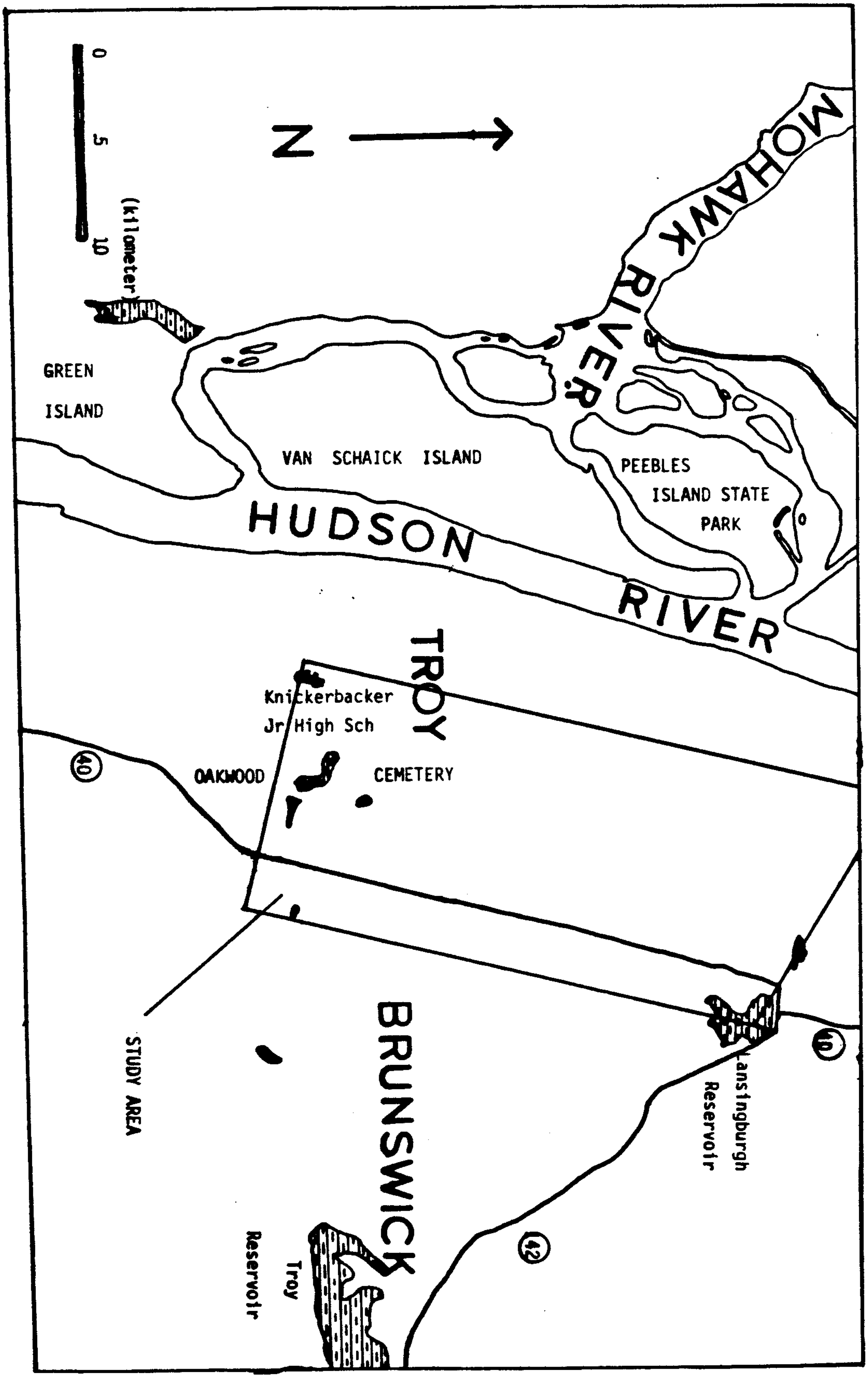
The study area is part of the Troy North 7 ½ minute quadrangle, New York. Its eastern boundary is about 250 meters eastwards from Route 40. The western boundary roughly follows the bottom of the hillside, that is, the eastern boundary of the City of Troy. It begins near the Devil's Kitchen in Oakwood Cemetery in the south and is bounded by the Northern Drive in the north. It covers an area of about 3.8 square kilometers (Figure1.1).

The topography of the area can be approximately described as a stairway-shaped topography. On the east side and west side of the area, topography is rather flat. Two flat surfaces are joined by a quite steep slope which is about 50 meters high and faces towards the west. The formation of the topographic relief is mainly owing to the large contrast in resistance to erosion between chert beds on the hilltop and shales in the Hudson River Valley.

Since the area is right in the suburbs of the City of Troy, the transportation is convenient. The Hudson River is located about 500 meters west of the area.

The exposure in the area is fair. Outcrops are mostly concentrated on the slope. However, some of the outcrops can not be easily reached due to the steepness of the slope and the dense woods during the summer season.

Figure 1.1 Geographic Location of the Study Area


N
0
5
10
(kilometer)
MOHAWK RIVER
GREEN ISLAND
VAN SCHAICK ISLAND
PEEBLES ISLAND STATE PARK
HUDSON RIVER
TROY
Knickerbacker
Jr High Sch
OAKWOOD
CEMETERY
40
STUDY AREA
BRUNSWICK
Lansingburgh
Reservoir
42
Troy
Reservoir

TECTONIC SETTING

The map area is on the west limb of the Middlebury synclinorium and contains the base of the Giddings Brook slice of the Taconic Allochthon (Figure 1.2). The so-called Logan's Line thrust which defines the western edge of the Allochthon passes through the map area.

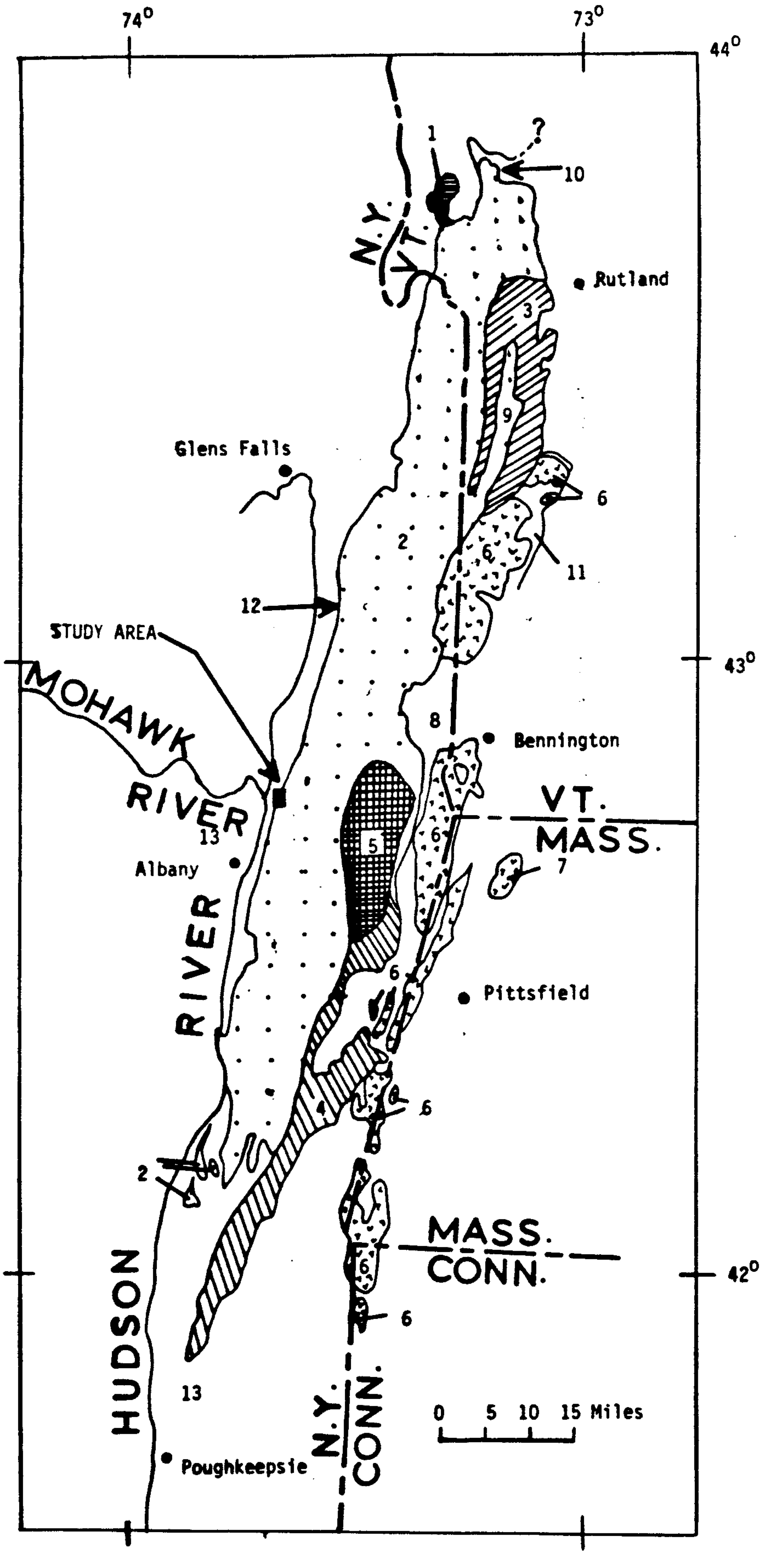
On the east side of the Logan's Line thrust, the Taconic Allochthon extends eastwards for about 20 kilometers. Adjacent to the Taconic sequence on the west are graywacke and shale deposits of the Hudson River Valley which are part of a nearly continuous Middle Ordovician flysch sequence extending along the Appalachian orogenic belt from Newfoundland to Alabama (Enos, 1969; Williams, 1978). Farther to the northwest is the Adirondack massif of Precambrian crystalline basement rocks. Adjacent to the Taconic sequence on the east is a narrow band of mainly dolomitic and sandy carbonates and sandstones of a sedimentary shelf sequence of Cambro-Ordovician age. Farther to the east are highlands of Precambrian crystalline basement rocks.

PURPOSES OF THE PRESENT STUDY

(1) It has long been claimed that the rocks in the southern Taconics were sufficiently different from the northern Taconics such that different names should be employed. Therefore, the Taconic geologists were often bogged down in a nomenclatorial labyrinth. Recently, Jacobi (1977), and Rowley et al. (1979) have done the most detailed stratigraphic studies in the Granville area and in Central

Figure 1.2 Tectonic Location of the Study Area

(1) Sunset Lake slice; (2) Giddings Brook slice; (3) Bird Mountain slice; (4) Chatham slice; (5) Rensselaer Plateau slice; (6) Dorset Mountain slice and equivalents; (7) Greylock slice; (8) Hoosick Falls embayment; (9) Edgerton half-window; (10) Sudbury slice; (11) carbonate sliver underlying Dorset Mountain slice; (12) Bald Mountain carbonate sliver; (13) Taconic autochthonous sequence (after Zen, 1967).


74°
73°
44°
43°
42°
1
?
10
N.Y.
VT.
Rutland
3
9
Glens Falls
6
2
6
11
12
STUDY AREA
MOHAWK
RIVER
8
Bennington
VT.
MASS.
5
6
7
13
Albany
RIVER
Pittsfield
6
4
6
2
MASS.
CONN.
6
6
HUDSON
13
N.Y.
CONN.
0 5 10 15 Miles
Poughkeepsie

Washington County, New York. Based on the previous work and their own investigation, they have proposed a comprehensive scheme of stratigraphic subdivisions and a set of systematic lithological descriptions. Jacobi (1977) also advocates a single column with a single set of descriptions and a single set of names for the entire Taconic Allochthon. The present study attempts to test the applicability of their scheme and to explore the possibility to unify the stratigraphic terminology in the Taconic region.

(2) In plate tectonics, melange has been used as one of the most important criteria for identifying the ancient convergent plate boundaries (Hsu, 1968). Besides the presence of exotic and/or native inclusions in a weaker matrix and widespread small folds, the pervasive development of anastomosing cleavages forms another most distinctive feature for recognizing melange bodies. Although this type of cleavage has been noticed by many previous workers (Hsu, 1968; Cowan, 1974; Moore and Karig, 1980), detailed studies have never been conducted on it. Therefore, the actual morphological characteristics and tectonic significance of anastomosing cleavages have never been fully understood. The present investigator intends to make the first move towards this unexplored subject, specifically, to find out the actual morphological characteristics, to understand the nature of individual cleavage surfaces and to explore the possible origin of the anastomosing cleavages in the dark gray to black shales along the Hudson River Valley near Troy. Bosworth and Vollmer (1981) suggested that anastomosing cleavages could be produced due to non-coaxial deformation under simple shear at high strain rates. They (Bosworth and Vollmer, 1982) also proposed that the formation of anastomosing cleavages was through the progressive development

and continued offset of conjugate microshears. Thus, a major aim of the present study has been to determine independently whether the anastomosing cleavage seen in Troy area represents a coaxial or non-coaxial progressive deformation.

(3) Like the other studies of small scale structures, one of the main objectives in studying anastomosing cleavage is to produce a better picture of the regional tectonics. In order to relate the anastomosing cleavage to the regional structures, a small area has been mapped at a scale of 1" : 200". Since the existence and the sense of the basal thrust of the Taconic Allochthon have previously been mainly determined by stratigraphic studies, it is hoped that they can also be demonstrated from the viewpoint of small scale structures.

CHAPTER 2 HISTORY OF GEOLOGICAL STUDY IN THE TACONIC REGION

Historically, the study of the Taconic geology can be roughly divided into four stages.

THE FIRST STAGE: 1800-1842 This stage may be called the early investigation.

The study of Taconic geology can be traced back to the early days of American geology. Amos Eaton prepared a section from the Catskill Mountains to the Atlantic ocean as early as 1819 and by 1820 he had examined the rocks along several sections between Massachusetts and the Hudson, besides making various excursions elsewhere----2000 miles of which were made on foot. Within ten years from 1818, he made fifteen sections from the Hudson River to the Taconic Mountains in order to ascertain the conformability and order of rock succession (Eaton, 1828). However, the name "Taconic" first came into topographic geology through Professor Chester Dewey.

In 1819, Dewey published a geological description of the Williamstown portion of the Taconic region. In this paper (on p. 377) he mentioned the Indian orthography of Taconic and gave the word its present shape. In 1820, this paper was followed by another on a "Geological Section from the Taconic Range in Williamstown to the City of Troy". In 1824, he published another article entitled "Geology of Western Massachusetts and a Small Part of the Adjoining States", illustrated with a colored geological map embracing all Berkshire, the southern portion of Vermont, Canaan and Salisbury of Connecticut, and eastern New York to the Hudson.

In 1836, the New York Geological Survey was established with W. W. Mather, Ebenezer Emmons, Lardner Vanuxem and James Hall in charge of the four geological districts. Emmons' department was responsible for the northern and northeastern part of the state. Six years later the monumental GEOLOGY OF NEW YORK appeared. In this publication, Emmons (1842) proposed the time-stratigraphic term "Taconic System" to include all the rocks above the Precambrian and below the base of the New York System (Potsdam Sandstone).

THE SECOND STAGE: 1842-1888 The second stage can be also called "stratigraphic controversy".

The proposal of the "Taconic System" initiated the "Taconic controversy" of the last century. This early "Taconic controversy" was mainly focused on the relative ages of large stratigraphic units.

Actually, the controversy started when a special discussion about the "Taconic System" was held in April of 1841. Professors Henry D. Rogers, Edward Hitchcock, Wm. W. Mather, James Hall and Lardner Vanuxem took a prominent part in this first discussion. Among them, Professors Hitchcock, Rogers, Hall and Mather objected to the views of Professor Emmons, and Professor Vanuxem favored his views.

The abrupt entrance of the "Taconic System" into geological science stimulated intensive investigations within the Taconic area. The objectors wanted to find more evidence against Emmons' views while the advocates wished to collect more data to support his proposal. During this period, Professor Emmons published his revision of the "Taconic System" with additions and extension of its limits as a pamphlet in 1844 and made his third presentation of the "Taconic System" in his book "AMERICAN GEOLOGY".

This controversy continued until Dana (1877, 1886a, 1886b, 1888) and Walcott (1888) announced the discovery of "Lower Silurian" (Ordovician) fossils in limestone of the "Taconic System".

THE THIRD STAGE: 1888-1970 This stage may be called "klippe controversy".

The systematic stratigraphic work of Dale (1899, 1904a) and the paleontologic studies of Walcott (1891, 1912) demonstrated the age equivalence of the Taconic sequence with the surrounding carbonate-quartzite rocks. This demonstration raised another question. What are the spatial relationships between these two contrasting suites of rocks? This has been the center of the second Taconic controversy that stirred imagination and tempers since the turn of the century.

Dale (1899) interpreted the Cambrian and Ordovician rocks of the slate belt as autochthonous, related to the surrounding carbonate rocks through a lateral facies change.

Dale's model can not explain the lithic similarity between the Berkshire schist and rocks of the Taconic sequence, and between the two belts of synchronous carbonate rocks east and west of the Taconic sequence. These relations, as well as the existence of a well-documented thrust fault along the western edge of the Taconic sequence, prompted Ruedemann (1909) to suggest distinct troughs that have since been thrust westward over each other.

Keith (1912, 1932) developed Ruedemann's idea and suggested that the Taconics represented a large scale allochthon with roots 20 miles away in the Green Mountains.

Prindle and Knopf (1932) elaborated on the "Taconic allochthon" for area around Mount Greylock, Massachusetts, and considered the thrust surface to be recumbently folded. Larrabee (1939), Kaiser (1945) and Fowler (1950) accepted the allochthonous hypothesis in their studies.

However, Lochman (1956) considered an allochthon as unnecessary on the basis of a detailed study of paleontology in the Taconic sequence. She postulated that the Taconic sequence was deposited in an elongate basin existing on the eastern portion of the shelf, with depths of 300 to 600 feet, and that the change in sediment type from the carbonates of the shelf to the muds of the basin was due to a rapid lateral facies change.

MacFadyen (1956), Bucher (1957), Craddock (1957) and Weaver (1957), working in the central and southern Taconic region, were also among the resolute objectors to the concept of an allochthon. Their main objections were: (1) lack of a clearly defined continuing boundary thrust (Craddock, 1957); (2) lack of intensive boundary deformation (Bucher, 1957) and (3) lack of a recognizable root zone for the thrust (Hawks, 1941).

Faced with the serious challenge from the "non-klippenists", Zen (1956, 1961), Theokritoff (1959, 1964), Thompson (1959) and Shumaker (1959, 1960) remapped portions of the northern Taconic region in detail, and all came to the same conclusion that only the allochthonous hypothesis can explain the areal relations adequately. Platt (1960) and Potter (1972) were among other klippenists.

Rodgers (1951, p. 540) suggested gravity sliding as the cause of the Taconic Allochthon and it would later be suggested that the gravity emplacement of the Taconics occurred as a soft-sediment phenomenon (Rodgers in Billings et al., 1952; Zen, 1967; Rodgers and Fisher, 1969).

THE FOURTH STAGE: 1970 - present This stage may be described as plate tectonic modelling.

The modern phase of geological studies in Taconic region began with the application of plate tectonic theory to the Taconic rocks . Bird and Dewey (1970) applied the plate tectonic model to the interpretation of Appalachian geology and suggested that the initiation of a west-dipping subduction zone created the complex and related tectonic features in the Appalachian Mountains. On the basis of regional analysis, analogy with other areas and model experiments, Sales (1971) suggested that the Taconic Allochthon is a remnant of a rooted, geosynclinal thrust and not a gravity detachment slide. Interpreting the gravity relations around the Taconic klippe, Zen (1972) accepted the movement of an oceanic plate north and west toward the North American continent as the cause of the tectonic processes.

Recently, Chapple (1973, 1979), Rowley and Delano (1979), Rowley et al. (1979), and Rowley and Kidd (1981) postulated that the emplacement of the allochthon probably resulted from attempted subduction of the Atlantic-type continental margin in an east-dipping subduction zone.

CHAPTER 3 CURRENT KNOWLEDGE ON THE GEOLOGY OF THE TACONICS

The Taconic Allochthon is oriented in a NNE - SSW orientation and extends from the north to the south for about 200 kilometers and from the east to the west for about 20-30 kilometers. It is situated in eastern New York and western Vermont, western Massachusetts, and western Connecticut.

The Taconic Allochthon consists of predominantly argillaceous and arenaceous, with less calcareous and siliceous rocks of Early Cambrian (possibly Precambrian) to Medial Ordovician (Medial Caradocian) age. The presence of chert, turbidites, radiolaria and graptolites within the sequence indicate a deep-water environment. It is surrounded by an autochthonous to parautochthonous sequence of dominantly shallow marine clastics and carbonate rocks ranging in age from Early Cambrian to Medial Ordovician (Zen, 1967, 1972). Bird and Dewey (1970), and Rodgers (1968, 1970) proposed that this coeval clastic-carbonate and argillite-clastic sequences represent a carbonate shelf - continental rise pair of east-facing, Early Palaeozoic, Atlantic-type North American continental margin. Zen (1972) and Fisher (1977) also followed this paleogeographic reconstruction with some modifications. Bird and Rasetti (1968), and Zen (1961, 1967) suggested that the original site of deposition of the allochthonous Taconic rocks was on the east side of the present eastern limit of the carbonate rocks, possibly over the present Green Mountain, Berkshire, and Housatonic massifs. However, a recent study proposes that the easternmost limit of the North American Early Palaeozoic continent lies somewhere to the east of the Chester, Ray Pond, and Athens Domes (Rowley and Kidd, 1981).

Traditionally, the Allochthon has been divided into seven major separate, but nested thrust slices. From lowest to highest, they are: the Sunset Lake slice, Giddings Brook slice, Bird Mountain slice, Chatham slice, Rensselaer Plateau slice, Dorset Mountain slice and Greylock slice (Zen, 1967) (Figure 1.2). Harwood (1975) identified several other slices farther to the south, the June Mountain and Canaan Mountain slices. Sedimentary and tectonic melanges are exposed around the Taconic Allochthon (A general discussion on melange is given in Appendix I). Sedimentary melange includes the Whipstock Conglomerate along the east edge (Potter, 1972) and Forbes Hill Conglomerate along the west edge (Zen, 1961). Tectonic melange has been referred to as the Taconic Melange (Bosworth and Vollmer, 1981) or Poughkeepsie Melange (Fisher, 1977). The boundaries of slices are sometimes marked by slivers of shelf-derived carbonate rocks (Zen, 1967) and, rarely, Grenville basement (Ratcliffe and Bahrami, 1976). Relatively large allochthonous or parautochthonous slices of shelf carbonate are also seen in many places at the base of the Taconic Allochthon (Thompson, 1967; Voight, 1965, 1972; Zen, 1967, 1972; Potter, 1979; and Bosworth, 1980). The Giddings Brook slice is the largest of all the slices and contains the most complete stratigraphic sections. The rocks of the lower slices display in places slump structures and soft sediment deformation.

Taconic rocks have undergone low grade (Chlorite to biotite zone) regional metamorphism. The minimum age of metamorphism by isotopic dating is about 440 m.y. west of the Green Mountain massif in Vermont and adjacent parts of New York and Massachusetts, but 350 (±) m.y. ages are found to the east (Zen, 1972). Each of the Taconic slices shows complex internal deformation. All the rocks show at least two generations of deformation (Zen, 1972; Potter, 1972; and Rowley et al., 1979). In general, the apparent complexity of deformation and intensity of metamorphic grade decrease from east to west within the Allochthon.

The Emplacement of the Taconic sequence onto the coeval shelf took place during the Medial Ordovician Taconic Orogeny. Rodgers (1951, 1952), Zen (1967), and Bird (1969) considered gravity sliding as the cause of the Taconic Allochthon. Zen (1967) suggested the sequence of sliding as follows: the Sunset Lake slice, the Giddings Brook slice, the Bird Mountain and Chatham slices, the Rensselaer Plateau slice, and finally the slices comprising the high Taconic sequence. Recently, Chapple (1973, 1979), Rowley et al. (1979), and Rowley and Kidd (1981) have provided a much different view about the origin of the Taconic Allochthon. Rowley and Kidd (1981) recognized three Pre-Silurian geological provinces in the western New England segment of the northern Appalachians, i.e., a Cambro-Ordovician rifted continental margin, a Medial Ordovician suture zone and a volcanic arc terrain, from west to east. They claimed that the attempted subduction of the North American Atlantic-type continental margin in an east-dipping subduction zone is most likely responsible for the emplacement of the Allochthon. Based on the stratigraphic and petrographic studies of the flysch sequence of the Taconic Allochthon (Pawlet Formation/Austin Glen Graywacke) and surrounding parautochthonous and autochthonous flysch sequence (Austin Glen Graywacke), Rowley et al. (1979), and Rowley and Kidd (1981) suggested that the initial stacking sequence of Taconic rocks propagates from east to west. Meanwhile, Rowley et al. (1979) argued that structural evidence from within the low Taconics also supports the emplacement of the Taconic Allochthon by "hard rock" thrusts rather than by soft-sediment gravity sliding.

CHAPTER 4 STRATIGRAPHY

INTRODUCTION

It is well known that the study of stratigraphy plays a very important role in the interpretation of structures in the regions of sedimentary rocks and low grade metamorphic rocks. For this reason, the stratigraphy of the Taconics and surrounding area has been the subject of many geological investigations and discussions for more than one hundred and sixty years. It formed the focus of the Taconic controversy in the last century.

Eaton (1818, 1822, 1824, 1828) and Dewey (1819, 1820, 1824a, 1824b) made the pioneering stratigraphic investigations in the Taconics. During the first years of the New York Geological Survey (1836-1843), Mather, Emmons, Vanuxem and Hall promoted the "New York System" to encompass all sedimentary rocks in New York from the base of the Potsdam Sandstone through the Catskill red beds, i.e., from the early late Cambrian through the Late Devonian. Emmons (1842) proposed the "Taconic System" to include all beds beneath the base of the "New York System". Later, Emmons (1844) discovered the trilobites *Elliptocephala asaphoides* and *Atops trilineatus* in deformed strata in western Rensselaer County. He believed that he had found the "Primordial Fossils" ---- the opening chapter of life history on the Earth. Dana (1888) and Walcott (1888) demonstrated that the carbonates on the west and argillites in the Taconic region were at least in part time equivalent sequences of Cambrian and Ordovician age. Dale (1899, 1904a, 1904b) did the most comprehensive studies on the slate belt and defined a fully detailed lithostratigraphic section which has served as a framework for all later stratigraphic discussions in the Taconics. Dale used letters and cryptic names in his description. Later, Ruedemann (in Cushing and Ruedemann, 1914) refined Dale's stratigraphy and introduced formal names which are followed by other workers (for example, Keith, 1932; Theokritoff, 1959, 1964; and Zen, 1961). Dale's work turned the Taconic controversy from the stratigraphic debate to the structural relationship between the Taconic sequence and the surrounding carbonate rocks.

Recently, many workers (Prindle and Knopf, 1932; Cady, 1945; Craddock, 1957; Weaver, 1957; Elam, 1960; Shumaker, 1960, 1967; Hewitt, 1961; Zen, 1961, 1967; Bird, 1962; Knopf, 1962; Theokritoff, 1964; Ratcliffe, 1965, 1974a, 1974b, 1974c; Zen and Hartshorn, 1966; Zen and Ratcliffe, 1971; Potter, 1972; Rickard, 1973; Jacobi, 1977; and Rowley, 1980) have done much detailed mapping in the Taconic region, which have greatly extended our knowledge about the stratigraphy in the Taconics, Lochman (1956), Berry (1962), Rasetti (1946, 1966, 1967), Bird and Rasetti (1968), and Landing (1974, 1976) made intensive paleontological studies in order to date the rocks in the Taconic region. Based on their own experience and previous work, Fisher (1961, 1962a, 1962b, 1977) and Zen (1964, 1967) correlated the rocks in different parts of the Taconics, which provided us a unified picture of the Taconic stratigraphy. However, some of the Taconic rocks are exceedingly complex, and many unresolved problems remain to be studied. For example, the ages of some of the stratigraphic units are still uncertain. The correlation of some rock units is still much controversial. This is so because:

(1) The lithology of strata with different ages in the Taconics is remarkably similar. Graywacke, shale, sandstone and their metamorphic

equivalents, slate and quartzite, comprise most of the whole Taconic sequence. Only very small amount of carbonate rock exists. It can be difficult in some cases to distinguish to which map unit the rock in a particular small outcrop belongs.

(2) Definitive paleontological data are scarce. In particular, very few fossils have been found in the stratigraphically lowermost part of the Taconic sequence and in the higher Taconic thrust slices.

(3) The rocks are usually intensively folded and faulted. Complete stratigraphic sections are not common throughout the sequence and within the whole Allochthon. Strong intra-strata deformation in weaker rocks, folding and lateral flow of materials make it impossible to measure the original thickness of a given rock unit precisely.

(4) There exist large lateral variations in lithostratigraphy across the Taconic region. Even within one single thrust slice, several regions can be identified, each of which is characterized by a first order coherence of the internal stratigraphy and marked difference with adjoining regions. For example, Rowley et al. (1979) observed a striking lateral lithostratigraphic variation in the Giddings Brook slice and defined two different lithostratigraphic columns for the west and east of the South Poultney Thrust near Granville.

CAMBRIAN (?) AND CAMBRIAN

Cambrian (?) and Cambrian rocks related to the present study in the Taconic region were considered as Lower Cambrian before the early sixties (Dale, 1899, 1904a; Ruedemann, 1914, 1930, 1942; Zen, 1961; and Fisher, 1962 a). They have been called the "Georgian Group" (Walcott, 1891), "Waucoban Group" (Walcott, 1912) and "Taconian Series" (see Ruedemann, 1930, p. 73).

During the very late nineteenth century, Dale (1899, 1904a) conducted the first systematic stratigraphic study in the Taconic region. In his monumental report on the slate of eastern New York and western Vermont, Dale (1899) divided the "Lower Cambrian" into five units: (A) Olive Grit, (B) Cambrian Roofing Slates, (C) Black Patch Grit, (D) Cambrian Black Shale, and (E) Ferruginous Quartzite and Sandstone". Several years after, he (Dale, 1904a) published another valuable paper within which a systematic description on the stratigraphy of the southern Taconic region can be found. Although different symbols were used for the stratigraphic units in the southern Taconics, it can be clearly seen from Dale's description that these sections are obviously comparable with the rock sequences in the northern Taconic region. For example, Dale (1904a, p. 14) considered that the "Metamorphic Olive Grit" in Rensselaer County and in Washington County belongs to the same formation. Dale (1904) also found a "Granular Quartzite" or "Calcareous Sandstone" underneath his Unit I and two additional thick beds of quartzite, each of which is both underlain and overlain by red and green shale with small quartzite beds. Also, a greenish shale unit was identified above his "Cambrian Black Shale".

Later on, Ruedemann (1914) renamed Dale's stratigraphic units after type localities Ruedemann defined, more or less precisely, instead of their lithological and faunal characteristics. He tried to correlate the stratigraphic sections in the northern Taconics to the sections in the southern Taconics and took the name Schodack from the southern Taconic region for Dale's "Cambrian Black Shale" in Washington County. Apparently, he believed that the rocks in Schodack Landing and Dale's "Cambrian Black Shale" in Washington County represent the same unit. The detailed correlation between Dale's divisions and Ruedemann's formation names is listed in Table I and II.

After Ruedemann, much more field mapping has been done in the Taconic region. As a result, many new discoveries have been made. Some of the most important findings related to the Cambrian (?) and Lower Cambrian stratigraphy are:

(1) It is proved that the "Ferruginous Quartzite and Sandstone" at Zion Hill, Hubbardton described by Dale (1899, p. 183) was in a succession of green and purple slates thrusted over the "Cambrian Black Shale" (Zen, 1961, p. 314). It is actually a lenticular body within the Mettawee Slate facies of Zen (1961) and quite possibly equivalent to the "Granular Quartzite" observed by Dale (1904a, p. 23-24) on Curtis Mountain, Nassau and at Ashley Hill, Columbia County.

(2) People further confirmed that the "Eddy Hill Grit" and the "Zion Hill Quartzite" are not mappable units and therefore are combined with the other lithologies within the stratigraphic units they are contained.

(3) In the northern Taconics, a new green slate unit has been differentiated above Dale's "Cambrian Black Shale" (Jacobi, 1977; Rowley et al., 1979).

TABLE I CORRELATION OF DALE'S STRATIGRAPHIC SUBDIVISIONS IN THE NORTHERN TACONICS WITH RUEDEMANN'S FORMATION NAMES

HORIZON	Dale (1899) NAME	Ruedemann (1914) NAME	Dale (1899) DESCRIPTION OF STRATA
E	Ferruginuous Quartzite and Sandstone	Zion Hill Quartzite	Quartzite, usually with spots of limonite; in places, however, a bluish calcareous sandstone (grains of quartz with a calcareous and ferruginous cement) weathering rusty brown. Quartz veins abundant in both. A quartz conglomerate sometimes associated with the quartzite.
D	Cambrian Black Shale	Schodack Shales and Limestones	Black shale or slate, generally weathering blue black, sometimes pyritiferous, with thin beds of limestone and less frequently limestone breccia.
C	Black Patch Grit	Eddy Hill Grit	Dark gray grit or sandstone with black shaly patches, sometimes with calcareous nodules.
B	Cambrian Roofing Slates	Mettawee Slate	Roofing slate, grayish green, purple, or mixed green and purple, alternating with beds of calcareous quartzite up to 5 feet and limestone breccia up to 40 feet thick.
A	Olive Grit	Bomoseen Grit	Olive green grit (graywacke), more or less massive, spangled with minute scales of hematite or graphite, sometimes with small quartzite beds, frequently calcareous, generally weathering a pale brick red. Associated with it in places a bed of quartzite 12 to 55 feet thick.

TABLE II CORRELATION OF DALE'S STRATIGRAPHIC SUBDIVISIONS IN THE SOUTHERN TACONICS WITH RUEDEMANN'S FORMATION NAMES

Dale (1904a) SERIAL LETTER	Ruedemann (1914) NAME OF FORMATION	Dale (1904a) DESCRIPTION OF STRATA
J		Greenish shale.
I	Schodack Shale and Limestone	Thin-bedded limestone or dolomitic limestone, in varying alternations with black or greenish shale and calcareous quartz sandstone. Some of the limestone beds brecciated within the sandstone or shale and forming brecciation pebbles, in places, however, beach pebbles.
H	Troy Shale	Greenish, reddish, purplish shale, in places with small beds of more or less calcareous quartzite. At Troy, in upper part a 2.5 foot bed of calcareous sandstone.
G	Diamond Rock Quartzite	Granular quartzite, in places a calcareous sandstone.
F	Bomoseen Grit	Olive grit, metamorphic, usually weathering reddish; absent at south.
E		Greenish, or reddish and greenish, shale with small quartzite or grit beds.
D		Massive greenish quartzite, in places very coarse.
C	Nassau Beds	Reddish and greenish shale with small beds of quartzite or grit (rarely up to five feet thick).
B		Massive greenish quartzite, in places very coarse.
A		Reddish and greenish shale with small beds of quartzite or grit, from 1 to 12 and, rarely, 24 inches thick.

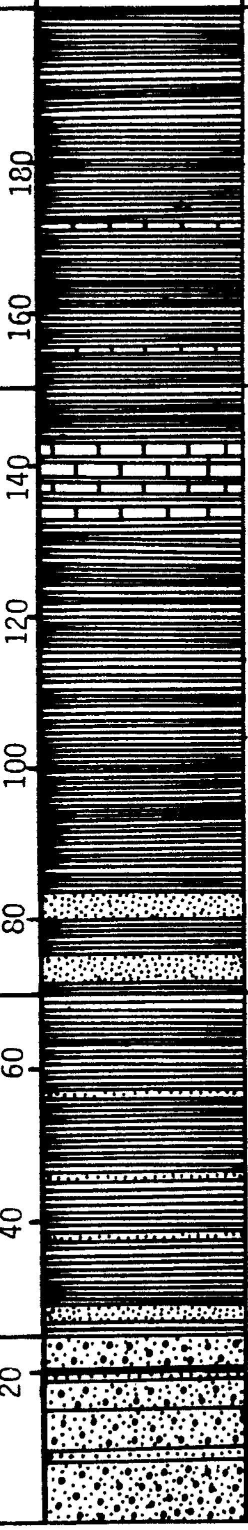
Figure 4.1 is a lithostratigraphic column for the western region of the Granville area based on the data from Jacobi (1977) and Rowley et al. (1979). By comparing their data with the upper part of the stratigraphic section (see Table II) established by Dale (1904a) for Rensselaer and Columbia Counties, we will find some amazing similarities in the rock types and the order of their occurence. However, the subdivision of rock units by Jacobi (1977) and Rowley et al. (1979) is superior because all their units are mappable and less confusing.

In the present area, all subdivisions of Jacobi (1977) and Rowley et al. (1979) expressed in Figure 4.1 have been observed. Figure 4.2 is a lithostratigraphic column for the North Troy area. As we can see, the rock types, the sequence of their occurrence and the thickness of each unit are all easily correlatable with their section. This consistency invalidates the previous conclusion that the rocks in the southern Taconics were sufficiently different from the northern Taconics such that different names should be employed. In fact, to devise a single column with a single set of descriptions and a single set of names for the entire Taconic Allochthon is completely possible and urgently needed.

BOMOSEEN FORMATION

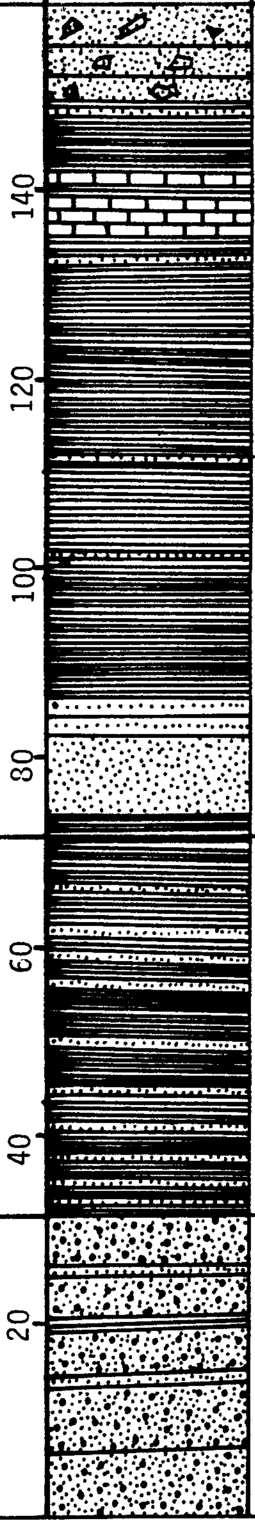
This is one of the rock units in the Taconic region which Dale (1904a, p. 14) considered so characteristic as to deserve special notice. He (Dale, 1899, p. 179) referred to this unit as the "Olive Grit" and specified the type locality on the west side of Lake Bomoseen, one-fourth mile west of the road running north from Hydeville, on the north side of the road to Fairhaven, Vermont. Later, Ruedemann (1914, p. 67) renamed it

Figure 4.1 Lithostratigraphic Column of Precambrian and Lower Cambrian for the Western Region of the Granville Area (Based on the Detailed Descriptions of Jacobi, 1977, and Rowley et al., 1979).



FORMATION	THICKNESS (M)	LITHOLOGY	DESCRIPTION
METTAWEE SLATE FORMATION	50		The slate is well cleaved, non-fissile, commonly buff weathering, purple, green and near the top gray with black bioturbated laminae. Thin (1cm), green micritic limestone may occur, and in places, lenses of micritic and arenaceous limestone are present near the base. Black phosphate pebble-bearing calcarenite and dolomitic matrix micrite breccia are rarely found in middle part.
BROWNS POND FORMATION	80		The Browns Pond Formation is a heterogeneous assemblage of lithologic types all lying within a predominantly black slate matrix. The slate is predominantly black with lesser dark gray, intermittently calcareous, finely cleaved, rather fissile, and forms the matrix of the formation. Other lithologic types include limestones, limestone conglomerates and breccias, black calcareous quartz wacke, thin dolomitic calc-arenites, and one or two thick clean quartz arenites.
TRUTHVILLE SLATE FORMATION	45		Truthville slate is soft, well cleaved, fissile, silty, mica spangled olive gray-green, tan weathering with rare, usually thin(1-2 cm) arenites. In places, thicker, clean quartz arenites are present near the base.
BOMOSEEN FORMATION	Incomplete		Bomoseen is predominantly composed of wackes, with lesser arenites and slates.

Figure 4.2 Lithostratigraphic Column of Precambrian and Lower Cambrian for the North Troy Area.



FORMATION	THICKNESS (M)	LITHOLOGY	DESCRIPTION
BROWNS POND FORMATION	80		The bulk of the Browns Pond Formation consists of black shales, dark gray to black silty shales or siltstones. About 10 to 20 meters of light gray granular quartzite occurs as a lenticular body near the base of the formation. It grades into tan to pink ferruginous calcareous sandstone. Conglomerates of limestone pebbles and thin limestone beds are seen in the upper part. At the top, a peculiar quartzite containing pebbles of fine-grained sandstone or siltstone is present.
TRUTHVILLE FORMATION	40		Olive green silty shales and thin quartzite beds. The green shales have a tan weathering and contain spangles of mica. The thin quartzite beds are commonly 1 to 2 centimeters thick or less and weather rusty brown.
BOMOSEEN FORMATION	Incomplete		Olive green graywacke, more or less massive, and spangled with micas. Frequently interbedded with it are white quartzite or arenite beds, each a few centimeters to tens of centimeters.

as "Bomoseen Grit" and used Dale's suggested type section. Since then, the name Bomoseen has been widely accepted (Resser et al. 1938, p. 203; Larrabee, 1939, p. 48; Kaiser, 1945, p. 1085; and Fowler, 1950, p. 46). On the other hand, however, Zen (1959) suggested that the Bomoseen did not constitute a continuous unit and defined it as a member of his Bull Formation (Zen, 1961, p. 301). Bird (1962, p. 136) also included the Bomoseen in his Nassau Formation which is equivalent to Zen's Bull Formation plus Biddie Knob Formation. Potter (1972, p. 7) followed Bird's usage.

Further studies (Theokritoff, 1964; Jacobi, 1977) show that although lithological variations do exist in the Bomoseen it is still separable from the overlying and underlying units. Therefore, Jacobi (1977, p. 27) recommended to change the Bomoseen's status from Member to Formation. Her name is adopted here.

The Bomoseen Formation is predominantly composed of wackes which are commonly dark olive green, rarely purplish and more or less massive. They are often interlayered with siltier, slightly softer wackes so that the weathered surfaces generally show a ribboned appearance due to the different resistance to erosion (Rowley et al., 1979). The weathered surface is usually light tan and in places shows a peculiar pale brick red color which forms one of the distinctive features of the Bomoseen Formation. Spangles of micas are so widespread that some people (Dale, 1899; Theokritoff, 1964) used it as a criterion for identifying the Bomoseen wacke although spangles of micas are not only restricted to this unit. Bedding is difficult to see in the Bomoseen wacke. Some possible sedimentary structures such as small cross beds (Jacobi, 1977, p. 25), cyclic beds of graywacke separated by partings of argillite or a slate (Potter, 1972, p. 13), slumps and channel features (Kidd, 1977, see Jacobi, 1977, p. 25) have been reported. Slaty cleavage is also poorly developed in the wacke and generally does not form a planar, readily measured feature.

Microscopic observations made by Dale (1899, p. 179) and Potter (1972, p. 13) show that the Bomoseen wacke consists of quartz, plagioclase and minor amount of detrital muscovite in a cement of sericite, clay, some clacite and small amounts of secondary quartz.

In the present area, the Bomoseen Formation is only exposed in Lansingburg, at Oakwood Cemetery, on the east side of the Devil's Kitchen. Dale (1904a, p. 15) mentioned this locality in his paper. It consists of olive green massive micaceous wackes (Figure 4.3). Exposed on the west side of the Devil's Kitchen is the Indian River Formation. The contact between them is the basal thrust of the Taconic Allochthon. Due to the effect of this thrust, only the top part of the Bomoseen Formation can be seen. The exposed thickness is only about 10 meters. The Bomoseen wacke often breaks into lenticular pieces along the basal thrust of the Allochthon.

Frequently interbedded with the Bomoseen wacke are white quartzite or arenite beds, each a few centimeters to tens of centimeters thick (Dale, 1899, p. 180; Zen, 1961, p. 301; and Jacobi, 1977, p. 25). Quartzites are massive and contain no cleavages. The spangles of mica characteristic of wacke are absent in the quartzite except on the margins of the beds. The Bomoseen Formation also contains local developments of green or purple slates (Theokritoff, 1964, p. 175; Jacobi, 1977, p. 23). Beds of quartz conglomerate have been noted by Dale (1899, p. 180) in the Bomoseen near

Figure 4.3
Olive green massive micaceous wacke of the Bomoseen Formation exposed at the Devil's Kitchen in Oakwood Cemetery, Troy.

Cambridge and Hebron in Washington County and by Zen (1961, p. 301) in Rutland County, Vermont. In the Hoosick Falls area, Potter (1972, p. 13) observed "gray siltstone with thin, wispy laminations of dark gray argillite, gray siltstone with tightly folded, light gray silty sands, and slaty siltstone besides the interbeds described above.

The full thickness of the Bomoseen Formation has never been accurately measured in the Taconic region. However, field mapping shows that it is much more extensive in the northern Taconics. In Washington County, Theokritoff (1964) estimated a thickness of more than 200 meters. Rowley et al. (1979) claimed that the thickness of the Bomoseen Formation is greater than 240 meters. In the Hoosick Falls area, Potter (1972) gave a thickness of about 183-350 meters. To the south of Taconic region, the thickness of the Bomoseen Formation gets smaller and smaller. Along the eastern edge of the Schuylerville quadrangle, it is 20 to 60 meters (Ruedemann, 1914). In Rensselaer and Columbia Counties, New York, it decreases down to 10-20 meters (Dale, 1904a). In the Catskill quadrangle, its thickness is no more than 10 meters (Ruedemann, 1942).

The Bomoseen Formation seems to be quite barren of fossils. As a matter of fact, the only record of a fossil is that of *Obolella crassa* in Walcott (1912, p. 188). Moreover, it is not certain that the reddish sandstone bearing this fossil about one mile east of Lansingburg, north of Troy, New York, is equivalent to the Bomoseen wacke. Therefore, the age of the Bomoseen Formation is not conclusively determined. Fisher (1977, p.33) suggested that the base of the Cambrian in the geological time table should be selected at the lowermost level of recorded organic life. In the allochthonous Taconic sequence, the Early Cambrian trilobite fauna extends down to the Ashley Hill limestone Conglomerate. Elsewhere, archaeocyathids were found in the allegedly earliest lower Cambrian rocks. Therefore, Fisher regarded the level of the Zion Hill or Curtis Mountain Quartzite as the base of the Cambrian in the Taconics. The Bomoseen Formation lies below this level. Thus, it should be considered as Upper Proterozoic or Cambrian (?) (Zen, 1964, p. 22; Rowley et al., 1979, p. 194).

TRUTHVILLE FORMATION

This unit is equal to the Division H of Dale's (1904a) Rensselaer series except the calcareous sandstone bed in its uppermost part. From field mapping in the North Troy area and comparing the stratigraphic section there with Dale's description, it becomes clear that this calcareous sandstone is equivalent to the Diamond Rock Quartzite in Lansingburg. Ruedemann (1914, 1930) named Dale's Division H as the "Troy Shale". Fisher (1956, p. 344), Elam (1960, p. 38) and Zen (1964, p. 83) pointed out that Ruedemann's "Troy Shale" was not adequately defined and thus opposed the continued use for the wrong reason. A restudy of some of Ruedemann's papers will indicate that this is not a reasonable criticism. In his 1930's paper, Ruedemann wrote: "The Troy Shale is closely associated with the Schodack beds, which it underlies. It consists of 25 to 100 feet of colored shales with small beds of clacareous quartzite. The shale has furnished Oldhamia occidens Walcott, a calcareous alga; ... These beds are well exposed at Troy, at the dam in the Poestenkill below Mount Ida Lake, and in the gorge of the Poestenkill, there with Oldhamia. Below the Poestenkill dam the shale is overlying the overthrust". From this statement, we can see that Ruedemann provided information on the following five aspects: (1) He pointed out the relationship between the "Troy Shale" and the overlying unit; (2) described the lithological characteristics of the basic rock types; (3) estimated the thickness of the unit; (4) listed the characteristic fossils; and (5) designated its type locality. Therefore, it is surely adequately defined although the statement is rather concise. The actual defects of his Troy Shale include: (1) the lower contact of the "Troy Shale" has not been directly observed at its type locality; and (2) Ruedemann mistook the Zion Hill Quartzite for the Diamond Rock Quartzite and included the real Diamond Rock Quartzite in his "Troy Shale"; and (3) Ruedemann made the same mistake as Dale did and misplaced the same lithological unit at two different stratigraphic positions. From Dale's description, it is clear that lithologically his unit H is essentially the same as his units A, C and E except there are two quartzite interbeds in the latter case. Zen (1961, 1964) suggested that these two quartzite interbeds are equivalent to the Zion Hill Quartzite of the northern Taconic region which implies that the rock unit containing these quartzite interbeds is equivalent to the green slate unit directly underlying the "Cambrian Black Shale". This relationship can also be seen from Dale's work (Dale, 1904a). On Curtis Mountain, the fossiliferous limestone is underlain by a calcareous quartzite which overlies the reddish and greenish shale with granular quartzite interbeds. In the Troy area, the so-called "Diamond Rock Quartzite" grades laterally into calcareous sandstone. It is overlain by s dequence of black shale with limestone conglomerates and thin limestone beds and underlain by the greenish shale of Dale's unit H. Thus, it is very likely that Ruedemann's "Troy Shale " and his "Nassau Beds" are actually the same stratigraphic unit.

In the northern Taconics, the Truthville Formation of Jacobi (1977) and Rowley et al. (1979) consists of soft, well cleaved, fissile mica spangled olive gray-green, tan weathering slate with rare, usually thin arenites. Slates are so well cleaved in some places that they are quarried for industrial purposes. Dale (1899, p. 179) called this unit the "Cambrian Roofing Slate". However, it should be pointed out that what Dale covered in his "Cambrian Roofing Slate" in Washington County and western Vermont actually includes two parts, that is, the olive green silty slate below the black shale and limestone which he gave the name "Cambrian Black Shale" and the olive fine-grained slate above them (Jacobi, 1977; Rowley et al., 1979). Dale (1899, p. 180-182) placed all these green slates below the "Cambrian Black Shale". Until five years later, he (Dale, 1904a, p. 29) distinguished these two green shale units in the southern Taconics and named them units H and J respectively. Unfortunately, the mistake he made in Washington County and western Vermont was not realized by Ruedemann (1914). Ruedemann (1914, p. 69) simply renamed the "Cambrian Roofing Slate" as the "Mettawee Slate". Thus, it has caused much confusion among later workers. Some people used the term "Mettawee Slate" to include Dale's "Cambrian Roofing Slate", "Black Patch Grit" and "Cambrian Black Shale" (Theokritoff, 1964, p. 176). Others considered it as the matrix of the entire "Lower Cambrian" series of Dale (Zen, 1961, p. 300; Potter, 1972, p. 7; and Bird, 1962). Still others have restricted the name "Mettawee Slate" to the olive green fine-grained slate above the "Cambrian Black Shale" (Jacobi, 1977; Rowley et al., 1979).

Most recent field mapping conducted by Jacobi (1977), and Rowley et al. (1979) reveals that the olive green silty slate can be readily separated from the overlying and underlying rocks in the Granville area and suggested that they should be treated as a separate unit. Jacobi (1977, p. 29) proposed the term Truthville Slate Formation from their excellent development along the Mettawee River near Truthville, New York. Jacobi's name is followed here since the term "Mettawee Slate" was not suitably defined and is full of confusion. In the present area, however, the metamorphic grade is lower and most rocks do not approach a slate. Therefore, the word slate has been omitted from the formation name.

In the present area, the Truthville Formation consists of soft, fissile, olive green silty shales and thin quartzite beds (figure 4.4). It can be distinguished from the underlying unit by the common appearance of bedding, the presence of good slaty cleavage and the development of many quartzite beds and absence of massive greenish wackes and from the overlying unit by the color change from green to black and distinct lithological variations. The green shales have a tan weathering. Under the microscope, it is a very fine-grained aggregate of muscovite and chlorite scales, angular quartz grains, rarely plagioclase grains, with brownish dots which are possibly limonite. The thin quartzite beds are commonly 1 to 2 centimeters thick or less and weather rusty brown. Microscopic examination shows that angular quartz grains constitute the dominant part of the quartzite beds, and associated with them are always a few of plagioclase and of zircon, and sometimes scales of muscovite and of chlorite and grains of tourmaline (Dale, 1904a). The cement varies in quantity and in material. It is sometimes purely siliceous, or partly siliceous and partly calcareous or sericitic, and sometimes entirely dolomitic.

Figure 4.4
Olive green silty shale with thin quartzite beds of the Truthville Formation exposed in a quarry near the type locality of "Diamond Rock".

Rowley et al. (1979) have given a thickness of 20 to 60 meters for the Truthville Formation. Ruedemann (1914, p. 70) estimated it at the Poestenkill dam to be about 30 meters exposed. In the present area, the Truthville Formation is mainly exposed at two places. One is in the Oakwood Cemetery, at the Devil's Kitchen near the largest pond and another is about 5 meters west of the Diamond Rock Quartzite type locality. Near the Diamond Rock, the Truthville Formation shales are situated at the core of an anticline and the basal part of it is not exposed. In the Oakwood Cemetery, although the gradational contact with the underlying Bomoseen wacke is clearly observed at the Devil's Kitchen, the accurate measurement still can not be made because of the poor exposure of the upper part. However, it can be inferred from the map pattern based on the distribution of lithologies that the thickness of the Truthville Formation can not be less than 30 meters.

At the Poestenkill dam near Troy, the Truthville Formation green shale underlies a calcareous sandstone bed carrying the Olenellus fauna (Dale, 1904a, p. 27). In the northern Washington County, Dale (1899, p. 181) also found similar fossils in limestone conglomerate interbeds associated with the Browns Pond Formation. Therefore, he assigned an Early Cambrian Age for the Truthville Formation. However, these limited fossils have only been found within the immediately overlying rocks. Thus, it is possible that the rocks within this unit might have been formed during the Cambrian (?) time (Zen, 1961, p. 300; Rowley et al., 1979).

BROWNS POND FORMATION

In the studies of the slate belt of eastern New York and western Vermont, Dale (1899) identified a black shale unit and called it the "Cambrian Black Shale". He wrote: "Throughout the entire region there are long belts of black or gray shale or slate, which in weathering, usually assume a dark bluish tinge. They are rarely somewhat micaceous. ... Thin limestone beds, sometimes brecciated, are often associated with these shales". In the southern Taconic region, Dale (1904a) also observed this lithological unit near Troy, Chatham, East Greenbush, North Greenbush and Schodack Landing. Ruedemann (1914, p. 69) proposed the name "Schodack Shales and Limestones" for this unit and designated the Castleton cutoff of the New York Central Railroad 2 miles south of Schodack Landing as its type locality (Ruedemann, 1930, p. 80). This particular unit has also been called the "Schodack Formation" by Prindle et al. (1932, p. 277) Larrabee (1939, 1940), Kaiser (1945), Fowler (1950), Rodgers (in Billings and others, 1952), and Bucher (1957). Lochman (1956) and Elam (1960) called it the "Schodack Lithofacies". Ruedemann (1942, p. 64), Goldring (1943, p. 64), and Howell et al. (1944) also used the term "Schodack Formation" in an extended sense to include units other than Dale's "Cambrian Black Shale". On the other hand, however, much controversy arose about the value of the term "Schodack Formation" in geological nomenclature during the late fifties and early sixties. Fisher (1956, p. 344) matched Ruedemann's description to the olive silty shales with their associated limestones exposed at the type locality of the "Schodack Formation" and criticized Ruedemann for choosing the geographic name Schodack for Dale's

"Cambrian Black Shale" in the northern Taconics. Theokritoff (1959, 1963) also followed Fisher's track and rejected the further use of the term "Schodack Formation".

A restudy of literature reveals that what mistakes Ruedemann did make are: (1) He unsuitably included the green shale overlying limestones in his "Schodack Formation"; and (2) He considered the apparently lenticular quartzite bodies occuring at or near the base of the "Schodack Formation" as a separate unit. The recent field mapping by Jacobi (1977), and Rowley et al. (1979) indicates that the green shale overlying the black shale and limestone constitutes another separate mappable unit and should have an individual identity. Therefore, they proposed the term Browns Pond Formation to cover only the black shale and limestone which is equal to Dale's unit I plus the calcareous sandstone at the uppermost part of his unit H. Their scheme fits the strata of the map area best.

In the present area, the lithology of the Browns Pond Formation can be generally described as lenses of quartzite or sandstone, limestone or limestone conglomerate within black shales or silty shales and siltstones.

The bulk of the Browns Pond Formation consists of black shales, dark gray to black silty shales or siltstones (Figure 4.5). These are the surrounding material of quartzite and limestone conglomerate lenses. Black shales have only been observed locally above and below the Diamond Rock Quartzite or sandstones. Dark gray to black silty shales or siltstones are the dominant rock types. Near the top of the Browns Pond Formation, sooty siltstone underlies the quartzite with fine-grained siltstone pebbles. At an outcrop along Gurley Avenue, thin laminated

Figure 4.5
Dark grey to black silty shale of the Browns Pond Formation exposed along Gurley Avenue near the St. Johns Cemetery.

brown weathering siltstones are present in the black silty shales. At the same place, sandstone and graywacke lumps are observed in the black silty shales (Figure 4.6).

North of Oakwood Cemetery, north of Troy, about 10 to 20 meters of light gray granular quartzite occurs near the base of the Browns Pond Formation (Figure 4.7). It can be traced for more than 200 meters intermittently along its strike and grades into tan to pink ferruginous calcareous sandstone beds westwards (Figure 4.8). Quartzite visibly pinches out at the ends in many instances. The thickness of individual sandstone beds is from 10 to more than 50 centimeters. Quartzite weathers orange and has black markings on its surface. Sandstone usually shows rusty or brown weathering. Small Quartz crystals grow on the fracture surfaces in the quartzite gave the name "Diamond Rock" for this particular outcrop.

There is a beautiful Indian legend about this Diamond Rock. According to the legend, the glimmering quartz crystals of the Diamond Rock represent the petrified tears of a Mohican mother. She waited on this rock for 20 years for the return of her son after her son went to Canada to recover the bone of his brother from the Algonquins in order to secure rest for him in the other world. It is said that the Indian fulfilled his mission, but the mother's tears remain on the rock to this day.

Although the Diamond Rock Quartzite pinches out along its strike and does not constitute a mappable unit, similar rocks can be found at the same stratigraphic level intermittently in the entire Taconic region. Jacobi (1977) observed calcareous quartz wacke and one or two hard,

Figure 4.6
Browns Pond black silty shale containing sandstone and greywacke lumps.

Figure 4.7
Light gray granular quartzite near the base of the Browns Pond Formation exposed at the type locality of the “Diamond Rock Quartzite”.

Figure 4.8
Tan to pink, orange or rusty brown-weathering, ferruginous calcareous sandstone beds of the Browns Pond Formation.

white, clean, faintly rust-speckled arenites in the lower half of the Browns Pond Formation in central Washington County, New York. Dale (1899, p. 181-182) identified a "Black Patch Grit" at Eddy Hill, near Fairhaven, Vermont, which was named as the "Eddy Hill Grit" by Ruedemann (1914, p. 69-70). Since Eddy Hill is not shown on the topographic maps nor is the name now known to local inhabitants, Zen (1961, p. 303) replaced the term Mudd Pond Quartzite. He pointed out that locally the quartzite grades into a gray arkosic grit, with black argillaceous cement. However, Rowley et al. (1979) believe that the Mudd Pond Quartzite lie at a lower stratigraphic level than the "Eddy Hill Grit".

Fisher (1977, p. 49) interpreted the Diamond Rock Quartzite as the basal member of his "Germantown Formation" and correlated the "Germantown Formation" to the West Castleton Formation in the northern Taconic region. Actually his "Germantown Formation" is equal to the upper part of Zen's Bull Formation (Zen, 1961) plus the West Castleton and Hatch Hill Formations (Theokritoff, 1964).

Conglomerates of limestone pebbles and cobbles with a matrix of quartz sand cemented by argilli-calcareous mud are exposed along Route 40 near the Northern Drive, near the Randell School of Ice Skating and around the Troy Niagara-Mohawk Service Center. Near the Randell School of Ice Skating, it can be seen that they occur as lenses in dark gray to black silty shales or siltstones (Figure 4.9). At the construction site in front of the Troy Niagara-Mohawk Service Center, thin limestone beds are exposed. Chadwick (1946, p. 585) gave the name "Claverack Conglomerate" for these lenses. Since we can not trace these separate conglomerates with assurance from one area to the next, Fisher (1977,

Figure 4.9
Conglomerates of limestone pebbles in the upper part of the Browns Pond Formation. The matrix is sandy and dolomitic.

p. 48) suggested referring to all of these as the "Claverack Conglomerate Suite". Chadwick (1946) believed that these conglomerates were within the Early Cambrian "Schodack Formation". In the Granville area, the closely packed limestone breccias always occur at the top part of the Browns Pond Formation (Rowley et al., 1979). In the northern Taconic region, this type of rock has been called the North Brittain Limestone Conglomerate (Zen, 1961, p. 303). In the southern Taconic region, the name Ashley Hill Limestone Conglomerate has been applied (Bird, 1962, p. 135).

Near the intersection between Route 40 and the Northern Drive. a rather peculiar quartzite is exposed. It has light gray color on the fresh surface and contains many pebbles of fine-grained sandstone or siltstone (Figure 4.10). Pebbles are platy in shape and are from 2 to 20 centimeters long and from 1 to 10 centimeters wide. They commonly have a darker color than the surrounding material.

It should be pointed out that the stratigraphic position of limestone conglomerates and thin limestone beds by Route 40 and the quartzite containing dark gray siltstone pebbles exposed at the outlet of the Lansingburgh Reservoir has not been conclusively determined. Lithologically, they are very much like the rocks of the Hatch Hill Formation in the northern Taconics (Kidd, 1983, pers. comm). They are included in the Browns Pond Formation in the present study simply because no green slate unit has been observed between the Browns Pond black shale and the quartzite containing siltstone pebbles.

Fisher (1962a) states that his "Germantown Formation" rested disconformably on "Early Cambrian Mettawee argillite" without providing

Figure 4.10
Light gray granular quartzite containing pebbles of dark gray fine-grained sandstone or siltstone near the top of the Browns Pond Formation.

any specific evidence other than the absence (at that time) of Middle Cambrian faunas. In an earlier paper, however, he (Fisher, 1961) mentioned that "complete sections are unknown and its base is obscured within the black shale -- limestone terrane". Zen (1961) and Theokritoff (1964) included this unit in the upper part of their Bull Formation. Obviously, there is no disconformity identified below this unit in their areas. In the Granville area, a sharp conformable contact between the Browns Pond Formation and the underlying Truthville Formation has been observed on the north side of the Mettawee River 510-600 meters west of the Truthville Bridge (Jacobi, 1977, p. 34). At the type locality of the Diamond Rock Quartzite in Lansingburg, North Troy, the greenish silty shales or siltstone thin beds of the Truthville Formation occur a few meters below the quartzite although the contact between is not directly observed. The distance from the observed greenish siltstone to the Diamond Rock Quartzite is no more than 5 meters. About 100 meters northwest of the Diamond Rock Quartzite, 2 to 3 meters of black shale is exposed underneath the ferruginous sandstone.

Ruedemann (1930, p. 80) stated that the "Schodack Shale and Limestone" has furnished nearly all the known fauna of the Lower Cambrian of the Capital District, with the exception of the Oldhamias occurrences. He (Ruedemann, 1930) pointed out that the fauna consists for the most part of small primitive brachiopods, of the genera Obolus, Ligulella and Acrotreta, some very rare primitive sponges, and corallike forms; of primitive gastropods of simple cap-shape, Hyolithes and small and primitive trilobites as Goniodiscus, Olenoides, Solenopleura. The most common species are obolella crassa and Botsfordia caclata, Hyolithellus *micans*, *Goniodiscus labatus* and *Elloptocephala asaphoides*. Many of these fossils were found in limestones and limestone conglomerates around the Troy area (Walcott, 1912). Some of them have also been collected in northern Washington County, New York (Theokritoff, 1964).

The thickness of the Browns Pond Formation is variable. At the type locality, it is 130 meters thick (Jacobi, 1977, p. 32). However, Rowley *et al*. (1979, p. 195) gave a wide range between 25 and 130 meters and considered 80 meters as typical. Dale (1904a, p. 29) estimated a thickness of about 6 to 65 meters of equivalent strata in Rensselaer and Columbia Counties. In the map area, the Browns Pond Formation has a thickness of about 80 meters.

ORDOVICIAN

Of the Ordovician, only Middle Ordovician rocks have been observed in the present area. In the Taconic region, the Middle Ordovician rocks can be divided into two suites, an Allochthonous Suite and an Autochthonous Suite. The Allochthonous Suite refers to the Middle Ordovician rocks in the Taconic Allochthon and the Autochthonous Suite includes the Middle Ordovician rocks around the Taconic Allochthon as well as underneath it. In the past, the name "Normanskill Formation" originally proposed for the older "Utica Shale" in the Hudson River Valley (Ruedemann, 1901a) was widely used to encompass all these Middle Ordovician rocks (Ruedemann, 1914, 1930, 1942; Goldring, 1943; Fisher, 1961; Knopf, 1962; Berry, 1962; and Potter, 1972). Dale (1904a) applied the term "Hudson River Formation" to these sequences.

In general, the Allochthonous Suite is divided into three parts: a red and green slate in the lower part, a black white-weathering chert in the middle and a graywacke in the upper part. They are referred to respectively as the Indian River Formation (Keith 1932), the Mount Merino Formation (Ruedemann, 1942; Jacobi, 1977) and the Pawlet Formation (Zen, 1961) or Austin Glen Graywacke (Ruedemann, 1942). All these rocks lie conformably on the Early to Middle Ordovician Poultney Formation although the thickness of each formation is variable from place to place mainly due to the effect of secondary deformation (Rowley et al., 1979). The Pawlet Formation or Austin Glen Graywacke constitutes the uppermost stratigraphic unit within the Taconic Allochthon (Zen, 1961, 1967; Dale, 1899).

The Autochthonous Suite include two formations. The lower part of it consists of dark gray to black slates or argillites on the east side of the Taconic Allochthon (Zen, 1961; Potter, 1972). In the Hudson River Valley and the Mohawk River Valley, it is a very thick sequence of dark gray to black shales, slates, mudstones, siltstones and minor carbonates (Mather, 1840; Walcott, 1890; Ruedemann, 1901a, 1912; Bosworth, 1980). Different names have been used for this slate or shale sequence in different places. On the east side of the Allochthon, it has been referred to as the Ira Formation in the north (Keith, 1932), the Walloomsac Slate in the central part (Prindle and Knopf, 1932) and the Trenton or Trentonian Black Shale in the south (Craddock, 1957; Weaver, 1957). On the west side, it has been called the Benson Black Slate in the extreme north (Dale, 1899), the Hortonville Slate in the northern part (Keith, 1932), the Snake Hill Shale near the Saratoga Lake (Ruedemann,

1912) and the Normanskill Shale or Normanskill Formation in the south (Ruedemann, 1901a). Along the Mohawk River Valley it has been named as the Canajoharie Shale at the mouth of the River (Ruedemann, 1912) and as the Utica Shale to the farther west (Vanuxem, 1842).

The upper part of the Autochthonous Suite is a flysch sequence consisting of graywackes and dark gray to black slates or shales (Ruedemann, 1942; Zen, 1961). This flysch sequence has been given the name Austin Glen Formation to the east of Saratoga Lake and Albany, and the Schenectady Formation in the central part of the Mohawk River Valley, and the Frankfort Formation farther west (Fisher, 1977).

Stratigraphical and paleontological studies indicate that the age of the basal part of the flysch sequence and the shale or slate sequence decreases progressively from east to west suggesting westerly progradation of these rock sequences (Rickard and Fisher, 1973; Rowley et al., 1979). It is for this reason that so many different names have been applied to these progressive onlap sequences by previous workers. In the Hoosick Falls area, Berry (1960) collected graptolites characteristic of his Orthograptus truncatus var. intermedius zone and Climacograptus bicornis zone from the Wallomsac Slate, which gives the rocks bearing these fauna a Wilderness and Trenton age. On the west side of the Taconic Allochthon, Ruedemann (1912) has shown that the Canajoharie is of the Lower Trenton age and essentially contemporaneous with the Snake Hill Shale. At the type locality of the Snake Hill Shale, Berry (1963) has also found the graptolite fauna diagnostic of the Orthograptus truncatus var. intermedius zone, which has further confirmed Ruedemann's work. Farther west, fauna diagnostic of Latest Trenton age have been found at the type locality of the Utica Shale (Ruedemann, 1901a).

The "Normanskill Shale" now lying to the west of the Walloomsac Slate has been proved to be Late Porterfield in age in its basal part (Berry, 1962). Therefore, it is older than the Walloomsac Slate. One sensible explanation for this is that the "Normanskill Shale" was deposited to the farther east of the present position of the Taconic Allochthon and then transported westwards by thrusting (Rickard and Fisher, 1973; Rowley et al., 1979).

Sedimentary and tectonic melanges have been found within the soft, fine-grained pelitic rocks of the Autochthonous Suite adjacent to and underneath the Taconic Allochthon (Ruedemann, 1901b; Zen, 1961, 1967; Bird, 1963; Potter, 1972; Fisher, 1977; and Bosworth et al., 1981). These informative rock bodies have also been given various names. They have been called the "Rydesdorph Hill Conglomerate" near Rensselaer, Schodack Landing and Bald Mountain and the "Moordener Kill Bed" in Castleton, New York (Ruedemann, 1901b, 1914, 1930), the "Forbes Hill Conglomerate" in west central Vermont (Zen, 1961), and the "Whipstock Breccia" in the Hoosick Falls area (Potter, 1972). Berry (1962) described these rocks as "Blocks in Shales". Bird (1963) gave the name "Wildflysch-type Conglomerate". Fisher (1977) proposed the term "Poughkeepsie Melange" for the chaotic rocks along the Hudson River Valley while Bosworth and Vollmer (1981) used the name "Taconic Melange" to include these rocks. All these rock bodies are believed to be related in some way to the emplacement of the Taconic Allochthon (Fisher, 1977; Rowley et al., 1979; and Bosworth and Vollmer, 1981).

INDIAN RIVER FORMATION

Keith (1932, p. 403) first applied the name Indian River Slate to the " ... formation which furnished the well known red slate of the New York slate industry". Theokritoff (1959, p. 56) amplified Keith's description to include the bluish-green slate commonly found intimately associated with the red slate in northern Washington County, New York. Field mapping by Craddock (1957), Elam (1960), Platt (1960), Zen (1961), Theokritoff (1964), Potter (1972), Jacobi (1977), and Rowley (1980) shows that the Indian River Formation is a distinct rock unit, easily mapped in the field, and, by lithic and stratigraphic comparison, followed from one area to another throughout the entire Taconic region.

The Indian River Formation is Dale's (1899) "Hudson Red and Green Slate" and also unit 4 of Zen's (1961) Mount Hamilton Group. Ruedemann (1942), Fisher (1961), Berry (1962) and others considered it as the lower part of the "Normanskill Formation". The type locality of the Indian River Formation is along the Indian River, south of Granville, New York; Rocks there are mainly bright red slates.

In the present area, the Indian River Formation is only exposed along the basal thrust of the Taconic Allochthon near the Devil's Kitchen in the Oakwood Cemetery. Together with the overlying Mount Merino Formation, it occurs as a huge block in the melange body below the basal thrust. It consists of green slates (Figure 4.11) and grades into light gray siliceous argillites with dark gray chert ribbons (Figure 4.12) along their strike. The green slates have a rusty weathering. In contrast with the white-weathering of the Mount Merino chert beds, the green

Figure 4.11
Indian River green slate underlying the white-weathering black chert beds of the Mount Merino Formation.

Figure 4.12
Light gray siliceous argillite with dark gray chert ribbons in the Indian River Formation.

slates commonly have a black coating on the surface. The green slates are highly deformed. Small folds with a wavelength of less than half a meter are ubiquitous. The Indian River Formation directly rests on the soft, dark gray, chocolate weathering Hudson River Valley shale and has protected it from fast erosion. Therefore, a typical stairway topography is created in the area. Near the contact between the Indian River Formation and the Hudson River Valley shale, the Indian River rocks also stick out to form small cliffs.

Elsewhere in the Taconic region, the contact between the Indian River Formation and the underlying strata has been a controversial subject. Potter (1972) reported an unconformity beneath the Indian River Formation in the western part of the Hoosick Falls area. Fisher (1961) also claimed an unconformable relationship between the Indian River Formation and the underlying sequence. However, the gradational contact between these rock sequences has been confidently described by Keith (1932), Theokritoff (1964), Zen (1967), Jacobi (1977), and Rowley et al. (1979) in the northern Taconics. Rowley et al. (1979) further pointed out that in the Granville area the nature of the lower contact depends on the color of the lowest Indian River rocks. If the rocks are red, the contact is sharp, and if the rocks are green, the contact is gradational over 1-2 meters from gray to green.

Theokritoff (1964) estimated a thickness of 60 meters for the Indian River Formation in northern Washington County. The thickness in the western part of the Granville area varies from 20 to 55 meters while it is poorly developed in the east (Jacobi, 1977). In the present area, the Indian River Formation and the overlying Mount Merino Formation occur as a huge block in the melange body below the basal thrust of the Taconic Allochthon, thus the lower part of the Indian River Formation and the upper part of the Mount Merino Formation are missing. The observed thickness of the Indian River Formation is about 5 to 10 meters.

Mount Merino Formation

Like the Indian River Formation, the Mount Merino Formation has only been recognized in the Allochthonous Suite of Middle Ordovician. Its type locality is at Mount Merino, west of the town of Hudson, New York (Ruedemann, 1942).

The name Mount Merino was first introduced into geological literature by Ruedemann (1942, p. 90) and has been widely accepted among Taconic geologists since then. However, the Mount Merino had not been considered as a separate unit until Jacobi (1977) elevated its status to a formation to express its distinct characteristics from the overlying and underlying units. Dale (1904a) included this unit in his "Hudson Shales", and Ruedemann (1942) included it in his "Normanskill Formation".

The name "Mount Merino Formation" covers a different range to different people. Ruedemann (1930, 1942) only distinguished two lithologic divisions within his "Normanskill Formation" in the Capital District and Catskill quadrangle, a lower unit of shale and chert for which he proposed the name Mount Merino and an upper unit of shale and graywacke for which he suggested the name Austin Glen. Platt (1960) used the name Mount Merino in the same sense. However, Craddock (1957) found that in the Kinderhook quadrangle, New York, the graptoliferous "Normanskill" beds underlying the distinctive Austin Glen Graywacke is divisible into two parts : a basal red shale and an upper variegated to black chert unit interbedded with shale. He called the basal red shale the "Red Shale Unit" and the overlying red and black chert with shale the "Black Chert Unit". Actually, the divisibility of the Normanskill beds underlying the Austin Glen Graywacke was noticed by Keith (1932) much earlier. He named the red slate in the lower part as the "Indian River Slate" and the black slate in the upper part as the "Unnamed Black Shale". Furthermore, Ruedemann and Wilson's (1936, p. 1541) description indicates that the Mount Merino Formation can be further subdivided into two parts: the chert and interbedded shales in the lower part and the chert-free shale in the upper part. Potter (1972), and Rowley et al. (1979) actually distinguished these two members within the Mount Merino Formation in the northern and central Taconics. Berry (1962) also divided the Mount Merino into two parts, that is, " (3) white-weathering black and green chert and interbeded black and green siliceous argillite, and (2) gray mudstone and black shale". It is to be noted that in Berry's division, the chert beds occur at a different stratigraphic position from the sequences of other people.

In the present area, the Mount Merino Formation only occurs on the west side of the basal thrust of the Taconic Allochthon near the Devil's Kitchen in the Oakwood Cemetery. It occupies the core of a syncline with the Indian River green slates on the both limbs. Here, the Mount Merino Formation consists mainly of black chert beds (Figure 4.13). The chert has a peculiar way of weathering white or light gray,

Figure 4.13
The Mount Merino Formation: well bedded white-weathering black chert beds interlayered with black shale.

thus described by Dale (1899) as the "White-Weathering Chert" or "White Beds" of the "Hudson Shales". An individual chert bed is from 3 to 10 centimeters thick. Within the chert beds, there are some interlayered black shales. The ratio between chert and shale is roughly 10 to 1. This unit can be traced along the strike for more than 200 meters.

The lower contact of the Mount Merino Formation can be clearly seen in the present area. It is sharp and conformable. Elsewhere, the Mount Merino Formation underlies the Pawlet Formation (Zen, 1961) or the Austin Glen Graywacke (Fisher, 1961). The contact between them is also conformable in Columbia, Rensselaer and on the west side of the Hudson River (Ruedemann, 1942; Berry, 1962). In the northeastern and central portions of Washington County, New York, and adjacent parts of Vermont, this contact has been generally considered to be an unconformity (Zen, 1961; Shumaker, 1967; Potter, 1972; and Bird, 1969). However, recent detailed mapping within the Giddings Brook Slice in the northern Taconics, in the vicinity of Middle Granville, New York (Jacobi, 1977; Rowley et al., 1979) has revealed that a completely comformable section through Early and Middle Ordovician is present along the western side of the Allochthon. Farther to the east, features diagnostic of pre-Pawlet erosion and angular unconformity have not observed either. Therefore, Rowley et al. (1979) suggested that the contact is at most a disconformity.

Graptolites are easily found in the Mount Merino Formation. Ruedemann (1901a) did detailed paleontological study at its type locality and provided a list of 30 species of graptolites (Ruedemann, 1908, p. 13).

He (Ruedemann, 1942) also reported the finding of brachiopods and sponges in the Mount Merino Formation. Ruedemann and Wilson (1936) described 23 species of radiolarians from this unit. Afterwards, Berry (1962) made 42 collections from the "Normanskill Formation", but mainly from the Mount Merino chert and interbedded shale. He found that these assemblages are similar to those of the Climacograptus bicornis zone as delimited by him (Berry, 1960) in Marathon, Texas. Therefore, he assigned a Middle Ordovician age to the Mount Merino Formation.

The thickness of the Mount Merino Formation is variable from place to place. At its type locality, the exposed chert reaches 15 meters (Ruedemann, 1942, p. 94). However, Ruedemann and Wilson (1936, p. 1542) estimated a total thickness of about 180 meters on the southwest spur of Mount Rafinesque. The upper part of the Mount Merino Formation has not been seen in the present area. The exposed thickness of the black chert beds is no more than 10 meters.

SNAKE HILL FORMATION

As stated previously, there exists a very thick sequence of Ordovician dark gray to black shales, slates, mudstones, siltstones and minor carbonates in the Hudson River Valley and the Mohawk River Valley. This is perhaps the most problematical rock sequence in the Taconic region. Worst of all, it has not been given a generally acceptable name after more than one hundred and sixty years geological studies.

Mather (1840, p. 212) first proposed the term "Hudson River Slate Group" to describe the rock sequence exposed in the Hudson River Valley. Later, he (Mather, 1845) changed the name to "Hudson River Group".

Vanuxem (1842) accepted Mather's term to include the beds between the "Utica Shale" and the "Oswego Sandstone" in the Mohawk River Valley. He pointed out that in the upper Mohawk River Valley the "Hudson River Group" includes two divisions which are not coextensive. The lower division is the "Frankfort Slate" which passes from the Hudson River Valley through the Mohawk River Valley and extends north by Rome through Lewis County into Jefferson County; and the upper division is the "Pulaski Shale" which first appears in Oneida County and extends from thence north and west. Emmons (1842) described shales of the Hudson River Valley as the "Hudson River Series or Group" and stated their extension northward through New York and Vermont to Quebec and through Pennsylvania into the southern states. However, he proposed the name "Lorraine Shales" for the rocks between the "Utica Shale" and the "Oswego Sandstone" to the west. In speaking of the term "Hudson River Group", Emmons (1847) stated: "The only reason assigned for the name was that this subdivision presented certain peculiarities arising from a disturbance it had suffered along the Hudson River. The Hudson River region, however, presents no facilities for the examination of the upper part of the Lower Silurian; it is only at Lorraine or Pulaski, in the neighborhood of Rome in New York, that this part of the series can be examined satisfactorily." Walcott (1890) extended the term "Hudson River Group" to cover all the strata between the Trenton limestone and the Upper Ordovician.

Around the turn of the century, Ruedemann (1901a) did the most extensive paleontological study at the Normans Kill near Albany and found that the rocks considered as the "Utica Shale" by previous workers are actually of Lower Trenton age. He named these rocks as the "Normanskill Formation" and argued for the suppression of the term "Hudson River Group". Later, he (Ruedemann, 1919) demonstrated that the black shales in the lower Mohawk River Valley are also older than the true "Utica Shale" and proposed the name "Canajoharie Shale" to describe them. At the same time, he distinguished another stratigraphic unit in the Hudson River Valley mainly on the basis of the different fauna in the rocks and named it as the "Snake Hill Shale". He interpreted the "Canajoharie Shale" and the "Snake Hill Shale" as the contemporaneous deposits in two separate basins. According to Ruedemann, the "Snake Hill Shale" was first deposited above the upper division of the "Normanskill Shale" in the Levis basin and then pushed westwards into contact with the "Canajoharie Shale" by thrusting.

From the preceeding historical review, it becomes clear that even though extensive studies have been made no suitable name can be adopted for the dark gray to black shales widely distributed in the Hudson River Valley and the Mohawk River Valley. The term "Hudson River Group" is inappropriate because it has different meanings to different people and because it includes not only the dark gray to black shale sequence but also the overlying graywackes or sandstones. The "Utica Shale", Canajoharie Shale", Snake Hill Shale" and "Normanskill Shale" are not really acceptable because all these terms have specific time - and/or bio-stratigraphic implications. Besides, the "Normanskill Shale" and "Snake Hill Shale" also include the rocks referred to as the Austin Glen Graywacke (Ruedemann, 1942; Berry, 1962) or Schenectady Formation (Ruedemann, 1912).

Nevertheless, the name Snake Hill Formation is adopted in the present study. This is simply because the name Snake Hill has been widely used among Taconic workers. However, the present investigator strictly restricts this term in a pure lithologic sense. It also excludes the Austin Glen Graywacke or Schenectady Formation overlying the chocolate-weathering black shale. Thus, the Snake Hill Formation is correlatable with Vanuxem's (1842) Utica Shale in the upper Mohawk River Valley, Ruedemann's (1912) Canajoharie Shale in the lower Mohawk River Valley and with the lower part of his Normanskill Shale (Ruedemann, 1942).

The Snake Hill Formation has only been observed along the west edge of the map area. It underlies the basal thrust of the Taconic Allochthon and belongs to the Autochthonous Suite. The Snake Hill Formation consists of dark gray to black argillaceous shales and siltstone or sandstone thin beds. Shales commonly have a peculiar chocolate weathering and are pyritiferous. Under the microscope, many brownish spots can be seen, which are probably limonite. Some of them still have the pseudomorphs of pyrite crystals. In places, shales are intricately contorted and crumpled and cut by cleavage surfaces and smoothed slip planes until they have the character of the shales which were named as the "glazed and contorted slaty shales" (Ford, 1884). Yet, in other places, for example, along the Northern Drive at the northwest corner of the map area, shales can be rather slaty. According to Ruedemann (1914, p. 95), they have been quarried for slate near Argyle. Thin siltstone beds are usually about 1-2 centimeters thick or less. Very often, they have been boudinaged or broken into lenticular blocks. Thin siltstone beds or blocks commonly stand out on the weathered surfaces due to the higher resistance to erosion relative to shales.

Blocks of other lithologies have also been found within the Snake Hill Formation. Actually, all the rocks belonging to the Indian River Formation and Mount Merino Formation in the present area occur as a huge block within the Snake Hill Formation black shales. Small inclusions of greenish graywacke, green slate, greenish gray siliceous argillite and black or green chert have also been seen in places. At the Devil's Kitchen in Oakwood Cemetery, a dark gray wacke block is present. It is about 1.5 meters long and 1 meter wide, with its long dimension parallel to the basal thrust. Lithological characteristics suggest that this block possibly come from the Austin Glen Graywacke. At an outcrop along the Troy bike trail near the Rensselaer Park Elementary School, a lenticular block of sandstone with primary folds is exposed (Figure 4.14). Therefore, the Snake Hill Formation in the present area is actually part of the Taconic Melange underneath the Taconic Allochthon.

The thickness of the Snake Hill Formation and lithologic equivalents decreases from east to west (Fisher, 1977). In the Hudson River Valley, it reaches 2300 meters. In the lower Mohawk River Valley, the maximum thickness is 1000 meters. In the upper Mohawk River Valley, it decreases down to about 230 meters. To the farther west, the thickness of the Snake Hill Formation is less than 65 meters.

Figure 4.14
Sandstone block with primary folds contained in the dark gray to black shale of the Snake Hill formation.

CHAPTER 5 STRUCTURAL GEOLOGY

INTRODUCTION

The most remarkable structural features of the mapped area are the widespread distribution of various kinds of folds, the presence of the basal thrust of the Taconic Allochthon and the development of peculiar anastomosing cleavages.

Folds are tight, westward-leaning and frequently overturned. They have various sizes in space and various shapes in profile. The geometry and magnitude of folds are clearly controlled by the lithological characteristics of rocks in which they occur. In general, folds developed in the Taconic rock sequence are larger in magnitude and have round hinges while folds observed in the dark gray to black soft shales along the Hudson River Valley are mostly chevron folds with much shorter wavelengths.

The overall trend of the basal thrust of the Taconic Allochthon is northeast, but it runs in the north-south orientation in the present area. The existence of the thrust has been proved stratigraphically and structurally. It is to be noted that the dip of the thrust is rather steep. At the Devil's Kitchen, the attitude of the basal thrust can be measured directly and the dip angle there is greater than 60^{o}. Therefore, the basal thrust occurs as a relatively steep frontal ramp in the present area (Butler, 1982). The formation of this ramp is possibly because the existence of the competent chert beds beneath the basal thrust prevented the foreward motion of the Taconic Allochthon and forced the hanging wall to climb upwards.

Three kinds of cleavages have been identified in the present area, the bedding cleavage, axial plane cleavage and anastomosing cleavage. Among them, the axial plane cleavage is most widespread and the anastomosing cleavage is most peculiar. Anastomosing cleavage is uniquely seen in the dark gray to black shales along the Hudson River Valley and often consists of very irregular networks. Axial plane cleavage commonly dips towards the southeast.

FOLDS

Folds are widely developed in the map area. They occur within the Taconic sequence as well as within the flysch sequence along the Hudson River Valley. Regional study shows that folding occurs within the flysch sequence for a distance of 15 to 20 kilometers west of the Taconic front and farther west the rocks show gentle dips for several tens of kilometers before becoming flat-lying (Ruedemann, 1914, 1930; Bosworth and Vollmer, 1981). Folds can be observed at three different scales and have various styles in profile.

Regional Scale Fold:

The structural pattern of the regional scale fold can not be revealed within a small area. Regional mapping shows that the present field area comprises part of the west limb of the Middlebury synclinorium (Doll et al., 1961). The Middlebury synclinorium plunges southward from the latitude of Monkton and embraces the structure of the area between Snake Mountain on its west limb and Green Mountain Front on its east limb. The Taconic and Middle Ordovician clastic rocks are situated at the core of the fold and older carbonate formations make up the limbs. Although the center of the synclinorium is occupied by the Taconic Allochthon south of the lattitude of Brandon and its southern part is highly disrupted by faulting, the overall pattern of the Middlebury synclinorium can be clearly seen north of the Sunset Lake in Vermont (Cady, 1945).

Outcrop Scale Folds:

The wavelength of the outcrop scale folds ranges from less than one centimeter to tens of meters. Some of these folds involve more than one rock unit and can be mapped at the map scale. Folds near the Devil's Kitchen in Oakwood Cemetery, Northwest of the Diamond Rock Quartzite and along the Route 40 near the Lansingburg Reservoir may be classified in this category.

In the Devil's Kitchen, the Indian River and Mount Merino Formations form a syncline, with the white-weathering chert beds at the core and the green siliceous shale or argillite on its limbs. The observed half wavelength is about 20 meters. Although no younging evidence has been found at this place, the distribution of the chert beds and the green argillite indicates that this is an overturned syncline with the axial plane dipping to the southeast (Plate II, section A-A'). The sycline plunges southwards.

On the west side of the type locality of the Diamond Rock Quartzite, a series of north-plunging folds are observed (Plate II, section B-B'). About 20 meters from the Diamond Rock Quartzite to the west, an anticline has been mapped. The upper part of the Truthville Formation lies at its core and the Browns Pond Formation comprises its limbs. Farther west, another isoclinal anticline is well exposed. It can be traced along its axis for more than 200 meters but its wavelength is no more than 10 meters. On the east limb the load casts give the younging direction to the east and on the west limb cross-bedding indicates that the younger rocks lie to the west. Thin to intermediate sandstone beds are seen on both limbs. In most places along the axis of the fold, black shale is exposed underneath the sandstone beds and it forms the core of the fold. The attitude of the sandstone beds on both limbs of the anticline is almost vertical. Adjacent to this long vertical isoclinal anticline, an asymmetrical syncline lies to the west at the north end of this outcrop. The core of the syncline consists of dark gray to black silty shale, thin to intermediate bedded sandstones are exposed on the both sides. The east limb of this syncline dips 65^{o} to the southeast while the west limb has a dip of less than 15^{o} towards the same orientation. About 15 to 20 meters northwest from this outcrop, still another north-plunging anticline is seen. The exposed width is about 10 meters. The anticline consists of thin to intermediate sandstone beds. Its east limb dips 22^{o} towards the northeast and the west limb dips 60^{o} towards the northwest near the core and becomes steeper and steeper away from the core. In the north of this anticline, a rather massive orange or rusty weathering quartzite body is esposed. At the southwest of this quartzite exposure there exists a north-plunging syncline. Its axial plane dips about 40^{o} towards the east.

In the creek near the Lansingburgh Reservoir and at an outcrop along Route 40 about 50 meters south of the intersection between Route 40 and the Northern Drive, some gently south-plunging folds are seen. The half wavelengths of these folds are no more than 10 meters. The anticline by Route 40 is associated with well developed axial plane cleavages (Figure 5.1). These cleavages dip 58^{o} to the southeast. All these folds consist of the Browns Pond dark gray to black silty shale or siltstone.

Very often, outcrop scale folds are so small that they can not be mapped at the map scale. This type of fold is only developed in the less resistant rocks, specifically, in the green slates of the Indian River Formation and in the dark gray to black shales of the Snake Hill Formation in the Hudson River Valley. The half wavelengths of these folds are usually from about 1 meter down to about half a centimeter or less. The majority of folds at this scale are discontinuous with attenuated or disrupted limbs (Figure 5.2).

The style of folds are varied and are mainly controlled by lithology. The homogeneously layered shale sequences in the Hudson River Valley commonly form chevron folds (Figure 5.3). Thick bedded sequences of graywacke, sandstone and siltstone usually form folds with round hinges. Tight to isoclinal folds are formed when the amount of imposed strain is large enough.

The attitude of axial planes and hinge lines of folds has been measured systematically at several localities. Figure 5.4 shows some of the results. From these diagrams, we can clearly see that nearly all folds measured have axial planes dipping to the southeast and hinge lines plot as a great circle within the average axial plane orientation. Folds in the Taconic sequence consist of more competent rocks such as graywacke, sandstone and siltstone and have longer wavelengths and less frequency. Therefore, only several measurements have been made on these folds. However, these limited measurements still provide a

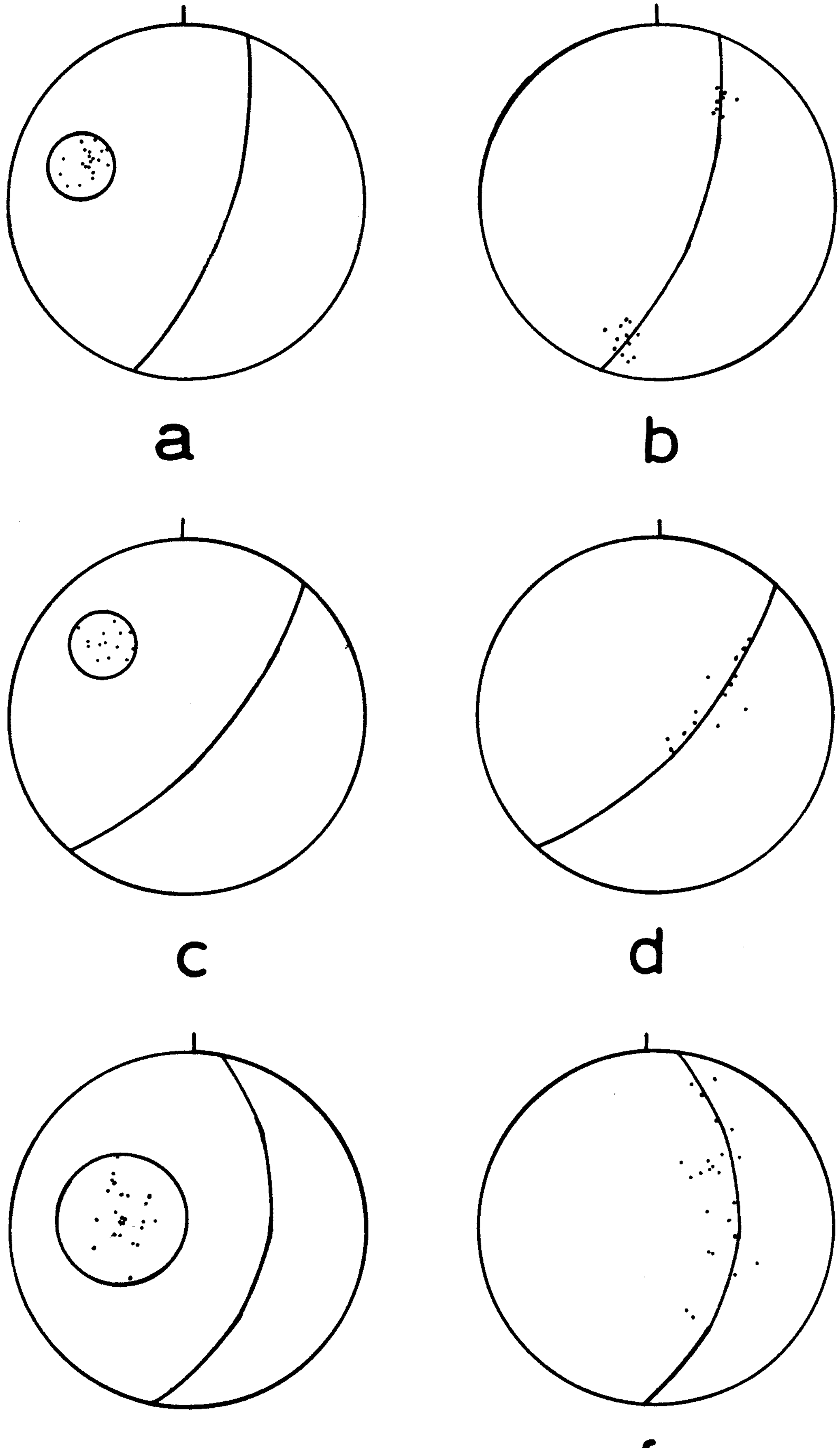
Figure 5.1
An anticline with well developed axial plane cleavage seen about 30 meters southwards from the intersection between Route 40 and Northern Drive.

Figure 5.2 Microfolds with attenuated or disrupted limbs seen in the chocolate-weathering black shale of the Snake Hill Formation. The blackened part is black shaly material. The unblackened part is brown-weathering shale. The rock sample is from an outcrop near the intersection between the Troy bike trail and Gurley Avenue.


0 2cm

Figure 5.3
Chevron folds commonly seen in the dark gray to black shale of the Snake Hill Formation along the Hudson Valley. The outcrop is near the intersection between Northern Drive and the Troy bike trail.

Figure 5.4 Sterographic projection of axial planes and hinge lines of folds in the Indian River Formation and Snake Hill Formation. a, c and e, are projections of axial planes of folds. The small circle is the smallest circle which can contain all the dots. The projection of its center is taken as the average attitude of the axial planes of folds at a particular outcrop. b, d and f are projections of hinge lines. The great circle represents the average attitude of the axial planes. Measurements for a and b are made in the Indian River green slate exposed about 30 meters west of the Devil's Kitchen; c and d in the Snake Hill Formation exposed about 350 meters north of the Devil's Kitchen; e and f in the rusty-weathering black shale near the intersection between the Troy bike trail and Northern Drive.


a
b
c
d
e
f

consistent orientation as do the axial planes and hinge lines measured in the green slates or siliceous argillites and in the dark gray to black shales along the Hudson River Valley.

Folds with an exceptional orientation are present at one locality about 300 meters north of the Devil's Kitchen. At this place, folds are developed in the white-weathering chert beds and associated black shales. They trend north and have nearly vertical axial planes. The hinge lines of these folds plunge about 50° towards the northeast.

FAULTS

The most important fault in the present area is the basal thrust of the Taconic Allochthon. It crosses the entire field area in a north-south direction and is well exposed at the Devil's Kitchen in Oakwood Cemetery. This thrust is supposed to be a segment of a more or less interrupted overthrust line that extends from Canada through Vermont and New York to the southern Appalachians. This line has been called "Logan's Line" after the former director of the Canadian Survey, Sir William Logan, who first pointed out its long extension and structural importance (Logan, 1863). In the present area, evidence for the existence of this major fault includes:

(1) At the Devil's Kitchen, the Pre-Cambrian Bomoseen greenish graywacke is directly in contact with the Middle Ordovician green slates or green siliceous argillites and white-weathering black chert beds (Plate II).

(2) The Indian River Formation and Mount Merino Formation can not be traced continuously along their strike. They occur as large blocks between the Bomoseen greenish graywacke or the Truthville olive silty shale and the Snake Hill dark gray to black shale.

(3) At the Devil's Kitchen, a highly foliated zone about 10 to 15 meters wide is present between the Bomoseen greenish graywacke and the Indian River green slates. Rocks from both sides occur as inclusions within the foliated zone (Figure 5.5).

(4) Where the foliated zone can not be observed, we can still see that rocks near the fault are usually highly disrupted.

(5) Shear surfaces with slickenside striations are more easily found along the trace of the thrust.

It has long been maintained that the rocks now found just to the east of the Hudson River were transported from farther east to the present position. This implies that a huge thrust exists between the Taconic sequence and the autochthonous sequence along the Hudson River Valley. Evidence obtained from the present study is consistent with this previous conclusion. The evidence is:

(1) At the Devil's Kitchen, graded bedding in sandstone beds indicates a normal sequence in the Bomoseen and Truthville Formations. The greenish graywacke of the Bomoseen Formation at a much lower stratigraphic level now overlies the Middle Ordovician Indian River green slates or light gray siliceous argillites.

(2) Less than one hundred meters eastwards from the major thrust fault, where a distinct sandstone marker bed is present, a small fault shows the reverse sense of shear which is consistent with the nature of the basal thrust (Figure 5.6).

Figure 5.5
The foliated zone between the Bomoseen greenish graywacke and the Indian River green slate seen at the Devil's Kitchen in Oakwood Cemetery. The large block at the lower right is dark gray wacke. Most small blocks are light gray siliceous argillite of the Indian River Formation. The matrix is the black shale of the Snake Hill Formation.

Figure 5.6 A small reverse fault indicated by a calcareous sandstone interbed in the dark gray to black shale of the Browns Pond Formation. The outcrop is about 25 meters south of the intersection between Route 40 and Northern Drive.

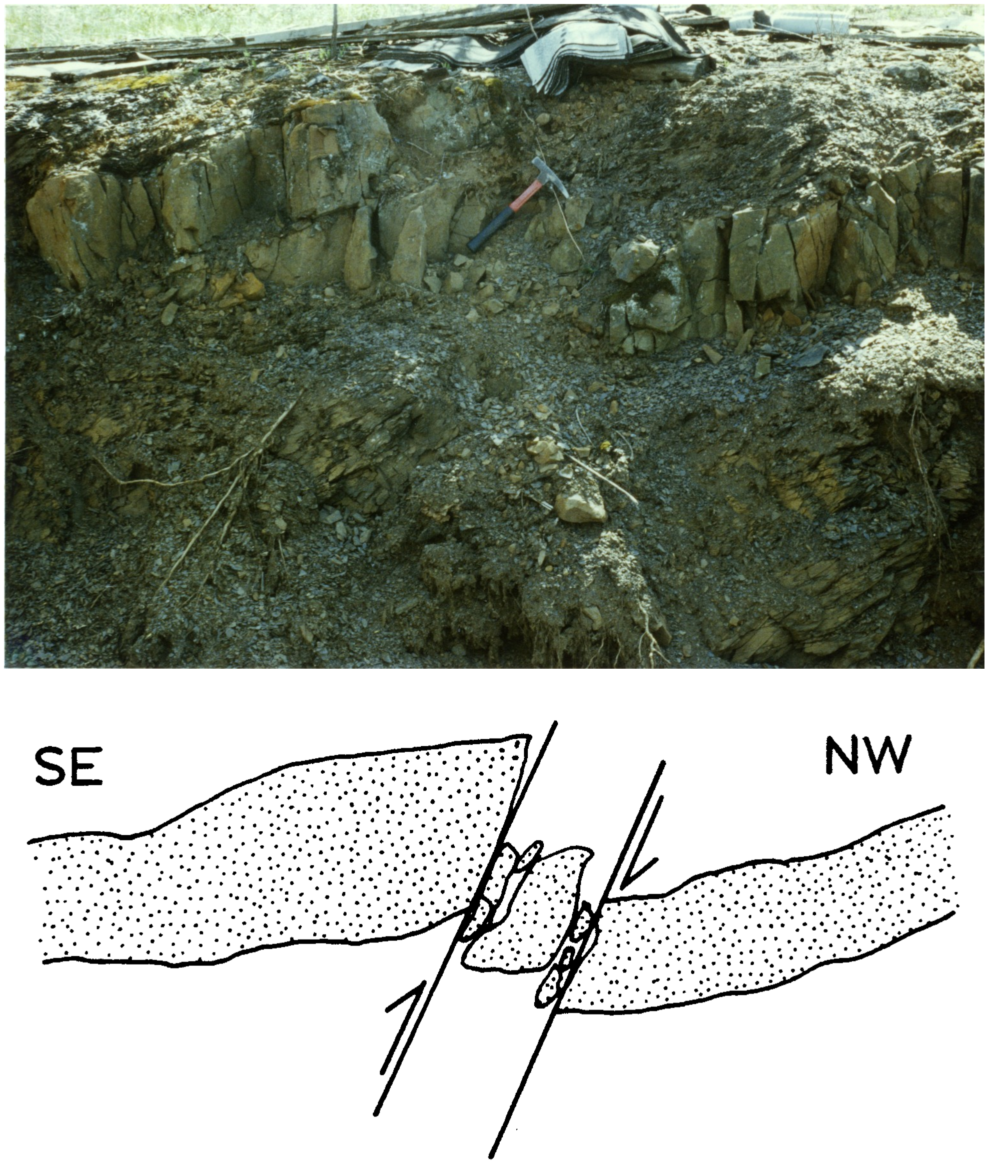


Figure 5.6
A small reverse fault indicated by a calcareous sandstone interbed in the dark gray to black shale of the Browns Pond Formation. The outcrop is about 25 meters south of the intersection between Route 40 and Northern Drive.

(3) About 8 meters above the basal thrust at the Devil's Kitchen near the largest pond in Oakwood Cemetery the Truthville green silty shales with quartzite thin beds are disrupted by many small faults. The strike of these faults is approximately parallel to the strike of the basal thrust of the Taconic Allochthon but the dip angle is higher. They are possibly the branch faults of the basal thrust. The bending of rocks between these small faults strongly suggests a westward transport of the Taconic sequence (Figure 5.7).

(4) Offsets of some silty beds within a sample collected from about 15 meters below the basal thrust of the Taconic Allochthon near the northern edge of Oakwood Cemetery also indicate reverse sense of shear (Figure 5.8). One side of this sample is a shear surface with slickenside striations. The shear surface is roughly parallel to the overall attitude of the basal thrust. The sense of shear indicated by steps associated with the slickenside striations is consistent with the offsets of silty beds, if the steps are interpreted in the classical way.

It should be pointed out that the bulk displacement of the Taconic sequence is not achieved along a single surface. Present investigation reveals that the amount of displacement is unevenly distributed among structural discontinuities of three different scales. The most prominent structural discontinuity lies between the Taconic sequence and the autochthonous sequence, that is, the basal thrust of the Taconic Allochthon. Very often, it occurs as a highly foliated zone which ranges from several meters to tens of meters thick. This thrust zone is probably responsible for a large part of the overall displacement of the Allochthon. The existence of this thrust zone can be easily recognized by the large lithological contrast on both sides of the thrust zone or by the

Figure 5.7 Bending phenomena of rock chips between small faults associated with the basal thrust of the Taconic Allochthon.

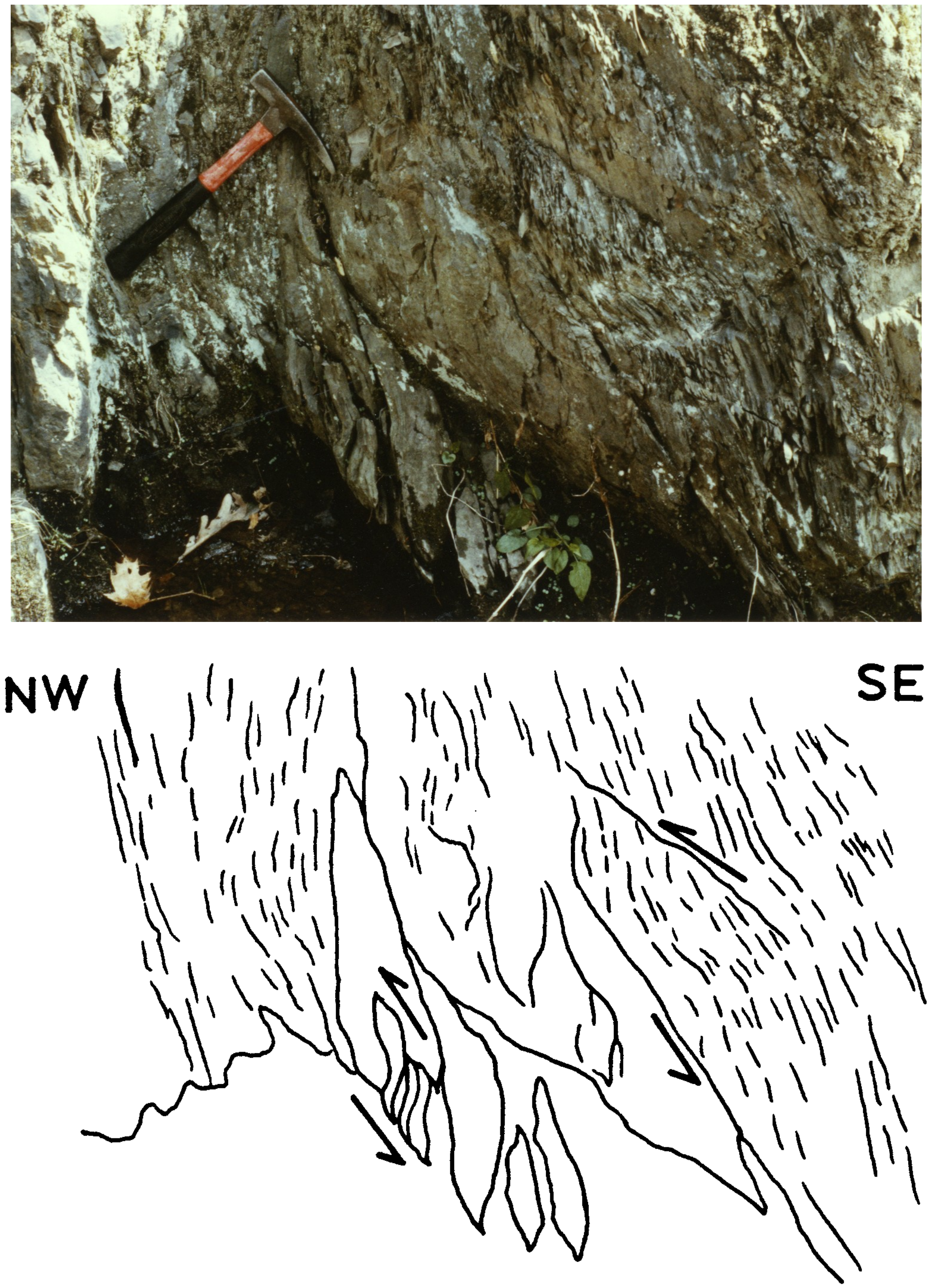
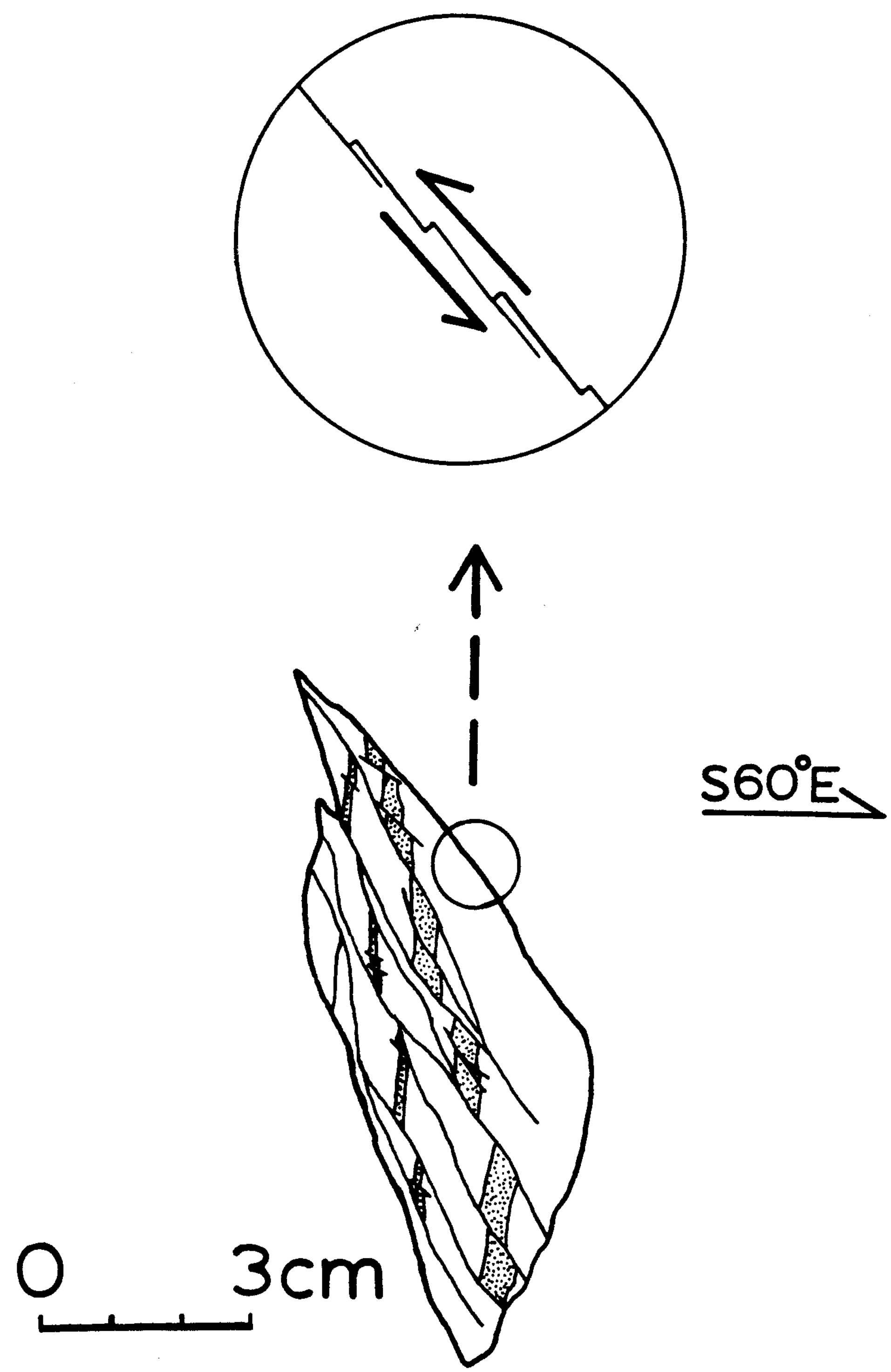


Figure 5.7
Bending phenomena of rock chips between small faults associated with the basal thrust of the Taconic Allochthon.

Figure 5.8 Offsets of silty beds within the black shale of the Snake Hill Formation. The enlargement shows schematically the step structure seen on the upper surface of the sample.


S60°E
0
3cm

presence of a highly foliated or disrupted zone.

Structural discontinuities at the next level are usually identified with difficulty due to the lack of lithostratigraphical marker horizons. In the monotonous shale sequence along the Hudson River Valley, the recognition of paleontological discontinuities is often the only way to determine their presence (Ruedemann, 1914; Rickard and Fisher, 1973). In a structural study of the Middle Ordovician flysch in eastern New York, Bosworth and Vollmer (1981) found that melanges containing exotic blocks occur as long and narrow belts. They interpreted these melange belts as the traces of thrust faults or shear zones. Using this as a criterion, another fault parallel to the basal thrust has been identified in the present area along the bike trail near the Rensselaer Park Elementary School. It occurs within the Snake Hill dark gray to black shales and can not be traced very far along its strike. In the Taconic sequence, many branch faults have also been recognized along the basal thrust of the Allochthon by other workers (Zen, 1967; Rowley et al., 1979).

Another type of structural discontinuities are zones of pervasive shear surfaces within the flysch sequence along the Hudson River Valley. These shear surfaces usually die out within a very short distance, commonly several centimeters along their strike as well as their dip. Ubiquitous slickenside striations indicate that displacements have taken place along these surfaces. In favorable situations, the amount of displacement can be actually calculated by adding up the offsets of some distinct silty beds observed in sections cut parallel to the movement direction and perpendicular to the structural surfaces. Obviously, individual shear surfaces of this kind can not achieve very large displacement, but, since they are so closely spaced, the total displacement achieved by them can still be astonishing.

CLEAVAGES

In the present area, three types of cleavages can be differentiated on the basis of their orientations, modes of occurrence and their relations to mesoscopic folds.

Bedding Cleavages:

Bedding cleavage refers to the cleavage that is parallel to the bedding plane. Morphologically, bedding cleavage looks very similar to bedding fissility which is the property possessed by a sedimentary rock of tending to split more or less parallel to the bedding and is a primary foliation that forms while the sediments is being deposited and compacted. Both bedding cleavage and bedding fissility are caused by the parallelism of the platy minerals to the bedding plane. There are three features to justify that it is called beddding cleavage rather than fissility in the sense of sedimentology. First, each individual surface can be traced for a rather long distance. Secondly, at an outcrop near the intersection between Route 40 and Northern Drive, where the best bedding cleavages are exposed,several bedding-parallel shear surfaces are also developed within a sandstone interbed. On one of these surfaces, slickenside striations indicate the movement parallel to the bedding and perpendicular to the axis of a mesoscopic fold. The third evidence is that in places empty open spaces are present around the hinges of small folds which suggest the slipping of sedimentary strata along bedding planes during folding. It is likely, however, that the primary fissility of rocks can facilitate the development of bedding cleavage to a large degree since this type of cleavage has mainly been observed in various kinds of shales. Some of the bedding cleavage surfaces may also simply represent the tectonically activated bedding fissilities.

In general, bedding cleavage can be easily distinguished from axial plane cleavage because it does not cut across the bedding near the hinge of folds although they can be identical in the situation of isoclinal folds. At one outcrop near the Lansingburgh Reservoir, the axial plane cleavages clearly cut across the bedding cleavages and break the rocks into small parallelograms. The spacing of bedding cleavages ranges from about half centimeter down to less than one millimeter. Bedding cleavage has been observed in shales of different ages and its intensity varies from place to place.

Axial Plane Cleavages:

This type of cleavage is most widespread in the map area in comparison with the other two kinds. It is seen in almost all kinds of rocks although the spacing and planarity of cleavages are varied in different rock units with different lithologies. It is for this reason that this type of cleavage has also been referred to as regional cleavage elsewhere. In two outcrops near the intersection between Northern Drive and the Boston-Maine Railroad and near the Lansingburgh Reservoir, where mesoscopic folds are well exposed, cleavages are obviously parallel to the axial plane of folds. In profile, cleavages cut across the bedding plane with an intersecting angle from 30° on the limbs to 90° at the core. At the outcrop near the intersection between Northern Drive and the Boston-Maine Railroad, where folds are close, axial plane cleavages are parallel to the bedding cleavages. Where round hinge folds consisting of more silty to sandy beds are seen, cleavages clearly cut across the bedding plane rather than parallel to it. In general, cleavages dip from 50° to about 80° toward the southeast. The spacing of cleavages in shales is much closer than in wackes. In shales, the spacing of cleavages is from 1 millimeter to about 5 millimeters, while it reaches about 2 centimeters in wacke beds. This difference in spacing is well expressed in an outcrop along Gurley Avenue near the St. John Cemetery. In the dark gray to black fine-grained shales with very thin brown-weathering siltstone interbeds, cleavages have a spacing of less than a millimeter while in the black siltstone or fine-grained sandstone below and above these shales cleavage planes are commonly about a half centimeter or one centimeter apart.

The refraction of cleavage planes has also been observed in an outcrop near the Lansingburgh Reservoir. At this outcrop, cleavages in shales dip at about 50° towards the southeast whereas the cleavages in an intermediate sandstone interbed dip towards the northwest. When the cleavages in the sandstone interbed dip toward the southeast, the dip angle is usually more than 80°. The orientation of cleavages in the sandstone interbed is also less regular.

Anastomosing Cleavages:

Anastomosing cleavage is only seen in the dark gray to black shales along the Hudson River Valley, which has been called as the

"Snake Hill Shales" by Ruedemann (1912). This specific structure has been noticed since the early investigation along the Hudson River Valley. Geologists of the first survey gave the names "glazed shale" or "semimetamorphic shale" to the rocks with this type of structure (Ford, 1884; Ruedemann, 1914). Ruedemann (1930, p. 118) also described: "the Snake Hill beds are, as a rule, intricately contorted and crumpled and cut by cleavage planes and smoothed planes".

The best exposure of anastomosing cleavage is around the northeast corner of the Uncle Sam Pipe and Supply Co. Inc. situated at the intersection between the Nineth Avenue and the Thirteenth Street of Troy City. The outcrop here consists predominately of dark gray to black shale with occasional siltstone interbeds. The shale has a cafe or chocolate weathering on the surface. Siltstone interbeds are usually about 1-2 centimeters thick or less. Very often, these siltstone thin beds are broken into pieces or sections. In places, however, they can still be matched along their strike.

Two kinds of structural surfaces can be recognized at the outcrop. One of them has a distinct preferred orientation which is approximately parallel to the axial plane cleavages observed elsewhere. Locally, where this kind of surfaces are better developed, rocks look rather slaty. This allows us to measure the attitude of cleavages quite accurately. Individual surfaces are very flat. The spacing of structural surfaces is about 1-2 millimeters or less. However, these surfaces, which are not too much different from the cleavages we see in slates, change very rapidly along their strike. Within half a meter or so, the slaty appearance of rocks becomes much less clear and the spacing of these surfaces becomes much wider. Nevertheless, if we look carefully, we can still recognize the existence of these structural surfaces. Even within a small piece of rock chip surrounded by the shearing surfaces of the second type which will be discussed afterwards, we can easily split the rock chip into very thin slabs along these surfaces. But, these surfaces become somewhat irregular and their orientations swing slightly. These surfaces generally have a rough look to the naked eyes and show no indication of shearing displacement.

The other type of structural surfaces are usually oblique to the first type. They are arranged in more than one orientations. Often, we can find these surfaces with four or five different directions in a piece of rock chip with a diameter of less than 5 centimeters. However, almost all these surfaces have an intersecting angle of less than 40° with the surfaces of the first kind. Structural surfaces in different orientations interwine together and break rocks into lenticular pieces or scales. The term anastomosing cleavage is employed to reflect this characteristic pattern of cleavages. This type of cleavage surfaces are exclusively smoothed and all have slickenside striations. Striations are commonly distributed in several different orientations. Sometimes, a radiative pattern of striations can be found. Measurements are hard to make in the field because the surfaces bearing slickenside striations are usually too small.

Borradaile et al. (1982) recommended that the average spacing of any particular cleavage be calculated by counting the number of cleavage traces crossed on a traverse normal to the general cleavage plane. This method is simple to use and convenient for comparison between different cleavages. By counting the number of cleavage traces which can be identified with nakes eyes, the average spacing of anastomosing cleavage in the shale studied is from 5 millimeters down to less than 1 millimeter. With the help of an ordinary microscope, much more cleavage traces can be differentiated, which gives an even closer average spacing. This value is greatly lower than the average spacing of anastomosing cleavage in sandy rocks given by Borradaile et al. (1982). They indicated a lower limit of about 5 millimeters which is the upper limit for the anastomosing cleavage in the shale studied.

CHAPTER 6 DETAILED STUDIES OF THE ANASTOMOSING CLEAVAGES IN TACONIC MELANGE

INTRODUCTION

1. Terminology

"Anastomosing cleavage" is used here as a pure descriptive term to designate non-planar cleavages with a reticulating or interconnecting pattern. There are only two conditions implied in this definition. First, the surfaces are close enough to be called cleavages. Powell (1979) gave a value of 10 cm as the upper spacing limit of cleavages. Price and Hancock (1972) suggested an upper limit of 5 cm separation, with a further restriction that the distance between the surfaces should be less than 1/20 of the thickness of the bed. The structural surfaces with a wider spacing are called "joints" by most geologists. It should be pointed out that in practice cleavages may pass gradationally into joints. Therefore, the boundary between cleavages and joints can be rather arbitrary. The second condition implied in the definition is that cleavage surfaces are interconnected and comprise an anastomosing pattern as a whole. As long as cleavages meet these requirements, they can be called "anastomosing cleavages", regardless of their origin. This type of cleavage has also been called "reticulate cleavage" (Crook, 1964), "phacoidal cleavage (Bosworth, 1980; Bosworth and Vollmer, 1981), or "lenticular cleavage" (Bradbury and Harris, 1982).

Powell (1979) also used the term "anastomosing cleavage" to describe this type of cleavages. In his cleavage classification, Powell divided his "disjunctive cleavages" into four types according to the planarity of cleavage domains. They include: styolitic, anastomosing, rough and smooth disjunctive cleavages. He considered the "anastomosing cleavages" as part of a progressive series of increasing planarity of cleavage domains. Later, however, Bayly, Borradaile and Powell (1982) placed "anastomosing cleavage" in their classification based on the patterns of cleavage traces. They distinguished three different patterns, anastomosing or reticulate, trapezoidal and conjugate cleavages and stated that to some degree they represent an increasing degree to which two distinct directions can be recognized in a cleavage. The present investigator agrees that "anastomosing cleavage" describes a cleavage pattern consisting of many cleavage surfaces rather than the characteristics of a single cleavage surface, but he prefers to use this term in a much broader meaning. In the ordinary sense, the word "anastomosing" means "net-like". Nets or networks can have very regular structures. Therefore, "anastomosing cleavage" should be used as the name for a large category which includes conjugate and trapezoidal cleavages (see Table III). The term "anastomosing cleavage" is compared with "parallel cleavage".

Under the category of anastomosing cleavage, we can further divide into four types according to the regularity of cleavage surfaces and the intersecting angle between them. These are: square, rhombic, trapezoidal and irregular. Their characteristic features are listed in Table IV). It should be pointed out that the irregular anastomosing cleavage is far more common than any other type of anastomosing cleavage. This is why many structural geologists prefer to use the term anastomosing

TABLE III CLASSIFICATION OF CLEAVAGE PATTERNS

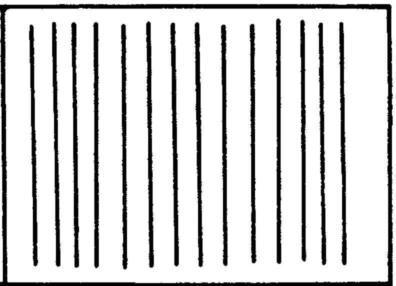
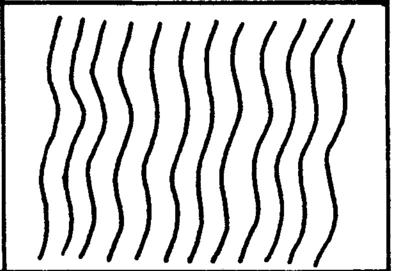
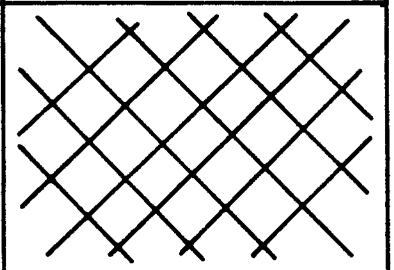
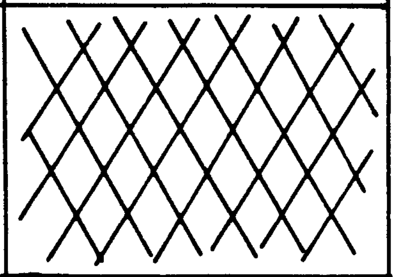
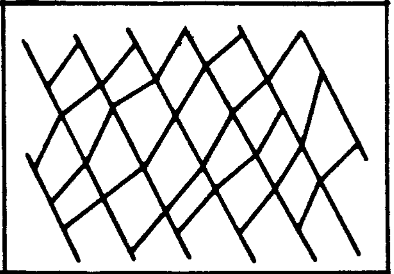
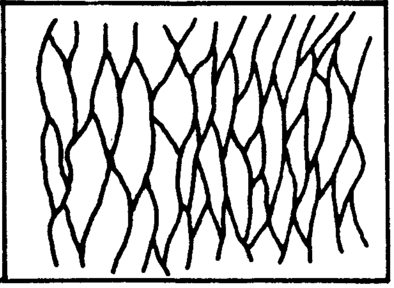
PARALLEL CLEAVAGES	STRAIGHT PARALLEL	
	SINUOUS PARALLEL	
ANASTOMOSING CLEAVAGES	SQUARE	
	RHOMBIC	
	TRAPEZOIDAL	
	IRREGULAR	

TABLE IV CLASSIFICATION OF ANASTOMOSING CLEAVAGES

CLEAVAGE TYPES \ PARAMETERS OF CLASSIFICATION	REGULARITY OF CLEAVAGE SURFACES	INTERSECTING ANGLE BETWEEN CLEAVAGES
SQUARE	Two sets of cleavage surfaces are distinct. Each set of cleavages are parallel to each other.	90^{o}
RHOMBIC	Two sets of cleavage surfaces are distinct. Each set of cleavages are parallel to each other.	$>0^{o}$ $<90^{o}$
TRAPEZOIDAL	Only one set of cleavage surfaces are parallel to each other, while the other group of cleavages have less regular orientations and intervals.	Variable
IRREGULAR	Two sets of cleavage surfaces are irregular but still show some statistically preferred orientations	Variable

cleavage to describe the irregular anastomosing cleavage only and use other terms for the other types.

Morphologically, "conjugate cleavage" is just a special type of square or rhombic anastomosing cleavages (Figure 6.1). However, the term "conjugate cleavage" usually has a genetic connotation. It refers to a pair of cleavages formed at the same time or during the same episode, related in deformational origin and having similar form symmetrically inclined about a plane of symmetry.

In Figure 6.1, only Figure 6.1c is conjugate cleavage. Although cleavage surfaces in Figure 6.1a can be formed at about the same time, the status of two sets of cleavage surfaces is not the same. Cleavages in one orientation are caused by the relative movements of the other set, that is, they are shears of the second order (McKinstry, 1953). Besides, two sets of cleavage surfaces do not show opposite senses of rotation. Cleavage surfaces in Figure 6.1b belong to the same order but they are sequential shears. Again, the senses of shear are counter-clockwise along cleavage surfaces in both orientations. Superficially, cleavages in Figure 6.1d are very much like conjugate cleavages because cleavage surfaces do show opposite senses of shear. However, if we take a close look we will find that one set of cleavage surfaces consistently offset the other set of cleavage surfaces which indicates that they are also sequential shears.

2. Historical review

An anastomosing cleavage pattern has been described in many different rocks including deformed mudstone (Crook, 1964), sandstone (Gray, 1978; Borradaile, 1982), limestone (Sansone, 1982), gneiss and

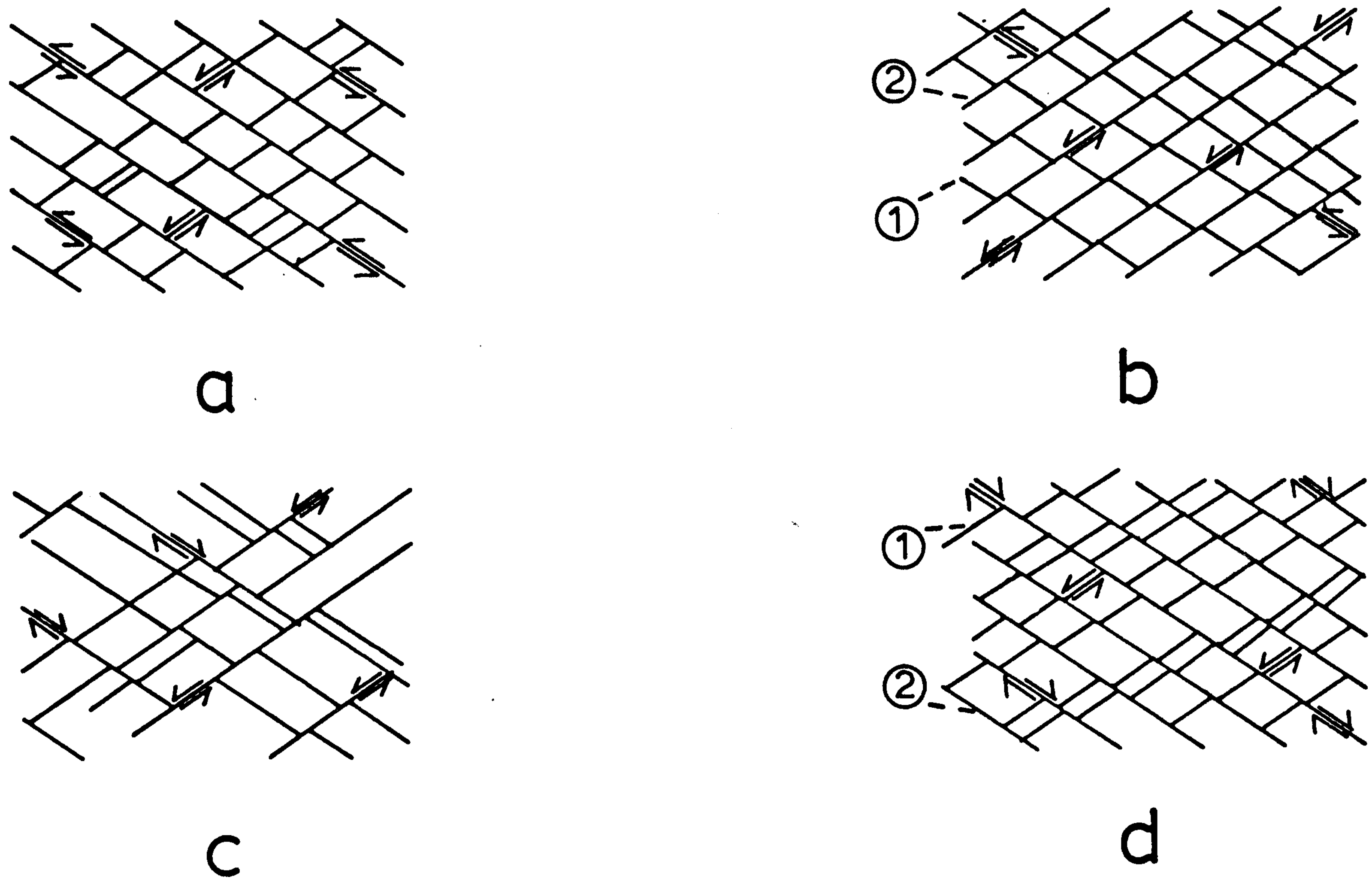


Figure 6.1 Four Types of Rhombic Anastomosing Cleavages

① first generation ② second generation

granite (Mitra, 1979). In spite of its widespread occurrence, attention has not been paid to this type of cleavage until about two decades ago.

Crook (1964) was the first to notice this distinctive pattern of cleavage. According to him, anastomosing cleavage is well developed in mudstone sequences in various parts of eastern Australia, especially in the Tamworth Trough. The mudstone sequences there are generally moderately indurated and are only weakly deformed. To the naked eye, neither recrystallization nor the growth of new minerals is visible.

The cleavage consists of non-planar fractures. Fractures anastomose in profile view and along the strike direction of the cleavage. Weathering of very strongly cleaved mudstone commonly produces a characteristic mass of acutely terminated elongate, polygonal fragments. Crook proposed the term "reticulate cleavage" in order to reflect this particular pattern of fractures.

In the mudstone sequences, the following significant features have also been described by Crook (1964):

(1) The form of the cleavage does not vary with changes in the thickness of apparent competence of interbedded siltstone and fine sandstone units. Coarser grained beds lack cleavage and are transected by widely spaced joints.

(2) Bedding planes are rarely slickensided, which suggests that relative movement between competent beds was not important.

(3) Irregular Intraformational mudstone blocks included in well-indurated rudites displayed a reticulate cleavage of the same morphology and orientation as that in adjacent mudstones.

These observations, the common absence of competent beds and the widespread development of anastomosing cleavage in thick mudstone sequences led Crook to believe that the anastomosing cleavage develops in response to bulk strain in the whole sequence attendant on folding and is not related to the relative movements between competent beds.

The origin of the chaotic rock bodies occuring in many orogenic zones throughout the world puzzled geologists for many years. The advent of plate tectonics changed this situation and provided a satisfactory explanation for the formation of these highly disrupted and mixed rock bodies or melanges. They have been considered as remnants of ancient subduction zones (Hsü, 1968, 1969; Hamilton, 1969; Dickinson, 1971). This inspiring view point has also given much courage to structural geologists frustrated by these "mysterious" rock bodies for decades and attracted much attention to do further researches about their characteristics and tectonic significance.

One of the major achievements of the studies on melanges is the recognition of the pervasive development of anastomosing cleavages in melanges (Hsü, 1974; Cowan, 1974; Moore and Kariq, 1980; Connelly, 1978). Some people (for example Hsü, 1968; Moore and Wheeler, 1978) consider that the development of anastomosing cleavages is the special "style of deformation" in melanges. For example, Cowan (1974) writes "The Garzas tectonic melange ... displays a distinctive deformational style characterized by small angular phacoids and larger geometrically and dimensionally variable blocks of resistent rock types enclosed in a pervasively sheared fine-grained matrix. ...Although the rock types and degree of shearing vary within the unit, the essential components of its chaotic structural geometry are penetrative mesoscopic shear surfaces. ... The shear surfaces occur as subparallel anastomosing fractures in brittle graywacke and more closely spaced fractures in less competent argillaceous rock".

However, most structural studies of melanges have concentrated on map scale relationships, variations in textural reconstitution, and the correlation of map scale structure to regional tectonic elements. Statistical structural studies of melanges have been hampered by their inherently poor exposure and the difficulty with which their fabric elements are studied. Microscopic examination of anastomosing cleavages has also been avoided due to the necessity of highly troublesome techniques in the preparation of rock samples and the fineness of the grain size in the shaly material bearing cleavages. What are the actual morphological characteristics of anastomosing cleavages? How do they originate and evolve? What is the relationship between individual cleavage surfaces? What can we tell about the regional tectonics from the studies of anastomosing cleavages? These questions have not been approached by most of the previous workers.

Recently, Bosworth and Vollmer (1981) have taken the first step to study anastomosing cleavages in the Taconic region in more detail. They described the highly irregular, anastomosing fabric characteristic of many outcrops in the Hudson shales. They measured the orientations of cleavage surfaces in sections cut perpendicular to the regional cleavages, both parallel and perpendicular to strike and noticed two discrete populations in each section although significant populations of cleavage surfaces with other orientations are also present. They suggested that a minimum of four sets of cleavage surfaces are required to define the crudely polyhedral shapes of shale phacoids which they observed at outcrops and in hand specimens.

Bosworth and Vollmer (1981) also found the following evidence which is relevant to the interpretation on the origin of the anastomosing cleavages: presence of down-dip striations on many individual phacoids, offset of phacoids in microstructure observed under microscope, asymmetrical microfolding of clast material between cleavage folia, pronounced hinge line reorientation within zones of phocoidally cleaved shale, association with macroscopic asymmetric folds, thrust faults and shear zones, and increasing areal extent towards an overthrust terrane. They concluded that anastomosing cleavages could be produced due to non-coaxial deformation under simple shear at high strain rates. Cleavages are initially formed perpendicular to the maximum compressive stress and then are rotated to planes experiencing a shear stress as deformation proceeds. When new folia develop perpendicular to successive σ_1 orientations, they cut across the rotated older cleavages. At the same time, the older cleavage folia could slice through younger folia. They interweave with each other to produce an anastomosing pattern.

However, further studies (Bosworth and Vollmer, 1982) suggest that the anastomosing cleavages in their rocks are the result of the progressive development and continued offset of conjugate microshears.

3. Purposes and methods of the present study

This work represents a start at discovering the morphological characteristics, nature of individual cleavage surfaces and possible origin of the anastomosing cleavages in the chocolate-weathering shaly rocks along the Hudson River near Troy, New York.

Observations have been made on outcrops, polished surfaces and thin sections. Serial sectioning has been used in order to asertain the three dimensional picture of the anastomosing cleavages.

The information we can get at outcrops includes: the general appearance of anastomosing cleavages on the outcrop scale, the shape and size of phacoids enclosed by anastomosing cleavages, the morphological characteristics and orientation of striations on the cleavage surfaces, the spatial variation on the outcrop scale and the relationship between anastomosing cleavages and regional axial plane cleavages. Statistical analysis is difficult to perform because the surfaces of phacoids are often so small that it is almost impossible to make accurate measurements at outcrops.

Cleavage surfaces are more visible on polished surfaces and in thin sections. Detailed arrangements of these surfaces can be traced from slices under the photographic enlarger. This procedure enables us to get relatively accurate cleavage orientation measurements from oriented samples which is a remedy for field observations. The cross-cutting and restricting relationship between cleavage surfaces in different orientations can only be determined on polished surfaces and in thin sections, which allows us to establish the sequence of the development of cleavage surfaces. Under the microscope, moreover, many thin beds of different lithologies can be identified in shales bearing anastomosing cleavages which appear rather monotonous in lithology on the outcrop scale. By observing the offsets of different marker beds, the nature of cleavage surfaces can be determined, which gives us some clues to infer the possible origin of these cleavages.

Shales bearing anastomosing cleavages are generally fragmented or easy to break up. Shale samples collected from the field are therefore impregnated with Bio-plastic prior to making polished surfaces and thin sections. The procedures for impregnating samples include three steps. First, dilute the Bio-plastic with the equal amount of styrene to get higher fluidity. Several drops of chemical catalyst are then added. The samples are immersed in the liquid. Air inside the samples is removed by vacuum in order to have samples impregnated throughly. Aluminum cake pans are good containers for impregnating samples.

Since the detailed studies of the anastomosing cleavages in melanges have not been conducted by previous workers, the results from the present study are still preliminary and incomplete. Much additional work on polished surfaces and thin sections as well as electron microscopy will be necessary to complete the description. Samples from other areas would have to be studied before any very significant generalization can be made.

THE MORPHOLOGICAL CHARACTERISTICS OF CLEAVAGES IN TWO DIMENSIONS

The morphological characteristics of anastomosing cleavages have mainly been examined on the polished surfaces of impregnated shale samples. In sections cut perpendicular to the regional cleavages, both parallel (Figure 6.2a) and perpendicular (Figure 6.2b) to their strike, two kinds of cleavage surfaces have been identified. One of them is approximately parallel to the regional cleavages measured at the outcrop scale. This type of cleavage is mostly parallel to bedding (Figure 6.2b). Commonly, they have longer extension along their strike and dip direction than the second kind of cleavage surface. Microscopic examination shows that these cleavage surfaces are often filled with quartz (Plate III). The other type of cleavage surface is oblique to the regional cleavages. They do not extend for very long distances and often terminate at the regional cleavage surfaces. However, the population of this kind is much larger than the first kind. This type of cleavage commonly truncates bedding planes (Figure 6.2b). Sometimes they are symmetrically arranged about the normal to the regional cleavages, but generally they are not equally developed.

These two types of cleavage surfaces interweave with each other and break rocks into small chips or fragments. The exact shape of individual rock chips depends on the types of cleavage surfaces surrounding them. If a piece of rock is surrounded by the regional cleavage as well as two sets of cleavage surfaces symmetrically oblique to it, the rock chip will have triangular or trapezoidal shape in two dimensions. If a piece of rock is only bounded by two sets of oblique cleavage surfaces or by the regional cleavages and one set of oblique cleavage surfaces, the rock chip will show rhombic picture in cross sections (Figure 6.2). In some cases, rhombuses bounded by cleavage surfaces on all sides have different lithologies from the surrounding materials (Figure 6.2a).

The orientation of the long axes of rhombuses depends on the types of boundary surfaces. If the rhombus is bounded by two sets of cleavage surfaces oblique to the regional cleavages, its long axis is roughly parallel to the regional cleavages, while if the regional cleavages and one set of oblique cleavages act as boundary surfaces the long axes of rhombuses commonly form an intersecting angle of about 20^{o} with the regional cleavage orientation.

Systematical measurements have been made in order to describe the anastomosing cleavages quantitatively. First, photographic transparencies were made of polished surfaces of the rocks. Then, all visible structural surfaces were traced from the transparencies using a photographic enlarger. Since cleavage surfaces are often curved, they have been divided into many segments of equal length in order to average the orientation changes most reasonably. After dividing them into segments, the orientation of each segment in two dimensions was measured and plotted in histograms (Figure 6.3). Therefore, Figure 6.3 shows the relative lengths of cleavage surfaces in different directions rather than the numbers of cleavage surfaces.

In Figure 6.3, there are two interesting features which should be mentioned:

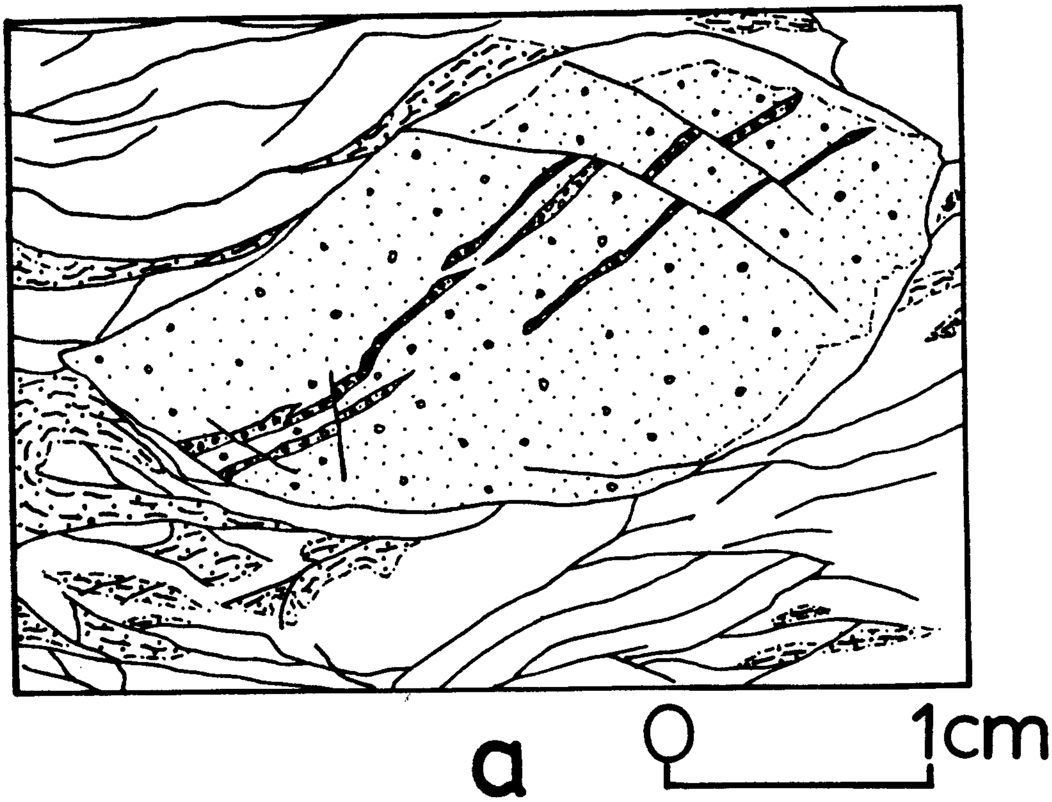
(1) Oblique cleavages are distributed on both sides of the normal to the regional cleavages. In sections parallel to the strike of the

Figure 6.2 Morphological Characteristics of Cleavages in Two Dimensions

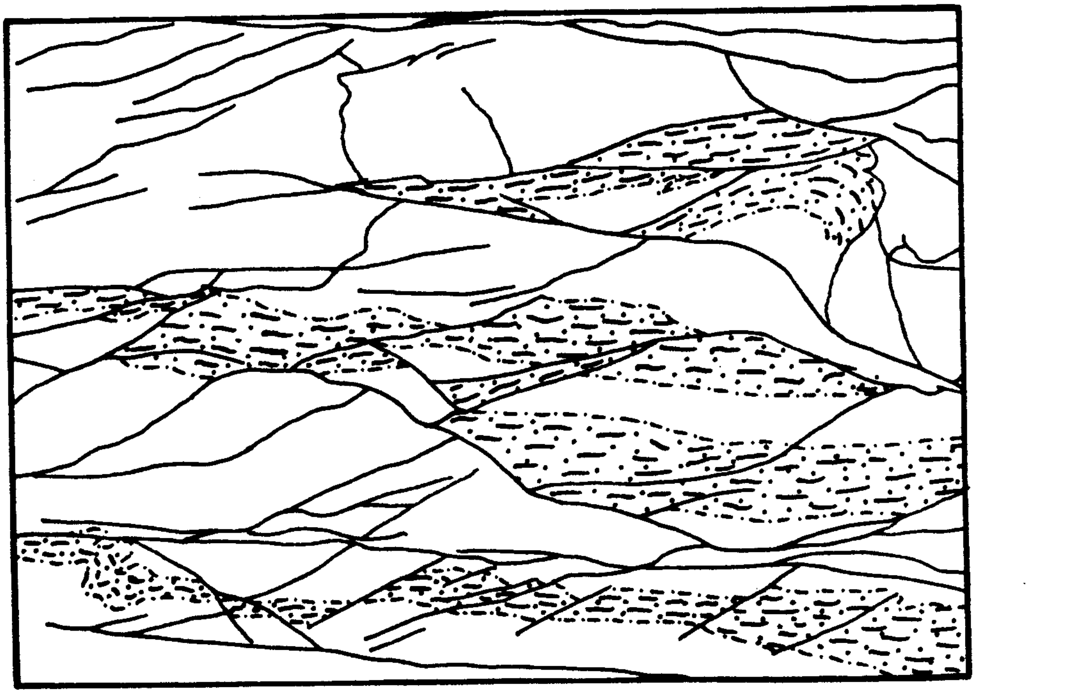
a. polished surface cut perpendicular to the regional cleavage and parallel to the strike. The sample is collected from the outcrop on the east side of the Troy bike trail near the Uncle Sam Pipe and Supplies Co., Inc.

b. polished surface cut perpendicular to the regional cleavage and perpendicular to the strike. The sample is collected from the outcrop on the west side of the Troy bike trail near the Rensselaer Park Elementary School. Viewing towards the south.

Dots with small circles represent quartz-rich shale. Lenticular thin beds in it are brown-weathering siltstones. Stippled lines represent black shales with limonite laminations. Blank area is brown-weathering shaly material. Black lines are cleavage traces.



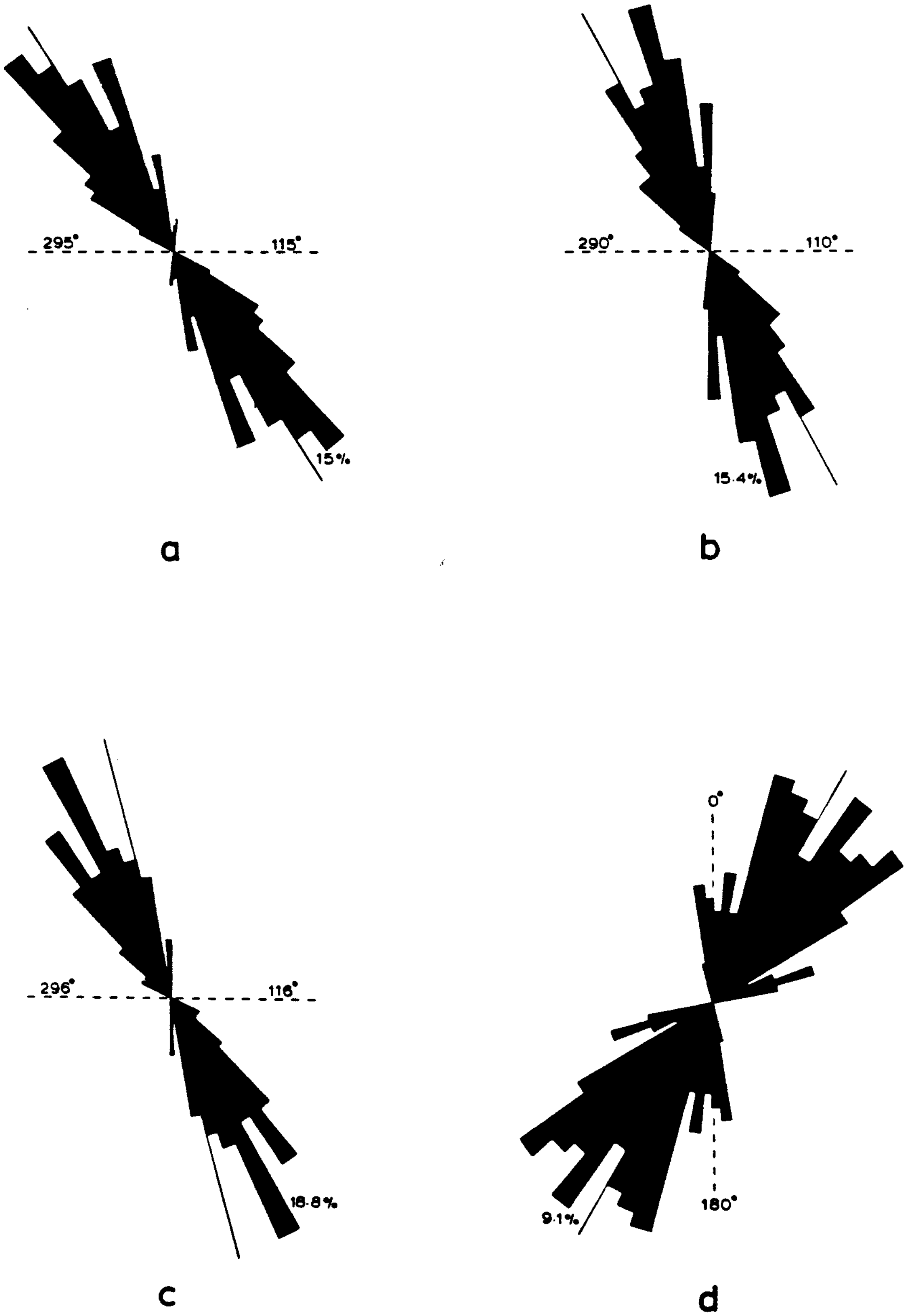
a



b

Figure 6.3 Circular Histograms Showing the Orientations of Traces of Cleavage Planes

a, b and c are sections cut perpendicular to the regional cleavage and perpendicular to its strike. d is a section perpendicular to the regional cleavage and parallel to its strike. a, b, c and d contain 254, 312, 266 and 209 measurements respectively. a, c and d are from an outcrop near the intersection between the Troy bike trail and Gurley Avenue. b is from the outcrop near the Rensselaer Park Elementary School. The solid line represents the trace of regional cleavage plane.


295°
115°
15%
a
290°
110°
15.4%
b
296°
116°
18.8%
c
0°
180°
9.1%
d

regional cleavage surfaces, oblique cleavage surfaces on both sides of the normal to the regional cleavages are more or less symmetrical. However, in sections perpendicular to the strike of the regional cleavages, histograms are mostly asymmetrical, which means that cleavages in certain orientations develop better than other orientations. Figure 6.3a and c show that cleavage surfaces with a lower dip angle in real space develop better than the ones with higher angles. Figure 6.3b is an example of the opposite situation.

(2) Oblique cleavage surfaces do not concentrate in one or two orientations and they commonly undulate within a certain range. In sections perpendicular to the strike of regional cleavages these cleavage surfaces undulate within the range of about 50° to 70° while they change directions within an angle of about 90° to 110° in sections cut parallel to the strike of the regional cleavages (Figure 6.3d).

THE MORPHOLOGICAL CHARACTERISTICS OF CLEAVAGES IN THREE DIMENSIONS

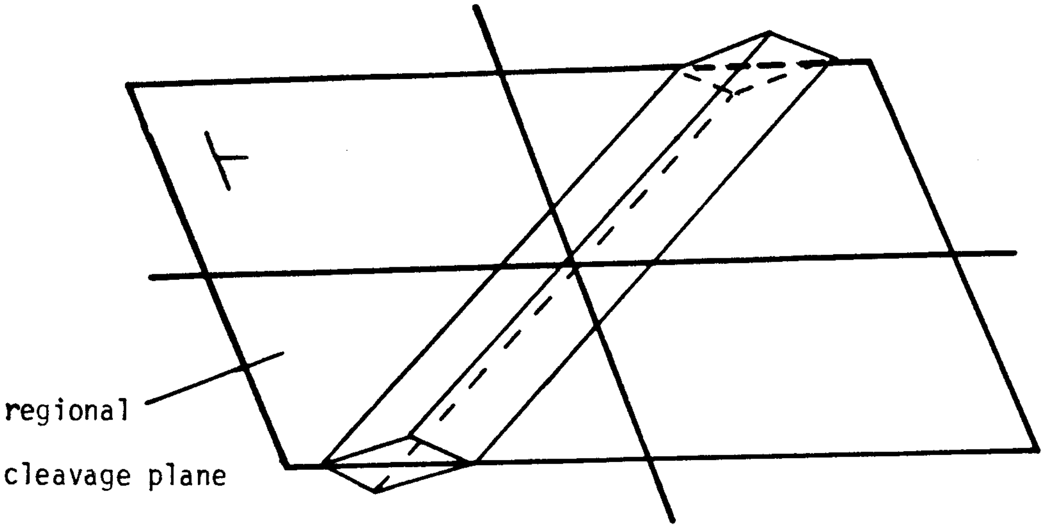
Three dimensional pictures of the anastomosing cleavages are somewhat difficult to ascertain. From the rhombic appearance of anastomosing cleavages in both sections parallel and perpendicular to the strike of the regional cleavages, we can think of two possibilities. The first possibility is that two sets of conjugate shear surfaces intersect each other, with the intersection line in the regional cleavage plane and oblique to its strike (Figure 6.4a). If this is the case, the rocks bearing anastomosing cleavages will form rhombic prisms in space. Even though cleavages interweave each other and show an anastomosing pattern in sections along most orientations, there is one special orientation along which cleavage surfaces are parallel to each other in sections. This special orientation is parallel to the intersection line of two sets of conjugate shear surfaces. In the present area, however, this special orientation has not been found, which rules out this possibility to produce anastomosing cleavage pattern.

The second possibility to produce the anastomosing appearance in both sections parallel and perpendicular to the strike of regional cleavages is that four independent shear systems intersect each other in space and break rocks into a number of small octahedra (Figure 6.4b). In structural studies of the Blue Ridge basement, Mitra (1979) described an example of this kind. He found that in three dimensions the "ductile deformation zones" define deformed octahedra whose acute solid angle is bisected by the regional cleavage. Bosworth and Vollmer (1981) have

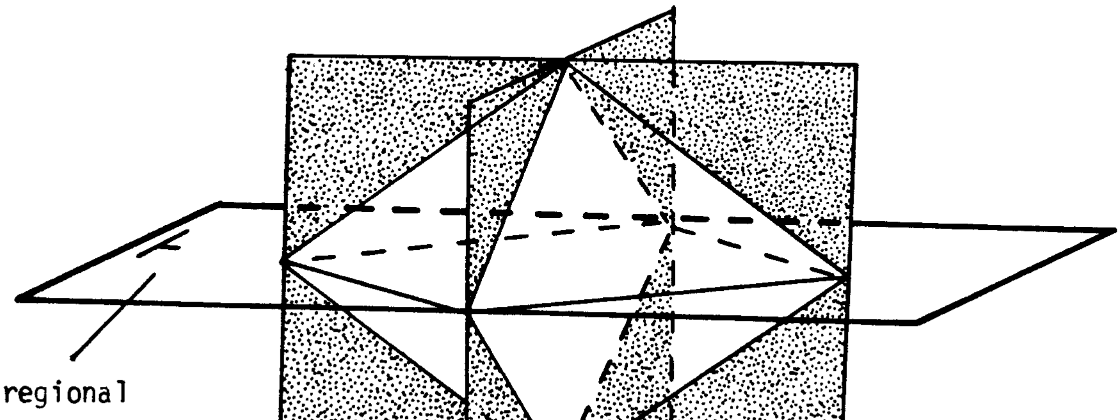
Figure 6.4 Two possible ways to produce anastomosing cleavages

a. Two sets of conjugate shear surfaces intersect each other with the intersection line oblique to the strike of regional cleavages.

b. Four sets of shear surfaces intersect each other and break rocks into many small octahedra in three dimensions.



a



b

done field mapping within several subareas in the Hudson Valley lowlands of eastern New York. One of the subareas they mapped is about 20 kilometers to the south. Another subarea is about 20 kilometers to the north. They did detailed structural analysis in the Taconic melange and found that rock chips bounded by cleavage surfaces are often crudely polyhedral and may appear rhombohedral in cross section, particularly parallel to the strike of regional cleavages. They proposed that a minimum of four sets of shears are required to define the polyhedral geometry of rock chips. In the present area, crudely octahedral rock chips have also been observed in places. When octahedral rock chips of more competent lithology transport and reside in the weaker shaly material, their geometry is much easier to be understood. Where shaly materials are so highly weathered that some of the materials have been washed away, these octohedral rock chips of more competent lithology will stick out. This can be best seen at the Devil's Kitchen in Oakwood Cemetery. Octahedra are usually not very regular. The lengths of lines connecting the two opposite apex of octahedra are not equal. The shortest line among them is approximately parallel to the normal to the regional cleavage plane.

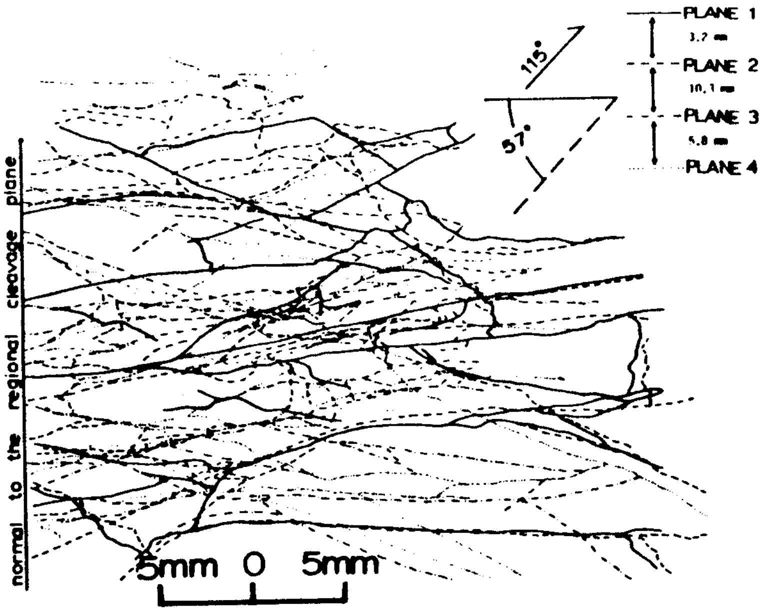
Besides outcrop scale observations, the three dimensional picture of anastomosing cleavages has mainly been obtained through serial sectioning. The technique of serial sectioning consists of four steps. First, we impregnate rock samples as described previously. And then, we cut the impregnated rock samples into cubic or rectangular blocks. Along what direction we cut the rock samples depends on our purposes. In the present study, all observations were made on polished surfaces perpendicular to the regional cleavage plane and either parallel or perpendicular to its strike. When cutting rocks, make sure that all intersecting edges of the block are perpendicular to each other because they will serve as a common reference frame for overlapping a series of sections together to show three dimensional pictures. The third step of serial sectioning is to polish a series of closely spaced parallel surfaces and to make a photographic transparency for each polished surface. In order to increase the visibility of structural surfaces, some colorless nail polish is painted on the polishd surface. Water can also be used for this purpose, but it does not last long. The last step is to trace all visible structural surfaces from the transparencies using a photographic enlarger and to overlap sections according to their natural order. Figure 6.5 shows some examples of the extension of anastomosing cleavages in three dimensions. Different symbols represent visible fractural surfaces at different levels or in different sections. Plane 1 or level 1 is the nearest section to the viewer and plane 4 or level 4 is the farthest.

From Figure 6.5, we can see that some cleavage surfaces do not extend for very long distances. Quite often, only few cleavage surfaces are correlatable between planes or sections of only several millimeters apart. Also, orientations of cleavage surfaces can be rather disperse. No simple and regular anastomosing cleavage patterns can be obviously identified. Therefore, rock chips surrounded by these cleavage surfaces are very irregular in shape. This is probably the far more common morphological geometry of anastomosing cleavages in the present area.

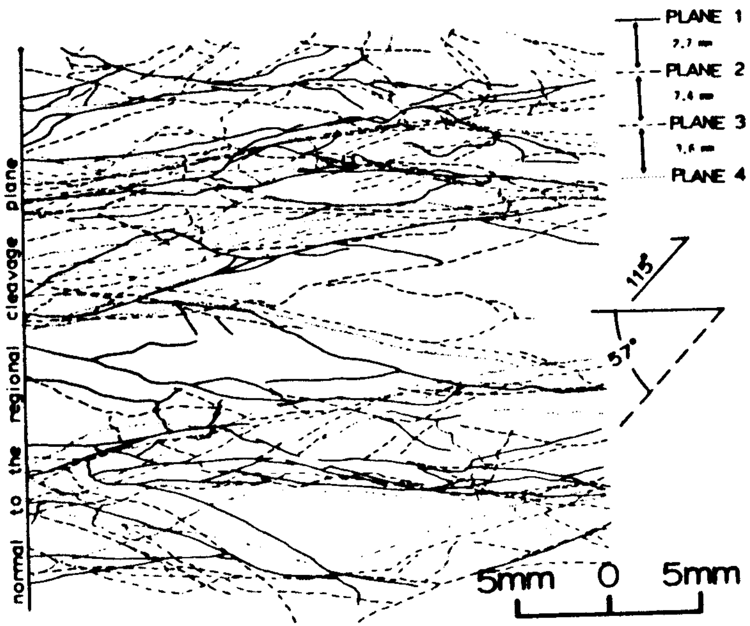
Based on the data shown in Figure 6.5, we can further calculate the actual attitude of cleavage surfaces, that is, the strike, dip

Figure 6.5 The Extension of Cleavage Surfaces in Three Dimensions

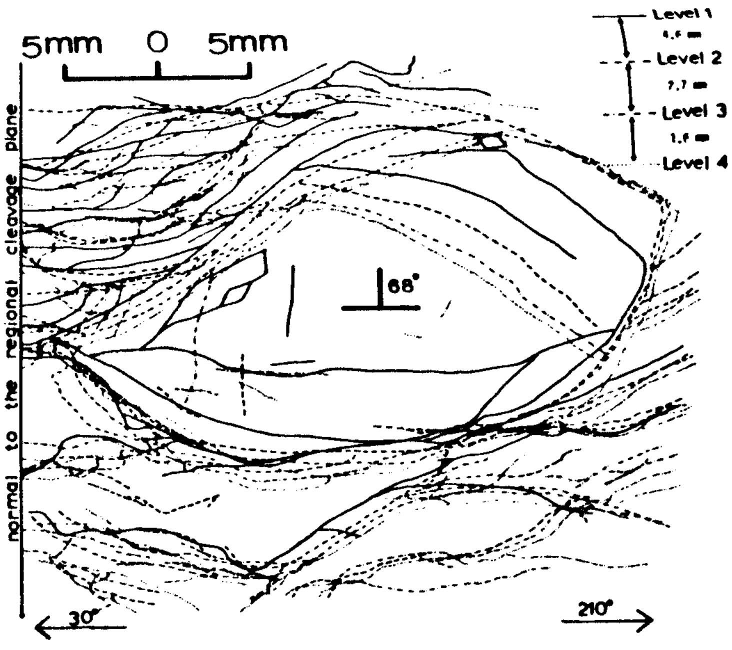
All samples are from an outcrop near the intersection between the Troy bike trail and the Gurley Avenue. a and b show sections cut perpendicular to its strike. c shows a series of sections perpendicular to the regional cleavage and parallel to its strike.



a

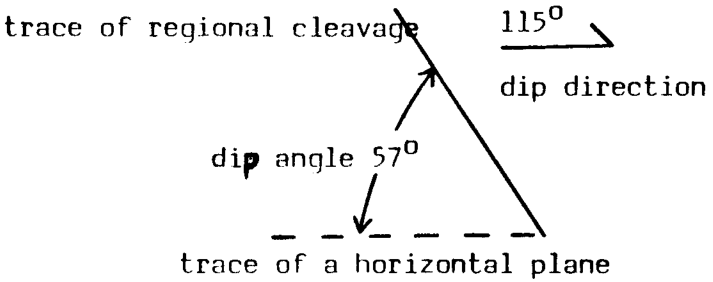


b



c

GEOGRAPHIC ORIENTATION SYMBOLS:



115° is equivalent to S65°E.

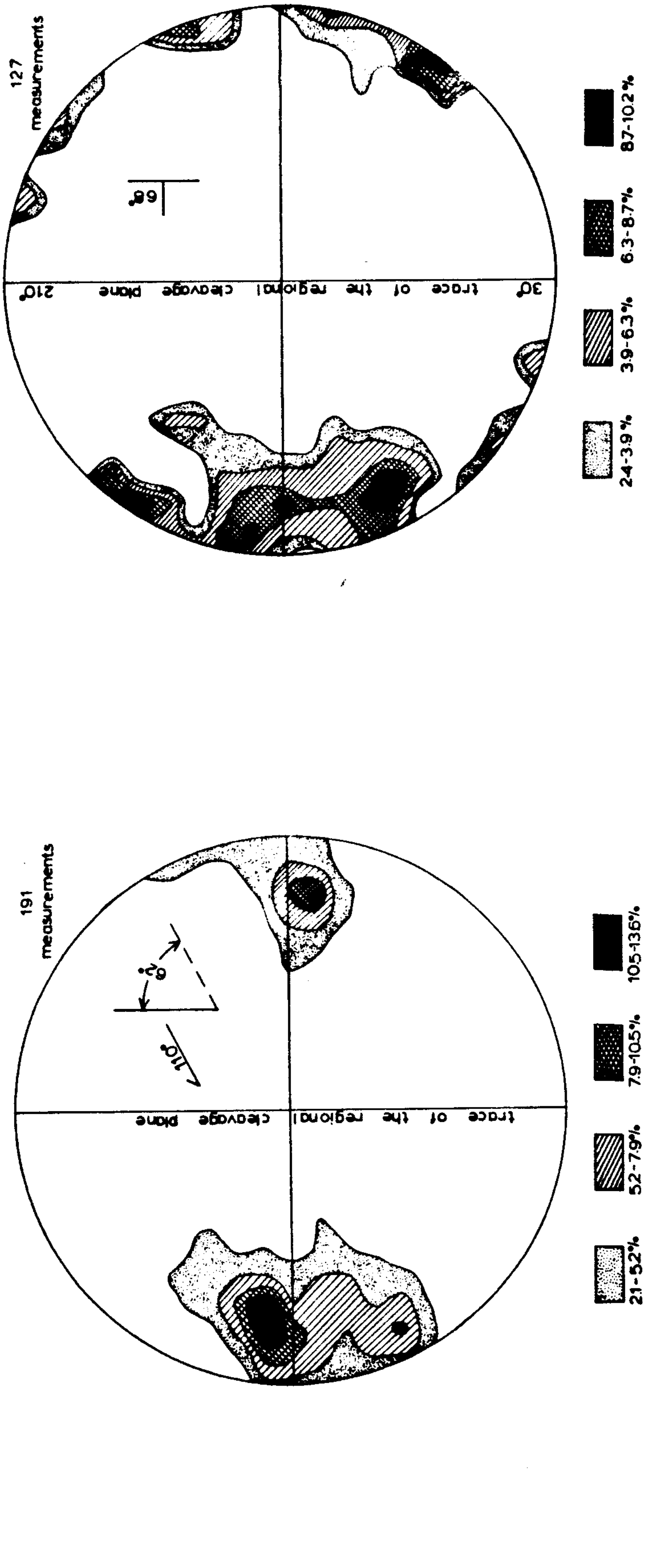
68° Strike and dip of the regional cleavage and dip angle. First, we pick out all correlatable structural surfaces between two different levels or sections and divide them into segments with equal length. Then, we measure the strike and dip directly from the figure. The dip angle can be obtained by doing some simple trigonomical calculations since we know the separation between two polished surfaces and we can easily find the length of the projection of cleavage surface on the planes perpendicular to the regional cleavage and either parallel or perpendicular to its strike. With these data, we are able to use sterographic projection to present the three dimensional pictures of cleavage surfaces (Figure 6.6). Figure 6.6b is made on the basis of Figure 6.5c.

Figure 6.6 Sterographic Projection of Anastomosing Cleavages

a. measurements made on a polished surface cut perpendicular to the regional cleavage and perpendicular to the strike.

b. measurements made on a polished surface cut perpendicular to the regional cleavage and parallel to the strike.

The geographic orientation is expressed in the same way as Figure 6.5.


127
measurements
68°
210°
trace of the regional cleavage plane
30°
2.4-3.9%
3.9-6.3%
6.3-8.7%
8.7-10.2%
b
191
measurements
110°
62°
trace of the regional cleavage plane
2.1-5.2%
5.2-7.9%
7.9-10.5%
10.5-13.6%
a

TEMPORAL SEQUENCE AND SPATIAL DISTRIBUTION OF CLEAVAGES

Geological structures we see in the field can be formed in a single deformational event. They can also be the final result of many sequential deformational regimes under a consistent or inconsistent stress field. However, most commonly, structures represent the compound picture of numerous deformational episodes under the ever-changing stress systems. Therefore, one of the main tasks of structural geologists is to differentiate structures formed at different times and to establish the sequence of their initiation, development and change. This approach of structural geology may be called "the temporal evolutionary analysis".

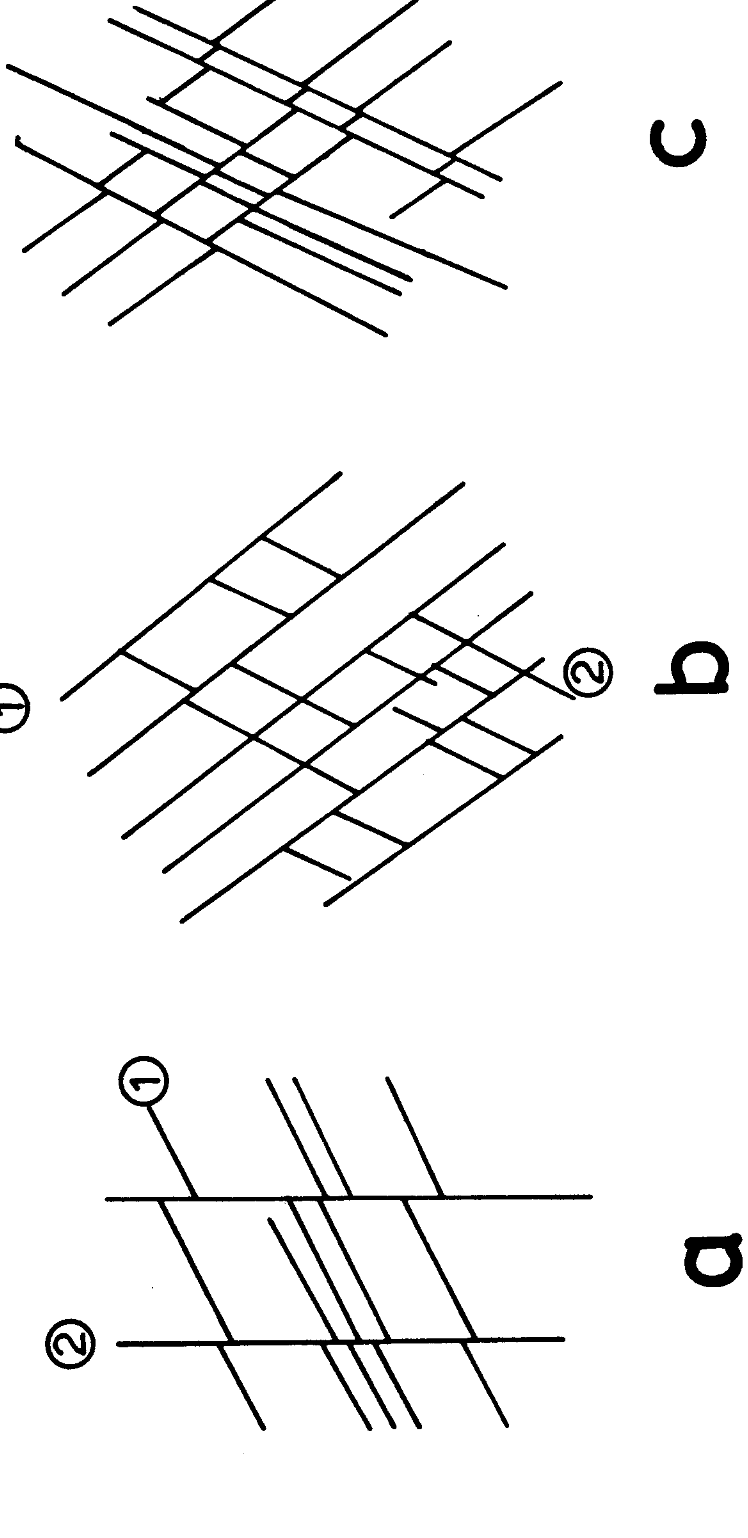
The most direct criteria for identifying structures of different deformational events, which are also widely employed by structural geologists working in the field, are the cross-cutting and restricting relations of structures. If a set of structural surfaces consistently offset another set of structural surfaces they are considered as later structures (Figure 6.7a). If a group of cleavage surfaces or faults restrict the extension of other structural surfaces they are earlier structures (Figure 6.7b). If two sets of structural surfaces offset or restrict each other they are formed at about the same time (Figure 6.7c). These two criteria have been used in the present study. Besides, the disruption of continuity of phyllosilicate preferred orientation which can only be observed under the microscope is also used for this purpose. Within the shale in which anastomosing cleavage develops, strong preferred orientation of phyllosilicates exists.

Figure 6.7 The cross-cutting and restricting relations of fracture surfaces

a. Later structural surfaces consistently offset the earlier structures.

b. Earlier structural surfaces restrict the extension of later structures.

c. Two sets of structural surfaces formed at the same time offset and restrict each other.


a
b
c
①
②

Small flakes of phyllosilicates are commonly aligned on or near the cleavage surfaces of different orientations. Under the microscope, it can be seen that along the cleavage surfaces formed at a later time phyllosilicate preferred orientation is much more distinct and continuous while those flaky minerals along the older cleavage surfaces only show a weak preferred orientation. Moreover, the distinctness and continuity of preferred arrangements along the earlier cleavage surfaces decrease as they approach the later cleavages. Under favorable conditions, where grain size is coarse enough that each individual mineral crystal can be identified, earlier micas are clearly cut by the phyllosilicates along the later cleavage surfaces (For example, Plate IIIb). The bending of earlier micas into the later cleavage planes has also been observed nearby, which proves that the truncated micas are not the result of restricted growth.

On the basis of the cross-cutting and restricting relations of structures as well as the distinctness and continuity of the preferred orientation of phyllosilicates, three stages of cleavage surfaces can be distinguished. Cleavages formed at different stages are filled with different minerals. The earliest cleavage surfaces are commonly filled with quartz. In places, they are cut by the cleavages with limonite fillings (Plate III a, h, i and k). Under the microscope, many cubic limonite aggregates can be found. They are likely to be the weathering product of pyrite crystals. Therefore, these limonite vein fillings may represent early pyrite veins. Cleavages formed at the third stage are characterized by the presence of strong preferred orientation of phyllosilicates. They offset both quartz veins (Plate III g and h) and limonite vein fillings (Plate III c, d and j). Some cleavage surfaces formed at this stage are coated with rusty thin films. Others appear as visible separating surfaces or unfilled openings. They may represent the actual fractures formed during the deformation. However, it is equally possible that these unfilled openings may have existed as discontinuous structural weak surfaces when they were formed and then the weathering process made them more visible. They may also be reinforced during the process of thin section-making.

Another main objective of structural geologists is to determine the spatial distribution of structural surfaces and make mechanical interpretations on the basis of their spatial arrangements, mutual relationship and the instantaneous movement picture of materials. This approach of structural geology may be referred to as "the spatial mechanical analysis". It can be done because although structures may be varied in their orientation, magnitude and property from one place to another they generally have a systematical relationship as long as they are formed under a common stress system.

There are two critical points which we should bear in mind when we make mechanical interpretations. First, all structural elements we consider ought to be the structures formed at the same deformational event. If we lump structures of different deformational events together we may either overlook some part of the deformational history or even not be able to provide a self-satisfied explanation. For example, if two deformational events take place under a constant stress field, we may easily interpret them as a result of one deformational event.

The second critical point is that all structural elements should belong to the same order. In other words, all structures are formed under the same stress system, but the formation of some structures are not controlled by the development of other structures. Here is an example. When we work in an area where rocks are strongly folded, we often see extensional structures around the fold hinges. The strike of these structures are usually parallel to the strike of the axial plane of folds. If we are not aware that they are second order structures relative to folds we may have difficulties to make mechanical interpretations or very likely overcomplicate the deformation history because these extensional structures suggest a stretching perpencicular to the axial orientation of folds while folds themselves suggest a shortening in the same direction.

Due to the first requirement for making mechanical interpretations, it is necessary for us to look at the spatial arrangements of geological structures stage by stage. As described above, there are three stages of cleavages in the present area. The earliest cleavages are filled with quartz. They are approximately parallel to each other. Microscopic examination shows that they are also parallel to the early phyllosilicate preferred orientation which is disrupted by the cleavage surfaces of the third stage. Quartz veins have also filled in the fractures associated with the first stage cleavages. These fractures have various orientations (Plate III e). Some of them have a lower intersecting angle with the cleavage surfaces. Others have higher angles.

Lines of inclusions are observed in the wider quartz veins (Plate III f). The inclusion lines consist of numerous individual inclusions. These inclusions vary in size and most of them have round, ellipsoidal and pear shapes although some of them look rather irregular. Three different directions of inclusions can be seen in the quartz veins shown in Plate III. One of them is oblique to the average wide quartz vein orientation with an intersecting angle of about 26°. This set has only been observed locally. Strictly speaking, inclusions are not arranged in a line in two dimensions. They are rather evenly distributed in a narrow band. Another set makes an angle of 68° with the wide quartz vein. Inclusion lines in this orientation are most widely distributed. They have been observed in almost all wide quartz veins in this sample. Inclusion lines are sub-parallel to each other, but individual inclusion line shows certain undulation. The separation between inclusion lines is about one tenth of a millimeter. The third set of inclusions is symmetrical to the first set in reference to the normal to the wide quartz vein, with an intersecting angle of about 32° with the boundary of the wide quartz vein nearby. This set is also only seen locally. Like the first set, inclusions are mainly concentrated in a narrow band.

Cleavages formed at the second stage are only manifested in some places. Where they can be seen they are roughly parallel to each other and parallel to the first stage cleavages (Plate III). In the plate, only wider limonite veins are shown. Actually, there are many narrower limonite lines parallel to bedding orientation, which can not be shown at this scale. Moreover, it is often seen that limonite veins are developed along the wall of quartz veins filled in the first stage cleavages. In other words, limonite fillings often follow the path of quartz veins.

The third stage cleavages are oblique to bedding, or the first stage and second stage cleavages. In sections, they are symmetrically distributed on both sides of the normal to the regional cleavage plane.

It should be pointed out that the distinction of three stages of cleavages is mainly based on the cross-cutting and restricting relations of cleavage surfaces and the displacement of vein fillings. This subdivision is not necessarily indicative of three separate deformational events. The cleavages of the first and second stages show the same morphological characteristics and have the same sense of shear along cleavage surfaces. They are subparallel to each other. In places, the limonite lines representing the traces of the second stage cleavages are distributed along the boundaries of quartz veins filled in the first stage cleavages. Therefore, they very likely represent two episodes of a single deformational event.

The relationship between the third stage cleavages and the cleavages of the first two stages can not be determined solely on the basis of the present study. They could be either the structures formed at a later stage of the same deformational event or the result of another deformational event. The final resolution of this matter will pretty much depend on regional structural studies. In the capital district, Ruedemann (1930) found that only weak manifestations of the post-Taconic movement can be seen in slight folds and small faults in the Helderbergs. Bosworth and Vollmer (1981) have observed that rocks containing both axial plane cleavages and anastomosing cleavages are unconformably overlain by the Silurian carbonates. They conclude that the most significant deformation of the Ordovician flysch along the Hudson River Valley has occurred prior to the deposition of Silurian sediments. Thus, it is possible that both axial plane cleavages and anastomosing cleavages in the present area are resulted from the same deformational event, that is, the Taconic Orogeny.

THE NATURE OF CLEAVAGE SURFACES AND THE SENSE OF SHEAR ALONG THEM

In order to make mechanical interpretations, we need to understand the nature of structural surfaces besides knowing the sequence of their formation and their spatial relationship. Various criteria have been suggested to allow distinction between extension fractures and shearing fractures. What follows are some widely used criteria for distinguishing extension fractures and shearing fractures in rigid materials.

(1) The straightness of fracture surfaces:

Shear fractures are usually rather straight while extension fractures are mostly curved or irregular although exceptions are present in many cases.

(2) The width change of fractures:

Shear fracture does not have very large width change along its trace, but extension fracture may.

(3) The presence of slickenside striations:

Fractures with slickenside striations are usually considered as shear surfaces or sheared extensional fractures. Extension fractures commonly appear as rough surfaces.

(4) The displacement orientation:

When marker beds or lines are present, their displacement will serve as a critical criteron for identifying shearing fractures and extension fractures. Actually, this is the basis for us to define these two types of fracture surfaces. The displacement of shearing fracture is parallel to the surface while the total displacement of an extension fracture is directed perpendicular to the surface.

(5) The length of individual surfaces:

Shearing fractures with large displacement are generally extended for a relatively longer distance while extension fractures can die out in a very short distance.

(6) The arrangement of individual surfaces:

Shear fractures of the same set are commonly parallel to each other and their orientation is quite stable. The arrangement of extension fractures can be very irregular.

(7) The preferred orientation of minerals:

The shapes or lattice directions of minerals near the trace of shearing fractures usually show certain preferred orientation when plastic deformation has taken place near shear surfaces. Minerals near the trace of extension fractures have no special orientations near the fracture surfaces.

(8) The end patterns of fractures:

The refractive tails (Figure 6.8a) and parallelogrammatic shear combinations (Figure 6.8b) are the common end patterns of shearing fractures. Extension fractures usually have tree-shaped ends (Figure 6.8c). Sometimes, sinuous fractures bifurcate and combine to form irregular loops (Figure 6.8d).

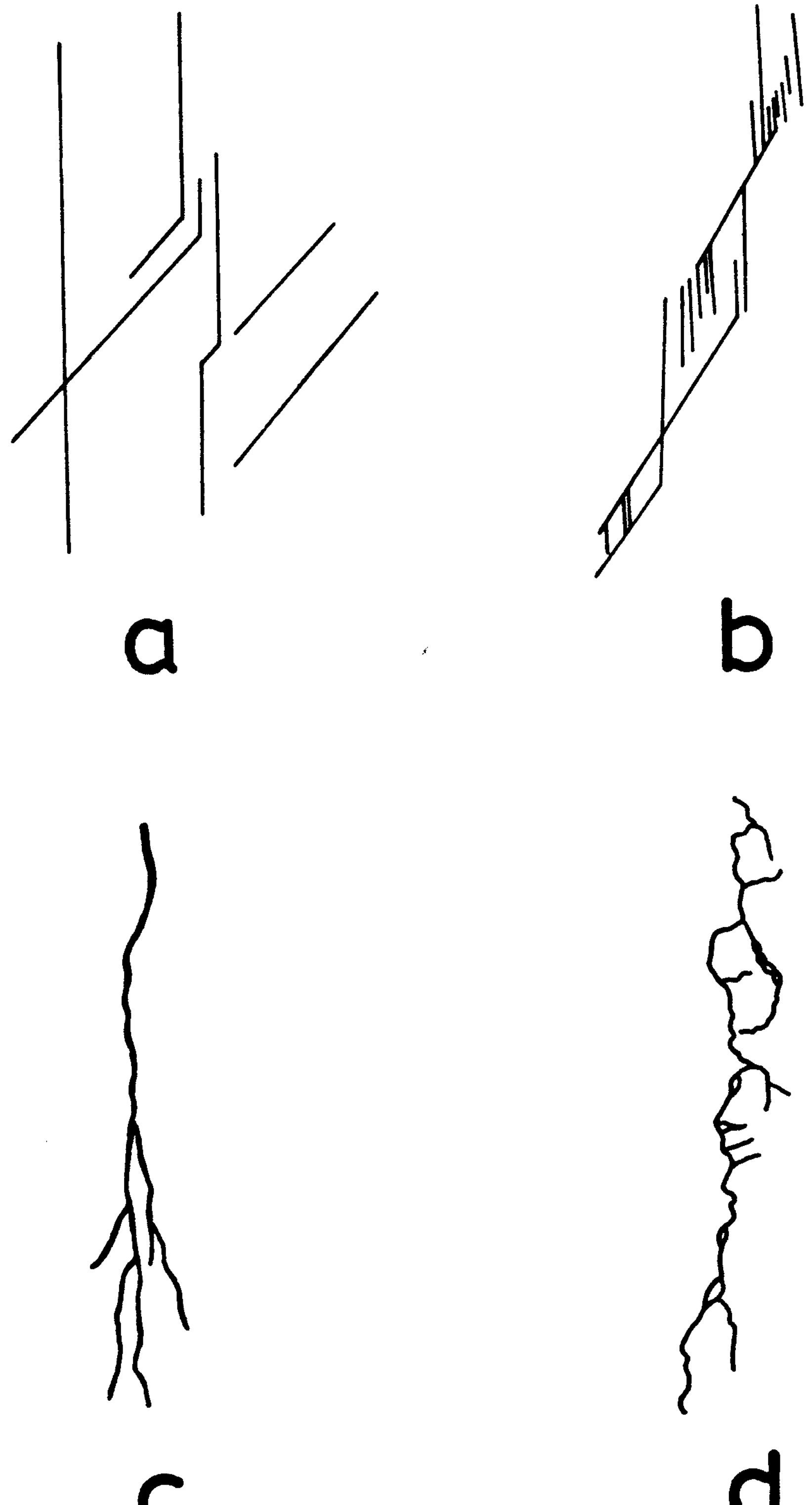
(9) The symmetry of the end branching:

The end branching of shearing fractures is asymmetrical whereas extension fractures commonly have symmetrical end branching.

It should be emphasized that when we apply these criteria to identify the nature of structural surfaces the property of material is an important factor to consider. If the material concerned is very ductile, these criteria may not be applicable. For example, shearing

Figure 6.8 The end pattern of fractures

a. the refractive tails of shear fractures; b. the parallelogrammatic shear combinations of fractures; c. the tree-shaped end of extension fracture; and d. irregular loops formed by the bifurcation of sinuous extension fractures (modified from Ma and Deng, 1962).


a
b
c
d

surfaces can be curved where synchronous ductile deformation or later ductile deformation plays an important role. Nevertheless, in semi-brittle or semi-ductile materials, these criteria may still be useful as long as we are aware of the effect of minor ductile deformation. Rocks investigated in the present study may fall into this category.

Evidences for ductile deformation include:

(1) In some places, rocks are broken into ear-, horn- or yoke-shaped chips (Figure 6.9). Striations are seen on all curved surfaces bonding the rock chips. Sometimes, striations converge at the tips of horns or meet at the sharp edges. However, it should be borne in mind that this criterion can only be used with other evidences.

(2) On the surfaces of numerous rock chips no clear step structures have been observed although striations and round bulges are ubiquitous.

(3) Where bedding can be seen, shaly thin beds show pinch and swell structures in sections (Figure 6.10).

(4) Widespread microfolds can be easily found on the outcrop scale or under microscope (Figure 6.2). Their presence certainly indicates some form of ductile deformation although the absence of folds does not indicate the absence of a pervasive deformation (Sylvester and Christie, 1968).

(5) Very often, we can see that cleavage surfaces in shales are strongly distorted where they cut across more competent material such as quartz veins (Figure 6.11).

On the other hand, however, it is evident that cleavage surfaces are actual broken surfaces. In many cases, they are filled with quartz or pyrite crystals. Therefore, we can say that the rocks studied are

Figure 6.9 Horn-shaped rock chips

Rock chips are bounded by strongly curved surfaces. Striations can be seen on all these surfaces and they often converge at the tips of horns. The rock sample is from an outcrop near the intersection between the Troy bike trail and Gurley Avenue at the bottom of the hillside.

Figure 6.10 Pinch and swell structures of black shaly material

The unblackened part is brown-weathering shale. The rock sample is from an outcrop near the intersection between the Troy bike trail and Gurley Avenue at the bottom of the hillside.

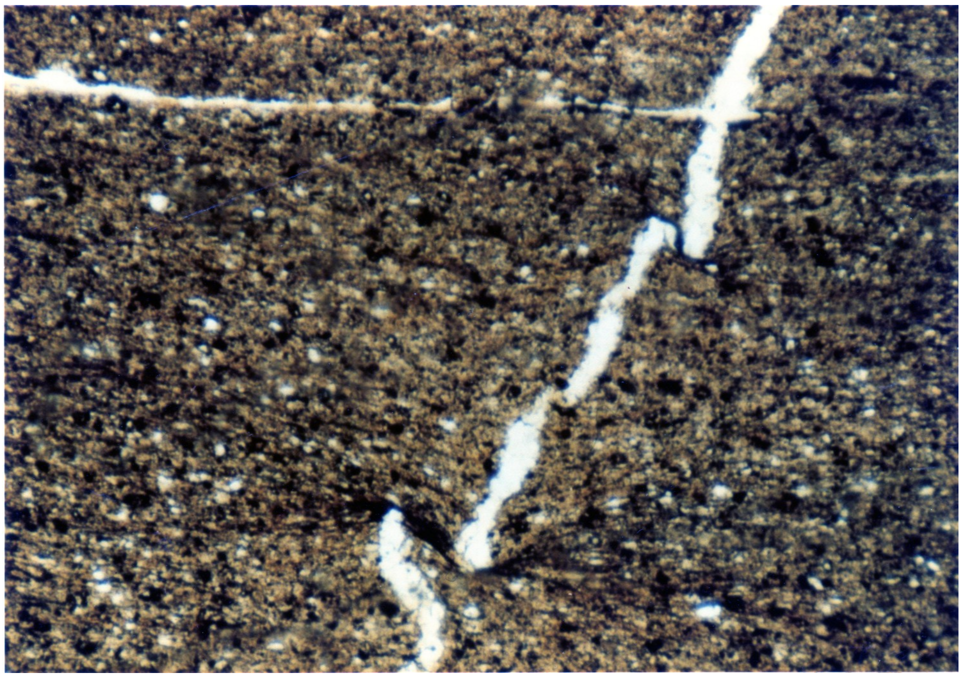


Figure 6.11
Strongly curved cleavage surfaces around quartz vein.

brittle enough to rupture and ductile enough to produce all features described above during the deformation.

Generally, not all the preceeding criteria be found along a single cleavage surface. Very often, only one or two of these criteria are applicable. Sometimes, the nature of a cleavage surface can only be inferred from its parallelism with other cleavages for which the nature can be relatively easily determined. The criteria (8) and (9) are included here only for providing a complete list of criteria for distinguishing shear fractures and extension fractures. They are not applied in the present study.

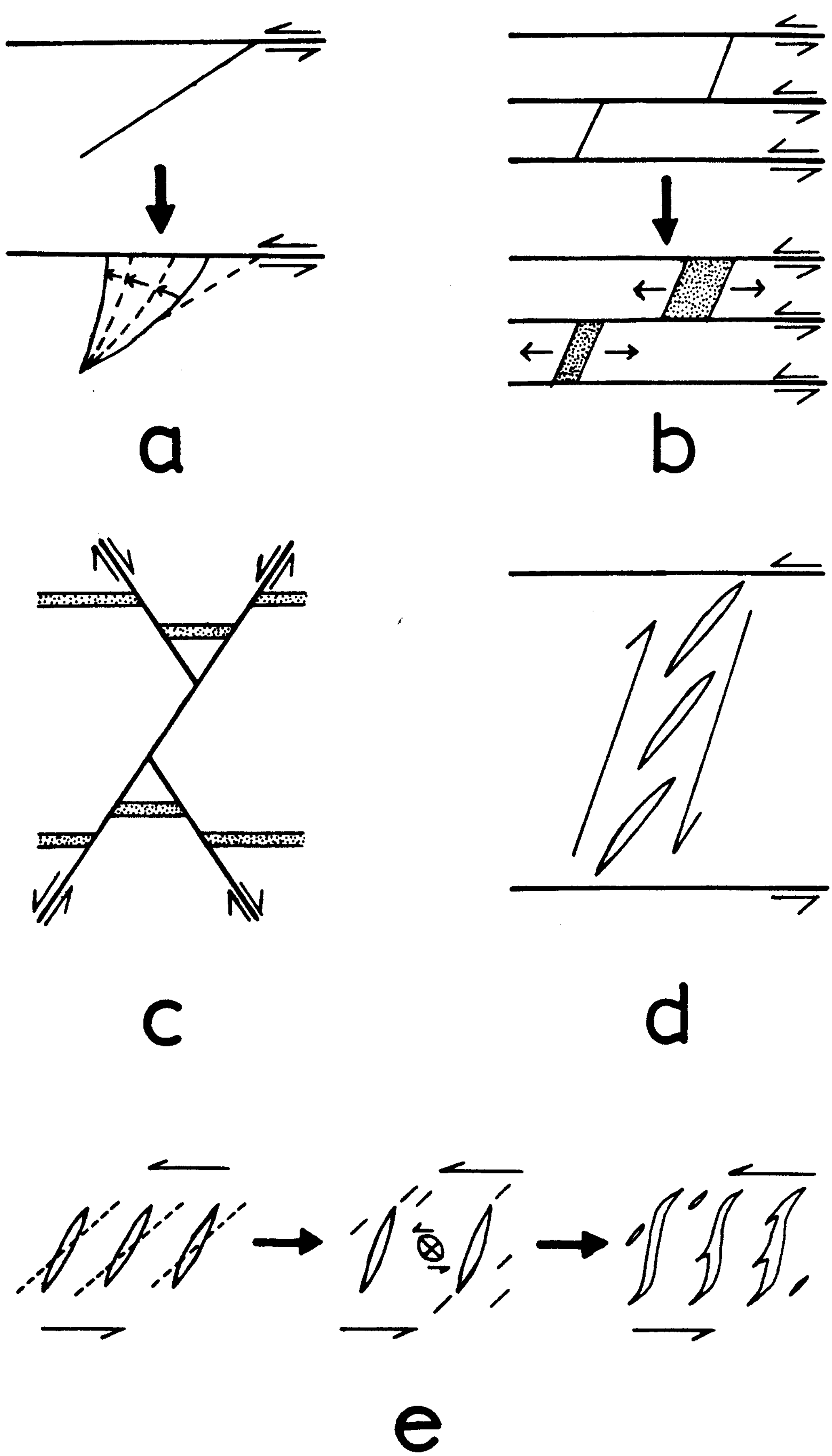
Using the criteria described above except the last two, it is found that all cleavage surfaces are shearing surfaces. There are two possibilities. They may either have originated as shearing surfaces or some of them may have undergone displacement at a later time after their creation. To decide which case is true, further work needs to be done.

The sense of shear along the cleavage surfaces has been determined. In Plate III, cleavages formed at the first stage show consistent sinistral sense of shear, which agrees with the thrust sense of the western boundary fault of the Taconic Allochthon accepted by previous workers (Zen, 1967, 1972). At least, three indicators can be listed here (Figure 6.12a, b, and e).

(1) Many asymmetrical wedge-shaped quartz bodies are present on both sides of cleavage surfaces. The walls of a wedge-shaped quartz vein originate as a secondary fracture relative to the main cleavage surface. They are opened up due to the dragging of the materials on the other side of the cleavage surface. The intensity of dragging is

Figure 6.12 Indicators used to tell the sense of shear along cleavage surfaces

a. The wedge-shaped quartz bodies; b. the systematic width change of quartz veins between main cleavage surfaces; c. offsets of distinct markers; d. en echelon array of tension gashes; and e. sigmoidal tension gashes.


a
b
c
d
e

strongest near the cleavage surface. Therefore, the opening space gets wider and wider towards the cleavage surface. The tips of the quartz wedges point towards the movement direction of the side without secondary fractures. The acute angle between the main cleavage surface and the fracture filled with quartz points towards the movement direction of the side with secondary fractures (Figure 6.12a).

(2) The systematic width change of quartz veins also indicate a sinistral sense of shear along the first stage cleavage surfaces. Quartz veins along the main cleavages are usually narrow and long while quartz veins developed between some main cleavage surfaces are usually wide and short. Fractures between main cleavage surfaces are believed to be shears of second order relative to the main cleavages. Since they are oblique to the main cleavages they tend to open wider and wider as the shearing along the main cleavage surfaces continues (Figure 6.12b).

(3) In Plate III, many sigmoidal quartz veins are present. According to Riedel (1929), the tips of sigmoidal tension gashes point to the opposite direction of the movement of adjacent block (Figure 6.12e).

Cleavages formed at the second stage also have a sinistral sense of shear. This is indicated by the offsets of earlier quartz veins (Plate III a), the en echelon limonite vein arrays (Plate III i, Figure 6.12d), sigmoidal tension gashes filled with limonite minerals (Plate III c, Figure 6.2e), and the wedge-shaped limonite bodies.

The sense of shear along the third stage cleavages is mainly judged by the bending of layer silicate preferred orientations and the offsets of some distinct markers (Figure 6.2, 6.12c), e.g. characteristic lithological thin beds, quartz veins and limonite fillings. As described above, cleavages of the third stage are oblique to the regional cleavage and in both sections parallel and perpendicular to the strike of the regional cleavages they are symmetrically distributed on both sides of the normal to the regional cleavage plane. The offsets along cleavage surfaces suggest that these surfaces are conjugate shears (Figure 6.13). This is also testified by their mutual cutting and by the existence of irregular extensional fractures perpendicular to the regional cleavages.

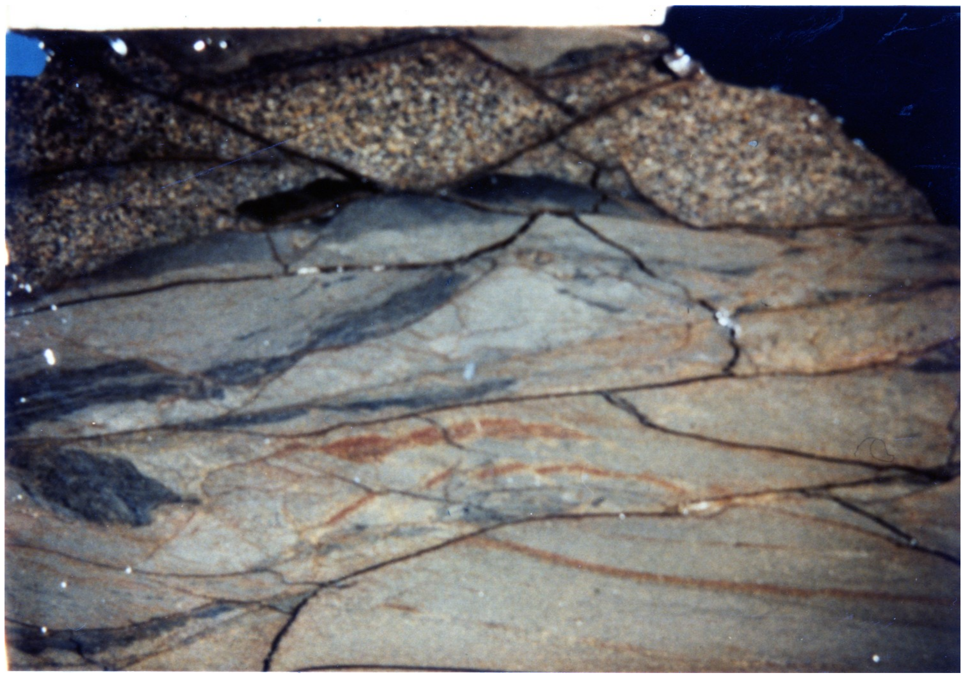


Figure 6.13
Offsets of marker beds indicating conjugate shears.

CONCLUSIONS

From the present study, the following conclusions can be drawn:

(1) In the map area, rocks ranging in age from Late Proterozoic to Middle Ordovician are exposed. These are: the Bomoseen Formation, the Truthville Formation, the Browns Pond Formation, the Indian River Formation, the Mount Merino Formation and the Snake Hill Formation. The divisibility of the Taconic allochthonous sequence in the present area is comparable with the northern Taconics. The lithological characteristics of individual rock units are rather similar to the descriptions of Jacobi (1977) and Rowley et al. (1979). Therefore, to devise a single column with a single set of descriptions and a single set of names for the entire Giddings Brook slice of the Taconic Allochthon appears possible.

(2) Dale (1899) confused the Truthville Formation under the Browns Pond Formation with the green slates above it and gave them the name "Cambrian Roofing Slate". He placed all green slates under his "Cambrian Black Shale". Ruedemann (1914) did not realize this and simply renamed the "Cambrian Roofing Slate" as the "Mettawee Slate". Thus, the "Mettawee" was not suitably defined from the very beginning. Later workers have also imposed various meanings on this term, and causes much confusion. Therefore, the term should be redefined or abandoned completely.

(3) Ruedemann (1914) mistakenly correlated the "Diamond Rock" in Lansingburgh with the granular quartzite near the base of the Truthville Formation observed at the Curtis Mountain. However, field

mapping indicates that the "Diamond Rock" actually lies at the base of the Browns Pond Formation which is at a much higher stratigraphic level than the Curtis Mountain quartzite. Therefore, the "Diamond Rock Quartzite" should be correlated with the Mudd pond quartzite in the Northern Taconic region. Moreover, from Dale's description (1904) It is clear that lithologically the "Troy Shale" of Ruedemann is very similar to his "Nassau Beds". They are very likely to be the same unit. Thus, the lithostratigraphic column established by Dale (1904) and Ruedemann (1914, 1930) should be modified as shown in Table V.

(4) In the map area, it is seen that the Precambrian Bomoseen Formation and Cambrian Truthville Formation now overlie the Middle Ordovician Indian River Formation or Snake Hill Formation, which indicates the existence of the basal thrust of the Taconic Allochthon. The presence of this important fault and the westward transport of the Taconic rocks have also been confirmed by the distribution of slivers of the allochthonous sequence in the Middle Ordovician Rocks, the development of a highly foliated zone, the displacement of distinct marker beds across small faults or cleavage surfaces parallel to the basal thrust, the bending phenomena associated with the branch faults and the widespread slickenside striations.

(5) Two types of cleavages have been observed in the present area. One of them is parallel to the axial plane of mesoscopic folds and thus named as the axial plane cleavage. Displacements of distinct marker beds have been found across the cleavage surfaces. The subsequent rotation of the axial plane cleavages during a non-coaxial progressive

TABLE V A MODIFIED LITHOSTRATIGRAPHIC COLUMN FOR THE SOUTHERN TACONICS

		J	Greenish shale				
BROWNS POND FORMATION	SCHODACK SHALE AND LIMESTONE	I	Thin-bedded limestone, or dolomitic limestone, in varying alternations with black or greenish shale and calcareous quartz sandstone, some of the limestone beds brecciated within the sandstone or shale and forming brecciation pebbles, in places, however, beach pebbles.				
			At Troy, in upper part of a 2½ foot bed of calcareous sandstone.	DIAMOND ROCK QUARTZITE	G	Granular quartzite, in places a calcareous sandstone.	
TRUTHVILLE FORMATION	TROY SHALE	H	Greenish, reddish, purplish shale, in places with small beds of more or less calcareous quartzite.	NASSAU BEDS	E	Greenish, or reddish and greenish, shale with small quartzite or grit beds.	
					D	Massive greenish quartzite, in places very coarse.	Zion Hill Quartzite (II)
					C	Reddish and greenish shale with small beds of quartzite or grit (rarely up to 5 feet thick).	
					B	Massive greenish quartzite, in places very coarse.	Zion Hill Quartzite (I)
					A	Reddish and greenish shale with small beds of quartzite or grit, from 1 to 12 and, rarely, 24 inches thick.	
BOMOSEEN FORMATION	BOMOSEEN GRIT	F	Olive grit, metamorphic, usually weathering reddish; absent at south.				

Based on the publications of Dale(1904), Ruedemann(1914, 1930), Fisher(1961, 1962, 1977), Zen(1961, 1964), Jacobi(1977) and Rowley et al.(1979) and the field mapping in the type locality of the Diamond Rock Quartzite (Xia, 1983).

deformation is the possible cause for the shearing along cleavages. Cleavages of the second kind are oblique to the axial plane cleavages. They comprise an anastomosing pattern in sections perpendicular to the axial plane cleavages and are thus called the anastomosing cleavages. The anastomosing cleavages are formed at a later time than the axial plane cleavages, but both types are possibly developed during a single deformational event.

(6) The anastomosing cleavages are only developed in some argillaceous shales of the Snake Hill Formation which comprise the matrix of the Taconic melange in places. Commonly, they have very irregular patterns in sections perpendicular to the axial plane cleavages. The average spacing is from 5 millimeters down to less than 1 millimeter which is much lower than the average spacing of anastomosing cleavages in sandy rocks given by Borradaile et al. (1982). Observations at the outcrop scale and under the microscope suggest that the anastomosing cleavage surfaces are possibly conjugate shears arranged in various orientations oblique to the normal to the axial plane cleavages.

(7) The intersecting angles between conjugate shears and the axial plane cleavages are varied. The cleavage surfaces undulate within a larger sector in sections parallel to the strike of the axial plane cleavages than sections perpendicular to the strike.

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APPENDIX I

MELANGE: DEFINITION, CLASSIFICATION AND ORIGIN

INTRODUCTION

The phenomena of mixing of different rock types of different ages has been described since the beginning of this century (Ruedemann, 1901; Matley, 1913). Greenly (1919) first referred to these chaotic rocks as "melanges". However, their origin remained a mystery for quite a long time. Geologists have paid much attention to these mixed rock bodies since Hsü (1968) redefined the term melange and emphasized the tectonic signaficance of some of these chaotic rock bodies. As a result, more and more melanges have been discovered and described and many different models for the formation of these bodies have been proposed.

As more and more observations are made, geologists are gradually realizing the inadequacy of the old concepts. To reflect what was seen in the field more accurately and thoroughly, many new terms were tentatively coined by different workers.

Unfortunately, people working in different places created new terms based mainly on their own experience and quite commonly they reflected some of the geological facts but overlooked other aspects. Therefore, much confusion has resulted. Melange has different meanings to different people. For example, some geologists restrict the term melange to describe the mixed rock bodies produced by tectonism (Hsü, 1968, 1971; Cowan, 1972, 1974) while others give it a broader meaning to include all chaotic deposits (Berkland et al., 1972). Some people use the term melange to refer to "a style of deformation" (Hsü, 1968; Moore and Wheeler, 1978), "a state of structural disorder" (Dickinson and Rich, 1972). Others treat it as "a distinct metamorphic facies" (Hermes, 1973), or "a type of tectonite" (Raymond, 1975). East European geologists, especially Soviet geologists, subdivide chaotic rock bodies on the basis of matrix composition (see Coleman, 1973). They only consider a chaotic rock body with a serpentinite matrix as melange. A chaotic rock body with a formerly clastic matrix is called an olistostrome.

A common terminology is needed in the study of melange. We should make a general agreement based on our current knowledge even though a full understanding of the significance of melanges is still ahead. Otherwise, the further studies of these important and informative chaotic rock bodies will be seriously handicapped.

In this short paper, I wish to give a general overview of our current knowledge of melange and to clear up some of the confusion in terminology. A nongenetic definition is suggested after a general discussion about the concept. Different genetic models of the formation of melanges are reviewed. Some of the criteria for distinguishing sedimentary melanges from tectonic melanges are presented.

DEFINITION

Melange is a French word which means a mixture, often of incongruous elements. Greenly (1919) first used the term melange to describe rock bodies in Anglesey characterized by the inclusions of fragments or blocks of more durable rocks embedded in a pervasively sheared matrix of materials. In the studies of the Franciscan rocks of the California Coast Ranges, Hsü (1968) revived the term and gave it a genetic meaning. He redefined the term melange as follows:

> 'Melanges' are thus defined as mappable bodies of deformed rock characterized in the inclusion of tectonically mixed fragments or blocks, which may range up to several miles long, in a pervasively sheared, fine-grained, and commonly pelitic matrix. Each melange includes exotic and native blocks and a matrix.

Many geologists accepted Hsü's idea that all melanges are formed by tectonism. For example, Dickinson and Rich (1972), Cowan (1974) referred to melanges as "styles of deformation" or "states of structural disorder". Cowan (1974) stated that, by definition, melanges record a deformation. However, he broadened Hsü's definition of melanges to include all similarly deformed rock bodies, regardless of the types of inclusions or the earlier history of the affected rocks.

On the other hand, however, some other geologists hold the view that genetic definitions are difficult to use in the field because the origin of some rock bodies is unclear. Thus, Berkland et al. (1972) suggested a descriptive definition of the term melange as follows:

> A melange is a mappable body of rock characterized by the inclusion of fragments and blocks of all sizes, both exotic and native, embedded in a fragmented and generally sheared matrix of more tractable material.

They emphasized that the critical factor in determining whether or not a rock body is a melange is the presence (or absence) of exotic blocks. A rock body that contains no exotic elements is called a "broken formation" (Hsü, 1968). However, this is very confusing in some cases.

For example, De Jong (1974) observed that in the same unit, both exotic and native blocks are present in one area while in another area, only native blocks are present. It is obviously inappropriate to give two different terms for essentially the same unit. Therefore, their definition may be modified as follows:

> A melange is a mappable body of rock characterized by the inclusion of fragments and blocks of all sizes and lithologic character, either exotic or native, or both exotic and native, embedded in a fragmented and generally sheared matrix of weaker material.

In fact, Hsü (1968) himself, was aware of the uncertainty of the origin of some rock bodies when he gave the term a genetic definition. He stated, "distinction between an olistostrome and a melange becomes difficult, if not impossible, if the olistostrome has undergone melange deformation". After an international excursion to Tienshan and Caucasus in 1973, Hsü realized this more thoroughly. In the addendum to his paper entitled "Melanges and Their Distinction from Olistostromes" (Hsü, 1974), he wrote, "it is not always clear in the field if a melange is a sheared olistostrome or if the fragmentation and mixing have been entirely tectonic". He accepted that the term melange should be used as a descriptive term. It is now important to come to a general agreement in the use of "melange" as a nongenetic term to designate all chaotic deposits.

COMPONENTS OF MELANGES

In general, each melange consists of two parts: blocks or fragments and a matrix. Blocks or fragments within each melange can be either exotic or native blocks, or both exotic and native blocks. "Exotic blocks are variably sized masses of rock occuring in a lithologic association foreign to that in which the mass formed" (Berkland et al., 1972). "Native blocks are disrupted brittle layers, which were once interbedded with the ductilely deformed matrix "(Hsü, 1968).

Some workers consider the presence (or absence) of exotic blocks as the critical factor in determining whether or not a rock body is a melange (Berkland et al., 1972; Hsü, 1974). This criteron may be difficult to use in some situations, because:

(1) The style of deformation in both "broken formation" and exotic-bearing melanges is identical.

(2) It is very difficult in practice to establish whether certain inclusions in a melange are fragments of rocks formerly interbedded in a discrete rock-stratigraphic unit.

(3) There exists a continuous transition between weakly deformed rocks, or even undeformed rock-stratigraphic units and highly disrupted and mixed melanges. The so-called "broken formation" obviously represents the less intensively deformed part of this spectrum. To what extent we can call a rock body "broken formation" is rather arbitrary.

(4) Exotic-bearing rock bodies and rocks only containing native blocks are sometimes seen in the same unit (De Jong, 1974).

(5) Some native blocks on a small scale may be well considered as exotic blocks on a much larger scale.

Thus, my view is that, as long as different rocks are widely embedded in a weak matrix as disconnected pieces and they comprise a mappable body, the rock body should be called melange.

The matrix of melanges is characteristically a material that could undergo very large permanent deformation without fracturing. Pelitic rocks are the most common rock types. Rarely some other rocks may form the melange matrix. The Colored Melange of Central Iran (Davoudzedeh, 1969), the Masirah Melange in Oman (Moseley and Abbotts, 1979), and the Kaweah Melange of the southwest Sierra Nevada foothills in California (Saleeby, 1979) have a serpentinite matrix. Gansser (1955, 1974), Peyve (1969), Knipper (1973), Makarchev and Visnevsky (1973) also observed melanges with a serpentinite matrix in the Soviet Union and some parts of the Tethyan realm. Tectonic fragments of calc-silicate rocks or of dolomite are sometimes found in marble matrix in some metamorphic terranes (Hsü, 1974). In some very unusual instances, the matrix of a melange is gypsum (Leine and Egeler, 1962). Silver and Beutner (1980) reported that in a number of cases, such as parts of the Colored Melange of Iran, described by Jacqueline Desmons, there is no matrix at all. If this is true, it may be more suitable to call these rocks mixed blocks, or simply chaos. According to Noble (1941), one of the characteristic features of chaos is that "they are tightly packed together, not separated by much finer-grained material".

The composition of inclusions is quite variable. For example, in the Coast Ranges of California, the chaotic rock bodies contain serpentinite, gabbro, diabase, extrusive lava, radiolarian chert, blueschist, mica schist and sedimentary matrix (Hsü, 1969; Maxwell, 1974).

ORIGIN OF MELANGES

The mode of origin of melanges has been a matter of speculation. So far as I know, seven principal models have been proposed.

(1) Taliaferro (1943) considered the chaotic appearance as the result of the repeated folding and faulting of dissimilar rocks, further complicated by landsliding.

(2) De Jong (1974) suggested that the Titicaca Melange was produced by landsliding and was the result of fragmentation of lithified rocks of the so-called Titicaca Group after a detailed stratigraphic and structural study near Lago Titicaca in Peru. He compared the Titicaca Melange with the Amargosa Melange in California and stated that the similarity between the two suggested a similar origin for the Amargose Melange.

(3) Based on the widespread existence of major strike-slip faults in the Coast Ranges of California, Coleman and Lee (1963), Bailey et al. (1964), and Dickinson (1966) interpreted Franciscan melanges as megabreccias in vertically oriented great shear zones. Saleeby (1979) believed that the Kaweah serpentinite melange developed along a fracture zone by the combined effect of protrusive activity and wrench faulting.

(4) Many workers attribute the formation of melanges to large scale underthrusting (Hsü, 1968, 1971; Suppe, 1973; Blake and Jones, 1974; Cowan, 1974; Connelly, 1978; and Jones et al., 1978). For example, Bailey and Blake (1969), Page (1970) and Ernst (1970) have stressed subduction underthrusting as the chief mechanism for the formation of the Franciscan. Moore and Karig (1980) believed that thrust-related shearing on the lowermost trench slope created the melanges of the Oyo Complex. Brown (1964) suggested that at least part of the melange masses in the Coast Ranges of California were friction breccia beneath a great overthrust.

(5) Some other people (Hsu and Ohrbom, 1969; Hsü, 1969; Abbate et al., 1970; Suppe, 1973; Kleist, 1974; Maxwell, 1974; Gucwa, 1975; and

Robertson, 1977) proposed that some melanges might have been formed by submarine debris flows or olistostromes.

(6) Another possibility is that melanges represent zones of diapiric flow (Maxwell, 1974) or extrisive flow (Suppe, 1973). For example, Moseley and Abbotts (1979) interpreted the Masirah Melange as the result of the diapiric rise of serpentinite along a transform fault. They stated that the serpentinization of ohiolitic rocks in the lower part of the oceanic crust would result in volume changes. The resulting low-strength, low-density rock would tend to move to the place of less pressure, under the influence of complex stress system near the ridge-transform fault intersection. Similar complexes are also found in the Alpine belt of southern Spain, where Triassic gypsiferous mudstones have risen upwards along linear wrench zones, carrying with them exotic blocks of limestone and volcanic rocks hundreds of meters in diameter (Moseley, 1973).

(7) Some of the mechanisms mentioned above may work together to produce melange formation (Maxwell, 1974; Page, 1978). Quite often, melange bodies originate as olistostromes and are subsequently tectonized. The early Ordovician melange in the Central Volcanic Belt of Northeastern Newfoundland (Horne, 1969), the Franciscan melanges of California (Cowan, 1978; Page, 1978) and the Boones Point Melange of the North-central Newfoundland (Nelson, 1981) are some examples of this kind. The Anglesey melange of Wales (Wood, 1974; Silver and Beutner, 1980) and the melange units in the northern Appennines of Italy (Hsü, 1974) could also be formed in the same way. Therefore, it provides evidences supportive of both groups of people with completely different views about its origin.

In my view, no one single model listed here can account for the formation of all melanges in general. Different melanges in different places may involve different mechanisms. In some places, perhaps only one single mechanism is involved. In some other places, however, different mechanisms may have made contributions to produce melanges, though one of them may predominate. Moreover, if more than one mechanism is involved, they could work at the same time or take place one after another (Horne, 1969; Hsü and Ohrbom, 1969; Page, 1978). Therefore, we should be aware that the existence of a subduction zone can not be affirmed simply by viewing the chaotic appearance of some rock bodies. What we need to do is to find out what meachnisms are involved in the formation of these rock bodies. In the next part, I shall discuss how we can distinguish melanges of different genisis.

DISTINCTION BETWEEN TECTONIC MELANGES AND SEDIMENTARY MELANGES

The term melange is used here in a very broad sense to include all chaotic deposits. This usage is synonymous with Hsu's definition of "wildflysch" (Hsü, 1974). Melanges can be first classified into two large categories on the basis of their evolutionary history (TableI). If a melange body has not been modified after its formation, it is called single cycle melange. However, if a melange body has been redeformed (Hsü, 1974) or has been eroded and redeposited after its formation (Cowan and Page, 1975), it is called double cycle melange. In principle, there should exist triple cycle melange. Nevertheless, it may not be possible at the present time to distinguish these different stages.

According to the origin of mixed rock bodies, single cycle melanges can be further divided into two types: tectonic melanges produced by tectonic processes and sedimentary melanges produced by sedimentary

TABLE I. CLASSIFICATION OF MELANGES

Melanges (Wildflysch) (Hsü, 1974)	SINGLE CYCLE MELANGES	Tectonic Melange
		Sedimentary Melange (olistostrome) (Hsü, 1968)
	DOUBLE CYCLE MELANGES	Tectonized Sedimentary Melange
		Recycled Tectonic Melange
		Redeformed Tectonic Melange
		Recycled Sedimentary Melange

processes. Sedimentary melanges have also been called olistostromes by some workers (for example, Hsü, 1968).

Double cycle melanges can be also subdivided into several types, depending on the types of processes involved in the formation of melanges and the sequence of their occurrence. If a melange body was produced by sedimentary processes and then redeformed, it is called tectonized sedimentary melange. If a melange body was produced by tectonic processes and then eroded and redeposited, it is called recycled tectonic melange. Sometimes, melanges can be the result of two stages of tectonic deformation or two cycles of sedimentation. Then, they can be named as redeformed tectonic melanges or recycled sedimentary melanges.

The distinction between melanges produced by tectonic processes and melanges produced by sedimentary processes is a critical step in tracing the tectonic history of certain regions. The two alternative interpretations for a given body could lead to completely different geological conclusions (Hsü, 1974). As many people have stated, in the field, it is often very difficult to prove that a particular chaotic rock body is a sedimentary melange or a tectonic melange because many of the melange characteristics are not unique to a single meachism. However, it is so important to carry on this work that we can not come to a final conclusion about the tectonic evolution of a given region without understanding the genesis of melange bodies. We must make a great effort to look for the subtle indicative field evidence and to further our research at the microscopic scale in order to figure out the processes responsible for the formation of a particular rock body and the nature of a given melange body prior to its formation.

What follows are some criteria used by different workers for distinguishing sedimentary melanges from tectonic melanges (Table II). Anyone of these criteria may not give us a conclusive evidence about the genesis of a given rock body. However, if we are trying to look for as amny clues as possible, it may be possible to come fairly confidently to a conclusion.

TABLE II

CRITERIA FOR DISTINGUISHING SEDIMENTARY MELANGES FROM TECTONIC MELANCES

	TECTONIC MELANGES	SEDIMENTARY MELANGES
SHAPE OF INCLUSIONS	From rectangular through barrel-shaped to phacoidal blocks bounded by fracture surfaces	Very rounded autoclasts
NATURE OF INCLUSIONS	Contain blocks from both the underlying and the overlying units.	Contain blocks of the underlying unit, but not of the overlying unit.
SIZE OF INCLUSIONS	The inclusions of tectonic melanges can be huge slabs hundreds of square miles in extent and a few miles thick(Hsu, 1968, p.1066).	Usually smaller than tens or hundreds of feet long (Hsü, 1968, p.1066).
ORIENTATION OF INCLUSIONS	The lenticular blocks are parallel to each other and subparallel to thrust faults.	The blocks appear to have rotated around inconstant axes during the movement of the mass(Page, 1978, p.225).
DISTRIBUTION OF INCLUSIONS	Examples representing progressive stages of separation can be found (Hsü, 1974, p.322).	Blocks of one lithology are separated by distances ten to twenty times greater than the block size(Wood, 1974, p.337).
FABRIC OF MATRIX	The matrix of tectonic melanges is pervasively sheared. Shear surfaces show an anastomosing pattern.	The matrix of sedimentary melanges is not necessarily pervasively sheared.

	TECTONIC MELANGES	SEDIMENTARY MELANGES
NATURE OF MATRIX	In general, brittle sandy beds are embedded in a pelitic matrix	Sometimes the fragmented beds are shaly interbeds, with unconsolidated sands flowed into the interstices of fragmental shales(Crowell et al., 1966).
PRESENCE OF SLICKENSIDE STRIATIONS	Slickenside striations and step structures are ubiquitous.	Commonly, slickenside striations and step structures are not formed or preserved.
SIZE OF THE WHOLE ROCK BODY	Tectonic melanges may form a whole mountain range(Hsü, 1968, p.1066).	Sedimentary melanges are usually lenticular sheets from a few feet to several hundred feet thick(Hsü, 1968, p.1066).
NATURE OF ADJACENT UNITS	Not necessarily in contact with marine sediments	Sedimentary melanges are underlain, overlain and laterally bounded by normal marine sediments (Page, 1978, p.225)
NATURE OF CONTACTS WITH ADJACENT UNITS	Their contacts with adjacent units are almost invariably shear surfaces	The contact with overlying and underlying units should be depositional and conformable.
AGE RELATIONSHIP BETWEEN MELANGES AND ADJACENT UNITS	The age of exotic blocks could cover a very wide range of time. Some blocks may contain fossils younger than the matrix fauna(Hsü, 1974, p.329).	The chaotic material has nearly the same age(or the same epoch) as the overlying and underlying sediments (Page, 1978, p.225).
SOFT-SEDIMENT DEFORMATIONAL STRUCTURES	No soft-sediment deformational structures can be seen in the tectonic melanges derived from a	Soft-sediment deformational structures may be preserved in the matrix or inclusions of the melange(Wood, 1974, p.337)

	TECTONIC MELANGES	SEDIMENTARY MELANGES
DEFORMATIONAL CHARACTERISTICS NEAR THE CONTACT	The distribution of strain is related to the mechanical properties of the rocks involved, regardless of stratigraphic boundaries(Gucwa, 1975, p.107).	The deformation is not strongly penetrative at stratigraphic contacts, regardless of similarity of mechanical properties (Gucwa, 1975, p.107).
LAYERING IN MELANGE	No layering can be found in tectonic melanges. When tectonic melanges can be subdivided into domains or units according to the composition of their inclusions. These domains are usually separated by shear surfaces.(Hsü, 1969).	The chaotic mass may be faintly layered. The layering may be expressed by color, predominant rock types of the inclusions, predominant sizes of inclusions, density of the inclusion population, etc. The layers are most meaningful when they are not bounded by shear surfaces (Page, 1978, p.225).

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