Structural Studies of the Ordovician Flysch and Melange in Albany County, New York

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Department of Geological Sciences

Frederick W. Vollmer

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State University of New York at Albany

College of Science and Mathematics

The thesis for the master's degree submitted by

Frederick W. Vollmer

under the title

Structural Studies of the Ordovician Flysch and Melange in Albany County, New York

has been read by the undersigned. It is hereby recommended for acceptance by the Faculty with credit to the amount of six semester hours.

(signed) [illegible]

(date) 18th May 1981

(signed) W. D. Means

(date) May 18th 1981

(signed) [illegible]

(date) [illegible]

Recommendation accepted by the Dean of Graduate Studies for the Graduate Council.

(signed) ______________________

(date) ______________________

ABSTRACT

The middle Ordovician rocks of the Albany 15 minute quadrangle comprise interbedded graywacke and shale, and in the east, coarse cobble or olistostromic deposits. The detrital composition, westward fining and regional westward transgression of these deposits indicate that these were sediments shed off the westward thrusting Taconic Allochthon. Primary sedimentary structures show that these rocks were deposited by turbidity currents flowing into a longitudinal trough, probably formed in response to increased load during overthrusting. Although strongly dependent on lithology, deformation intensity generally increases from west to east; from essentially undeformed bedded flysch through asymmetrically folded and thrust beds to highly deformed melange containing isoclinally folded, transposed and boudinaged beds within a phacoidally cleaved shaly matrix. Folds in the least deformed flysch are generally open and have horizontal hinge lines. In more highly deformed rocks folds are isoclinal with hinge lines plunging to the SE. This suggests that with increased strains overturned folds in the flysch rotated into the direction of maximum finite extension. This direction corresponds with the overthrust direction indicated by slickenside striations on minor fault planes. Fold development apparently occurred as a two phase progressive event, with initiation of buckle folds followed by the development of extreme noncylindrial hinge lines accompanying brittle failure and boudinage. Locally, a third phase of folding has occurred. In addition, an early phase of chaotic folding occurred within a chert and siliceous argillite unit. The formation of the Taconic melange in this area can be explained through the

progressive disruption of a syndepositionally deformed turbidite fan complex, which included coarse proximal or olistostromic facies. Additionally, thrusting has led to the incorporation of slivers or klippes of older facies into the melange.

Department of Geological Sciences
State University of New York at Albany
1400 Washington Avenue
Albany, N. Y. 12222

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"Such an apparent inability to correlate properly a terrane with such a rich fauna would seem inconceivable, specially so in a state which, by the labors of Professor Hall and of his many followers, has furnished the standard scale of formations for all America, were it not for the indescribably folded, tilted and crushed condition of the beds . . . "

- Rudolf Ruedemann, 1901,
  on the "Hudson river beds"
  near Albany.

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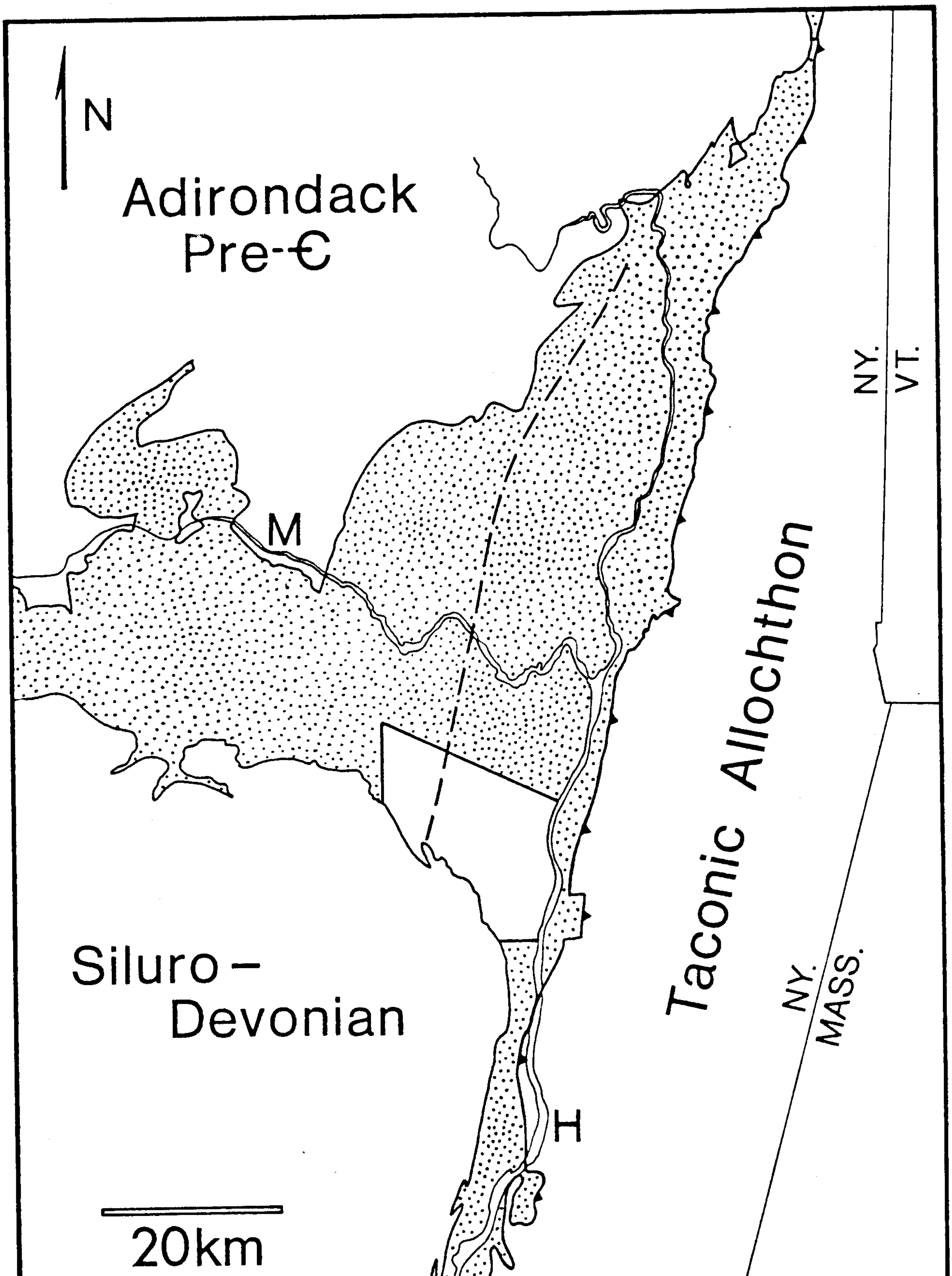
CHAPTER I

INTRODUCTION

The observations and conclusions presented within this thesis are mainly the result of field work undertaken during the field season of 1979. This work was done under the direction of Dr. W. D. Means while enrolled in the Master of Science degree program in the Department of Geological Sciences at the State University of New York at Albany.

The field area (figure 1, plate 1) covered comprises portions of four United States Geological Survey 7.5 minute quadrangle topographic sheets: Voorheesville, Albany, Clarksville, and Delmar in Albany County, New York. The boundaries of the study area within these quadrangles are: the present exposure of the unconformity of the Helderburg Group limestones with the underlying middle Ordovician shales and arenites (Ruedemann, 1930) on the south and west; the Hudson River on the east; and State Route 20 on the north. The bedrock of this area consists entirely of middle Ordovician rocks, dominantly greywacke and shale, which are locally highly deformed and disrupted into mélange. Outcrop exposure of the Ordovician rocks is poor owing to the erosion of the soft shales, and to the extensive glacial deposits within the area (Cook *in* Ruedemann, 1930). Outcrops are generally limited to stream, road, and railway cuts, and quarries.

The basic objectives of this study were to formulate a structural model which could explain how the complex structures observed in various outcrops within the area are related, and to explain how these structures might have evolved through time. During the course of this study, these objectives were supplemented by other objectives which mainly involved the relationship of these rocks to the regional geology, and to similar rock units found worldwide. These secondary objectives


N
Adirondack
Pre-Є
M
NY.
VT.
Taconic Allochthon
Siluro –
Devonian
NY.
MASS.
H
20km

include: how the structures found within these middle Ordovician rocks relate to the emplacement of the Taconic Allochthon, and to models proposed by others for the emplacement of the Taconic Allochthon; and how the structures and structural history of these rocks might relate to the formation of mélange in other areas throughout the world.

Study procedures used for the field work involved mainly detailed structural analysis of individual outcrops. Pace and compass maps with scales ranging from 1:240 to 1:2400 were made of selected localities to determine local structural styles. Delineation of larger, megascopic structures is difficult as the outcrop is not generally continuous enough over long distances. A traditional stratigraphic approach to mapping of large scale structures is impeded by the general lack of stratigraphy due to the monotonous and discontinuous nature of the interbedded greywackes and shales, and the general description of stratigraphic layering within the mélange. The choice of the field area boundaries allows a broad range of structural styles to be observed, from nearly undeformed, near-horizontal strata in the west, to highly deformed and disrupted mélange in the east. It was believed that this apparent west to east increase in deformation intensity might be correlated with the structural history of these rocks.

As the objectives of this study involved a comparison of detailed structural features, rather than the delineation of major stratigraphic boundaries, the bulk of the field time was spent studying the larger and best exposed outcrops, rather than searching out small isolated outcrops with limited structural detail. Areas of good outcrop potential were located mainly by referring to Ruedemann's (1930) map which indicates general areas of exposure. Traverses were also made through other areas, particularly along streams, railroads and roads where 7.5 minute topographic sheets indicated possible exposures through the overlying glacial deposits.

Although the bulk of this thesis is concerned specifically with structural geology, a chapter on sedimentary features is included. This section is included mainly for completeness; however, it is believed that the deformational environment of these rocks was closely linked with the depositional environment. That is, these sediments are believed to have been deformed syndepositionally, or soon after their deposition. The formation of mélange found throughout the world is commonly attributed to the interaction of depositional and deformational processes (Chapter 7), and it is therefore important to study both the sedimentary and structural features of these deposits.

CHAPTER II

GEOLOGIC SETTING

The shales, siltstones, arenites, and greywackes of the Hudson Valley (Fisher et al., 1970) are part of a nearly continuous belt of easterly derived, westwards transgressive medial Ordovician flysch (deep water, synorogenic sandstone-shale facies; see Enos, 1969, for discussion) which extends from Newfoundland to Alabama (figures 2, 3; Enos, 1969; Williams, 1978). These medial Ordovician sedimentary rocks overlie Cambrian to medial Ordovician shelf sequences and are mainly deep-water, longitudinally transported turbidite deposits (McBride, 1962; Enos, 1969; Stevens, 1970; Shanmugan and Walker, 1978). The transgression of these clastic deposits over the carbonate shelf is associated with the medial Ordovician emplacement of various allochthonous terranes including: the Hamburg klippe of Pennsylvania (Wright et al., 1979), the Taconic Allochthon of New York, Massachusetts, Connecticut, and Vermont (Zen, 1967), nappes of Quebec (St. Julien and Hubert, 1975; Hiscott, 1978) and the Humber Arm and Hare Bay Allochthons of Western Newfoundland (Rodgers and Neale, 1963; Stevens, 1970). The deformation of these synorogenic Ordovician clastic deposits is recorded by an angular unconformity between middle Ordovician and Silurian strata which is discontinuously present from at least Pennsylvania northwards into Newfoundland (Rodgers, 1967). Locally, "wildflysch" or mélange occurs within the flysch sequence near the allochthonous rocks in New York, Quebec, and Newfoundland. These have generally been interpreted as olistostromal deposits deformed in front of, and overridden by gravity-slide nappes (Rodgers and Neale, 1963; Zen, 1967; Bird, 1969; Bird and Dewey, 1970; St. Julien and Hubert, 1975; Williams, 1977).

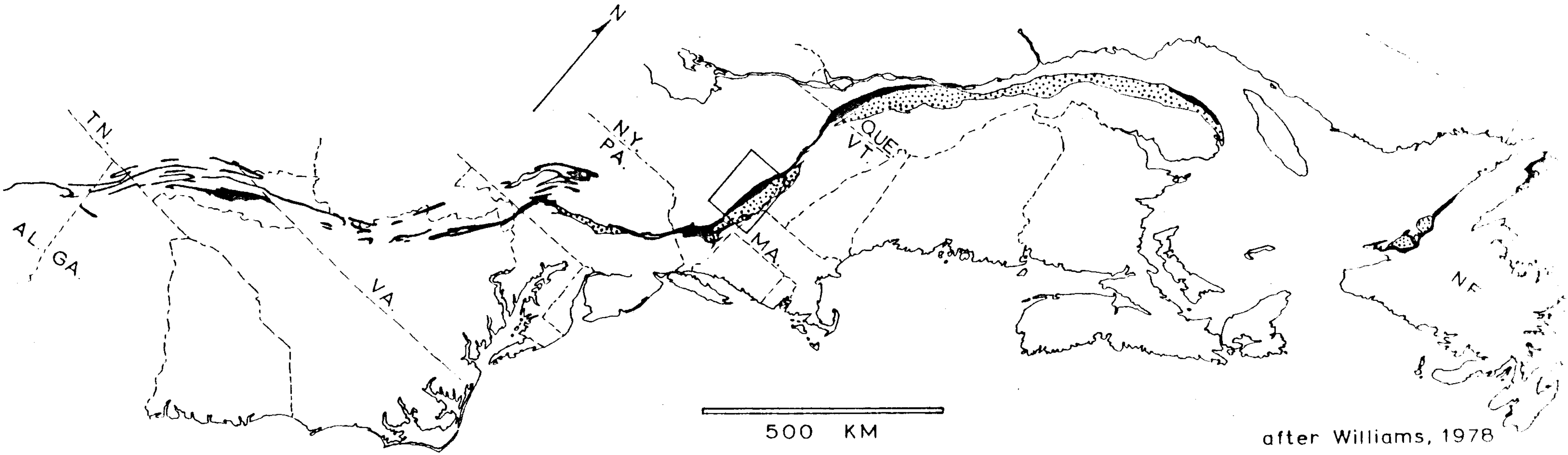
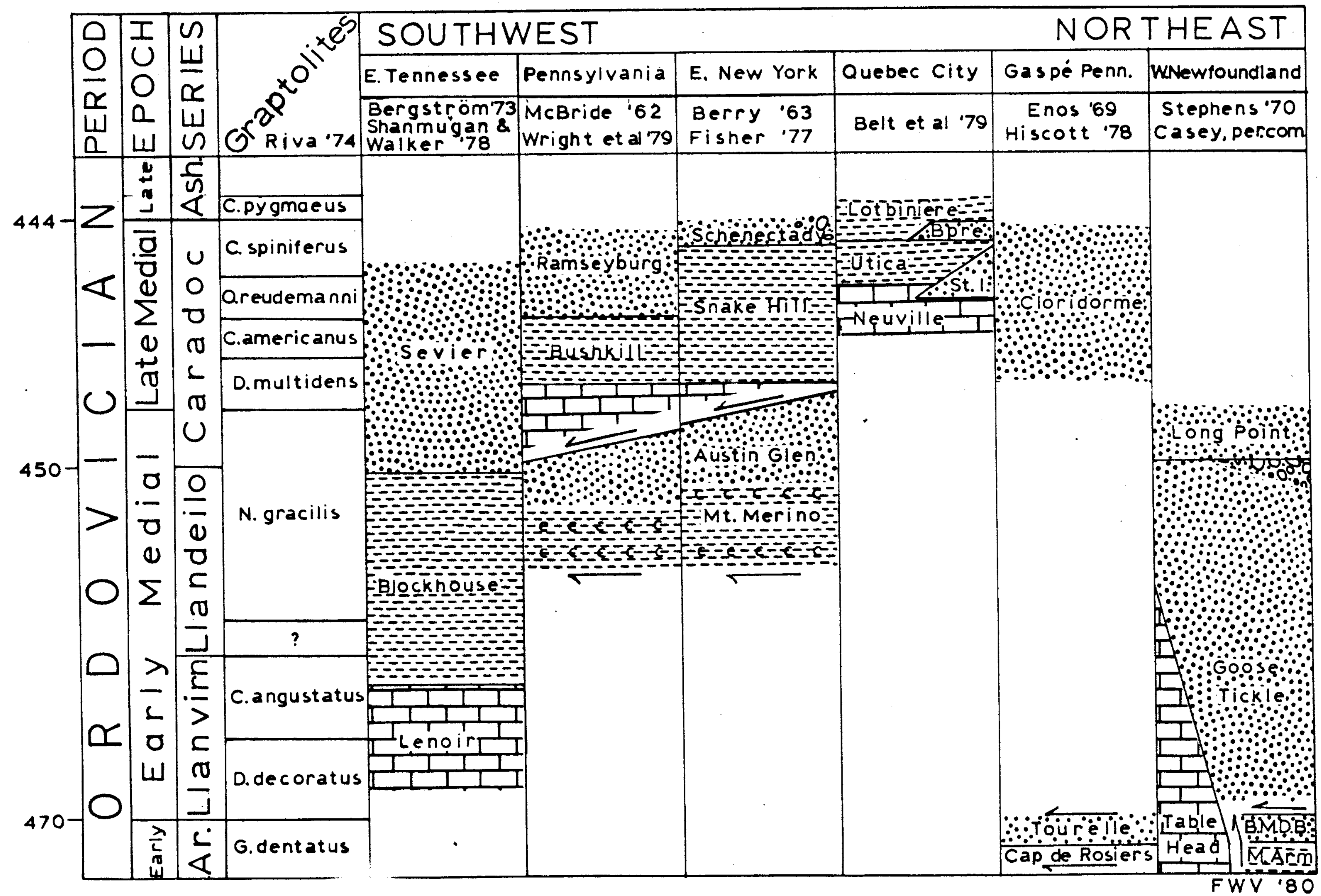


Figure 2. Distribution of medial Ordovician flysch (solid) and associated allochthons (stippled) of the Appalachian orogenic belt of eastern North America. Box indicates position of figure 1 (Bosworth and Vollmer, 1981).

Figure 3. Correlation chart of the medial Ordovician flysch facies of the Appalachian orogenic belt of eastern North America. "C" indicates chert or siliceous argillite.

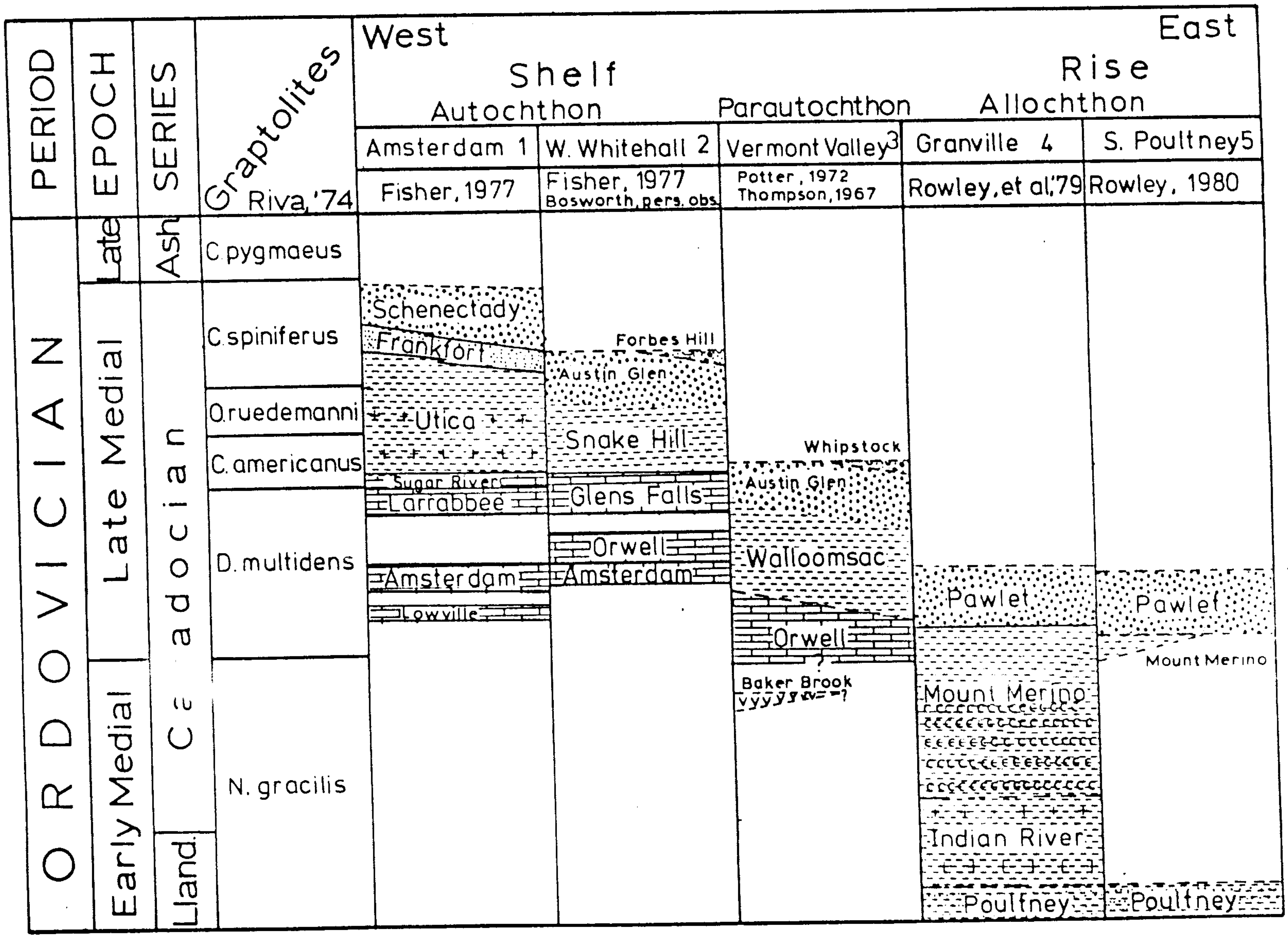


PERIOD
EPOCH
SERIES
Graptolites
Riva '74
SOUTHWEST
NORTHEAST
E. Tennessee
Pennsylvania
E. New York
Quebec City
Gaspé Penn.
W.Newfoundland
Bergström '73 Shanmugan & Walker '78
McBride '62 Wright et al '79
Berry '63 Fisher '77
Belt et al '79
Enos '69 Hiscott '78
Stephens '70 Casey, per.com
444
450
470
ORDOVICIAN
Late
Late Medial
Early Medial
Early
Ash.
Caradoc
Llandeilo
Llanvirn
Ar.
C. pygmaeus
C. spiniferus
O. reudemanni
C. americanus
D. multidens
N. gracilis
?
C. angustatus
D. decoratus
G. dentatus
Sevier
Blockhouse
Lenoir
Ramseyburg
Bushkill
Schenectady
Snake Hill
Austin Glen
Mt. Merino
Lotbiniere
Bpre.
Utica
St. I.
Neuville
Cloridorme
Tourelle
Cap de Rosiers
Long Point
Goose Tickle
Table Head
B.M.D.B.
M.Arm
FWV '80

Facies relationships within the medial Ordovician clastic sequences of eastern New York, Massachusetts, and Vermont suggest that these deposits are a time-transgressive, westerly progradational sequence which coarsens upwards (figure 4; Zen, 1967; Rowley and Kidd, 1981). The flysch is bounded on the east by a Cambrian (?) to medial Ordovician sequence of argillite, arenite, and carbonate rocks of the Taconic Allochthon, although equivalent flysch deposits are found within the uppermost Taconic sequence and to the east of, and beneath, the Allochthon (Pawlet Formation of Zen, 1961; Austin Glen Member of Ruedemann, 1942; Walloomsac slate of Prindle and Kopf, 1932; slates of the Ira Formation of Keith, 1932; see Zen, 1967, for discussion). The argillaceous Taconic sequence has been interpreted as slope deposits of a Cambrian(?) to medial Ordovician North American continental margin emplaced on to the continental shelf during medial Ordovician times (Bird and Dewey, 1970). Gravity-sliding (Zen, 1961, 1967, 1972; Rodgers and Fisher, 1969; Bird and Dewey, 1970; Potter, 1972) and hard-rock thrusting (Walcott, 1888; Keith, 1912; Ruedemann, 1914; Fowler, 1950; Rowley et al., 1979) have been proposed as emplacement mechanisms. Recent models proposed by Chapple (1973) and Rowley and Kidd (1981) suggest that the Taconic Allochthon was emplaced as a result of continued accretionary processes (e.g., Seeley et al., 1974; Karig and Sharman, 1975) during the attempted subduction of the medial Ordovician North American continental shelf in an east-dipping subduction zone.

To the southeast, the flysch of the Hudson Valley is unconformably overlain by the latest Silurian to Devonian carbonate rocks of the Helderberg Group, although exposures of the flysch continue southwards along the Hudson River Valley into New Jersey and Pennsylvania (figures

Figure 4. Correlation chart of the medial Ordovician shelf, rise and flysch sequences of New York and Vermont (Rowley and Kidd, 1981).



PERIOD
EPOCH
SERIES
Graptolites Riva, '74
West
East
Shelf
Rise
Autochthon
Parautochthon
Allochthon
Amsterdam 1
W. Whitehall 2
Vermont Valley 3
Granville 4
S. Poultney 5
Fisher, 1977
Fisher, 1977 Bosworth, pers. obs.
Potter, 1972 Thompson, 1967
Rowley, et al, '79
Rowley, 1980
ORDOVICIAN
Late
Late Medial
Early Medial
Ash
Caradocian
Lland.
C. pygmaeus
C. spiniferus
O. ruedemanni
C. americanus
D. multidens
N. gracilis
Schenectady
Frankfort
Utica
Sugar River
Larrabbee
Amsterdam
Lowville
Forbes Hill
Austin Glen
Snake Hill
Glens Falls
Orwell
Amsterdam
Whipstock
Austin Glen
Walloomsac
Orwell
Baker Brook
Pawlet
Mount Merino
Indian River
Poultney
Pawlet
Mount Merino
Poultney

1 and 2; Ruedemann, 1930). This unconformity dies out to the west becoming a conformable sequence in western New York (Fisher et al., 1970). The rocks of the Helderburg Group are themselves folded and faulted indicating a later episode of deformation (Ruedemann, 1930) associated with the deposition of the Catskill delta sequence and the Acadian Orogeny (Rodgers, 1967). The flysch sequence is truncated to the north by high angle faults which bring to the surface Cambrian(?) to medial Ordovician shelf carbonate and clastic rocks, and Precambrian metamorphic rocks of the Adirondack Massif (Fisher et al., 1970).

CHAPTER III

PREVIOUS WORK

Nomenclature and Ages

Amos Eaton first described, in a general way, the rocks of the Hudson River Valley in a series of publications from 1817 to 1832. In 1839, Mather proposed the name "Hudson River Slate group," later "Hudson River group," for the slates, shales and grits "with interstratified limestones" of the Hudson River Valley that unconformably underlie the Shawangunk grits and Helderburg group limestones. Mather, in 1843, classified the Hudson River group into two structural divisions: "the approximately horizontal, unaltered strata, west of the line of disturbance in the valley of the Hudson," and " the strata within the area of disturbance in the immediate vicinity of the river and to the east" (Walcott, 1890). Mather, Vanuxem and Hall also applied the name "Hudson River group" to westerly equivalents, such as the Utica shale, Frankfurt slate, shales and sandstones of the Pulaski and Lorraine shales, and similar units as far west as Iowa. Others, such as Emmons, favored the use of local names for these western units. Emmons (1847 in Walcott, 1890) recognized the structural complications of naming the units stating that "the only reason assigned for the name [Hudson River group] was that this subdivision presented certain peculiarities arising from a disturbance it had suffered along the Hudson River." In 1847, Hall published descriptions of graptolites from the shales of the Hudson River valley, mostly from exposures along the Normans Kill near Kenwood (Normans Kill gorge). These were the first descriptions of graptolites from North America. The Hudson River group was generally assigned to the Trentonian of the "Lower Silurian" (new equivalent to Ordovician) by the geologists of New York State (Walcott, 1890). Keith (1912, 1913), and later Ruedemann (*in* Cushing and Ruedemann, 1914), described Cambrian faunas from strata overlying Ordovician rocks, giving the first good evidence for the existence of a major overthrust.

Ruedemann's extensive mapping and paleontological work within the Hudson Valley during the first half of the 1900's lead to the naming of numerous new rock units and a succession of graptolite zones for dating the Ordovician sequences. Although Ruedemann's observations were consistently accurate (however, see Riva, 1974) and astute, he generally failed to differentiate between lithologic and biostratigraphic units, and commonly used them interchangeably (Berry, 1962, 1963). The more important of these units, which were mapped throughout a large portion of the Hudson Valley by Ruedemann (Cushing and Ruedemann, 1914; Ruedemann, 1930, 1942) include: the Normanskill shales (Ruedemann, 1901a; Normanskill Formation of Ruedemann, 1942), with the Mount Merino (chert) and Austin Glen (greywacke) members (Ruedemann, 1942), the Snake Hill shale, the Canajoharie shale, and the Schenectady beds (Ruedemann, 1912). The Normanskill Group (Fisher, 1961, 1977) is also mapped within the allochthonous Taconic sequence where it includes, from oldest to youngest: red slates of the Indian River Formation; green and black cherts, slates and siliceous argillites of the Mount Merino Formation, and interbedded slates and greywackes of the Pawlet or Austin Glen Formations (Berry, 1962; Zen, 1967; Fisher, 1977). The Snake Hill shale is lithologically similar to the Normanskill shale and is distinguished mainly by faunal criteria (Ruedemann, 1914). Berry (1963) and Zen (1967) recommended that the name "Snake Hill shale" be abandoned. The lower Canajoharie shale is essentially the shaly equivalent of the

Snake Hill shale (Ruedemann, 1912; Kay, 1937) and is probably also equivalent to, but slightly older than, the Utica shale (Fisher, 1977). The Schenectady beds are esentially the younger equivalent of the Austin Glen member (Krueger, 1963).

The graptolite zonations within these argillaceous Ordovician rocks have been studied by many workers. Notable references include: Hall (1847), Ruedemann (1908, 1912, 1919, 1925, 1947), Berry (1962, 1977) and Riva (1974). Using the graptolite zonation of Riva (1974) the Normanskill Group falls within the Nemagraptus gracilis and Diplograptus multidens zones. The Mount Merino cherts and shales contain only N. gracilis zone graptolites, whereas the Austin Glen greywacke contains both N. gracilis and D. multidens zone graptolites. The Snake Hill/Canajoharie shales range from D. multidens up into Climacograptus spiniferus zone age. The Schenectady beds are mainly C. spiniferus zone age (figure 5; Riva, 1974; Fisher, 1977). See appendix B for fossil localities.

Early references to the Taconic melange have commonly been to specific localities, these include: Moordener Kill bed of Ruedemann (1901a), Rysedorph Hill conglomerate of Ruedemann (1901b), Postenkill breccia of Ruedemann (1930), Forbes Hill conglomerate of Zen (1961), and Whipstock breccia of Potter (1963). Berry (1962) used the name "blocks in shale unit" for melange outcrops along the Taconic front from Troy south to at least Castleton, at Schuylerville, and later (Berry, 1963) at Snake Hill. He believed that the Rysedorph conglomerate occurred as blocks within this unit, and attributed its origin to "blocks dropped from the fronts of large sheets of previously-formed rock units being thrust or sliding westward." (see also, Zen, 1961). Bird (1963) called similar outcrops "Wildflysch-type conglomerate," but later preferred to use "Forbes Hill Conglomerate" for these rocks exposed along the entire

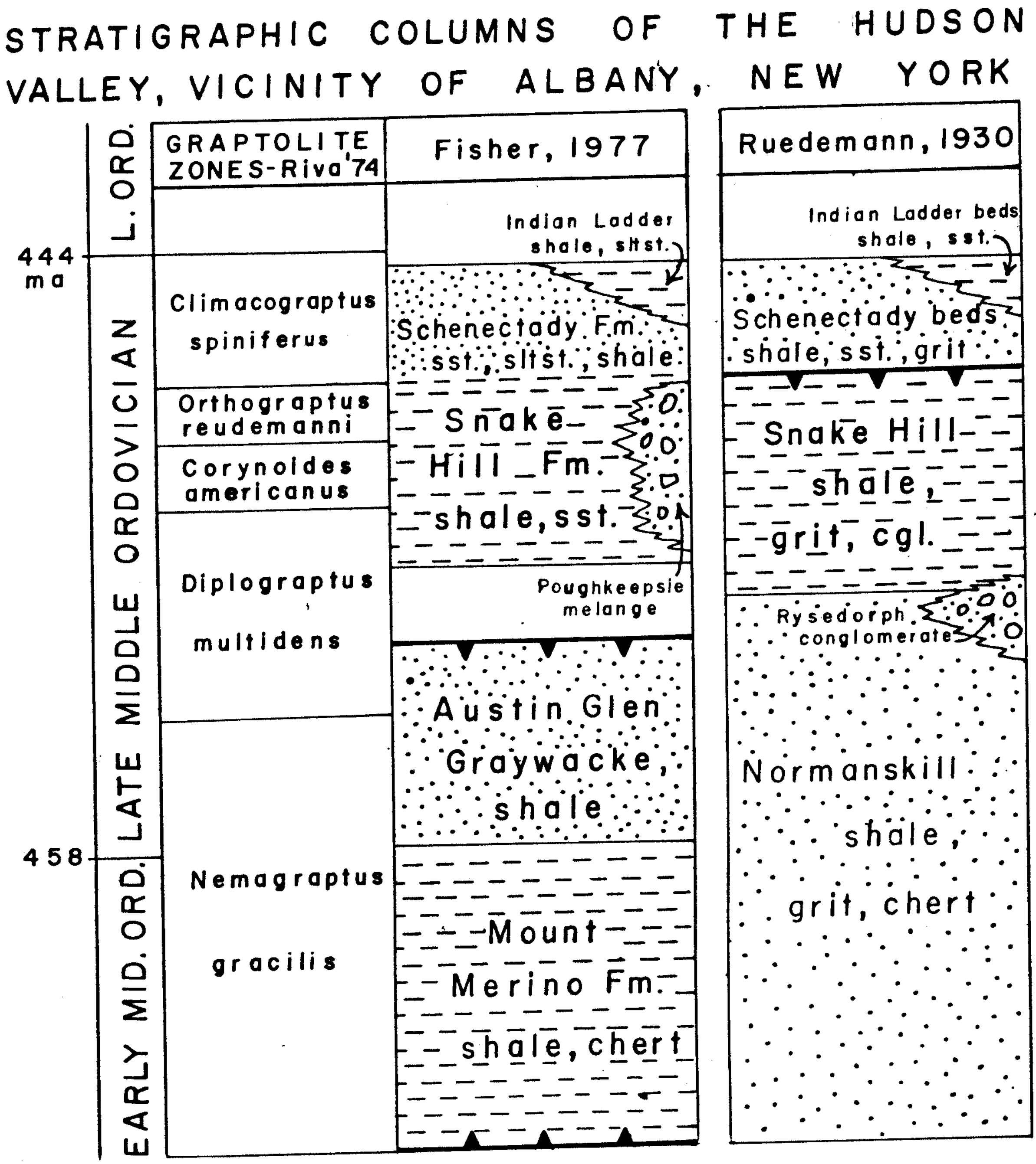


Figure 5. Biostratigraphy of the Hudson Valley flysch sequence as established by Ruedemann (1930) and Fisher (1977).

Taconic front, and including the Whipstock Breccia (Bird, 1969). Bird (1969) made a distinction between the Forbes Hill and the "conglomerates of the Austin Glen greywacke, well exposed in the Norsmanskill (Creek) gorge," that are monomictic. These monomictic conglomerates, Bird believed, were formed by being "bulldozed" in front of the advancing Giddings Brook slice. Fisher et al. (1970) used the name "Taconic Mélange" for patches of mélange exposed along the Taconic front. Finally, Fisher (1977) has advocated the use of "Poughkeepsie Mélange" for the "tectono-sedimentary breccia" within the mid-Hudson Valley, with a type locality at Kaal Park, Poughkeepsie. Fisher (1977) gives graptolite zones of *D. multidens* through *O. ruedemanni* for the Poughkeepsie Mélange (figure 5). For general usage within this thesis, I have used "Taconic mélange" as a general term for mélange associated with the Taconic Allochthon (section on "Mélange and Olistostromes").

Mapping

In 1930, Ruedemann published a map and descriptive text entitled "The Geology of the Capital District (Albany, Cohoes, Troy and Schenectady Quadrangles)." Within the area mapped in the present study, Ruedemann originally mapped four Ordovician units, mainly on faunal criteria: Normanskill shale, Snake Hill shale, Schenectady beds, and Indian Ladder beds (dark shales and sandstones exposed locally along the base of the Helderberg escarpment). Ruedemann distinguished two structural boundaries within the shales: the western boundary of intense Taconic folding and the western boundary of distinct Taconic folding. These are, for the most part, the boundaries of three main structural domains defined in the present study (but, see section on "Route 102"). The contact between the Snake Hill shale and the Schenectady beds was believed by

Ruedemann to represent a major, low angle thrust fault which had brought the two differing faunal assemblages into contact (plate 1). Recognizing the common east dipping faults and associated slickenside striations, Ruedemann suggested that the cumulative effect of small throws on individual faults would be to "bring progressively older beds to the surface as one goes east." Ruedemann also observed many of the structural features recognized within the present study. For example, the common isoclinal folds overturned to the west and some of the effects of lithology on fold styles were described in his 1930 paper.

Mapping of the Troy South and East Greenbush quadrangles, east of the present field area, was redone by Elam (1960). Elam distinguished two members within the Snake Hill Formation: silvery grey shale with large slide blocks, and a lower grey shale and subgreywacke member. Three members were distinguished within the Normanskill Formation: the Austin Glen member consisting of greywacke and grey shale; the Mount Merino member of black, green, and red chert and black shale; and the red shale member with red shale and quartzite. The eastern portions of these two quadrangles are Cambrian(?) to medial Ordovician age rocks typical of the Taconic sequence. The western portion of these quadrangles is dominantly composed of his Snake Hill Formation, which forms imbricate thrust sheets beneath the Taconic sequence.

CHAPTER IV

SEDIMENTARY FEATURES

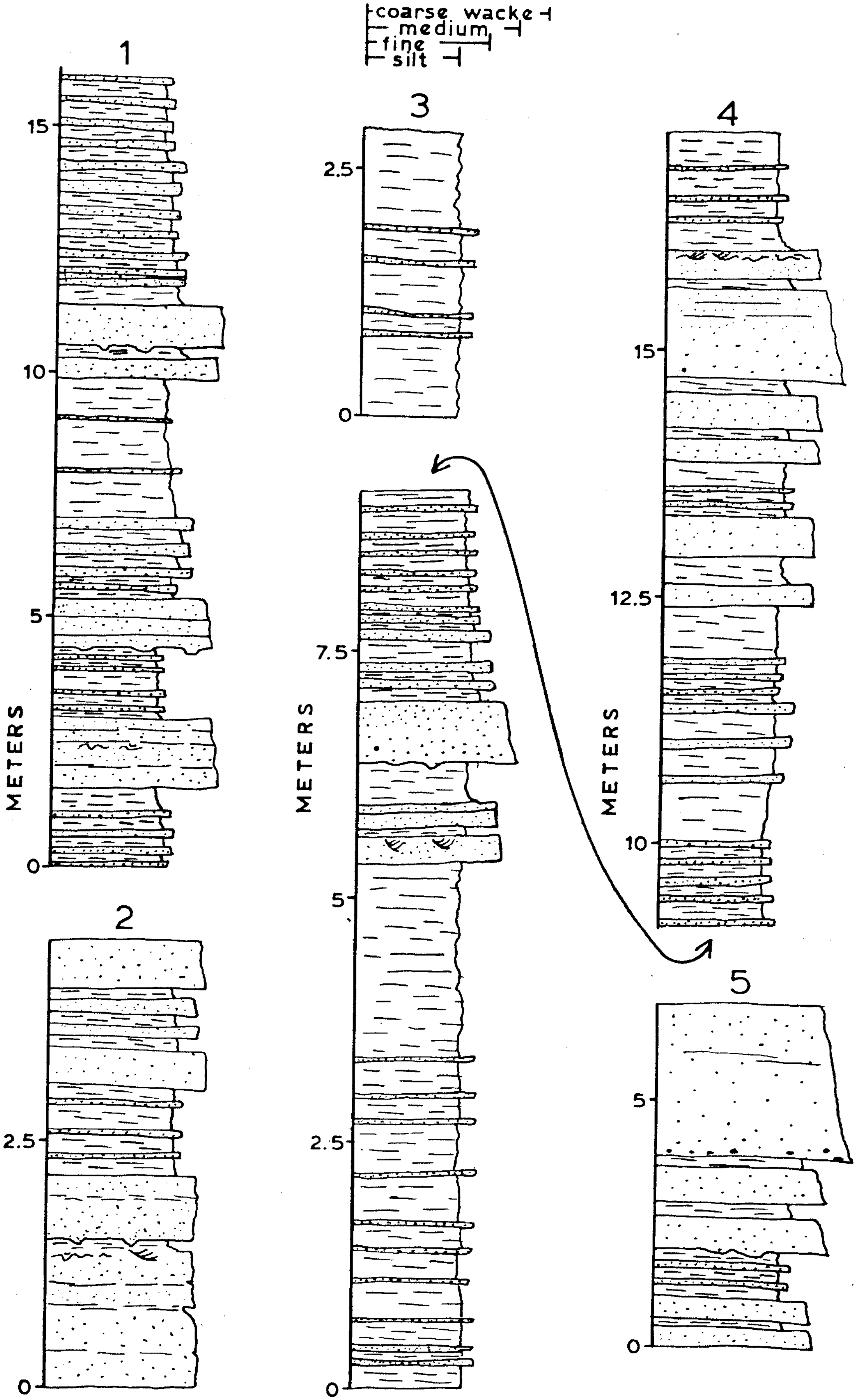
Lithologies and Distribution

Greywacke, Siltstone and Shale. The dominant lithologies within the field area are interbedded greywackes, siltstones and shales. Within an ill-defined belt near the eastern boundary of the field area, and at Normans Kill gorge (plate 1) coarse, massive, and thick-bedded greywackes dominate the exposures, locally forming up to 75 percent of the outcrop (figure 6). These greywackes with interbedded shales and siltstones form the Austin Glen member of the Normanskill Formation as defined by Ruedemann (1942). To the east and west are belts dominated by shale and siltstone which typically show pervasive deformation and blocks or clasts within a shaly matrix (section "Mélange and Olistostromes"). Further west are the mainly interbedded siltstones, shales and greywackes, mostly of Ruedemann's (1930) Schenectady beds. Locally, at Watervliet Reservior, Vly Creek and New Salem, thick greywacke beds dominate over the shale and siltstone beds (figure 6). These exposures are similar to those of the Austin Glen member, although generally finer-grained and better sorted.

The lithologies within these two areas are discussed together as the differences are slight, and locally they are indistinguishable (see also, Krueger, 1963). Important differences are brought out below and in the section on "Sedimentary Structures." Greywacke beds are locally as thick as three meters, although averaging about 20 to 30 centimeters or less. Typically, shaly interbeds are thinner; however, thick sequences of shale occur without greywacke interbeds (figure 6).

The greywackes are well indurated, grey and mostly medium to fine

Figure 6. Lithologic columns from localities within the field area. 1 - Watervliet Reservoir, west of Mill Road; 2 - Mount Pleasant Cemetary, State Route 85, New Scotland; 3 - southwest bank of Normans Kill two kilometers above State Route 146; 4 - southwest bank of Normans Kill one kilometer above State Route 146; 5 - Onesquethaw Creek, east of County Road 101, South Bethlehem. Columns 1 through 4 are from localities included within the "Schenectady beds" of Ruedemann (1930); column 5 is within his "Normanskill shale."



coarse wacke
medium
fine
silt
1
2
3
4
5
METERS
METERS
METERS
15
10
5
0
2.5
0
2.5
0
7.5
5
2.5
0
15
12.5
10
5
0

grained. Sorting is very poor with mostly angular to subangular quartz, feldspar and lithic clasts in a pelitic matrix which constitutes 10 to 30 percent of the rock. From east to west the greywackes become somewhat better sorted, finer-grained and contain fewer lithic fragments. In classification systems they fall mainly within the "lithic wackes" of Williams et al. (1954) or the "lithic greywackes" of Pettijohn (1954) and Pettijohn et al. (1972). However, the cleaner western rocks might better be termed "lithic arenites" in the sense of Williams et al. (1954) and Pettijohn et al. (1972), or "subgreywackes" in the sense of Pettijohn (1954). For the purposes of general discussion within this paper the term "greywacke" will include all of the above rock types.

Quartz is the most abundant mineralogical component and commonly occurs as clear, subrounded to angular grains. Most quartz grains show some underlose extinction, and many have subgrain boundaries or are polycrystalline with serrated interfaces. Deformation bands and ribbon textures found within some of these grains suggest deviation from highly deformed or even mylonitic rocks. Other detrital mineralogies include: orthoclase, plagioclase, biotite and muscovite. Carbonate occurs primarily as a calcite cement, with radial fibrous growths surrounding many of the lithic clasts. Secondary dolomite rhombs are also common. Minor detrital carbonate includes: calcite grains, limestone and dolostone fragments, and shell fragments of probable brachiopods and bryozoa. The only other fossils found are several graptolites from the Normans Killgorge and outcrops on Interstate 87 (figure 7).

Green, and less commonly black or red, chips of siliceous argillite are the most abundant lithic fragments. They are up to a centimeter across in unusually coarse specimens and, because of their platy shapes,

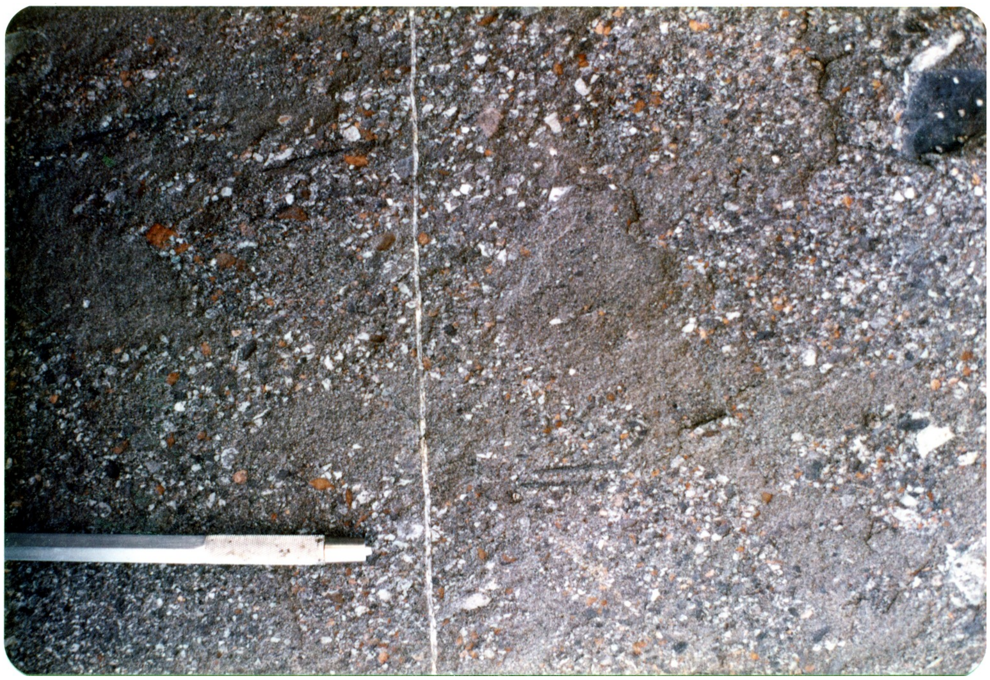


Figure 7. – Oriented graptolites and argillite chips on base of greywacke bed. Current flow was presumably parallel to the pencil. East side of Interstate 87, two miles north of New Baltimore Service Area, New Baltimore, N.Y.

appear larger than the average grain size of the greywacke (figure 7). Green and black chert fragments are less common, although all gradations from siliceous argillite to chert occur. Possible intraformational lithic fragments include fine-grained wacke, siltstone and shale clasts. Slate chips are also fairly common, with foliations in some defined by muscovite or chlorite. Other lithic clasts include: limestone, dolostone, shell fragments, opaques and pieces of dark, probably carbonaceous material.

Mélange and Olistostromes. Within the field area it is difficult to distinguish between tectonized coarse sedimentary, or olistostromic, deposits and units which have been formed through the disruption of well bedded sequences, i.e., "broken formation" of Hsü (1968). Due to the obscure origin of these deposits it is difficult to separate purely sedimentary features from tectonic features. In some cases, sedimentary and tectonic processes may have operated simultaneously to form these complex deposits (section "Mélange"). Approximately 30 percent of the areal extent of the field area contains rock types best described as mélange. The term mélange is used here according to the definition arrived at by the 1979 Penrose Conference on mélanges as "a general term describing a mappable (at 1:25,000 or smaller scale), internally fragmented and mixed rock body containing a variety of blocks, commonly in a pervasively deformed matrix" (Silver and Beutner, 1980). The use of the term "mélange" for rock units within this field area is based on the deformed nature of the shaly matrix which encloses clasts (large blocks occur locally) of various lithologies, and the complex and disrupted character of the structures seen within many outcrops (sections "Vly Creek" and "Eastern Domain"). This mélange is part of a belt of similar rock units which occurs along most of the western boundary of the Taconic Allochthon (Zen, 1967; Bird, 1969; Fisher et al., 1970), although much of the rock described here as mélange has not been previously recognized as such.

Although outcrop is not continuous enough to define the limits of the mélange precisely, it appears to occur in roughly north-northeast striking belts. A narrow, approximately 20-meter wide zone of mélange-type lithology occurs within the moderately deformed interbedded arenites and shales along the Vly Creek (section "Vly Creek"). To the east are two major belts of mélange (plate 1). The more western of these two belts is characterized by clasts of greywacke, siltstone and, more rarely, greenish siliceous argillite or chert, with an average size of about 10 centimeters or less across, although locally up to 30 meters across. These clasts lie within an argillaceous phacoidally cleaved matrix (section "Cleavage"). The eastern belt is similar in appearance; however, it also contains clasts of dolostone and limestone, and more abundant siliceous argillite and chert clasts. The structures associated with these mélange terranes and evidence for their tectonic disruption are presented in chapters V and VI.

The best example of a clearly sedimentary olistostromic deposit known within the Hudson River lowlands outcrops just east of the field area, on the east side of the Hudson River, south of Rensselaer on State Route 9J. Here cobbles and blocks of carbonate up to 1.5 meters across, and clasts of dolomitic sandstone, greywacke and shale float in a pebbly mudstone matrix (figures 8 and 9). Bird and Dewey (1975) correlated the lithologies found as clasts within this outcrop with the rocks of the Giddings Brook slice of the Taconic Allochthon and the

Figure 8. – Olistostrome on east side of State Route 9J, south of Rensselaer, N.Y. Note large boulder of carbonate.

Figure 9. – Close up showing pebbly mudstone matrix of olistostrome in Figure 8. Note carbonate clasts.

underlying carbonate shelf. On the east side of the Hudson, within the field area, outcrops near Cedar Hill and Mull Cemetery (section "Eastern Mélange") contain clasts of dolostone, chert, greywacke, argillite and some limestone within a phacoidally cleaved, argillaceous matrix. The absence of these "exotic" cobble-sized clasts of dolostone and limestone in the bedded or disrupted sequences to the west, and their presence in olistostromic deposits to the east suggests that at least the units containing these exotic lithologies were formed through the tectonization of coarse sedimentary deposits. Possibly then, at least some of the similar units which contain only greywacke and argillite clasts within a phacoidally cleaved matrix have also been formed in a similar manner, although structural evidence suggests this is not the dominant process (Chapters V and VI).

Chert and Siliceous Argillite. Green to black, usually white weathering, siliceous argillite gradational into chert occurs in bedded sequences in outcrops near Glenmont. One large block, approximately 10 by 30 meters, also occurs within phacoidally cleaved argillite on the Normans Kill west of Normansville (plate 1). Beds average about 4 to 8 centimenters thick, although some sections appear quite massive with obscure bedding planes. Nowhere within the field area can a sedimentary contact between the siliceous argillite and the greywacke and shale sequences be observed. The only locality where the contact is exposed is in a small creek just northwest of Glenmont; here bedded siliceous argillites appear to overlie highly disrupted greywacke and shale along a low angle structural contact (section "Glenmont"). Although no clear stratigraphic evidence can be found to suggest the relative ages of the units, the presence of abundant clasts of green siliceous argillite and chert within the greywacke (section "Greywacke, Siltstone and Shale") strongly suggests that the chert unit is older. This is in agreement with the known faunal data (figures 3, 4, and 5; Chapter III). The siliceous argillites and cherts of the Glenmont area are correlative, lithologically and faunally, with the Mount Merino Formation (or member) as defined by Ruedemann (1942) with its type locality at Mount Merino, New York, within the Hudson South 7.5 minute quadrangle.

Siliceous argillites and cherts of eastern New York, called "Lydian stone" by Amos Eaton and "siliceous slate, basanite, touchstone, hornstone and ptroxilex" by W. W. Mather (Ruedemann and Wilson, 1936), have been extensively studied for their abundant graptolite and radiolarian fauna (Ruedemann, 1930; Ruedemann and Wilson, 1936; Berry, 1962; Riva, 1974). Mount Merino cherts and black shales occur both within the "autochthonous" Normanskill Formation and within the allochthonous Taconic sequences, and are associated with stratigraphically younger greywackes and shales (e.g., Berry, 1962; Zen, 1964; Fisher, 1977). The Mount Merino siliceous argillites and cherts contain graptolites (the localities near Glenmont are classic collecting grounds; see Lang, 1969, for a review of fossil localities) which fall within the N. gracilis zone of Riva (1974; zone 12 of Berry, 1962). The Mount Merino Formation is underlain by the Indian River slates and Poultney slates and quartzites of probable slope affinity within the Taconic sequence (e.g., Berry, 1962; Rowley et al., 1979) and, to the west may be underlain by shelf facies limestone, although conclusive stratigraphic evidence has not been demonstrated (Berry, 1962; Zen, 1963; Ricard and Fisher, 1973). At the Mount Merino type locality, in a road cut on State Routes 9G and 23B, south of Hudson in the Hudson South 7½ minute quadrangle, Mount Merino cherts and argillites appear to overlie an over two-meter thick carbonate breccia, possibly of shelf or shelf edge affinity. Again, however, structural complexities permit other interpretations.

Sedimentary Structures

Sedimentary structures larger than those contained within single bedding units are not commonly observed within the field area, although the geometry of the structures within the Normanskill gorge exposures may be explained by a large slumping event (section "Normanskill Gorge"). Other large sedimentary structures, such as channels, are commonly larger than the average outcrop size and are therefore not easily detected. One example of a large channel fill structure occurs just south of the field area on Interstate 87, on the east side, two miles north of the New Baltimore service area (figure 10). Here an approximately eight-meter thick bed of massive wacke pinches out within about 100 meters, truncating thinner wacke beds on either side.

Small-scale sedimentary structures, such as cross-laminations, graded bedding, and sole marks, are abundant within greywacke beds and are often useful in determining younging directions. Cross-laminations are normally confined to two to twenty-centimeter thick horizons within the upper portions of greywacke beds, and are probably due to current-induced ripple migration (figure 11); Pettijohn et al., 1972). However, locally within some of the western outcrops entire arenite beds up to a meter thick are internally cross-laminated (figure 12). These occur as orderly, climbing ripples with approximately centimeter-thick laminations, and appear to be a type of ripple-drift cross-lamination. Ripple-drift laminations are believed to be the result of a high rate

Figure 10. – Channel fill structure in bedded greywacke, east side of Interstate 87, two miles north of New Baltimore Service Area, New Baltimore, N.Y. Hammer at lower right is approximately 40 centimeters long.

Figure 11. – Small-scale cross-laminations in greywacke bed, Normans Kill gorge, Albany, N.Y.

Figure 12. – Large-scale cross-laminations in lithic arenite bed, Vly Creek, New Scotland, N.Y. Pencil, at left, is 15 centimeters long.

of deposition in a low flow regeime (Pettijohn et al., 1972). Convolute laminations are sometimes associated with cross-laminations or may occur by themselves within the upper portions of greywacke beds. These are characterized by small disharmonic, polyclinal or convolute folds and are confined to single bedding units.

Graded bedding commonly occurs as a gradation from fine-grained arenaceous beds up into shaly horizons. In coarser-grained greywackes gradations from coarse to medium or fine-grained rock are typical.

Sole marks are the most abundant and most easily interpreted primary structures. These are found throughout the field area on the undersides of greywacke beds where underlying shale has been weathered away. Flute casts are the most common sole marks, although morphologically they grade into load casts. One example of a detached load cast or load ball, was found in the Vly Creek exposures (figure 13). Flute casts generally show a rounded, bulbous nose and flare out into bedding planes. They often occur in groups, all with similar orientations, and are sometimes associated with less abundant groove casts (figure 14). Groove casts are generally linear and are up to three meters long. Sole marks are the result of rock grains and debris being swept along the bottom by currents, and modification of irregularities by current flow (Pettijohn et al., 1972).

All of these small-scale sedimentary structures are found in an orderly sequence within greywacke bedding units, although the sequence is not generally complete in any one bed. Flute and groove casts are found only at the base of massive greywacke beds, in sharp contact with underlying shales. Shale rip-up clasts sometimes occur near the base of coarse beds. Above, the beds grade into finer-grained greywacke.

Figure 13. – Load ball of lithic arenite in shale, Vly Creek, New Scotland, N.Y.

Figure 14. – Flute and groove casts on base of greywacke bed, west side of State Route 9W, south of Hannacroix, New Baltimore, N.Y.

In some cases this is succeeded by parallel laminations, or the massive unit may be lacking entirely. Occasionally, the massive bedding unit may be repeated; this amalgamation may occur due to partial erosion of beds prior to the deposition of the next bed (Mutti and Lucchi, 1978). In the uppermost portions of the greywacke beds cross-laminations and convolute laminations are common. Finally, the wacke grades into parallel laminated siltstones and shale. This sequence of sedimentary structures, often called the "Bouma sequence," has been described from many similar greywacke-shale sequences and is usually attributed to turbidity current deposition with an initial high influx of coarse sediment followed by finer sediments deposited in lower flow regiemes (Bouma, 1959; Stanley, 1963; Kuenen, 1967; Mutti and Lucchi, 1978).

One final type of primary(?) structure observed within the field area is polygonal cracks. In the western portion of the field area they have only been observed in float in the vicinity of Watervliet Reservoir, although Ruedemann (1930) reported them from rocks within his Schenectady beds. However, one outcrop on the east side of Interstate 87, approximately one mile south of the New Baltimore service area, contains several good examples (figure 15). The cracks narrow downward and form polygonal patterns within the upper portion of a fine-grained greywacke to siltstone bed. The cracks have been infilled with a fine mud or shale, which appears irregular and somewhat deformed. The significance and origin of these cracks is discussed in the section "Depositional Environment and Provenance."

Depositional Environment and Provenance

The interbedded greywackes and shales found within the study area are extremely immature sediments. The high percentage of labile

Figure 15. – Close-up of polygonal cracks in top of fine-grained greywacke bed. Disturbed shale infills the cracks. East side of Interstate 87, approximately one mile south of the New Baltimore service area, New Baltimore, N.Y.

lithic fragments, poor sorting, high angularity of clasts, and high percentage of matrix suggest that a nearby high relief source was rapidly shedding these sediments into a basin or trough. Sedimentary structures within the area, in particular the rythmic interbedding of greywackes and shales, the abundant sole marks and the sequential ordering of structures within individual beds ("Bouma sequence"), strongly argue for deposition by deep-water turbidity currents (Bouma, 1962; Kuenen, 1967; Mutti and Lucchi, 1978; see also Bird, 1963; Krueger, 1963; Middleton, 1965). This is in accord with other studies of correlative medial Ordovician flysch units in Newfoundland (Stevens, 1970), Quebec (Enos, 1969, Belt et al., 1979), New York, New Jersey, Pennsylvania and Virginia (McBride, 1962), and Tennessee (Shanmugam and Walker, 1978).

One problem with the interpretation of these deposits as a deep-water turbidite sequence is the presence of mud cracks. Mud cracks are commonly formed by water loss and shinkage during subaerial exposure, and are often cited as conclusive evidence for subaerial exposure. Ruedemann (1930) noted the presence of "shrinkage cracks" within thin sandstone beds of his Schenectady beds, and concluded that these were shallow-water deposits. Richard and Fisher (1973) followed this interpretation citing cross-bedding within the Schenectady Formation as evidence for shallow-water deposition; although more recently Fisher (1977) has called them distal shelf to proximal slope deposits. As the evidence for turbidity current deposition is strong, an alternate explanation is required for the presence of these cracks. A number of authors (e.g., Burst, 1965; Donovan and Foster, 1972) have shown that shrinkage cracks may occur in clay-rich muds due to a subaqueous synersis mechanism, possibly triggered by a change in water salinity or ion concentrations. This offers a possible explanation for the presence of shrinkage cracks within deep-water deposits. Alternatively, these beds may have been subjected to axially symmetric flattening, possibly during a rapid compaction event, and deformed brittly forming polygonal cracks infilled with shale. This explanation is preferred as the cracks occur within a sandy layer, and are infilled with disturbed shales.

Mutti and Lucchi (1978), from extensive work with the turbidite sequences of the Northern Apennines, have categorized a number of turbidite facies by lithology and sedimentary structures. These facies occur in associations which commonly occur in local depositional environments of turbidite fan complexes. Although a detailed facies analysis was not attempted within the present study, it is possible to broadly correlate the facies types within the present study area with those categorized by Mutti and Lucchi, and to infer their general depositional environment. Eastern outcrops include most of Mutti and Lucchi's (1978) facies types including: coarse sandstones with channeling, conglomeratic units and chaotic deposits (section "Normanskill Gorge") as well as the more common interbedded sandstones and shales and interbedded shales and siltstones. This facies association suggests fairly proximal deposition within an inner or middle submarine fan environment. Outcrops within the western portion of the field area mainly comprise interbedded sandstone and shale, or interbedded shales and siltstones. Parallel laminations and ripple-drift laminations are more common here, and massive coarse-grained wacke beds are less common. This facies association is common within outer fan or basin-plain environments, and suggests that the western outcrops represent a more distal fan environment than eastern outcrops.

This east to west change in facies associations suggests an eastern source for these sediments. This is supported by the large-scale westwards fining of the deposits, the relative westwards increase in maturity of the sediments, and the westwards younging of the shelf-flysch contact. Although detailed petrographic provenance studies of these rocks have not been made, it is clear from the eastwards source, high pelitic clastic component of the greywackes, and the regional geology of the area (e.g., Zen, 1967; Bird and Dewey, 1970; Rowley and Kidd, 1981) that these sediments have been shed off the rising Taconic orogen; an allochthonous argillaceous sequence emplaced during the medial Ordovician. Carbonate, common as clasts and cement within the greywackes, occurs both within the Taconic stratigraphic sequence and as slivers of probable shelf carbonate incorporated along major thrust faults within the Allochthon (Zen, 1967). The presence of slate clasts, muscovite, biotite and strained quartz fragments (section "Greywacke, Siltstone and Shale"), suggests that the source area was well lithified, highly strained and metamorphosed to at least greenschist facies (see also, Middleton, 1965; Rowley and Kidd, 1981).

The orientations of 31 linear sole marks, including flute and groove casts, and one example of oriented graptolites (figure 7), show a paleocurrent direction of approximately north-south (figure 16). Unidirectional flute casts, which indicate a vectoral current direction, were measured in ten cases and indicate that current was not unidirectional, but included both north and south transport. (However, see Krueger, 1963, and Middleton, 1965, who suggest current flow was dominantly to the northeast.) These were measured from the undersides of greywacke beds throughout the field area (figure 17), and from outcrops along Interstate

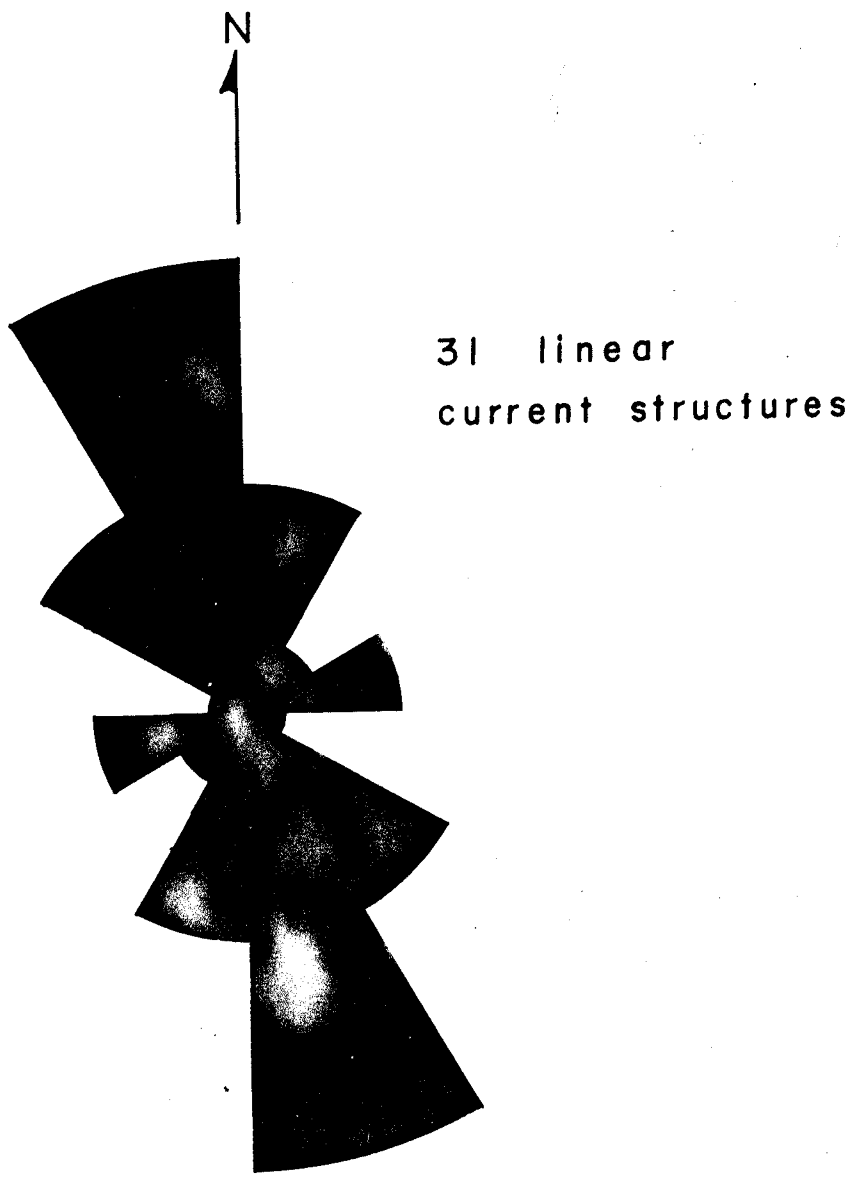
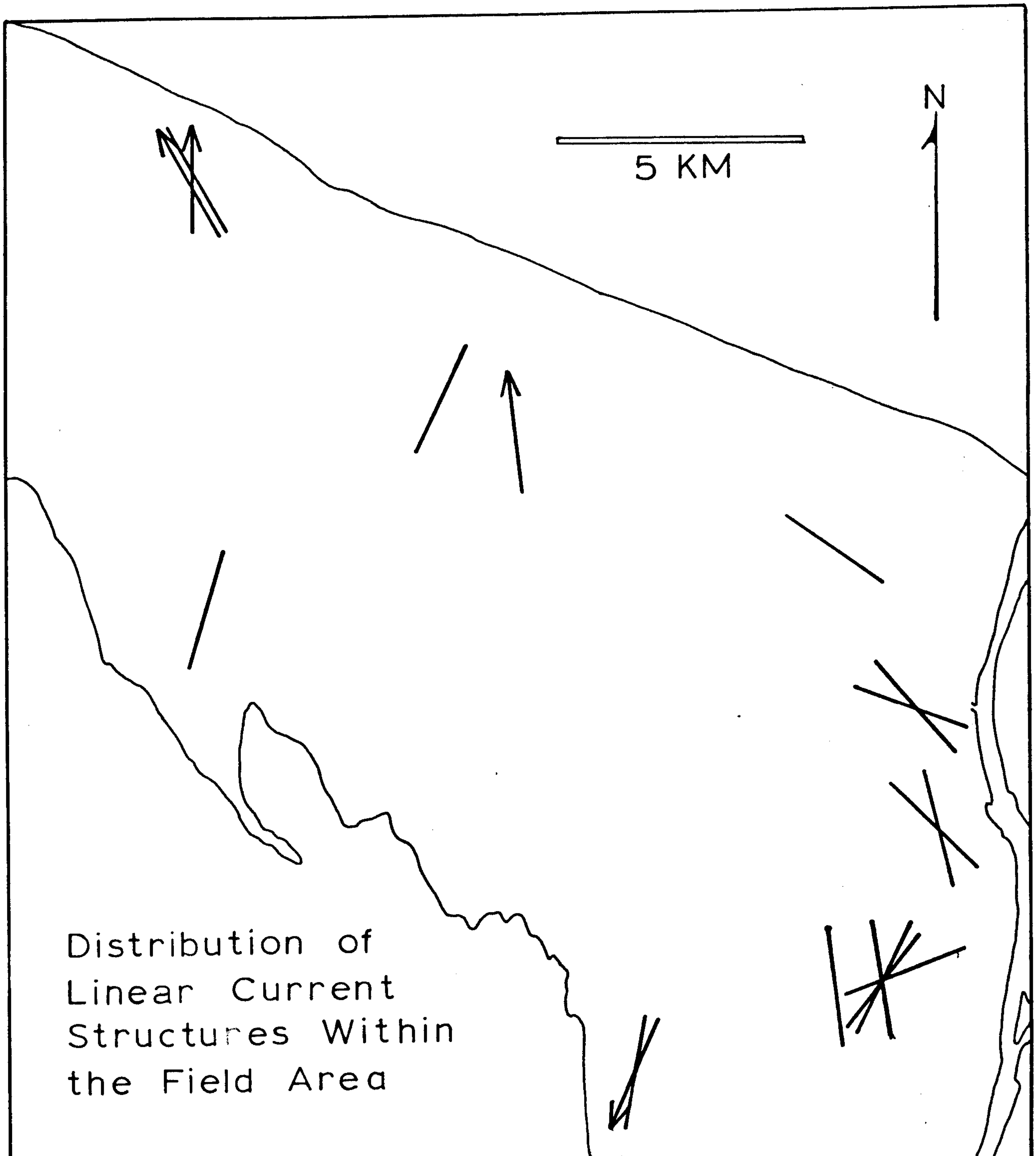


Figure 16. Rose diagram of 31 reoriented (see text) linear current direction features, including 13 measured from outcrops south of the main field area, within the Ravena 7.5 minute quadrangle.

Figure 17. Distribution of linear current structures within the field area. Lines are parallel to reoriented (see text) flute or groove casts. An arrowhead indicates direction of flow as determined from flute casts.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Distribution of
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the Field Area

87 within the Ravena 7.5 minute quadrangle. Measurements from Normans Kill gorge were not incorporated into this plot because of the structural complications in that area (section "Normans Kill Gorge"). A plot of 11 flute and groove cast orientations from Normanskill gorge shows a complete range of orientations with no discernible maximum. (Middleton, 1965, shows two flute measurements from this outcrop giving northerly current directions.)

In most cases flute and groove cast orientations were rotated to the horizontal about the strike of the containing bedding plane. Sole marks on bedding planes dipping less than 25^{o} were not reoriented because of the negligible resulting error (Ramsay, 1961). Where hinge line orientations were known, the casts were rotated to bring the fold hinge line to horizontal, and then rotated to horizontal about the resulting bedding strike line. As the neglect of fold hinge line dips in the reorientation of current directional structures on steeply-dipping beds may result in significant error (Ramsay, 1961), an initial plot was made using only data collected from beds dipping less than 60^{o}, unless the hinge line was known. Addition of data from steeply-dipping beds, although weakening the maximum, did not alter the orientation of the maximum. This may be because the flute casts are generally found in thick greywacke beds, which in most cases show fold orientations with low hinge line plunges (section "Vloman Kill Gorge"). Although the sample is small for statistical confidence, the strong maximum suggests that the inferred paleocurrent direction is a good estimate.

This north-south orientation of current direction structures suggests that the dominant sediment transport was longitudinal, although the principle sediment source lay to the east. It is likely then that submarine canyons fed sediment from the east which, upon reaching submarine fans, spread longitudinally to fill a linear trough. Transport may also have been affected by structural features, such as fault blocks, which would tend to impede east to west transport of sediment. This type of longitudinal transport with a lateral source is apparently common within many similar flysch-type sedimentary troughs (e.g., Kuenen, 1958; Pettijohn et al., 1972; Reading, 1978). McBride (1962) in his extensive study of the correlative Martinsburg Formation from Virginia to southern New York found similar results, with paleocurrents paralleling the present structural trends and with an easterly or southeasterly source.

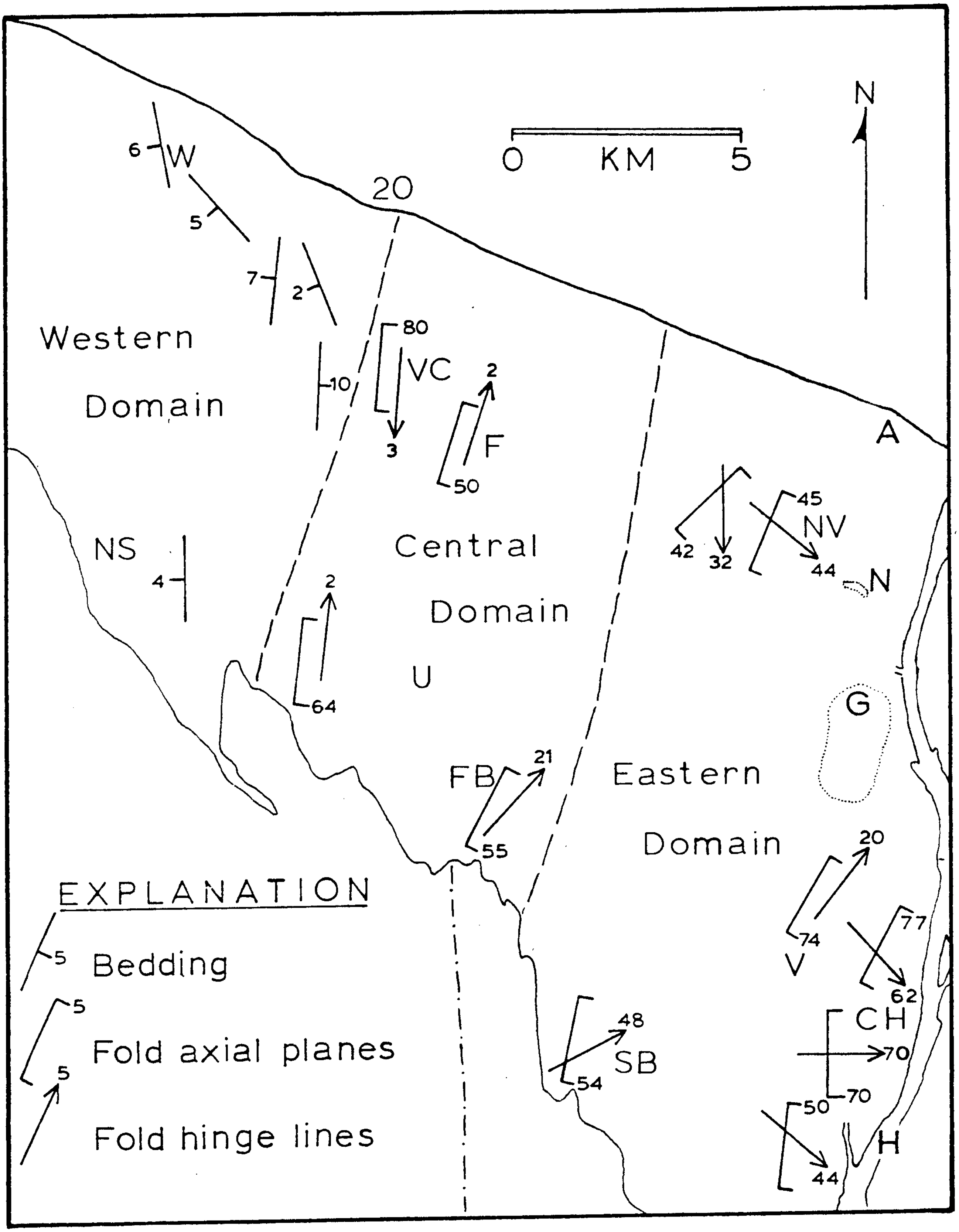
CHAPTER V

STRUCTURAL GEOLOGY

The structural geology of this area was studied mainly at the mesoscopic, or outcrop, scale. Large-scale, macroscopic structures have not generally been recognized within the field area (although, see section "Font Grove Road"), mainly because of the lack of outcrop continuity and lack of stratigraphic marker horizons. However, the progressive surfacing of older rock units to the east suggests the dominance of asymmetric folding and thrusting with an east over west vergence (plate 1).

The field area has been subdivided into three structural domains: the western domain, the central domain, and the eastern domain (figure 18). The boundaries between these areas correspond roughly (although, see section "Route 102") to Ruedemann's (1930) "western boundary of intense Taconic folding" and his "western boundary of distinct Taconic folding." These areas are discussed below in order of increasing structural complexity; from west to east. Within each structural domain individual outcrops or clusters of outcrops are discussed as structural subdomains. Three such outcrops had sufficient areal continuity and structural complexity to warrant small-scale mapppng on oversize plates. These are included as plates 2, 3 and 4 in the map pocket. Other maps (figures 25, 29, 39, 41) and sections (figures 23, 26, 27, 40) are included as figures within the text. Plate 1 is a summary map of the main structural data with interpreted boundaries of major macroscopic structures. Stereographs summarizing the structural orientation data are presented in Appendix A (figures A1-A7).

Figure 18. Main structural domains of the field area. The western domain is characterized by gently-dipping strata. The central domain is characterized by folded strata. The eastern domain is characterized by folded and disrupted strata. Symbols represent mean fold and bedding orientations for single outcrops or clusters of outcrops. A = Albany, CH = Cedar Hill, F = Font Grove Road, FB = Feura Bush, G = Glenmont, H = Hudson River, N = Normanskill Gorge, NS = New Scotland, NV = Normansville, U = Unionville, V = Vloman Hill Gorge, VC = Vly Creek, W = Watervliet Reservoir, 20 = State Route 20. Dot-dash line represents the western limit of distinct folding in the Helderberg limestones, after Ruedemann (1930).



N
0 KM 5
20
W
6
5
7
2
10
80
VC
3
2
F
50
Western Domain
NS
4
Central Domain
2
64
U
A
45
NV
42
32
44
N
G
FB
21
55
Eastern Domain
20
74
V
77
62
CH
48
SB
54
70
70
50
44
H
EXPLANATION
5 Bedding
5
5 Fold axial planes
Fold hinge lines

Western Domain

Rocks exposed within the western domain are the least deformed. The maximum dip of bedding within this area is 20°W, and the average is approximately 04°W (figures 18, A1); no outcrop scale folds have been observed. The unconformity between the Helderberg limestones and the Ordovician flysch, west of mesoscopic Acadian folds (Ruedemann, 1930), decreases in elevation from approximately 800 feet above sea level at the western edge of the field area to approximately 400 feet south of Feura Bush. This is due to an average dip of 1.2° to 190° of the unconformity between Altamont and New Salem (Darton, 1894). Thus, the westerly dips within the Ordovician rocks must reflect pre-Devonian altitudes. Similar gentle dips, up to approximately 30°, can be seen along the New York State Thruway as far west as Little Falls, New York.

The only small-scale structural feature observed within the western area is an approximately one-centimeter thick, nearly bedding-parallel, shear zone. The shear zone is in an outcrop on the Normans Kill, upstream from the bridge on State Route 146, within a sequence of mostly thin, 1-3 centimeter thick, fine-grained silty arenites, dark siltstones and grey shales (figures 19, 20). The bedding here strikes approximately 125° and dips 05°SW. The shear zone can be traced for approximately 46 meters and makes an apparent angle of 0.2° with the bedding; it is approximately 15 centimeters lower with respect to a reference bed to the southeast than 46 meters to the northwest. Calcite occurs along most of either edge of the shear and locally within the central portion. Slickensides measured on the calcite surfaces trend towards 130°. Within most of the shear zone is a buff-colored, soft clay-like shale which shows a fine parting. This parting strikes approximately 000-

Figure 19. – Near-horizontal, centimeter thick shear zone in bedded silty arenites and shales, southwest bank of Normans Kill, approximately 1.5 kilometers above State Route 146, Guilderland, N.Y. Pencil on left is parallel to the trace of the shear zone.

Figure 20. – Close-up of narrow shear in figure 19. Bedding strikes approximately 125º and dips 05ºSW. Shaly parting within shear zone strikes 000-040º and dips 30-40º E-SE.

040^{o} and dips $30-40^{o}$ E-SE.

The striations and parting within the shear zone suggest a relative southeast to northwest overthrusting which cuts gently up section. This may be prior to the gentle folding event which gave rise to the gentle southwesterly bedding dips. No offset horizons or lineations can be found to determine the total displacement across the fault. If the shaly parting has remained as a passive marker within this shear zone, the total displacement cannot be large, as it is at a high angle to the shear plane and would have been rotated subparallel to the shear plane if a large displacement occurred (Ramsay and Graham, 1970). However, the shaly parting does not occur outside of the shear zone, and is therefore likely to be associated with the shearing process. If the parting has remained as a remnant of the last increment of strain, or if the strain rate was so slow as to allow the parting to retain its orientation with respect to incremental strains, then the total displacement may be large.

Central Domain

This domain is characterized by moderate to tight folds with near-horizontal, north-south trending hinge lines and variable, although dominantly steeply east-dipping, axial planes (figures 18, A2). Faulting is mostly limited to narrow, moderately-dipping and north to northeast-striking thrust faults, commonly associated with bedding flexures or kink folds. One notable exception occurs within the Vly Creek exposures (section "Vly Creek") where a highly disrupted and apparently sheared zone cuts a bedded arenite and shale sequence. In general, outcrops within the central domain show at least moderately-dipping beds and are undisrupted, with bedding planes and folds traceable within the limits of the outcrop.

Vly Creek

The best exposures within the central domain are those which crop out along the Vly Creek, downstream from Voorheesville, just below County Road 306 (Krum Kill Road). Here, the Vly Creek reaches a nick point with a 25 meter high waterfall capped by a meter thick arenite bed; below, good outcrops continue intermittently for about a kilometer. The lithology here is mostly fine-grained lithic arenites averaging about 5-10 centimeters thick, but locally medium-grained and up to a meter thick, interbedded with equal or greater amounts of dark grey, buff-weathering siltstone and shale. Some arenite beds are slightly calcareous and occasionally reddish weathering or weakly pyritiferous

Beds mostly dip approximately 15°W, striking 000-020°. Localized folds and flexures occur giving a complete range in bedding dips, although little variation in strikes (plate 2). Most of the folds occur as small, widely spaced kinks or flexures associated with narrow, small offset thrusts (figures 21, 22, 23). The largest fold has a half wavelength of about 27 meters, and occurs as a highly asymmetric flexure. This flexure may have been initiated on a local channeling feature, as the thick beds of the eastern syncline do not reappear on the western limb of the adjoining anticline (plate 2).

Towards the western limit of the outcrop is a structurally complex zone which can be traced along strike through several exposures. In the southernmost of these exposures (section B-B´, plate 2) beds steepen abruptly approaching this apparently sheared zone. On the east side, beds dip steeply to the east. This zone may reflect disruption or shearing initiated within the core of an assymetric fold, similar to the one in section A-A´. To the north, in section C-C´, is a similar

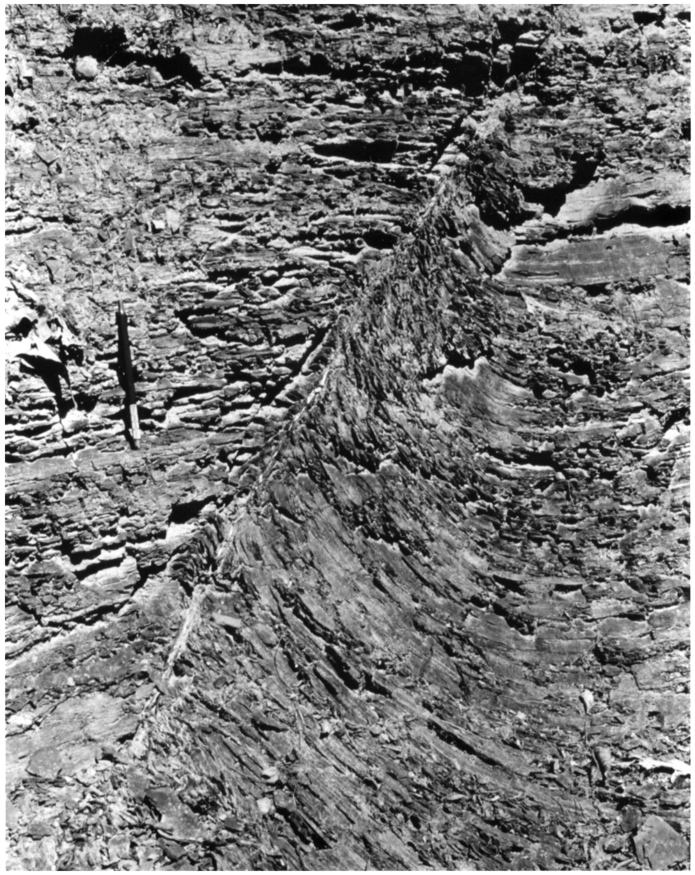


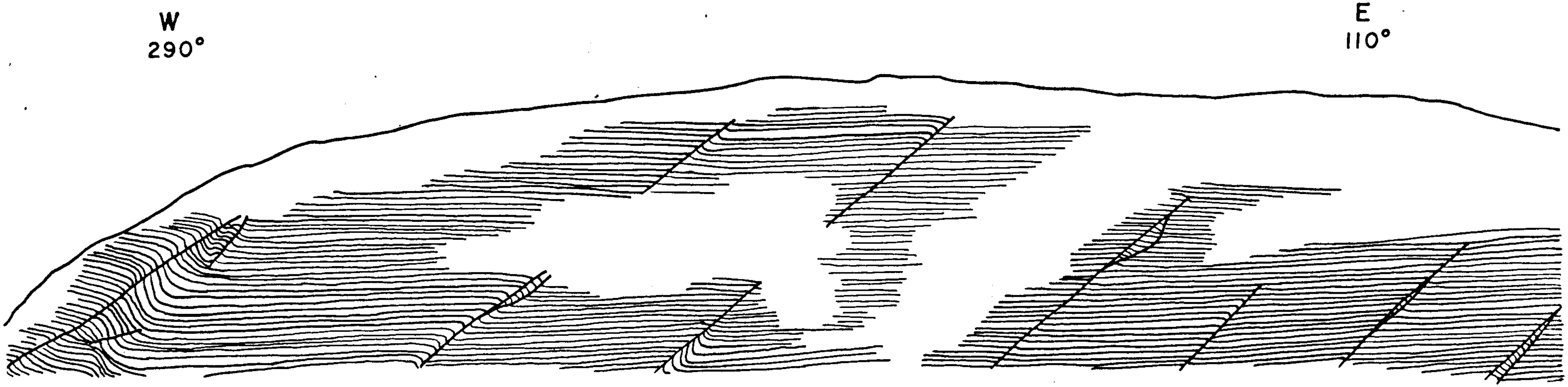
Figure 21. – Narrow fault with associated bedding flexure. Fault strike is 031º; dip is 60ºW. Vly Creek below Crum Kill Road, New Scotland, N.Y.

Figure 22. – Kink fold in lithic arenite and shale. Fold axial plane strikes approximately 170º and dips 40ºE, hinge line plunges 03ºN. Arenite bed is approximately 8 centimeters thick.

Figure 23. Stream section from north bank of Vly Creek, New Scotland, N.Y. Photograph in figure 21 is from lower portion of fault in center. Bedding flexures and rotation suggest overthrust solutions for these fault planes.

SECTION OF BEDDED SILTSTONE AND SHALE FROM VLY CREEK, EAST OF VOORHEESVILLE, N. Y.

NE/4 SE/4 Voorheesville 7.5' Quad., N 42° 39' 46" W 73° 53' 47"



SCALE 1 : 240

0 — 10 meters

0 — 40 feet

F. W. Vollmer, 1979

Bedding strikes approx. 065° and dips approx. 12° NW.
Fault planes strike 011° to 050° and dip 39° to 80° NW.

relationship. Here a fault occurs as a shaly, clay-rich zone. Small folds, apparently associated with the faulting, occur with hinge lines plunging up to 14^{o}. Finally, in section D-D´, a fairly wide zone contains discontinuous blocks of greywacke up to four meters long within a highly disrupted phacoidally cleaved shale (figure 24). The cleavage within the shale strikes $350-010^{o}$, and dips variably to the east. It is defined by aligned chips or phacoids of dark shale and siltstone surrounded by anastomozing pelitic films. Down-dip striations can be found on individual siltstone phacoids. Several thick beds of wacke are truncated at the boundary of this zone, and show anomalous northwest strikes. One small fold, approximately 20 centimeters across, occurs near the western edge of the zone. Its axial plane strikes 025^{o} and dips 30^{o}E, and its hinge line plunges 28^{o} to 140^{o} (plate 2). This hinge line orientation is steeper and more easterly-trending than any other found within the central domain (figure A2). To the north and northeast outcrops of dark shale and siltstone dip steeply east, showing no indication of cleavage.

This localized zone of lithic arenite blocks within a phacoidally cleaved shaly matrix is the westernmost known occurrence of the fabric which is common within eastern outcrops of mélange. In the east, this mélange fabric is associated with steeply east-plunging folds (section "Eastern Domain"). It is believed that the structure within this zone has been caused by large, localized shear strains. This is suggested by the common down-dip striations on individual phacoids, along strike association with faulting, association with anomalously plunging folds, and the easterly dip (towards the Taconic Allochthon) of the phacoidal cleavage. Overthrusting is inferred because of the dominance of compressional and overthrusting type structures within the surrounding area.

Figure 24. – Block of lithic arenite enclosed within phacoidally cleaved shales. This zone is approximately 20 meters wide, and occurs within otherwise undisrupted strata. Cleavage dips steeply to the east, and forms phacoids of shale and siltstone with down-dip striations. Vly Creek, New Scotland, N.Y. Viewed towards east.

The orientations of surrounding beds suggest that this thrusting may have been initiated within the core of an asymmetric fold.

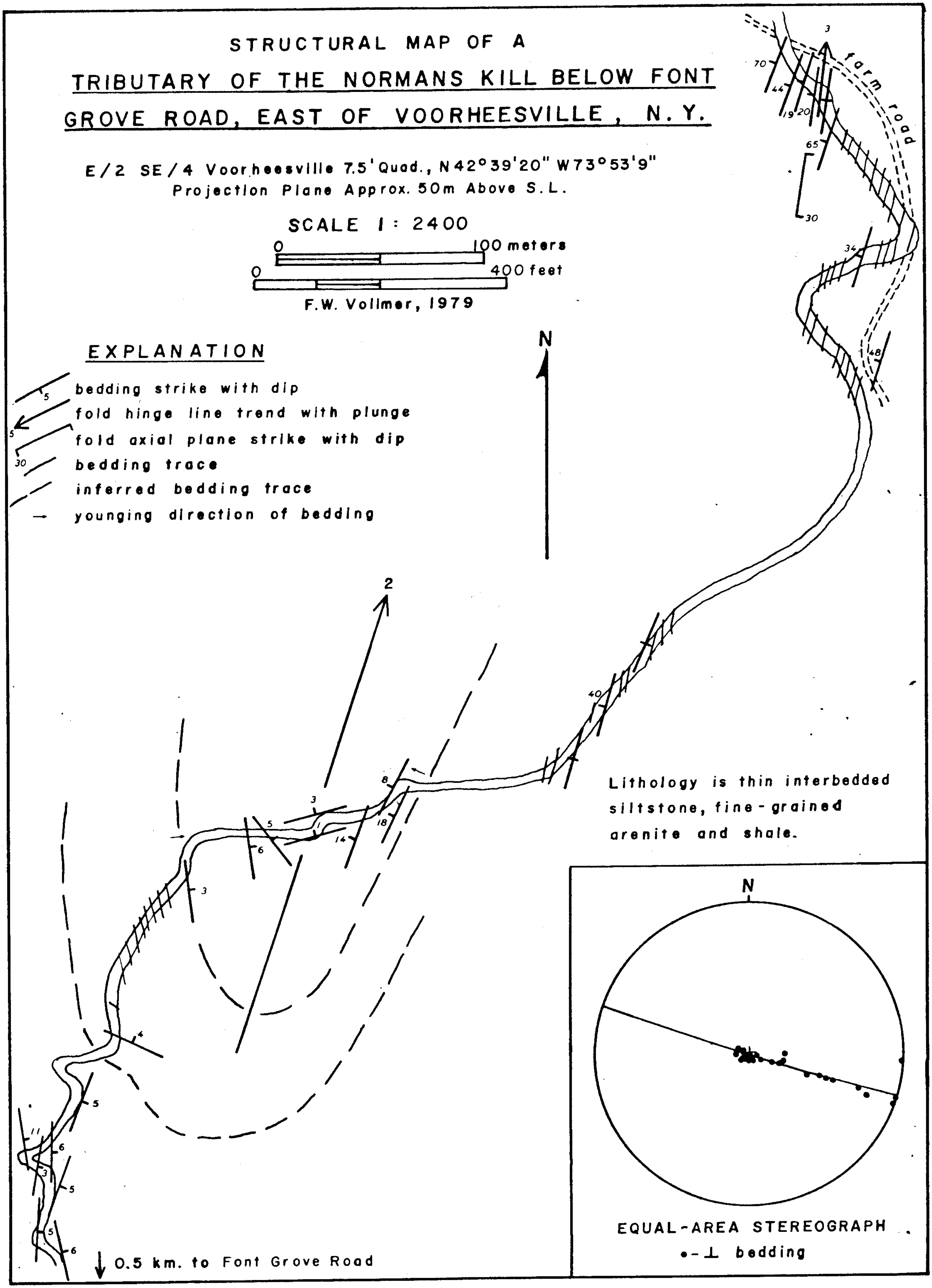
The arenite blocks appear to be disrupted beds formed in a localized shear zone. An origin through boudinage is consistent with the nature of the surrounding rocks. Lithic arenites interbedded with shales would be likely to show the high ductility contrasts required for boudinage. The precise origin of the phacoidal cleavage is not known, but it is probably associated with shearing (section "Cleavage"). Near the western edge of the shear zone there is a steeply east-dipping planar cleavage which makes a 55° angle with the west-dipping bedding fissility. This suggests that the phacoidal cleavage may form through the modification of earlier cleavage surfaces.

Font Grove Road

The next small tributary of the Normans Kill to the southeast of Vly Creek also affords some good outcrop. Below the crossing of County Road 306 (Font Grove Road) the stream enters a wooded area after crossing pasture-land. Outcrops occur intermittently downstream from here for somewhat less than a kilometer (figure 25). The rocks here are mainly grey to black siltstone with beds up to a centimeter thick, and lesser dark shales, interbedded with 1-5 centimeter thick beds of fine-grained and thinly laminated arenites, weathering to a red-brown. One medium-grained, 8 centimeter thick lithic arenite bed occurs with measurable flute casts (figure 17).

Bedding dips in the southwest are mostly about 04°E. Farther north-east bedding strikes swing to the southeast and then northwest with gentle westerly dips. Downstream to the northeast, several outcrops show steep westerly to vertical dips. This zone of steeply-dipping beds can be traced for approximately 340 meters along strike. One small open

Figure 25. Form line map of Font Grove Road outcrops, on a tributary of the Normans Kill, New Scotland, N.Y. The strata here are folded into a large, open syncline with a steep eastern limb and a near-horizontal hinge line.


STRUCTURAL MAP OF A
TRIBUTARY OF THE NORMANS KILL BELOW FONT GROVE ROAD, EAST OF VOORHEESVILLE, N.Y.
E/2 SE/4 Voorheesville 7.5' Quad., N42°39'20" W73°53'9"
Projection Plane Approx. 50m Above S.L.
SCALE 1 : 2400
0
100 meters
0
400 feet
F.W. Vollmer, 1979
EXPLANATION
bedding strike with dip
fold hinge line trend with plunge
fold axial plane strike with dip
bedding trace
inferred bedding trace
younging direction of bedding
N
farm road
Lithology is thin interbedded siltstone, fine-grained arenite and shale.
0.5 km. to Font Grove Road
N
EQUAL-AREA STEREOGRAPH
•-⊥ bedding

syncline has an axial plane dipping 30°E, with a vertical eastern limb (figure 25). These data suggest a large synclinal fold with a moderate or steep eastern limb, and with parasitic folds developed on the limbs. A πS diagram (Turner and Weiss, 1963) gives a hinge line plunge of 02° to 018° and a bisecting plane striking 005° and dipping 50°E. Several narrow faults with apparently negligible offsets occur throughout the outcrop. These strike generally north-northeast or northeast and dip moderately east (figure A2).

Unionville

Northwest of Unionville outcrops occur on a small tributary of the Vloman Kill, which feeds a small dammed lake within the Five Rivers Environmental Education Center. These outcrops consist of grey shales, siltstones and interbedded, mostly fine-grained, laminated silty-arenites forming beds less than five centimeters thick. A few local beds of parallel-laminated arenite, showing sole marks, convolute laminations and cross-laminations, are up to 25 centimeters thick. Reddish, concentrically zoned concretionary nodules are locally common in the siltstones and are up to 15 centimeters across. The easternmost outcrop shows consistent dips of about 25°SE and the westernmost (approximately a kilometer to the west) shows dips of about 12°E (plate 1).

Farther west, a small, well-jointed outcrop on Orchard Hill Road of similar lithology shows the hinge area of a large syncline. A plot of poles to bedding gives a fold hinge line plunging approximately 02° to 006°, with a bisecting surface of 005°-65 E (figure 26).

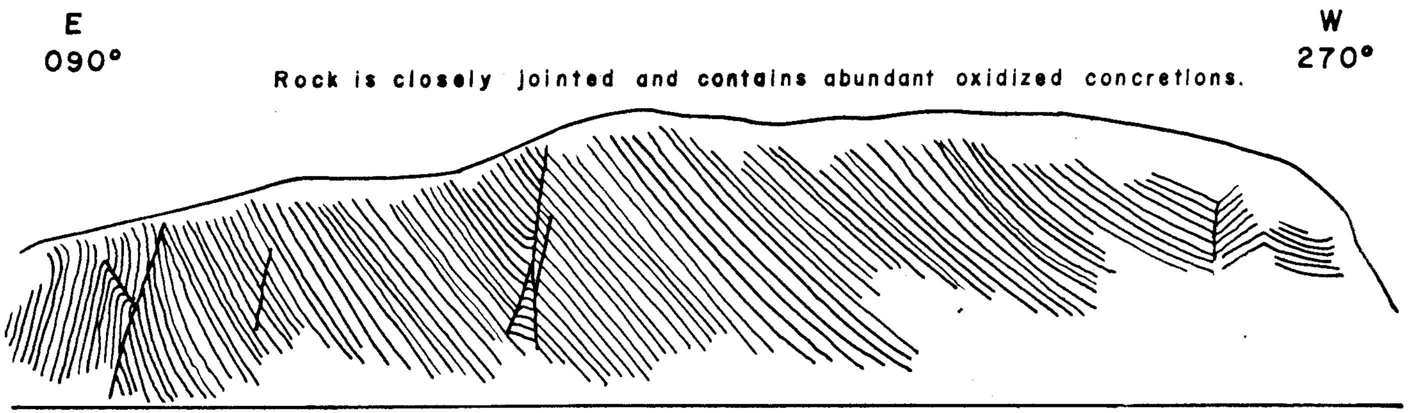
Feura Bush

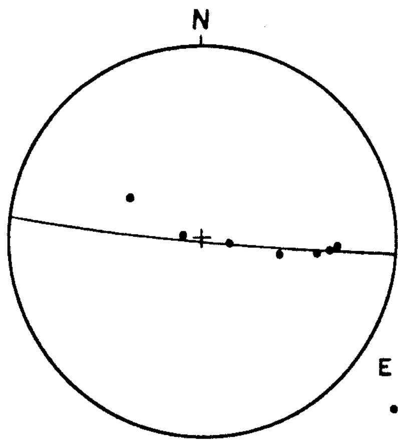
South of Feura Bush at the junction of County Road 102 and Collabeck Road is a low outcrop of grey and black siltstone and fine-grained arenite, with micaceous wacke beds up to five centimeters

Figure 26. Sketch of outcrop on Orchard Hill Road (old road metal quarry), New Scotland, N.Y. The strata here are folded into a large syncline with a steep to overturned eastern limb.

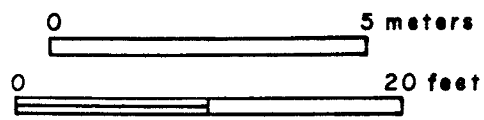
SECTION OF INTERBEDDED FINE-GRAINED ARENITES, SILTSTONES AND SHALES ON ORCHARD HILL ROAD, WEST OF UNIONVILLE, N.Y.

NW/4 NE/4 Clarksville 7.5' Quad., N42° 36' 25" W73° 55' 11"





SCALE 1 : 120



F. W. Vollmer, 1979

EQUAL-AREA STEREOGRAPH

•-⊥ bedding.

thick, but averaging less than a centimeter thick, interbedded with fissile grey, rusty-weathering shale. Two folds with northeast-plunging hinge lines (15° to 041° and 26° to 044°) and moderately southeast-dipping axial planes (striking 205°, dipping 46°SE and striking 210°, dipping 65°SE, respectively) isoclinally fold the moderately southeast-dipping beds. One narrow shear zone occurs striking 210°, dipping 25°SE with faint lineations plunging 27° to 128° (figure 27).

Eastern Domain

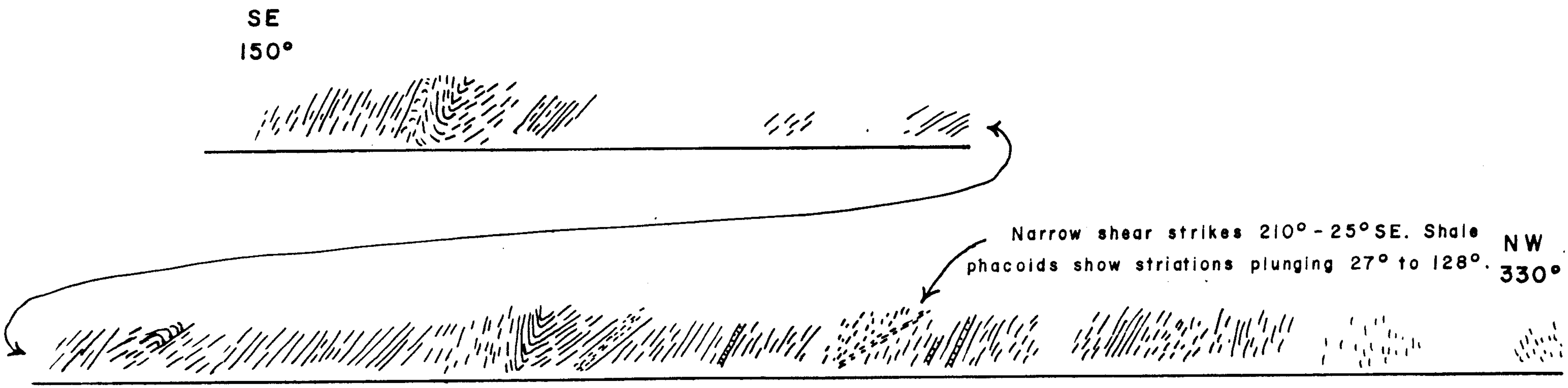
The eastern domain (figure 18) shows a wide diversity of structural styles and deformation intensities. Probably the most characteristic structural style is that shown by the relatively small shaly outcrops. These outcrops generally show an irregular, phacoidal cleavage within disrupted siltstones and shales enclosing blocks of greywacke and other lithologies, and may be best described as mélange. Blocks, lenses and discontinuous beds and folds of greywacke and siltstone are common. Most bedded sequences occur as blocks enclosed within the disrupted shale. In eastern outcrops of mélange, chert, siliceous argillite, dolostone and limestone clasts are common as well as greywacke. This lithologic distinction is a useful mapping criteria and two informal mélange units are recognized: the western mélange, which contains blocks of greywacke and chert; and the eastern mélange, which additionally contains blocks of carbonate (plate 1). Characteristic exposures of these two mélange units are at Normansville and Cedar Hill, respectively. Discontinuous fold hooks found within the shaly matrix of the mélange show consistently east to southeast-dipping axial planes and hinge lines which are commonly steeply east to southeast plunging.

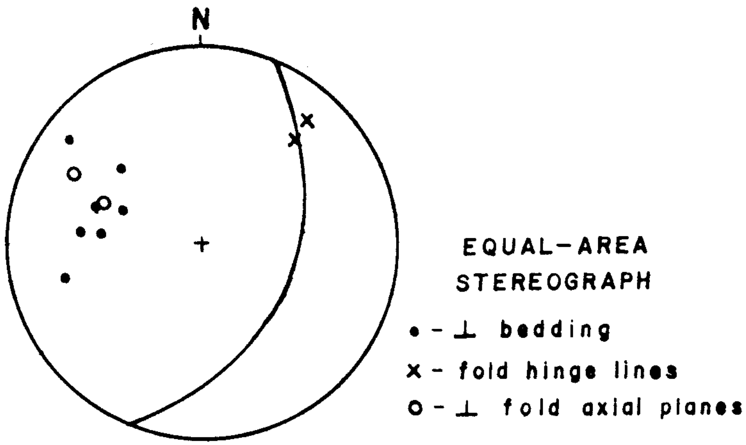
Although possibly less important in total areal extent, the largest

Figure 27. Sketch section from road outcrop on County Road 102, near intersection with Collabeck Road, south of Feura Bush, New Scotland, N.Y. Bedded siltstones, shales and fine-grained arenites are isoclinally folded, and cut by narrow shear zones. The folds have northeast-plunging hinge lines.

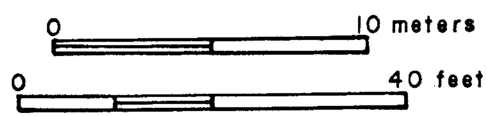
SECTION OF INTERBEDDED SILTSTONES, SHALES AND FINE-GRAINED ARENITES ON COUNTY ROAD 102 SOUTH OF FEURA BUSH, N.Y.

SE/4 NE/4 Clarksville 7.5' Quad., N 42° 34' 27" W 73° 52' 35"





SCALE 1:240



F. W. Vollmer, 1979

and best exposures occur within the more resistant thick-bedded greywackes (Vloman Kill Gorge) and chert (Glenmont). In general, these lithologies appear to have remained as coherent bodies during deformation and occur as blocks or slivers within the mélange. One final section concerns the outcrops within the Normans Kill gorge where a slumping event appears to have complicated the structural history.

Western Mélange

County Road 102. The westernmost outcrop included within the eastern domain is on County Road 102, just below the Helderberg Group limestones. Ruedemann (1930) records fossils from this locality (plate 1), and includes it within his zone of "distinct Taconic folding." This is a small, 15 meter long outcrop of phacoidally cleaved black siltstones and shales which strike 190° and dip 50°E. Bedding is not apparent within the outcrop. The rock contains fragments and polished lenses of siltstone. Faint lineations on some of the surfaces plunge approximately 40° to 106°.

Normansville. Outcrops near Normansville contain some of the best and most easily accessible examples of the mélange fabric and phacoidal cleavage typical within the field area. They are located on the Normans Kill below the overpass of State Route 443 (Delaware Avenue), south of Albany. Similar outcrops occur upstream for about 2.5 kilometers (plate 1). The easternmost outcrop at this locality consists of discontinuous, thick massive greywacke beds and thinner greywackes interbedded with grey shales and siltstones. This outcrop apparently consists of a large steeply east-plunging, assymetric fold in steeply east-dipping beds which have been extensively disrupted. Measurable shear planes show general easterly dips, but are variable (figures 28, 29).

Figure 28. Map of a portion of the outcrop on the Normans Kill at Normansville, N.Y., below the Delaware Avenue bridge. Map suggests the disruption of a steeply east-plunging asymmetric fold.

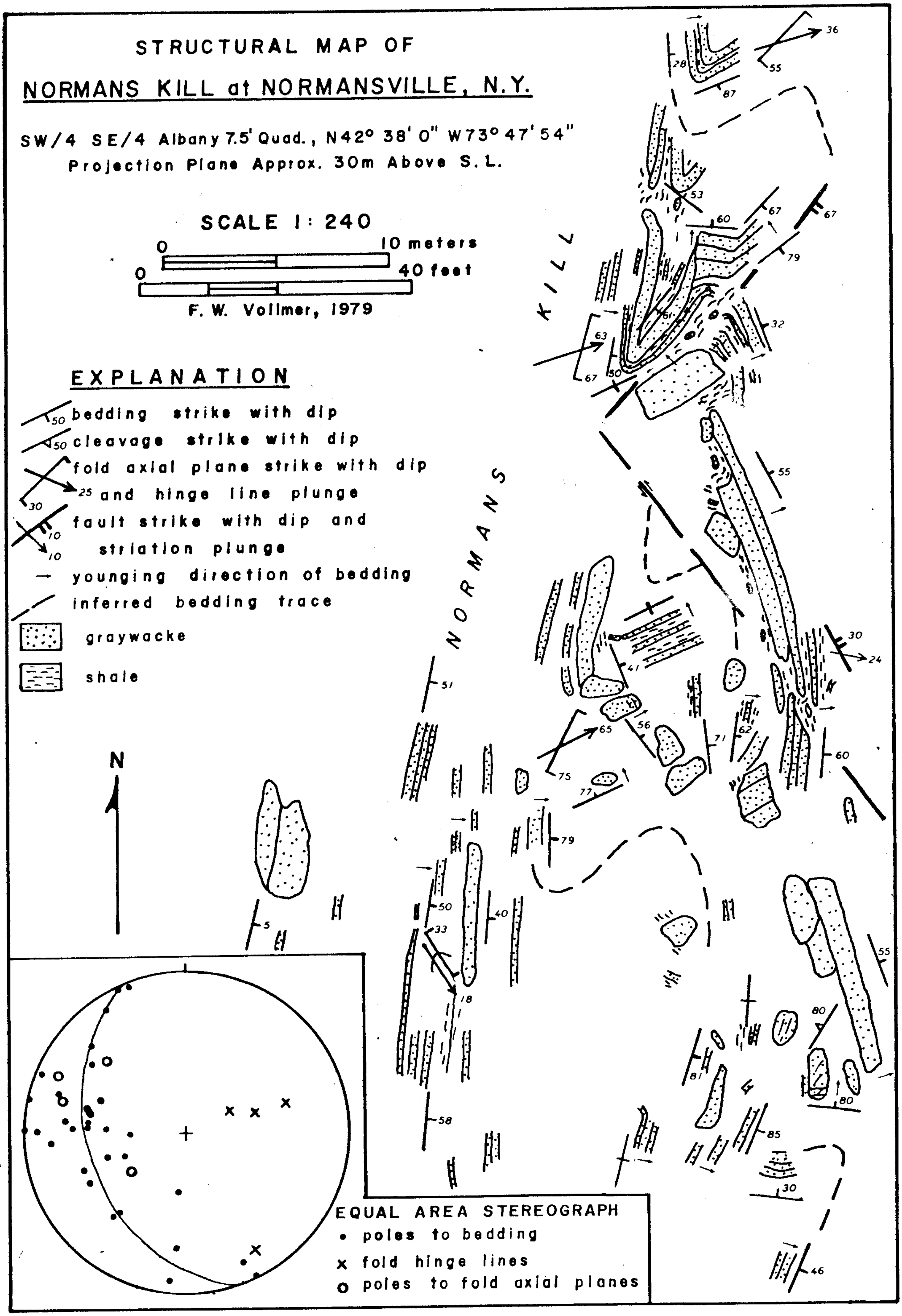

STRUCTURAL MAP OF
NORMANS KILL at NORMANSVILLE, N.Y.
SW/4 SE/4 Albany 7.5' Quad., N42° 38' 0" W73° 47' 54"
Projection Plane Approx. 30m Above S.L.
SCALE 1 : 240
0
10 meters
0
40 feet
F. W. Vollmer, 1979
EXPLANATION
50 bedding strike with dip
50 cleavage strike with dip
fold axial plane strike with dip
30 25 and hinge line plunge
10 10 fault strike with dip and striation plunge
younging direction of bedding
inferred bedding trace
graywacke
shale
N
NORMANS KILL
EQUAL AREA STEREOGRAPH
• poles to bedding
x fold hinge lines
o poles to fold axial planes

Figure 29. – Discontinuous reclined fold, east bank of Normans Kill at Normansville, N.Y. Fold axial plane strikes 195º and dips 67ºE; hinge line plunges 63º to 073º. shear zone to the right strikes 200º and dips 67ºSE. Pocket knife, circled, is 8 centimeters long.

To the northwest is a long outcrop of phacoidally cleaved shales, with cleavage dipping 40-50^{O}E to ESE (figure 30). This outcrop contains numerous small fold hooks of siltstone and fine-grained wacke floating within the shaly matrix (figure 31). Several of these small folds fold calcite veins, and in at least one case calcite fibers within the vein are perpendicular to the vein walls around the fold hinge. This indicates that extensional fibrous veins, and therefore brittle behavior, existed prior to at least some of the folding.

Further upstream, near the Delaware Avenue bridge, bedding again becomes apparent within the outcrop. Here beds dip moderately southeast. Convolute laminations and cross-bedding are common within the thicker wacke beds. The contact between bedded greywackes and disrupted greywackes is gradational, and beds become more broken and disrupted until all continuity is lost (figure 32 shows similar relationships on Interstate 87). In several cases, shaly beds between thicker greywacke beds show signs of intense deformation, although the stronger surrounding wackes remain undeformed.

Further east, upstream along the Normans Kill, other outcrops of phacoidally cleaved shales and siltstones continue. One unusual outcrop, however, occurs near the next southerly bend in the Normans Kill (plate 1). This is an approximately 30 by 10 meter outcrop of bedded black and green chert, silty chert and siliceous argillite. The main body of chert is fairly massive and hard, distinguishable bedding is 5-10 centimeters thick and complexly folded. To the southwest, this body of chert grades into silty chert and black siltstone showing an irregular cleavage and cherty phacoids up to 8 centimeters across. This phacoidal cleavage strikes approximately 230^{O} and dips 50^{O}SE. Ruedemann (1930) apparently

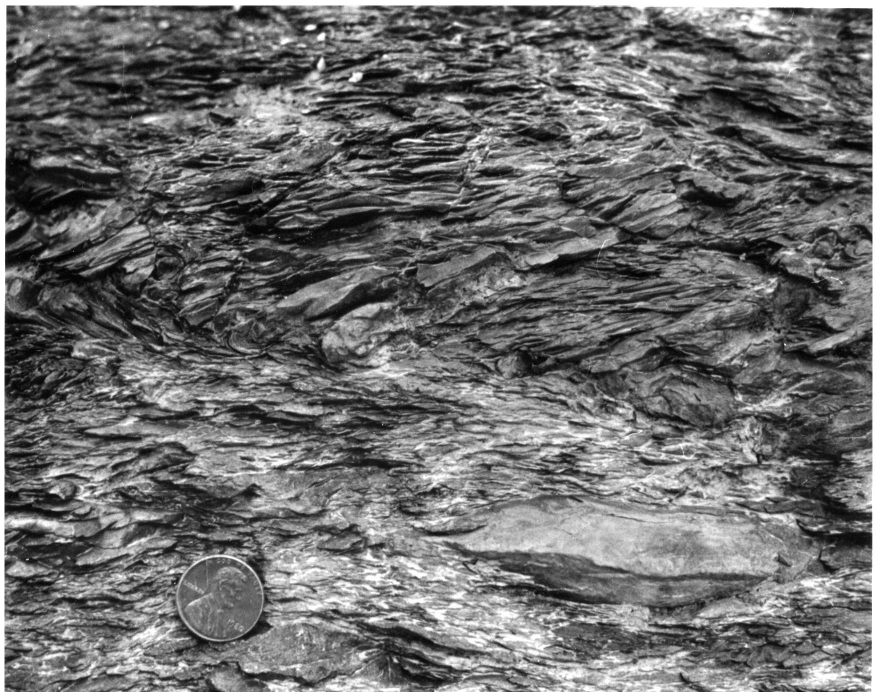


Figure 30. – Phacoidal cleavage in shale, east bank of Normans Kill, Normansville, N.Y. Note phacoid of fine-grained arenite, and broken sliced fold in center. Cleavage strikes approximately 010º and dips 45ºE. Striations occur on many of the phacoids and plunge down-dip.

Figure 31. – Discontinuous steeply inclined, moderately-plunging fold, east bank of Normans Kill at Normansville, N.Y. Fold axial plane strikes 189º and dips 71ºE; hinge line plunges 40º to 172º. Phacoidally cleaved shales enclosing fold strike 206º and dip 53ºE.

Figure 32. – Sequence of greywacke and shale showing transition from well-bedded rock to highly disrupted melange-type fabric. This exposure is believed to be the eastern boundary of the Austin Glen (?) greywacke sliver (Plate 1). Similar transitions can be seen at the Normansville and South Bethlehem outcrops. Hammer at lower center is approximately 40 centimeters long. West side of Interstate 87, 0.5 kilometers south of the Vloman Kill bridge, Bethlehem, N.Y.

found graptolites within this outcrop and included it within his Normanskill shale (plate 1).

South Bethlehem. Good exposures of greywacke and shale occur southwest of South Bethlehem along Spruyt Creek, a tributary of Coeymans Creek, and within a large limestone and gravel quarry. On the east side of County Road 101, outcrops of undeformed, massive medium to coarse-grained greywackes up to three meters thick, interbedded with lesser grey siltstone and shale occur within the creek (figure 6). These beds dip approximately 12^{o}NW and strike 210^{o}. West of County Road 101 medium-grained, mostly laminated greywackes up to a meter thick interbedded with dark grey to black, buff-weathering siltstone and less fissile grey shale outcrop within a west-facing quarry wall above the creek. These beds dip 13^{o}SE and strike 224^{o}. Overlying the wackes along a very low angle unconformity, less than 05^{o}, are medium-grained grey and red-brown weathering laminated dolostones. These dolostones belong to the Rondout Formation, the lowest formation recognized within the Devonian Helderberg Group (Rickard, 1975).

Upstream, into a wooded area below the main quarry, wacke and shale beds maintain strikes of $195-205^{o}$ but show moderate to steep southeast-dips. Disruption of bedding occurs locally within steeply-dipping strata, and seems to be related to the shale content. Gradations between fairly well-bedded greywackes and shales into siltstones and shales containing blocks of wacke occur in several outcrops (figure 32). Finally, the westernmost outcrops show mainly small blocks and phacoids of greywacke, siltstone and some green to black siliceous argillite within an irregularly cleaved shaly matrix striking 190-200 and dipping $40-45^{o}$E (figure 33). Discontinuous folds, mainly in siltstone beds, show axial planes striking $170-212^{o}$ and dipping $40-65^{o}$E. Hinge lines plunge $34-56^{o}$E. In

Figure 33. – Block of fine-grained greywacke, approximately 30 x 50 centimeters, enclosed within phacoidally cleaved shales. Phacoidal cleavage strikes approximately 190º and dips 45ºE. Down-dip striations occur on many of the phacoids. Spruyt Creek above South Bethlehem, N.Y.

one outcrop, the furthest to the west, limestone of the Manlius Formation (Ruedemann, 1930) unconformably overlies this mélange fabric (figure 34).

Eastern Mélange

The eastern mélange forms a roughly north-northeast trending belt of outcrops along the Hudson River, east of Selkirk (plate 1). Good exposures can be seen at Cedar Hill on State Route 144. An outcrop of phacoidally cleaved shales and siliceous argillite containing dolostone clasts, and no greywacke, is included within the eastern mélange, although it may be part of a separate sliver beneath the Glenmont chert body (section "Glenmont"). Similar, although less deformed outcrops at Staats Point on the east side of the Hudson River (Bird and Dewey, 1975) may be a continuation of the eastern mélange. Outcrops on the western side of the Hudson River consist of dark, phacoidally cleaved shales and siltstones with cleavage striking 190-210° and dipping 45-70°E. Discontinuous beds, fold hooks, blocks and phacoids of dark siltstone, green to black chert and siliceous argillite, reddish dolostone and some limestone occur within the cleaved shaly matrix. The dolostone is mostly fine-grained, often laminated, grey, red-brown weathering dolomitic sandstone (figure 35). Limestone occurs as a block less than a meter across in one small stream outcrop off of State Route 144, south of Vanderzee Road. The limestone is a grey micrite with beds up to eight centimeters thick, interbedded with black calcareous silty shale, and is partially brecciated. Carbonate lithologies are not found within similar outcrops of the western mélange.

Structurally, however, the eastern mélange outcrops are similar to those found further west. They show a similar east-dipping phacoidal cleavage defined by siltstone lenses and anastomosing pelitic material.

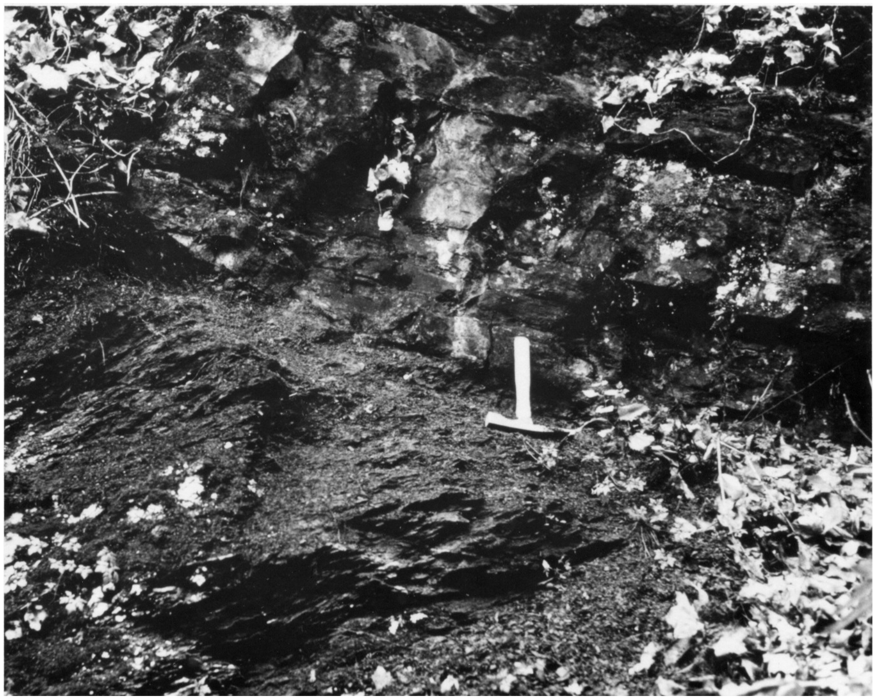


Figure 34. – Exposure of unconformity at Spruyt Creek above South Bethlehem, N.Y. Middle Ordovician phacoidally cleaved shales of Ruedemann's (1930) Normanskill shale lie below Devonian limestone of the Manlius Formation. Shale encloses phacoids of greywacke and green siliceous argillite. Phacoidal cleavage strikes approximately 220º and dips 35ºE. No bedding is present in the shale.

Figure 35. – Dolostone clast within phacoidally cleaved argillite. Cleavage strikes approximately 190º and dips 60ºE. East side of Interstate 87, three miles south of Narmans Kill bridge, Bethlehem, N.Y.

Small folds have axial planes parallel or sub-parallel to this cleavage, and steeply-plunging hinge lines (figure A5). These folds are all small and discontinuous, generally less than ten centimeters across, and float within the shaly matrix. Calcite veins folded about steeply east-plunging hinge lines are found in outcrops on a small hill (a road metal quarry) northeast of the Vloman Kill bridge on State Route 144 at Cedar Hill. Several of these folded veins show medial surfaces and calcite fibers perpendicular to the vein walls around the entire fold hinge (figure 36).

Orientation data from these outcrops suggest that fold axial planes and phacoidal cleavage planes have steeper average dips than those in similar outcrops within the western mélange belt. Phacoidal cleavage here dips 45-70°E; in the western mélange terrane phacoidal cleavage dips 30-56°E. Fold axial planes here dip 45-85°E; in the western mélange belt they dip 33-73°E (Appendix).

Vloman Kill Gorge

A large exposure of deformed greywackes and shales crops out along the Vloman Kill below the Interstate 87 and Penn Central railroad bridges and continues downstream to the east for about 0.5 kilometers. This outcrop is easily approached by taking Clapper Road west for 1.0 kilometer from State Route 144 and walking south for 0.4 kilometer on the Penn Central railroad tracks. Several smaller outcrops occur farther south along the railroad tracks and on Interstate 87 (plate 1). Lithologies within these outcrops are interbedded coarse to fine-grained greywackes and grey to black siltstones and shales. Greywacke beds average about 20-40 centimeters thick, although coarse to medium-grained greywackes occur as massive beds up to two meters thick. Medium to fine-grained greywackes are often laminated, and many show cross-laminations

Figure 36. – Discontinuous, reclined fold in extensional calcite vein enclosed within phacoidally cleaved argillite. Note medial surface. Axial plane strikes 203º and dips 68ºE; hinge line plunges 68º. Cleavage strikes approximately 205º and dips 70ºE. Road metal quarry on east side of Route 144, north of the Vloman Kill at Cedar Hill, N.Y.

or convolute laminations. Sole marks are common on the bases of greywacke beds. The proportion of greywacke varies locally with greywacke beds making up 40-60 percent of the outcrop.

Structurally, this area is complex with much disruption and numerous discontinuities (plate 3). The overall structural style within this exposure indicates large scale folding with a wavelength of 60-100 meters, with disruption through brittle failure and shear mainly in the hinge areas. Three main fold hinges pass through the mapped area, separated by sections of consistent younging direction. Near the southwestern end of the main exposure within the Vloman Kill gorge is a section of thick greywacke beds dipping moderately east and younging east. To the northeast is a section of disrupted and faulted rock including one large, fairly coherent synclinal hinge area (plate 3). This is followed by a section of mostly steeply northwest-dipping and northwest younging strata. Farther northeast, in the central portion of the mapped area, is a large, well-exposed and coherent anticlinal hinge on the southern bank of the Vloman Kill. This fold hinge cannot be traced directly along its trend, and may be faulted out, cropping out to the northeast (plate 3). Again to the northeast, past a section of moderately east-dipping upright strata, is an unexposed syncline and an anticline-syncline pair. The hinge of the anticline plunges gently south, while the syncline plunges gently north-northeast, resulting in an unusual map pattern. As these folds are bounded to the northeast by a thick section of steeply east-dipping, overturned strata, it is believed that these three folds represent disharmonic folding within the hinge area of a larger, overturned syncline.

These large folds, as well as smaller folds, are mostly gently north-northeast plunging with steep east-southeast dipping axial planes.

A plot of bedding attitudes supports this general trend giving a π axis (Turner and Weiss, 1963) of about 20° to 036°. Bedding - slaty cleavage intersections also mostly plot plunging gently to the north-northeast (plate 3). Axial plane and limb orientations indicate that the folds are overturned to the northwest. One fold near the south-western end of the mapped area shows calcite filled extensional fractures along its outer arc, or extrados, indicating brittle behavior was associated with at least a portion of the folding history.

The Vloman Kill gorge is the only locality in the study area in which slaty cleavage is moderately well developed. A fairly planar, closely-spaced slaty cleavage can be found locally here within siltier beds. Shaly horizons are often disrupted and generally do not show good slaty cleavage. Phacoidal cleavage is not well developed here. Slaty cleavage varies in orientation from moderately to steeply east-dipping on moderately-dipping fold limbs, to steeply northwest-dipping on steeply-dipping limbs (plate 3). In all cases cleavage is steeper than upright beds. This large variation in slaty cleavage orientations, approximately 60°, has several possible explanations. The simplest explanation is that cleavage formed as a divergent fan within the silt-stone interbeds during folding, in response to variable strain (or stress) orientations (Ramsay, 1967). This fanning may appear exaggerated, as cleavage is only found within the silty interbeds and not within the greywacke beds where it should be refracted (e.g., Hobbs et al., 1976, p. 216). Alternatively, cleavage orientations may have been reoriented by relatively rigid rotation of a block during faulting. As bedding - cleavage intersections show fairly constant orientations, any rotation must have occurred about a pole plunging gently north-northeast. However, stereographic rotations about this, or other poles, do not lead to a simple solution, and therefore a cleavage-fan explanation is preferred.

A section of fine-grained bedded wackes in the northwestern - central portion of the mapped area shows several extensional calcite veins parallel to the moderately northwest-dipping bedding and cut by a steep slaty cleavage. Calcite fibers within the vein make an acute angle with the vein walls as small as 30°, indicating an oblique opening history, with the extensional direction near vertical and with no rotational component (Durney and Ramsay, 1973). These veins are then folded and thrust across planes approximately parallel to the cleavage surfaces (figure 37). These relationships suggest that the bedding - parallel extensional veins opened in response to horizontal compression during folding and were later folded and thrust during continued shortening associated with cleavage development in the host rock.

Faulting and brittle behavior is probably the most evident deformational style within the rocks exposed in the Vloman Kill gorge, however this brittle behavior has led to complex disruption which is not easily interpreted geometrically. Most observed and inferred faults strike generally northwest, however there are many exceptions, and dips are variable. Narrow, mostly calcite slickenside surfaces, 1-2 centimeters across, occur in some areas, but do not show consistent orientations (figure A6). Larger faults are indicated mainly by bedding discontinuities or disrupted shales. In cases where the terminations of greywacke beds can be observed, they are found to be enclosed by contorted shales. The shales in general have behaved plastically and infill spaces between broken greywacke beds, locally resulting in a blocks-in-shale appearance.

It seems likely that the complex geometries within this area are

Figure 37. – Oblique-extensional calcite veins thrust across cleavage planes. This suggests that shortening associated with cleavage development occurred after the development of the calcite filled veins and that brittle behavior pre-dated cleavage formation. Vloman Kill gorge, Bethlehem, N.Y.

the result of the folding and shearing of this heterogeneous sequence of thick bedded greywackes and shales. Folding of sequences with widely varying material properties should result in disharmonic fold styles and complex strain distributions. Brittle failure of less ductile beds may occur through differential extension in limb areas and through compression in hinge areas. Room problems due to the tightening of disharmonic folds may also cause disruption in hinge areas. Shearing of these structures along variably oriented planes of weakness, probably both during and after fold development, further complicates the structural style.

Glenmont

This area includes exposures of mostly black to green, hard siliceous argillites and bedded cherts near Glenmont, New York. Good exposures occur north of Glenmont in a small stream cut and to the south where State Route 144 crosses the Penn Central railroad. Other exposures occur south along the railroad and on steep hillsides in this area, which are the topographic expressions of these resistant lithologies. Much of the outcrop consists of fairly homogeneously bedded cherts gradational into siliceous argillites. Beds average 3-8 centimeters thick. In some areas, outcrops appear massive, with indistinct or undiscernible bedding planes.

In the stream cut north of Glenmont, the lower contact of the cherts can be observed. The lowest outcrops here show complex deformation with blocks of dark grey to black fine-grained greywackes and siltstones up to a meter across enclosed within irregularly cleaved shales and siltstones. The blocks include disrupted beds and fold hooks as well as rounded clasts. Closer to the main chert body large blocks and disrupted beds of chert are intermixed with the shales and greywacke blocks. Many small clasts are lensoid and are enclosed in disrupted shale showing an irregular cleavage, which strikes roughly 255° and dips 40°S. Four fold hooks measured within this chaotic outcrop have variable orientations, although they generally plunge south and have east striking axial planes. Slickensides and slickenside striations are similarly variable, although the majority dip and plunge southeast (figure A7).

The contact between the chert body and this mélange appears to be near-horizontal, with cherts occurring above the highly deformed mélange. A near-horizontal contact is further supported by the relatively constant topographic elevation of the lower limits of exposure of the chert unit, approximately 50 feet above sea level.

Two other outcrops show similarly complex deformation with intermixing of the siliceous argillites and cherts with other lithologies; these also apparently represent the mélange-chert body contact. One of these exposures occurs in a small stream cut to the south, off of the Penn Central railroad tracks. Here reddish-weathering calcareous, fine to medium-grained greywackes with green chert clasts, and dark grey to black siltstones occur with brecciated and broken black and green chert beds. Black, irregularly cleaved siltstone encloses greywacke clasts and chert, truncating bedding. The irregular cleavage within the siltstone strikes approximately 360° and dips 60°E. One tight overturned fold in greywacke beds has an axial plane orientation of 185-48E, with a hinge line plunging 10° to 010°. A planar slaty cleavage within the shale interbeds parallels the fold axial plane. Another gentle fold has a hinge line plunging 02° to 005°.

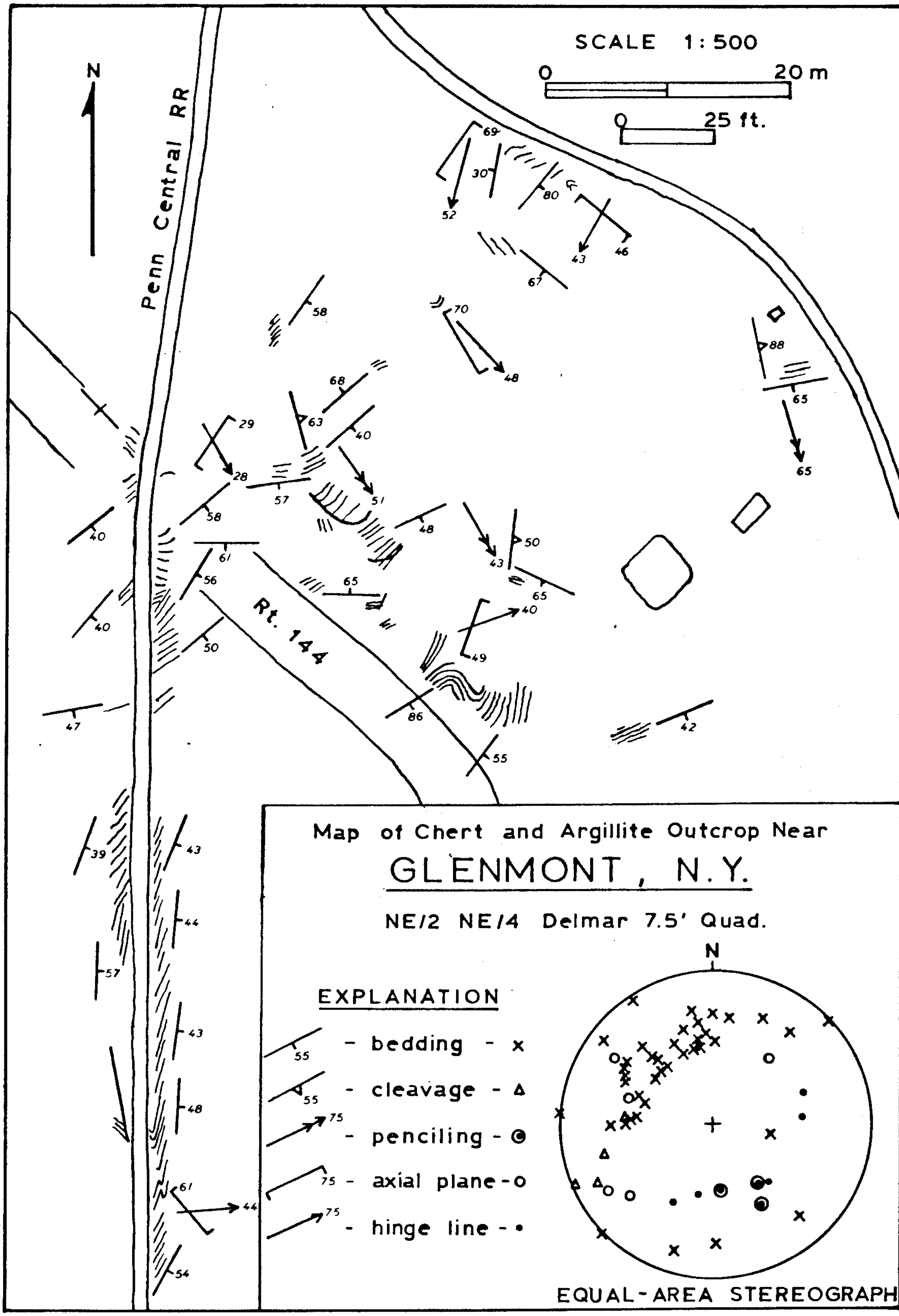
The third exposure of highly deformed siliceous argillite intermixed with other lithologies occurs along the east side of Interstate 87 0.5 miles north of the Wemple Road overpass. The outcrop is well cleaved with an irregular, phacoidal cleavage striking 190-200° and dipping 45-60°E. The main lithology is grey-green and black siliceous argillite, which occurs as shiny surfaced phacoids. Red-brown weathering, fine-grained grey dolostone occurs as a minor constituent, forming lumps, clasts and small folds (figure 35). Three small, discontinuous folds measured within siliceous argillite beds show axial planes striking 166-206° and dipping 50-58°E. Hinge lines plunge 38-42°E.

Folds within the bedded cherts of this area tend towards a more parallel style than is common within the interbedded greywackes and shales seem elsewhere within the field area (figure 38). The largest observed fold within these bedded cherts has a half wavelength of approximately 10 meters; smaller ones with half wavelengths as small as 20 centimeters are common locally. Fold orientations within the main body of siliceous argillite and chert may be subdivided into two groups. The first includes folds within the large outcrops located near the intersections of State Route 144 and the Penn Central railroad (figure 39), and the main body of chert overlying the disrupted structural contact north of Glenmont (plate 1). Folds within this area show a preferred orientation with fold axial planes dipping moderately to the east. Fold hinge lines are somewhat variable, although dominantly plunging moderately to the southeast (figure A7). The large outcrop exposed west of Glenmont conforms to this pattern, with folds plunging moderately to the south-southeast and axial planes dipping moderately (figure 40).

The second group of fold orientations are mainly from outcrops along the Penn Central railroad south of its intersection with State Route 144. These outcrops continue for approximately one kilometer and consist of disrupted green to black cherts and siliceous argillite beds. To the south these occur as mostly fault bounded blocks in highly disrupted and faulted outcrops where bedding is not traceable for more than

Figure 38. – Fold in the bedded cherts of the Glenmont body. Axial plane strikes 199º and dips 49ºE; hinge line plunges 40º to 070º. East side of State Route 144, Glenmont, N.Y.

Figure 39. Form line map of exposures of black and green chert and siliceous argillite on State Route 144 and the Penn Central Railroad, Glenmont, N.Y. Outcrops to the southwest may represent the limb area of a large fold, with more disrupted outcrops in the hinge area. Cleavage referred to here is a planar, slaty cleavage.

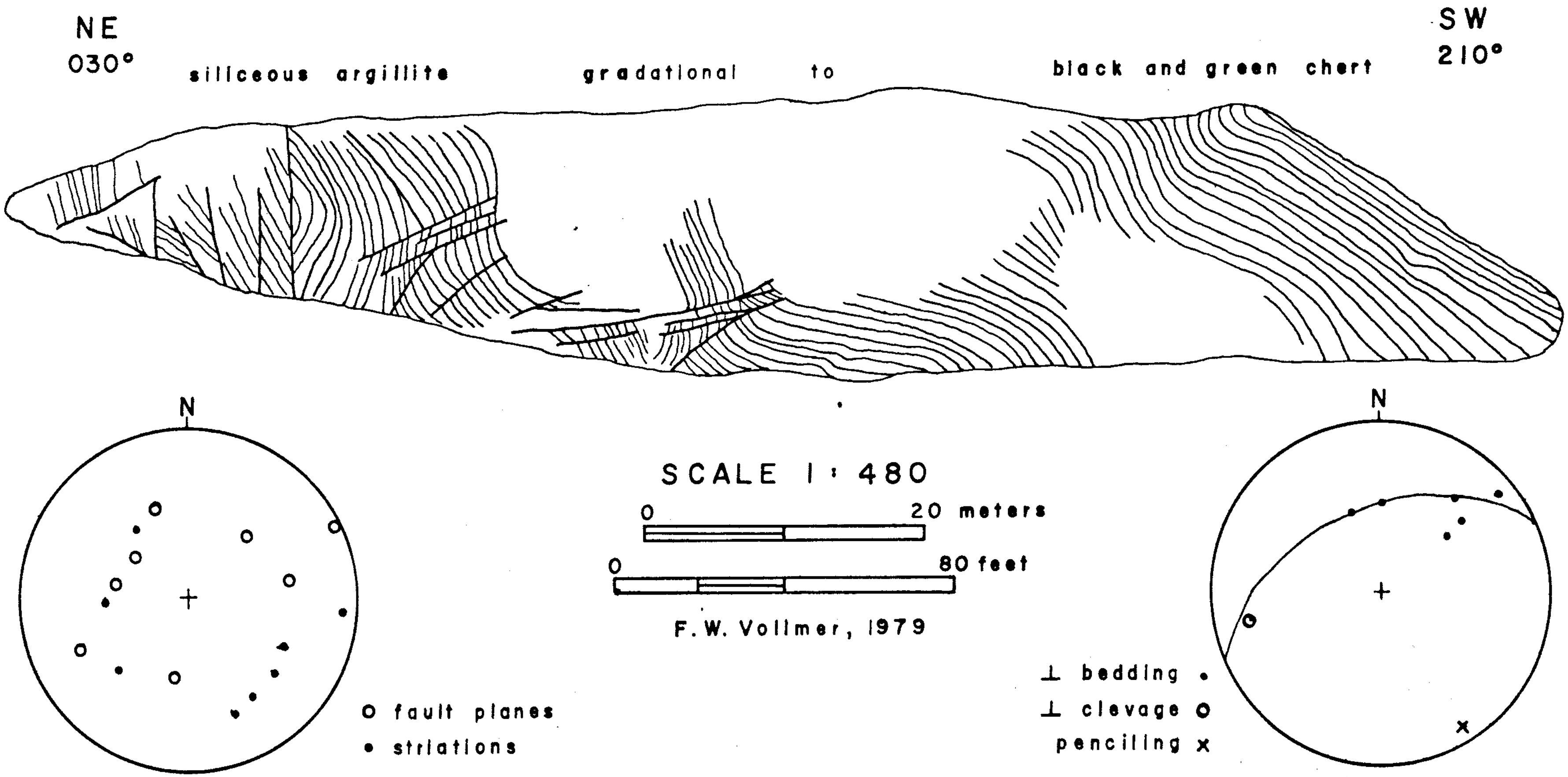


SCALE 1:500
0 20 m
0 25 ft.
N
Penn Central RR
Rt. 144
Map of Chert and Argillite Outcrop Near
GLENMONT, N.Y.
NE/2 NE/4 Delmar 7.5' Quad.
EXPLANATION
- bedding - x
- cleavage - Δ
- penciling - ◉
- axial plane - o
- hinge line - •
N
EQUAL-AREA STEREOGRAPH

Figure 40. Section view of exposure of bedded chert and siliceous argillite in stream cut west of Glenmont, N.Y. Note the increase in fault density in the more argillaceous rock. Stereographs are on equal-area nets.

SECTION OF BEDDED CHERTS FROM STREAM
CUT WEST OF GLENMONT, N. Y.

N/2 NE/4 Delmar 7.5' Quad., N42°36'17" W73°46'33"



several meters. Further north in a few outcrops bedding is more continuous and the outcrop is less faulted. Eight fold orientations measured within these outcrops show no obvious preferred orientation (figure A7).

Both phacoidal and slaty cleavages occur within the Glenmont area. An irregular, east-dipping phacoidal cleavage occurs in the three areas that have intermixed lithologies, apparently along the boundaries of the chert body. A planar slaty cleavage occurs within some of the argillaceous lithologies with a fairly consistent moderate to steep easterly dip. This slaty cleavage is roughly axial planar to the folds in outcrop. Bedding-cleavage intersections and occasional penciling coincide with the fold hinge line orientations (figures 39, A7). The transition from slaty cleavage within the main body of chert to phacoidal cleavage along its margins suggests that the phacoidal cleavage was preferentially formed within areas of high shear strain beneath the chert body.

Narrow shears are common throughout the chert body, with both calcite and quartz fillings. Slickenside striations are common on the surfaces of these shears. Measurable offsets are generally small or negligible; however, many are indeterminate. Orientations of the shear surfaces are variable, although they dominantly dip moderately southeast. This variation is probably due to shears developing along older planes of weakness, including bedding planes along which striations can often be found. Slickenside striation orientations show less variation and plunge gently to moderately east-southeast (figures 40, A7). In eight of these faults, steps in fibrous slickenside surfaces were observed - all giving overthrust solutions (Durney and Ramsay, 1973).

This chert terrane near Glenmont, then, appears to be an older stratigraphic unit (section "Chert and Siliceous Argillite") which now structurally overlies the younger greywackes and shales along a near-horizontal thrust fault. The direction of overthrust, as suggested by the fold vergence and fault orientations, is from southeast to northwest. The majority of fold orientations are consistent with those found in the surrounding greywackes and shales. Apparently chaotic fold orientations are, for the most part, localized. That cleavage and penciling orientations show a correlation with the majority of fold axial planes and hinge lines, and do not show chaotic orientations, suggests that an early episode of local chaotic sedimentary folding may have preceded a later tectonic folding event associated with cleavage development. Although the formation of early slump folds may indicate some early gravity-related deformation, the dominance of east-dipping folds with moderately southeast-plunging hinge lines suggests that the structural history of this area was similar to the structural history of the surrounding greywacke and shale terrane. It seems unnecessary to postulate a separate emplacement mechanism, such as gravity sliding (e.g., Bird, 1969), for this chert body.

The only significant differences in structural style between the chert terrane and the greywacke and shale terrane can be explained by their different material behaviors. The homogeneous nature of the bedded cherts has lead to a more parallel fold style. The absence of shaly interbeds has impeded the preferential thinning of limb areas which leads to a more similar fold style in the interbedded greywackes and shales. The homogeneous nature of the bedded cherts has also lead to a different style of brittle behavior. Shear displacements within the interbedded greywackes and shales seem to be mostly taken up along wide, disrupted shaly zones, the orientations of which are not usually well constrained. Within the bedded cherts, however, faulting is mostly restricted to narrow, planar slickenside surfaces. Finally, the relatively homogeneous nature and strength of the cherts may have allowed them to remain as a relatively coherent body, unlike the greywacke and shale sequences which have probably undergone extensive disruption as a result of the high ductility contrasts between greywacke and shale.

Normans Kill Gorge

Exposures along the Normans Kill and the Delaware and Hudson railroad below, and to the southeast of the Interstate 87 and State Route 9W bridges , south of Albany, are the most extensive exposures of mélange within the field area, and are some of the most spectacular within the entire Hudson River lowlands. Much of this area consists of greywacke blocks in highly contorted and disrupted shales. The greywacke occurs in all size gradations from massive, coarse-grained beds and blocks several meters thick to fine-grained laminated beds and clasts less than five centimeters across. Greywacke constitutes approximately 40 to 60 percent of the outcrop.

Mapping at this locality was done at a scale of 1:240 within an area of approximately 80 X 300 meters exposed along and within the bed of the Normans Kill, east of the State Route 9W bridge (plate 4). The observations from this area were combined with observations and measurements taken from the surrounding outcrop. This mapping area was chosen as it offers some of the best continuous exposure within the gorge and it is apparently the least deformed, with the most continuous bedding planes.

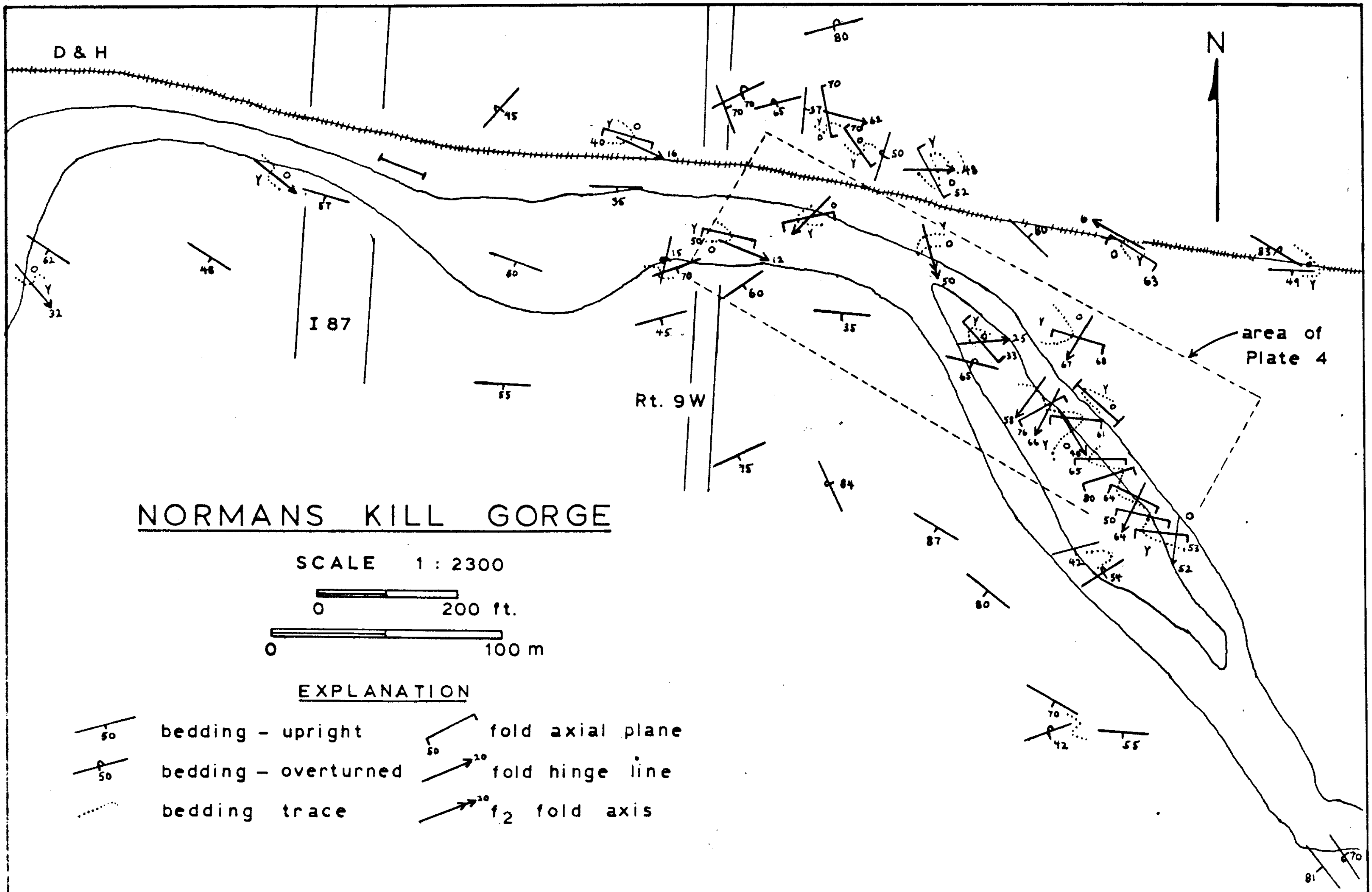
Stream outcrops to the west and southeast show complex blocks-in-shale geometries. Locally, greywacke beds as thick as several meters have been disrupted, occurring as large blocks discontinuously traceable through a matrix of highly faulted and contorted greywacke and shale. To the northeast, embankments and railroad outcrops show mainly disrupted greywacke beds, and shear zones with glazed or polished shales and siltstones. Cliff exposures to the southeast are mainly steeply dipping, southwest younging thick greywacke beds (figure 41). As the structural geometrics are so complex here, it was felt that large-scale mapping was necessary to define a local structural style which then might be applied to explain the geometry of the area as a whole.

Folds are abundant within the gorge with half wavelengths varying from over 30 meters to less than 10 centimeters. Fold styles are variable, although shaly beds are relatively thickened in hinge areas, resulting in similar style folds. Most of the folds are tight to isoclinal, although some interlimb angles are as great as 110°. Hinge curvature tends to be tight, giving fairly angular folds. In many cases, faulting has occurred within the hinge areas leaving only remnants of the fold hinge between sequences of oppositely younging strata (plate 4).

Within the mapped area folds are not traceable for long distances and the relationships between adjacent folds are not always clear. The most continuous fold train occurs in the southeasternmost portion of the mapped area. Here four fold pairs can be traced discontinuously along the southern stream bank, mainly by younging directions and the remnants of fold hinges that have been faulted through. The fold orientations within this fold train vary considerably, although their axial planes dip moderately south and their hinge lines are steep (plate 4). To the north other folds can be similarly located, although here fold orientations are further obscured by faulting and bedding discontinuities. The northeasternmost portion of the map shows considerable disruption and fold relationships here are obscure, with discontinuous beds in many orientations.

A number of structural features within this area indicate that these

Figure 41. Generalized structural map of Normans Kill gorge area. Lithologies are greywacke, siltstone and shale. Structural complexities decrease to the southwest, and are replaced by mainly south to southwest younging beds. Bedding is everywhere highly disrupted, commonly forming blocks within a disrupted shaly matrix. Beds to the south are, in general, less disrupted. Portions of the data on this map are from a sketch map by W. D. Means (1971).


D & H
N
area of Plate 4
I 87
Rt. 9W
NORMANS KILL GORGE
SCALE 1 : 2300
0 200 ft.
0 100 m
EXPLANATION
bedding - upright
bedding - overturned
bedding trace
fold axial plane
fold hinge line
f2 fold axis

rocks must have a polyphase deformation history. Juxtaposition of incongruent fold styles occurs on the northeast side of the island in the central portion of the mapped area. Here an open, parallel or concentric style fold is formed within beds which are folded in a tight, similar and angular style immediately to the southeast. The orientations of these two folds differ significantly, suggesting that these two folds may belong to two different generations. However, a general correlation between fold profile or tightness, and fold orientation cannot be made; both tight and open folds show equal variations in orientation. Axial planar foliations have not generally been observed in the folds within this area, and offer no help in distinguishing possible fold generations.

Multiple deformation of these rocks is further suggested by the presence of downward-facing folds, or folds which young downwards along the dip of their axial planes (Hobbs et al., 1976). The best example is a large, gently-plunging antiformal-syncline beneath and southeast of the State Route 9W bridge. Prominent flute casts can be observed on the upper surface of this fold, demonstrating that the beds are overturned (figure 42). Another example occurs along the north embankment of the railroad approximately 50 meters west of the 9W overpass (figure 41). In the hinge region of this gently east-plunging antiformal-syncline a fiberous calcite vein parallel to bedding has been folded around the hinge, with calcite fibers remaining approximately perpendicular to the vein walls. Another downward-facing fold occurs east of the 9W overpass as a discontinuous fold in the southern embankment of the railroad. On the cliff exposures to the southwest bedding-cleavage relationships also suggest a complex deformational history (figure 43).

Actual refolding of folds is not common, although many small folds show slightly curved axial planes or hinge lines. The only good example

Figure 42. – Downward-facing fold, an antiformal-syncline, in the Normans Kill gorge below the Route 9W bridge. Flute casts can be seen in the hinge area. Fold is structurally discontinuous on all sides (plate 4). Distance between exposed limbs is approximately four meters.

Figure 43. – Slaty cleavage intersecting overturned greywacke bed at Normans Kill gorge. This relationship indicates that the deformation within this area probably occurred as a polyphase event. Slaty cleavage strikes 232º and dips 54ºSE.

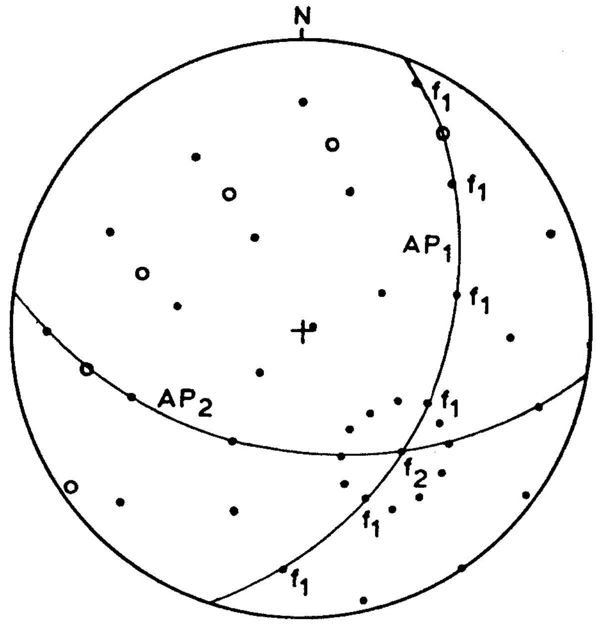
where a change in axial plane orientation can be measured within a single fold is a broken fold within the Normans Kill in the northeastern-central portion of the mapped area. Although the fold is broken and discontinuous, the axial plane seems to be folded about a hinge line plunging 51° to 165°, with a maximum interlimb angle of 110° (plate 4).

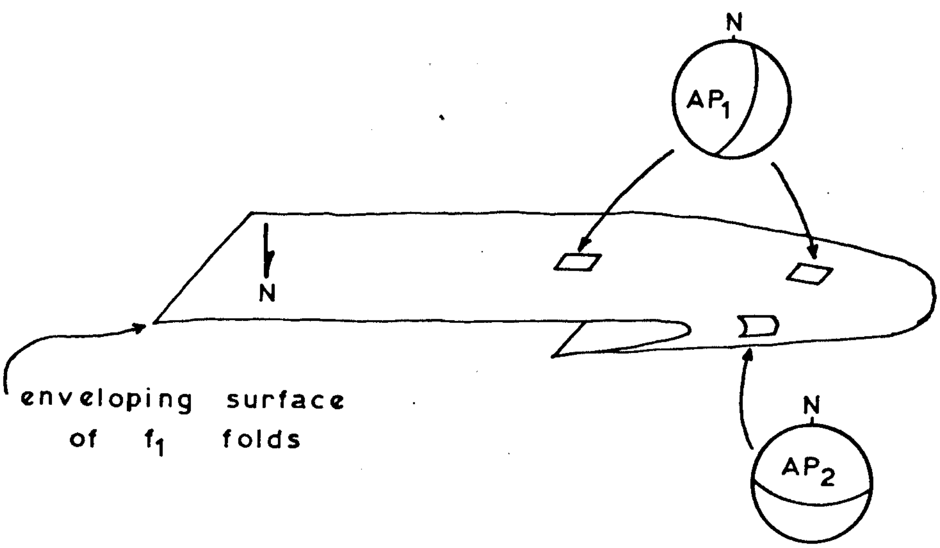
Equal-area stereographs of fold and bedding orientations within the map area (plate 4) and within the entire Normans Kill gorge area (figure A4) were made to identify any statistical orientation trends. Poles to 41 fold axial planes show a maximum of approximately 35° to 010°, and form a weak great circle whose π - pole is approximately 55° to 155°. The fold hinge lines of 59 folds show a maximum at approximately 45° to 145° with approximately 50 percent of the hinge lines showing highly variable orientations. A plot of 158 poles to bedding is similar to that of fold axial planes, with a broad maximum centered at 30° to 015° and a wide scatter of poles in all quadrants except the southeast (figure A4).

One possible explanation for the anomalous orientations of these structural elements, compared with other outcrops within the field area, is that a sequence of tight to isoclinal folds with variably-plunging hinge lines sharing a common average axial plane, has been refolded about a moderately southeast-plunging axis. A hypothetical construction is presented in figure 44. In this construction the average axial plane orientation of the eastern domain (appendix), AP_1, with six variably-plunging hinge lines, f_1, has been rotated about an axis approximated by the weak great circle of axial planes from Normans Kill gorge, f_2. A hypothetical axial plane, AP_2, is chosen with its pole at the maximum of poles to axial planes. The resulting orientations of poles to AP_1, and its contained fold hinge lines, are plotted at 30° intervals. This

Figure 44. Equal-area stereograph illustrating refolding model for Normans Kill gorge area. AP_1 represents the mean axial plane of folds from the eastern domain, f_1 are variably-plunging hinge lines (figures A5, A6). AP_2 represents the mean axial plane of folds from Normans Kill gorge (figure A4). AP_1 is rotated about the f_2 axis. Open circles represent poles to fold axial planes, filled circles represent fold hinge lines (cf. figure A4).

Figure shows possible location of refolding in hinge area of large, non-cylindrical f_2 fold (see text).


N
f_1
f_1
AP_1
f_1
AP_2
f_1
f_2
f_1
f_1


N
AP_1
N
enveloping surface of f_1 folds
N
AP_2

This model can explain much of the observed field relations including the downwards facing folds, the southeast-plunging refolded fold, and the distribution of fold orientations. A comparison of figure 44 with figure A4 shows that the observed maxima in fold hinge lines, and poles to fold axial planes and bedding (assuming tight to isoclinal folds); as well as the broad distribution of these structural elements can be explained by this refolding model.

A problem with this model, however, is the kinematic interpretation of a second generation folding episode with moderately to steeply plunging hinge line and an apparently south-dipping axial plane. One possibility, illustrated in figure 44, is that rotation and folding occurred during the development of a large, highly non-cylindrical fold. An alternative explanation is that a marked change in the trend of the axis of maximum compression occurred, possibly due to a local shouldering effect of a thrust block, causing more northerly directed flattening.

Although slump folding of the sediments on an oversteepened slope could result locally in steeply plunging folds (Hansen, 1971), clear slump folds cannot be demonstrated within the gorge. Folds generated in a slump environment would be expected to differ from tectonically induced folds; however, two such style groups cannot be demonstrated. The presence of folded extensional veins argues that at least some of these rocks behaved in a brittle manner prior to folding and are therefore unlikely to have been able to deform plastically in an essentially instantaneous slump deformation.

One further problem with a refolding model is the apparently localized nature of the complex deformation. Nowhere else within the field area, or in correlative areas studied to the north (Bosworth and Vollmer, 1981), are similar structures found. In light of these problems, one final hypothesis for the formation of these structures is advanced. The observed structures may have been produced by the chaotic slumping of sediments, either prior to their tectonization or after the formation of a highly disrupted tectonic mélange. (See Underwood and Bachman, 1980, for a discussion of post-tectonic slumping in trench environments.) This may have occurred on an uplifted fault scarp, or along a large, undercut channel. Subsequent straining of this chaotic sediment pile could result in a preferred orientation of fabric elements with poles to material planes rotating towards the direction of maximum shortening (λ_3) and linear elements rotating towards the direction of maximum extension (λ_1) (Flinn, 1966). This suggests a strain ellipsoid oriented with λ_1 plunging moderately southeast, λ_3 plunging gently north-northeast, and λ_2 plunging gently west. A simplistic comparison with the general strain ellipsoid orientation suggested by the orientations of structural elements in the rest of the eastern domain indicates that λ_1 in both cases plunges moderately southeast (parallel to the maxima of fold hinge lines), but that λ_2 and λ_3 have been reversed (if λ_3 is roughly perpendicular to the average fold axial planes; e.g., Ghosh, 1966). The apparent local deviation in the inferred strain orientations may be due to the effects of overthrusting of the nearby Glenmont chert terrane from the southeast (section "Glenmont"); possibly a shouldering effect has locally caused a more northerly directed flattening. This hypothesis seems to explain the observed features outlined above, in particular the apparent absence of slump folds, the irregular variations in structural orientations seem within the outcrop, and the localized nature of the deformation. Additionally, this model is in accord with processes which are known to occur within the surrounding terrane.

Cleavage is in general very poorly developed within the rocks of the

Normans Kill gorge. Locally, a planar slaty cleavage can be found within siltstones or fine-grained wackes cutting across an early bedding - parallel fissility. From the limited number of observations, cleavage is generally steep but with a poor preferred orientation. Exposures of thick bedded greywackes with interbedded shales and siltstones on the cliffs to the south of the mapped area locally show good cleavage development with a 50° to 70° southeasterly dip. Bedding-cleavage intersections and some penciling here show variable south to southwest plunges. In one instance here a steep cleavage clearly cuts moderately south-dipping overturned bedding, demonstrating that deformation has been complex within this area (figure 43). These relationships suggest that slaty cleavage may have formed both prior to the inferred episode of incoherent slumping, resulting in scattered cleavage orientations, and after, allowing the overprinting of a moderately southeast dipping cleavage on overturned bedding. Phacoidal cleavage is also poorly represented in the Normans Kill gorge. In several cases, there is an irregular fabric developed within the deformed shales dipping steeply to vertically east. In most cases, however, the shaly matrix, which commonly surrounds blocks of greywacke and locally forms injection structures, appears chaotic forming chips and lumps in irregular orientations. Phacoidal cleavage may have never been developed in this area because of the abundant resistant greywacke beds or an early phacoidal cleavage may have been disrupted during the inferred slumping event resulting in the present apparently chaotic shaly matrix.

In the Normans Kill gorge exposure, the most obvious deformational structures are the abundant faults and discontinuities. Faults and bedding truncations occur every few meters or less, resulting in the highly broken appearance of the outcrop (plate 4). In most cases, these discontinuities cannot be defined as planar surfaces, nor can specific bedding planes or lineations be traced across them. Continuity of folds with broken hinge areas is in many cases based on bedding orientations and younging directions rather than tracing specific beds around the hinge; possibly large displacements have occurred across these fold axial planes. In general, the only faults from which orientations can be determined are narrow, mostly calcite, slickensides. An equal-area stereograph of 15 poles to slickensides and 12 slickenside striations shows a wide distribution of orientations, although many slickenside striations plunge easterly (figure A4). For four planes on which relative motions could be determined from stepped calcite fibres, two solutions are obtained for strike-slip faulting on perpendicular, moderately-dipping planes and two show normal solutions on perpendicular, near vertical planes. This erratic distribution of fault planes and movement directions may be related to the complex geometrics present here, with rocks faulting along diverse planes of weakness in response to local stress heterogeneities. Again, however, these structures may have been reoriented during a slumping event.

CHAPTER VI

STRUCTURAL SYNTHESIS

The following is an attempt to synthesize the data and interpretations from the various and often widely spaced outcrops within the field area into a coherent structural model. The structures present within individual outcrops, and interpretations regarding their deformational history, have been presented in Chapter V. The development of the area as a whole will now be considered. Plate 1 is a summary map showing inferred relationships of the outcrops within the field area, with two schematic cross-sections. Stereographs of structural data from the seven main litho-structural domains are given in the appendix (figures A1-A7).

Folds

The western boundary of the western domain is the furthest extent of observed mesoscopic folds. To the west are mainly gently westerly-dipping strata which may indicate gentle, long wavelength macroscopic folds. This deformation is Ordovician in age (section "Western Domain"), and occurs within strata as young as C. spiniferus or possibly C. pygmaeus zone age (Fisher, 1977), giving the uppermost known limit on the age of Taconic deformation (the deformed Schenectady beds of the central domain are also C. spiniferus zone age). Some near-horizontal thrust faulting apparently predates this gentle folding (section "Western Domain").

Fold styles within the field area are variable and are dominantly controlled by lithology and the amount of imposed strain. No attempt was made to quantify fold styles, although numerous sketches and general observations were made. Kink folds occur within the thin interbedded siltstones of the Vly Creek exposures (figure 22; plate 2). Similar folds are probably the most common within the interbedded greywacke and shale sequences, with relative thickening of shaly horizons within hinge areas (plates 3 and 4). More parallel fold styles are common within homogeneously bedded greywackes, siltstones and cherts (figure 38). Hinge angularity is similarly variable with the most angular folds occurring in more heterogeneously layered sequences and more rounded or concentric folds occurring within massive bedded greywackes, cherts and siltstones.

The majority of folds found within the eastern domain are discontinuous within outcrop, usually consisting of a single hinge area of greywacke or siltstone within a shaly matrix (figures 28, 29, 31; plate 4). Most folds within the central domain, however, are continuous through the outcrop and do not appear to be attenuated. Also, some of the large folds in the cherts of the Glenmont area are continuously traceable through the outcrop (figure 40). Large folds in the bedded greywackes of the Vloman Kill exposures are broken, but generally traceable (plate 3). This dominance of rootless folds has made the determination of fold asymmetry difficult or impossible. Most traceable folds, however, are assymetric and the dominance of east-dipping axial planes has been generally assumed to indicate an east over west fold asymmetry in other cases. This fold assymetry is consistent with the observed east over west overthrust asymmetry (sections "Western Domain" and "Faults").

Evidence for the formation of these folds through tectonic processes, as opposed to soft sediment deformation, includes: folded extensional veins (sections "Normansville," "Eastern Melange" and "Normans Kill Gorge;" figure 36), brittle failure of folds in hinge areas (section Vloman Kill; plates 3 and 4), axial plane parallel cleavage which cuts extensional calcite veins (section "Glenmont"), and consistent axial plane orientations (appendix A). Together with the absence of any criteria indicating soft sediment deformation, such as folds sandwiched between undeformed bedding planes or sedimentary truncations of folds (Hobbs et al., 1976), this evidence indicates that these folds were formed in a tectonic deformation.

Fold orientations for separate areas are plotted on stereographs in figures A1-A7. Summarized fold orientations are plotted on figure 18 and plate 1. It can be seen from these figures that a nearly continuous orientation change occurs from west to east. Nearly all of the folds have easterly dipping fold axial planes and plunging hinge lines. From west to east, hinge lines become gradually more steeply plunging and easterly trending; from near-horizontal north-south trending to steeply plunging, east-southeast trending. Fold axial planes in the central domain are mostly steep, and a few dip to the west. To the east, the axial planes first become moderately east-dipping, and then more steeply east-dipping. Additionally, tight to isoclinal folds are common in the east; western folds are more open.

It is believed that this progressive west to east change in fold orientations and styles represents the progressive development of folds through time and that the more westerly folds represent the earliest stages of fold development, which have later become tightened and reoriented to give fold styles seen in the east. This correlation of progressive west to east spacial changes with temporal changes is consistent with the known east to west time transgression of the flysch facies (Chapter III) and the east to west transport of the Taconic Allochthon (Chapter II). The deformation of these sediments is thus viewed as a part of a continuous westerly migration of structural events associated with the emplacement of the Taconic Allochthon (Chapter VII). Complications introduced by fold geometries found within the Normans Kill gorge and the Glenmont chert terrane have been treated in sections "Normans Kill Gorge" and "Glenmont," respectively.

Apparently, then, folding initiated as upright buckle folds and kinks associated with east-west compression, probably with a moderate component of east over west shear strain creating a dominance of east-dipping axial planes (e.g., Ghosh, 1966). These folds then develop constant moderate easterly dips, probably associated with an increasing east over west shear component, and variably oriented hinge lines showing mostly steep plunges. This reorientation of hinge lines can be explained in several ways. In many areas where fold hinge reorientation is associated with overthrusting or high strain zones, hinge line reorientation has been attributed to the rotation of linear elements into the principal elongation direction under homogeneous strain (Flinn, 1962; Sanderson, 1972; Escher and Watterson, 1974). While this may have played an important part in the reorientation of hinge lines here, it seems likely that along strike strain gradients are also important. With the large lateral lithologic variations common within this area, as within most flysch terranes (Mutti and Lucchi, 1978), and the probable along strike variations in applied stresses, it is to be expected that strains will vary considerably along strike. These strain variations, both on very localized and regional scales, should result in hinge line culminations and the formation of plunging hinge lines (e.g., Ramsay, 1967, p. 436). With increased straining these local variations may then be amplified to give the observed west to east change in fold orientations (e.g., Minnigh, 1979; Cobbold and Quinquis, 1980). The importance of lithology on fold reorientation seems well demonstrated by comparing the fold orientations found within the thick greywacke beds of the Vloman Kill gorge with the fold orientations found within the shaly outcrops near Cedar Hill or at Normansville. Within the Vloman Kill outcrops fold plunges average approximately 20 degrees; in the shaly outcrops fold plunges average 40 to 70 degrees (plate 1). The Vloman Kill folds are correspondingly more open and less disrupted than the folds within the shaly outcrops. This suggests that the thick greywacke beds were less easily strained and, therefore, folds underwent less hinge line rotation.

Generalized strain orientations for the central domain can be derived by assuming λ_3 to be perpendicular to the average fold axial plane orientations (e.g., Ghosh, 1966), and λ_1 to lie within the average fold axial plane, perpendicular to the average fold hinge lines (e.g., Wood, 1973). This gives a hypothetical strain ellipsoid with λ_1 plunging 68° to 083°, λ_2 plunging 05° to 185°, and λ_3 plunging 22° to 276°. In the eastern domain, however, different assumptions must be made if hinge lines have been rotated. Here with hinge lines rotating into λ_1, a hypothetical strain ellipsoid is oriented with λ_1 parallel to the fold hinge maximum plunging 47° to 127°, λ_2 plunging 10° to 028°, and λ_3 plunging 41° to 290°. The main differences are that the $\lambda_1 - \lambda_2$ principal flattening plane has shallowed and that the entire pattern is rotated slightly towards the southeast. This suggests that horizontal shear strains have become more important as the deformation progressed, causing the $\lambda_1 - \lambda_2$ plane to be rotated towards the west. The southeastwards shift in orientation suggests that these two areas may have been experiencing compression in slightly different directions.

Strain magnitudes are more difficult to estimate, but are presumably very large in areas where hinge line rotation has occurred. A simplistic calculation can be made assuming a fold initially forms with an axial plane parallel to the $\lambda_2 - \lambda_3$ flattening plane (e.g., Ghosh, 1966), and with a hinge line pitching 15° from the λ_2 direction (for a worst case). If we assume the fold undergoes plane strain, an elongation of approximately 14 ($\lambda_1^{1/2}$) is required to passively rotate the hinge line to within 15° of λ_1 (e.g., Sanderson, 1972). If rotation of hinge line has occurred as postulated, rotations of more than 60° are apparently common (figures A2, A3, A5) and the total strains must be extremely high. Unfortunately, independent strain measurements are not available for confirmation.

Cleavage

Slaty cleavage is generally poorly developed within the field area and is only locally well developed within the Vloman Kill, Glenmont, and Normans Kill exposures (sections "Vloman Kill Gorge," "Glenmont," "Normans Kill Gorge"; figures 37, 43). In these exposures, slaty cleavage occurs as a penetrative, planar foliation which is best developed within the siliceous argillites, siltstones and fine-grained greywackes. Many exposures of siltstone show strong bedding-parallel fissilites. However, only foliations nonparallel to bedding have been used in the determinations of cleavage orientations. Slaty cleavage generally dips moderately to steeply east and is parallel with associated fold axial planes (appendix A). Some apparently random cleavage orientations occur within the Normans Kill gorge outcrops, possibly due to post-cleavage slumping (section "Normans Kill Gorge"). Steep westerly dipping slaty cleavage occurs locally within siltstones of the Vloman Kill exposures, associated with a strongly divergent cleavage fan (in the sense of Ramsay, 1967) probably due to the effects of folding heterogeneously layered strata (section Vloman Kill). As slaty cleavage occurs only within those outcrops dominated by relatively strong lithologies; that is, greywackes and cherts which may have resisted deformation (sections "Eastern Domain," "Folds"), it is suggested that phacoidal cleavage replaces, or develops in place of, slaty cleavage in areas dominated by easily strained shales. At Glenmont and Vloman Kill gorge, for example, slaty cleavage dominates with phacoidal cleavage occurring at the boundaries of these resistant lithologies (sections "Vloman Kill Gorge," "Glenmont"). Within the Normansville exposures, blocks of siltstone or fine-grained arenite with a planar slaty cleavage are enclosed by shales with a phacoidal cleavage (figure 45).

The irregular, east-dipping phacoidal cleavage (figures 24, 30, 31, 33, 34, 35, 36, 45) is the most common secondary foliation within the field area. Phacoidal cleavage occurs within the shaly outcrops of the central domain as well as within a narrow disrupted zone in the Vly Creek exposure (sections "Vly Creek," "Eastern Domain"). Phacoidal cleavage is defined by the aligned long axes of lensoid chips or phacoids of siltstone and shale, and commonly lenses or clasts of greywacke or other rock fragments, including fold hooks. Often the surfaces of siltstone chips appear polished and show down-dip striations. Microscopically, the cleavage is defined by anastomozing dark films of pelitic material surrounding lensoid shale or siltstone chips. Truncations of earlier foliations are common in thin-section and offsets and asymmetric folds have been observed. A shear origin for this phacoidal cleavage is suggested by the common down-dip striations and is in agreement with microstructural observations and the general association with asymmetric folds and overthrusting. Mesoscopically, phacoidal cleavage is associated with disrupted beds and steeply plunging fold hooks, suggesting

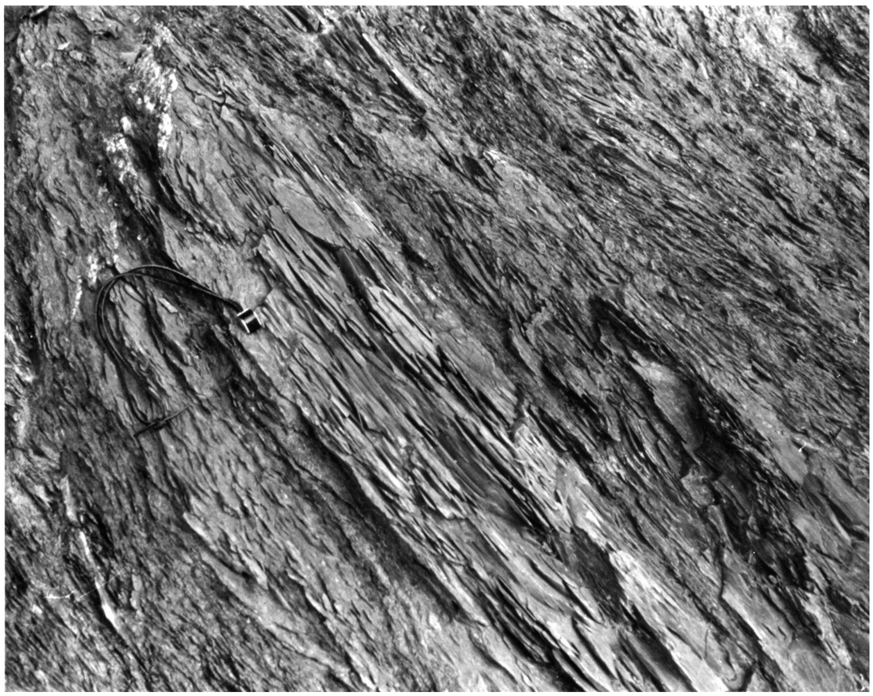


Figure 45. – Block of fine-grained arenite with a planar slaty cleavage enclosed by phacoidally cleaved shales. Normansville, N.Y.

an association with large strains (section "Folds").

The main problem in trying to develop a model for the origin of this cleavage is that the magnitudes of the strains associated with its development are not known, and the orientations of these strains are not well constrained. The orientations of folds within the eastern domain suggest that the principal flattening plane dips roughly 45° east-southeast and that the principal elongation direction plunges to the southeast (section "Folds"). Less well constrained evidence for the orientations of major fault planes suggests that they dip gently in an easterly direction (section "Faults"). This suggests that phacoidal cleavage planes dip at moderate angles to principal shear planes and that they are subparallel to the principal flattening plane. This geometry suggests a model to explain the origin of phacoidal cleavage through the rotation of material planes (in this case, cleavage folia) with respect to the infinitesimal strain ellipsoid in a simple shear deformation. Thus, it is not believed that phacoidal cleavage planes are parallel to major shear planes. Rather, they may represent surfaces which have been rotated out of the principal flattening plane into planes experiencing shear strain during a continuous, non-coaxial, shear deformation. New cleavage folia may then form, cross-cutting the rotated older folia to produce the complex anastomosing fabric (Bosworth and Vollmer, 1981).

Faults

Although faulting appears to be one of the principal modes of deformation within the field area, the orientations, offsets, and locations of large faults are not well constrained. In many cases, the deformation due to faulting may be impossible to distinguish from the general disruption caused by brittle failure suffered during differential extension. Small scale faults are generally the only brittle features easily measured. Within the western portion of the field area only one fault was observed, a near-bedding parallel thrust fault showing an east over west shear sense (section "Western Domain"). In the central domain narrow faults dip both northwest and southeast and are locally associated with kink folds and bedding flexures, indicating that they are related to east-west compression (figures 21, 22, 23; section "Central Domain"). Within the eastern domain most slickensides dip to the southeast with southeast-plunging striations (appendix). Within the Vloman Kill outcrops the orientations are more complex, possibly due to the influence of lithologic contrasts (section "Vloman Kill Gorge"; figure A6; plate 3). At Normans Kill gorge, slickenside orientations may have been additionally complicated by a slumping event (section "Normans Kill Gorge"). Within the Glenmont chert body, narrow slickenside surfaces are common, and striations and stepped fibers clearly indicate thrust solutions with a southeast over northwest fault throw (section "Glenmont"; figure A7).

The only large-scale fault whose location and orientation can be at all well constrained is the contact between the Glenmont chert body and the underlying mélange. This fault contact appears to be near-horizontal (section "Glenmont"). If it is true, however, that the phacoidally cleaved mélange represents a shear fabric (section "Cleavage"), then overthrusting may have taken place over fairly wide zones rather than on individual faults. This may account for the progressive surfacing of older units to the east (Ruedemann, 1930). Boundaries have been drawn on plate 1 along the known extent of areas whose structural style is dominated by phacoidally cleaved shales and discontinuous fold hooks with common steeply plunging hinge lines. These areas represent, in accord with the evidence presented within this thesis, regions of high strain bounded above and below by rock units whose deformation has been less intense. These boundaries thus represent zones across which high strain gradients exist.

Thus, the Glenmont chert terrane, and the small chert body within the Normans Kill (section "Western Mélange"), are believed to be structurally coherent bodies which have been overthrust onto more plastic shales. These chert terranes may have been brought up as hard fault slivers along major displacement horizons. To the east another fault slice is defined by greywacke outcrops seen in the vicinity of South Bethlehem, the Vloman Kill outcrops and small outcrops on State Route 144 (plate 1). Although poorly constrained, this area consists of mainly thick-bedded greywackes interbedded with shales. These greywacke outcrops have undergone relatively less strain than the surrounding shales (section "Vloman Kill Gorge").

Mélange

The formation of mélange within this area was the result of the interaction of sedimentary and tectonic processes. Sedimentary processes, in particular olistostrome deposition, became increasingly important as the Taconic front is approached. This is presumably due to the increased development of fault scarps, and the development of significant relief to allow slumping and the deposition of olistostromes. Evidence for these processes can be seen in outcrops east of the Hudson River (figures 8, 9; section "Mélange and Olistostromes"). It is believed that most of the carbonate lithologies were introduced into the mélange as olistostromes shed off of thrust slivers of shelf carbonate or Taconic lithologies (section "Mélange and Olistostromes"). Similarly, much of the siliceous argillite and chert may have been shed of off uplifted thrust slivers; chert is clearly present as detritus within the greywacke (sections "Greywacke, Siltstone and Shale," "Chert and Siliceous Argillite"). However, it is believed that the Glenmont chert body, and probably other smaller ones, were emplaced as thrust slivers rather than slide blocks. This is suggested by the correlation of structures within the chert body with those of the surrounding rock (section "Glenmont").

For the most part, the Taconic mélange appears to have formed through the tectonic disruption of an original stratigraphic sequence. If the observed spatial west to east increase in deformation intensity represents the progressive deformation of these rocks through time (section "Folds"; Chapter VII), then mélange formation has occurred through initial folding (sections "Western Domain, "Central Domain"), tightening,boudinage, and shearing (sections "Central Domain," "Eastern Domain"). In more shaly units, and closer to the Taconic front, strains were higher and disruption was more complete. Local areas of resistant lithologies have remained as coherent blocks and slivers (sections "Vloman Kill Gorge," "Glenmont"). Surfacing of older lithologies due to asymmetric folding and thrusting has lead to the incorporation of older lithologies into the mélange (plate 1).

The formation of the mélange at Normans Kill gorge remains somewhat enigmatic. Although the mélange here clearly has a tectonic history, the structural evolution of these rocks has not been uniquely defined. A refolding model with abundant shearing and general disruption can account for the deformation in this area. However, the unusual orientations of the structures and their apparent localization to this single area suggest the influence of a local perturbation in structural style. The simplest explanation may be that a slumping event has occurred here (section "Normans Kill Gorge").

Post-Taconic Deformation

The present study area was chosen partially because of its proximity to the post-Ordovician unconformity with the overlying Devonian Helderberg carbonates (Ruedemann 1930, 1942; Goldring, 1943; Chadwick, 1944). These Devonian carbonates have been folded and thrust during a later, probably middle Devonian (Acadian) deformation (Ruedemann, 1930; Rodgers, 1967). It was believed that a comparison of structures within the Helderberg plateau with those found within the Ordovician flysch sequence might allow an estimate to be made of the strain partitioning between these two sequences, or at least to give a control on the amount of post-Ordovician deformation within the flysch sequence. However, a complete study of the deformation within both sequences was found to be beyond the limits of this work.

The extent of obvious mesoscopic folding and faulting within the Helderberg plateau was mapped by Ruedemann (1930; figure 18). This limit is four to five kilometers west of the extent of obvious mesoscopic folding within the Ordovician flysch sequence. Probable Acadian age cleavage, however, can be found for another ten to twenty kilometers to the west (Geiser, 1978; Bill Gregg, 1979, pers. comm.). Bedding-parallel thrust faults can be seen within several exposures of the unconformity within the lowermost carbonate horizons. One thrust is well exposed on the State Route 23 ramp near Catskill, New York, and similar thrusts occur at the exposure of the unconformity in Spryt Creek near South Bethlehem. Other examples are cited by Murphy et al. (1980). This bedding-parallel thrust faulting suggests that much of the shortening envolved in the Acadian deformation may have been accommodated above one, or possibly many decollément surfaces.

Perhaps the best evidence that Acadian deformation was not important in producing significant structural changes within the Ordovician rocks occurs at the Spryt Creek exposure near South Bethlehem. Here the Devonian Helderberg Group unconformably overlies phacoidally cleaved shales containing clasts and lenses of siliceous argillite and siltstone and, in nearby outcrops, greywacke blocks and steeply plunging fold hooks (section "Eastern Melange"; figure 34). Other known exposures of this unconformity show that in general it is a high angle unconformity and truncates Ordovician structures. From field observations it seems likely that any post-Taconic deformation resulted only in the tightening of older structures; no clear interference structures are observed.

CHAPTER VII

DISCUSSION

The regional relationships, depositional environment, structural features and interpreted structural histories presented in the proceeding pages suggest a model for the development of these deformed middle Ordovician flysch deposits involving their syndepositional deformation in front of the advancing Taconic Allochthon. The westwards transport of the Taconic Allochthon and the westwards progradation of the associated flysch deposits (section "Geologic Setting") suggests that west to east changes in structural styles may represent the progressive development of structures through time (section "Folds"). Thus, perhaps structural development occurred as an east to west migration of a deformation "front." One problem with applying this model to a general progressive deformation is that the present geometries do not reflect an arbitrary time frame, but rather the moment at which deformation ceased. Thus, it is possible that the structures seen at present are the result of special characteristics, such as slower strain rates, atypical of the entire deformation process. The possible effects of slower strain rates, or deaccelerating strain rates, on the development of structures within the area is not clear. Slower strain rates should increase the ductility of some rocks under certain conditions (Handin, 1966) resulting in less brittle structures; however, the possible behavior of a multilayered greywacke-shale sequence is not known. Slower strain rates might also affect the sedimentation rate within this environment. With slower uplift along fault scarps, erosion will occur more slowly and sediments should be generally finer. This might produce deposits with different material properties (i.e., more shale) and should reduce the amount of large-scale slumping. However, the observed sequence of structures and sedimentary features seems best explained by a continuous deformational process. Also, many characteristics of the Taconic mélange are common to other mélanges suggesting that similar processes occur elsewhere, and that this is not a unique deposit.

Overthrusting of the Taconic Allochthon onto the continental shelf from the east or southeast during the medial Ordovician resulted in high relief and the shedding of sediments into a trough to the west (section "Depositional Environment and Provenance") created by the flexure of the loaded lithosphere (e.g., Dickinson, 1977). Deposition of sediments into this trough probably resulted in the formation of submarine fan complexes, with localization of very coarse deposits nearest to active uplifts. As the Allochthon advanced, sediments furthest to the west may have undergone gentle, very open folding (possibly as far as 90 kilometers west of the Taconic front; section "Western Domain"). This was followed by folding and faulting on the limbs of these folds. The orientations of these structures suggest a dominantly east-west compressional origin with a slight east over west asymmetry (sections "Central Domain," "Structural Synthesis"). Continued deformation appears to have lead to the tightening of folds and to the rotation of fold hinge lines. The rotation of fold hinge lines is most pronounced in shaly outcrops where discontinuous fold hinges float in a phacoidally cleaved matrix. Fold axial planes of these folds shallow to 40 to 50°, probably due to increased east over west shear strain (section "Folds"). Striations on cleavage phacoids indicate that shear strains may have been important in its formation, and the presence of abundant steeply-dipping, rootless fold hooks indicates that large strains must have occurred (section "Folds"). In outcrops where thick-bedded greywackes are common, fold hinges appear to have remained near-horizontal, bedding is less disrupted and phacoidal cleavage is not generally present, although slaty cleavage may be (section "Eastern Domain"). This suggests that the observed structural features and the amount of strain undergone were strongly dependent on lithology. Apparently, high shear strains have been concentrated within zones of phacoidally cleaved shales.

One final structural event seems to involve the steepening of structures as the Allochthon is approached. This can be seen in the phacoidal cleavage orientations and the easternmost fold axial plane orientations (plate 1, figure A5). This may have occurred due to rotation during progressive overthrusting on listric fault surfaces, or to an increased component of east-west flattening (Bosworth and Vollmer, 1981). Fold development, then, cannot be explained completely through a progressive simple shear model. An additional component of rigid body rotation or pure shear is required to explain the observed fold orientations. Finally, it seems unreasonable to assume that strains have been homogeneous at most scales, primarily because of the continuous lithologic variations.

The source of blocks within mélange terranes has been a subject of debate among many geologists, in particular the incorporation of exotic blueschist and high grade metamorphic blocks within essentially unmetamorphosed shales (Karig, 1980). In the Taconic mélange, many of the blocks found within the phacoidally cleaved shales are best explained by the boudinage and disruption of bedded greywacke-shale sequences (sections "Vly Creek," "Eastern Domain"). However, the presence of chert and siliceous argillite blocks within the western mélange terrane and carbonate blocks within the eastern mélange terrane (section "Eastern Mélange") requires a different explanation, as these lithologies are not found interbedded with the greywacke. If these two mélange terranes represent zones of high shear strain with an east over west sense (section "Cleavage"), then rock to the east of these zones much have been uplifted, creating high relief and rapid erosion. Thus, the western mélange terrane may have received sediments cannabilized from older uplifted greywackes, and from the Mount Merino cherts. The Glenmont chert body probably represents one such fault sliver. Additionally, slumping of uplifted, deformed sediments along a fault scarp may have created the complex structures seen within the Normans Kill gorge (section "Normans Kill Gorge"). Further east, similar uplift of the older rocks of the Taconic Allochthon, and underlying shelf carbonates allowed the incorporation of blocks of Taconic and shelf affinities into the eastern mélange (figure 46).

Although many early models for the emplacement of the Taconic Allochthon suggested hard-rock thrusting from the east (Walcott, 1888; Keith, 1912; Ruedemann, 1914), recent interpretations have been dominated by the ideas of Zen (1961, 1967; Bird, 1969; Bird and Dewey, 1970) who advocated a soft-rock gravity slide for the emplacement of the lower Taconic slices (Giddings Brook and Sunset Lake slices, Zen, 1967). Rickard and Fisher (1973) by analogy, argued that the Austin Glen greywackes and Mount Merino cherts of upper Normanskill age represented an earlier, pre-Giddings Brook, gravity slide, although their fossil data has been disputed by Berry (1973). Recent mapping within the Giddings Brook slice (Jacobi 1977; Rowley, 1979; Bosworth, 1980) has demonstrated that a coherent stratigraphy exists within the slice and that large, coherent folds are truncated by major thrust faults. These relationships, as well as regional constraints, have been used by Rowley and Kidd (1981) to suggest that the Taconic Allochthon represents an

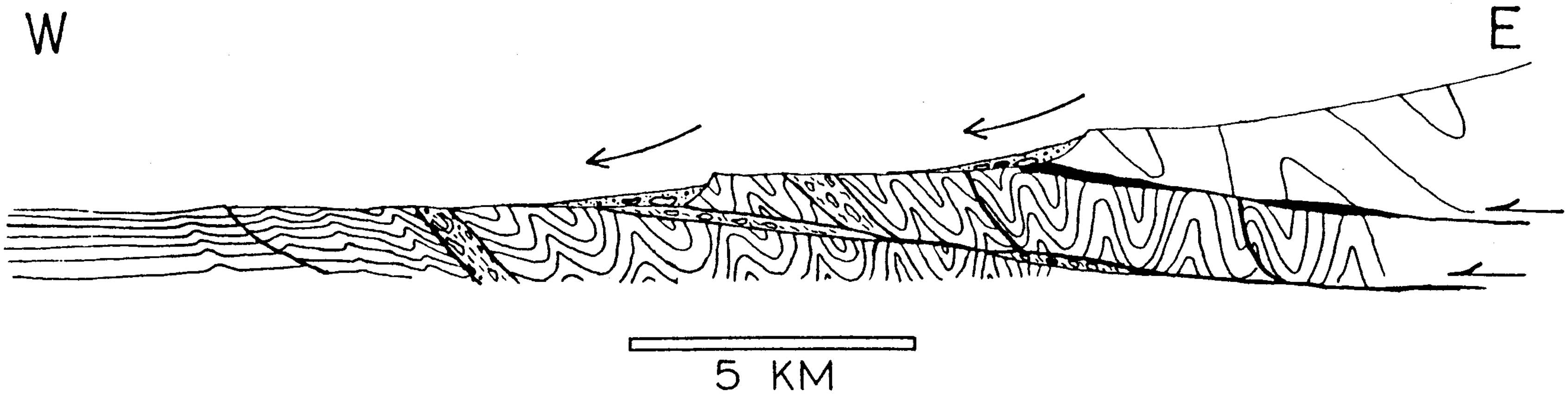


Figure 46. Schematic cross-section from the Taconic Allochthon to the foreland showing depositional and deformational processes inferred to have occurred during the medial Ordovician (Bosworth and Vollmer, 1981).

imbricate thrust package which was progressively stacked from east to west during its emplacement, similar to the proposed history of the correlative thrust sheets of Newfoundland (Stevens, 1970; Williams, 1975) and Quebec (St. Julien and Hubert, 1975).

Structures within the present field area suggest that deformation within the flysch occurred dominantly as a progressive hard-rock deformation associated with thrusting from the east or southeast (section "Structural Synthesis"). The data seem inconsistent with a model proposing a large-scale, gravity-driven slumping event (section "Folds"). Furthermore, the presence of slate, schist and highly deformed rock fragments occurring as detrital grains within the flysch (section "Greywacke, Siltstone and Shale"; Rowley and Kidd, 1981) suggests that significant tectonic deformation of the Taconic Allochthon had occurred prior to, or during, its emplacement. This is in contradiction to Zen's (1967, p. 38) observations which lead him to propose that rocks of the Allochthon were undeformed prior to their emplacement, and that the lowest slice was emplaced first.

The proposed depositional-deformational environment of these greywacke and shale deposits is similar in many ways to that proposed for oceanic trenches (Karig and Sharman, 1975; Seely et al., 1974). Proposed models generally involve the deposition of turbidites within an oceanic trench followed by folding, thrusting, and back-tilting of these sediments during underthrusting. These deformational features have been observed within many oceanic trenches, although variations are common (Chase and Bunce, 1969; Carson et al., 1974; Moore and Karig, 1976; White, 1977; Ladd et al., 1977; Talwini et al., 1977; White and Ross, 1979). Studies of subaerially exposed deposits related to subduction-accretion processes show that mélanges are a major constituent of these assemblages

(Hsü, 1968, 1971; Cowan, 1974; Moore, 1973; Moore and Karig, 1976; Moore and Wheeler, 1978; Hamilton, 1979; Karig et al., 1979). Mélanges are also found in similar overthrusting environments which do not directly involve the underthrusting of oceanic lithosphere (Gansser, 1974; Homewood, 1977; Robertson, 1977; Silver and Beutner, 1980). One aspect of the Taconic mélange which is unusual when compared with other mélange terranes is that the deformation can be traced out into the flat-lying sediments of the foreland. Thus, a structural progression may be observed which allows some interpretation as to the structural history of the mélange. That other mélanges may have formed in a similar manner is suggested by the similar appearance of most mélanges, commonly blocks within a phacoidally cleaved or sheared, "scaly" shaly matrix, and by their common occurrence in overthrust environments. Many mélanges also show discontinuous folds, although their mode of formation is not generally agreed upon, and may include both sedimentary and tectonic histories (Kleist, 1974; Horne, 1969; Maxwell, 1959; Williams, 1977; Hibbard and Williams, 1979; Pajari et al., 1979; Silver and Beutner, 1980).

In a structural study of the Uyak melange of the Kodiak Islands, Alaska, Moore and Wheeler (1978) made systematic measurements of fold orientations. Fold axial planes were found to have average steeply landward (northeast) dipping axial planes striking parallel to the Aleution trench, and fold hinge lines that lie at all orientations within the average fold axial plane. This pattern of fold orientations is similar to that observed in the Taconic mélange, although fold axial planes are less steeply inclined. This suggests that at least some of the processes which lead to the formation of these two mélanges were similar, and that the structural development of the Taconic mélange may have features in common with other mélange terranes.

CHAPTER VIII

CONCLUSIONS

The main conclusions which can be drawn from this study are as follows:

1) The depositional environment represented within the middle Ordovician sediments of this area is a submarine turbidite complex with an eastern source and north-south transport, similar to correlative deposits found along strike within the Appalachian orogenic belt.

2) The structures within this area show a progressive west to east increase in deformation intensity, from nearly flat-lying strata in the west to highly disrupted mélange in the east. This sequence is interpreted to represent the progressive deformation of synorogenic deposits in front of the advancing Taconic Allochthon.

3) Fold development occurred as the progressive tightening and rotation of initially developed near-horizontal folds within a shear environment. This resulted in the formation of discontinuous fold hinges, commonly steeply southeast plunging, but with a spread of orientations within an average moderately east-southeast dipping axial plane.

4) The common irregular, phacoidal cleavage found within the shales and siltstones of outcrops where blocks and discontinuous fold hooks are common is interpreted as a shear fabric developed where strains have been high. This is indicated from its association with east plunging striations, apparently boudinaged greywacke beds and steeply east plunging, discontinuous fold hinges, as well as its regional association with the overthrusting of the Taconic Allochthon.

5) The formation of mélange in this area involved a complex interaction of deformational and sedimentary events. Initial disruption may

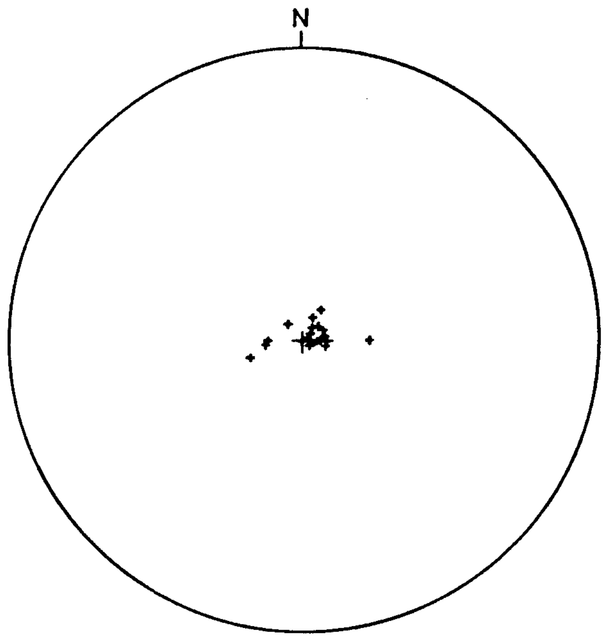
occur through the localization of shear strains within fold hinges, or in thick shaly sequences. High strains result in the boudinage of the brittle greywackes, forming a tectonic mélange of greywacke blocks within a deformed shaly matrix. Imbrication of the original stratigraphic sequence has lead to the formation of sheets or slivers of older lithologies separated by mélange zones. This imbrication has also allowed the local erosion of older units and the incorporation of sedimentary blocks into the mélange. Thus, the Taconic mélange appears to be formed in high strain zones structurally below sheets of more coherent lithologies, dominantly through a progressive tectonic deformation.

APPENDIX A - STRUCTURAL ORIENTATION DATA

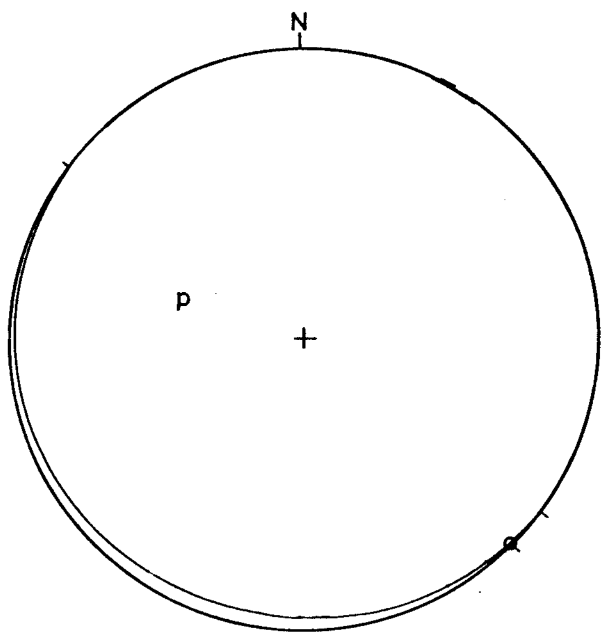
The following seven figures consist of 22 lower hemisphere Lambert equal-area stereographs of structural data from the seven litho-structural domains recognized on plate 1. A separate symbol is used for plotting each type of structural element:

STRUCTURAL ELEMENT	SYMBOL
pole to bedding	✦
fold axis	•
f_2 fold axis	•'
pole to fold axial plane	o
pole to fault or slickenside plane	x
slickenside striation	ϙ
pole to phacoidal cleavage	p
pole to slaty cleavage	s
bedding/slaty cleavage intersection	✝

Where stepped fibrous slickenside striations are present on a slickenside surface the surface is represented as a great circle. The sense of shear parallel to the striation, as determined by the steps (Durney and Ramsay, 1973), is then plotted as a split circle with the solid half representing downward directed motion and the open half representing upward directed motion (Ramsay, 1967, p. 6).

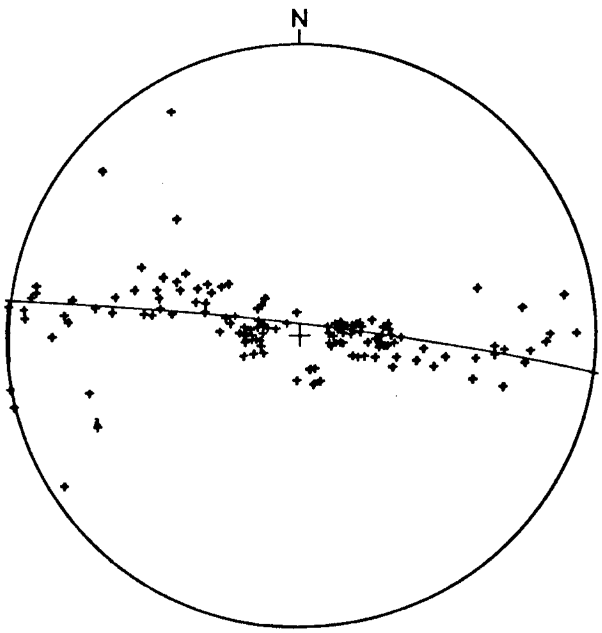


22 ⊥ bedding

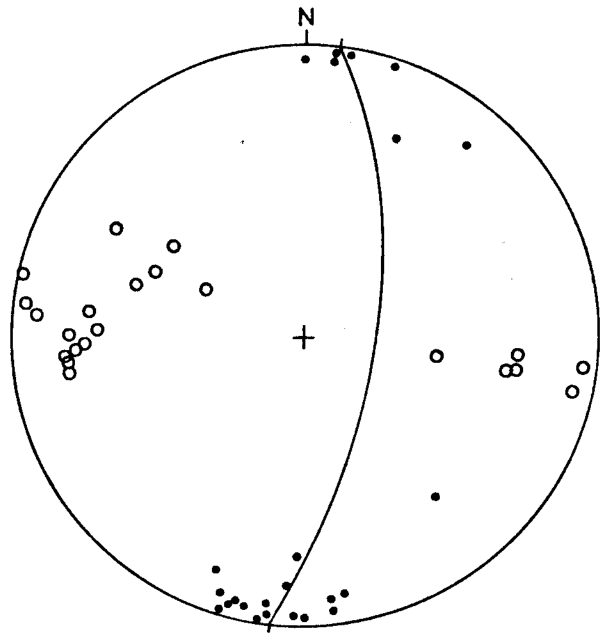


fault
⊥ cleavage
striation

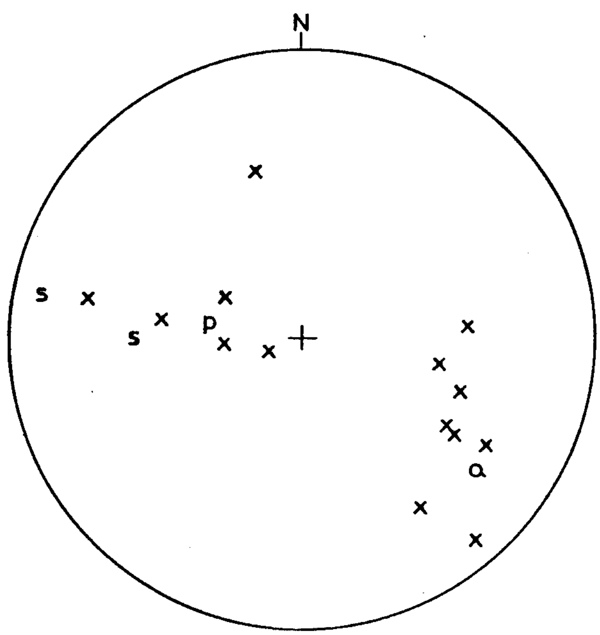
A1 - Western Domain



141 ⊥ bedding

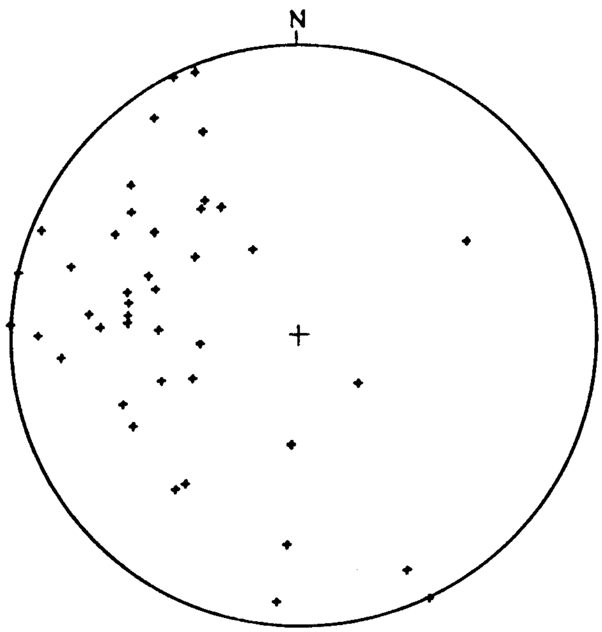


24 fold axes
22 ⊥ axial planes

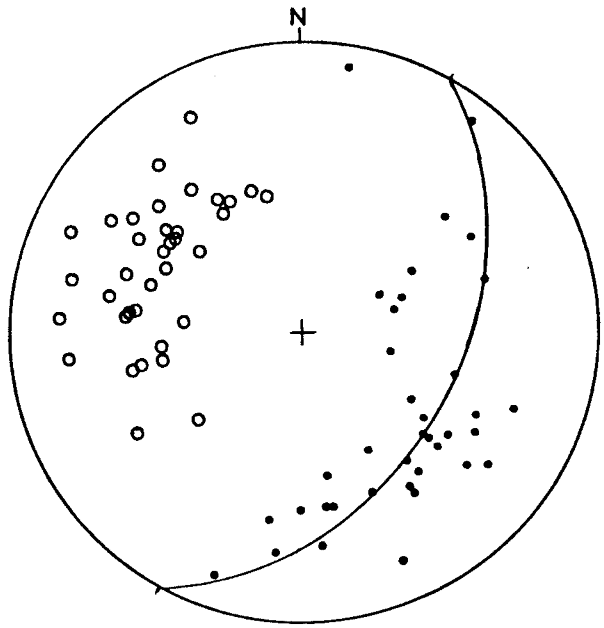


14 ⊥ faults
3 ⊥ cleavage
striation

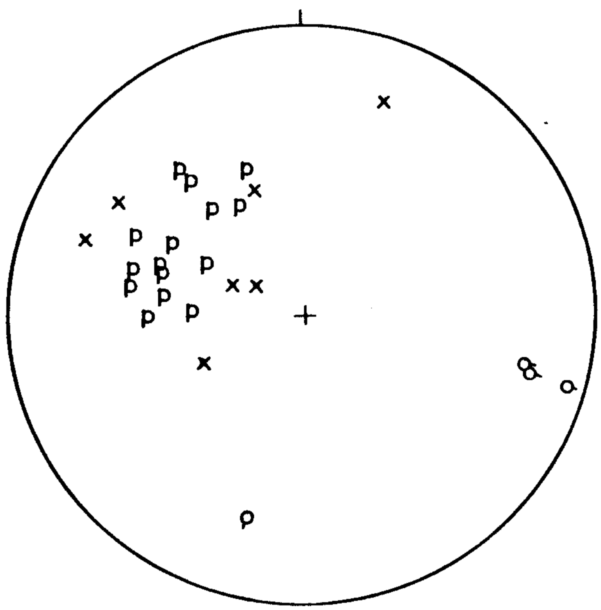
A2 - Central Domain



42 ⊥ bedding

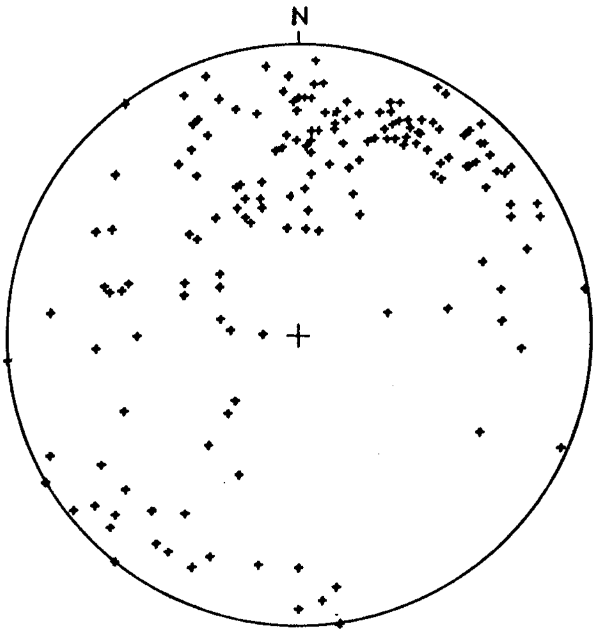


38 fold axes
37 ⊥ axial planes

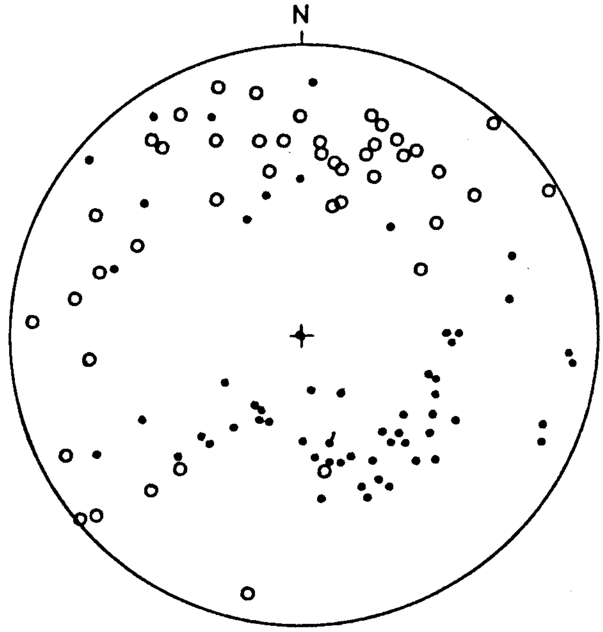


15 ⊥ cleavage
7 ⊥ faults
4 striations

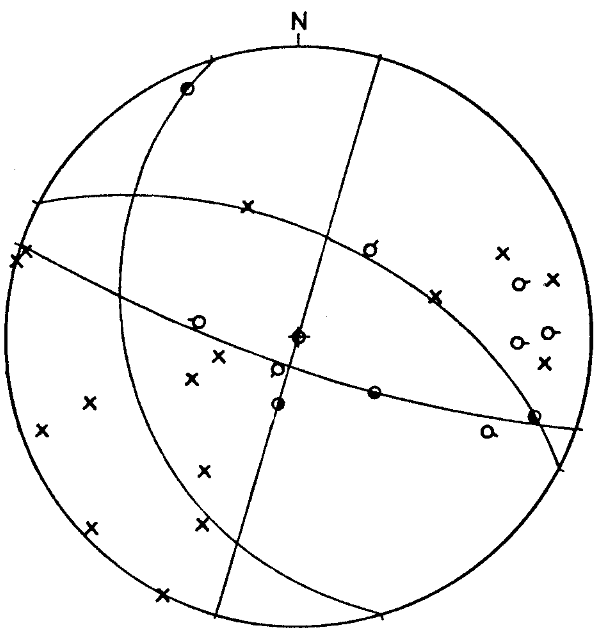
A3 - Western Melange



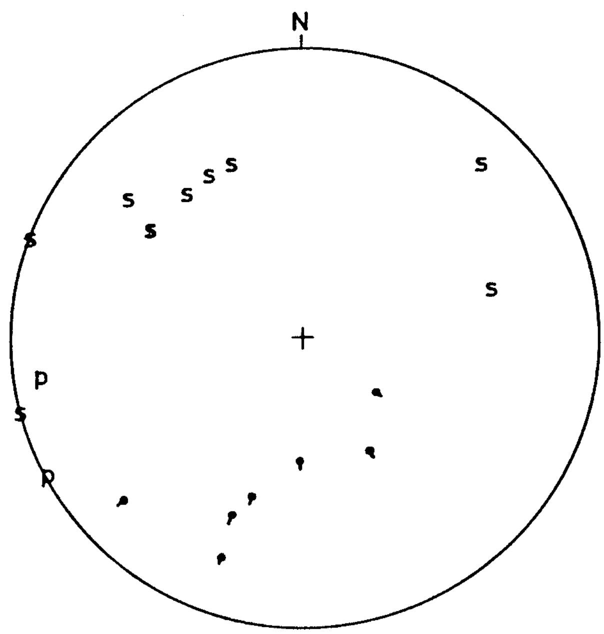
164 ⊥ bedding



57 fold axes
44 ⊥ axial planes
f_2 axis

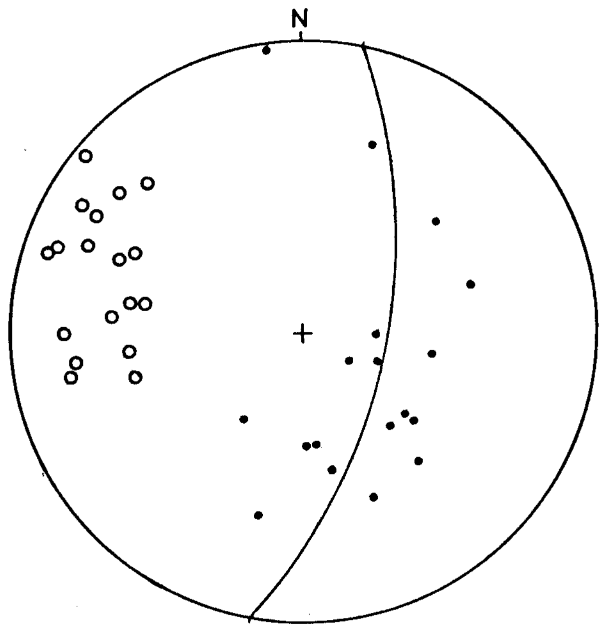


15 ⊥ faults
12 striations

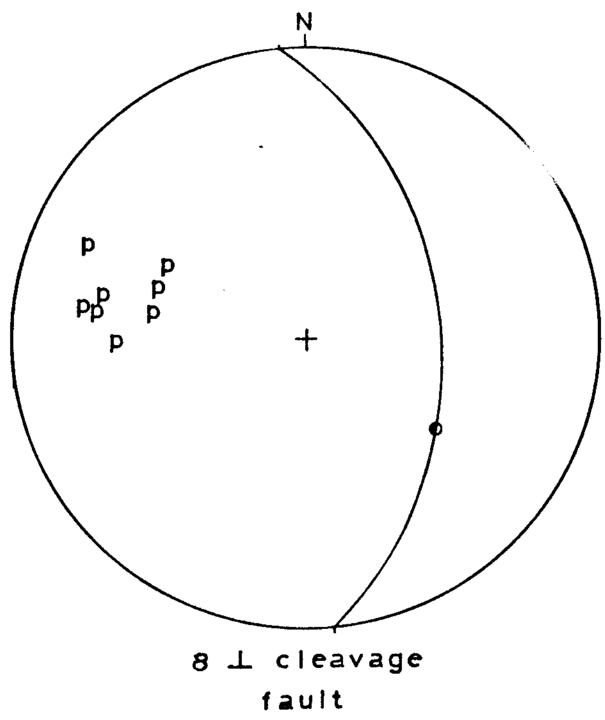


11 ⊥ cleavage
7 bedding/cleavage

A4 - Normans Kill Melange

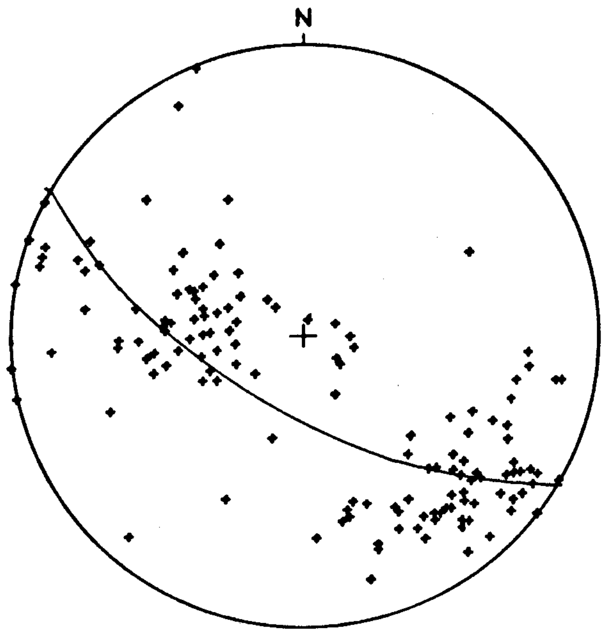


18 fold axes
18 ⊥ axial planes

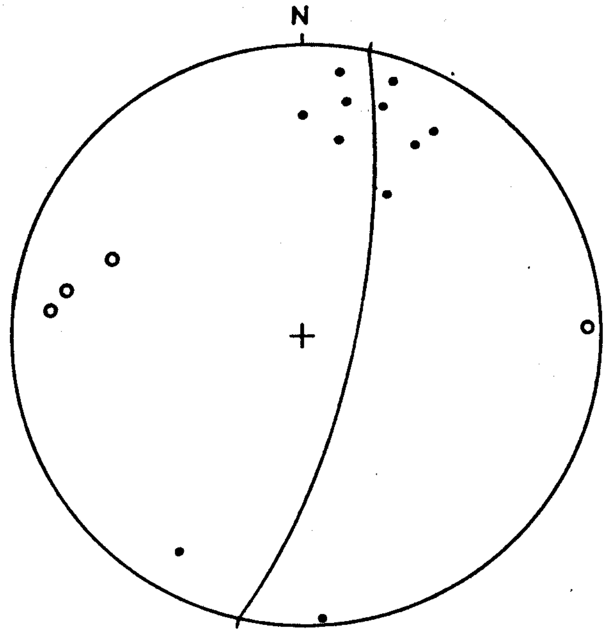


8 ⊥ cleavage
fault
striation

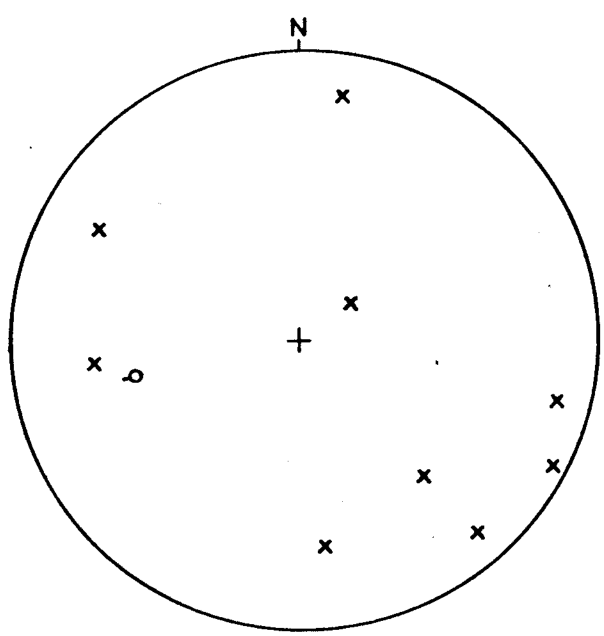
A5 - Eastern Melange



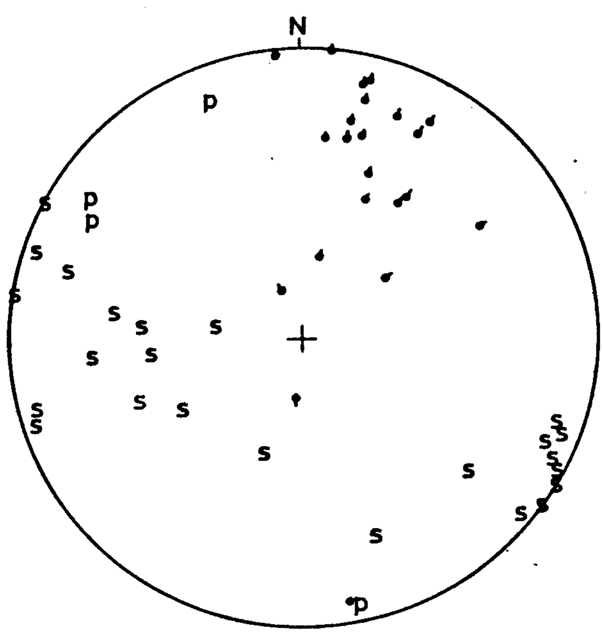
140 ⊥ bedding



11 fold axes
4 axial planes

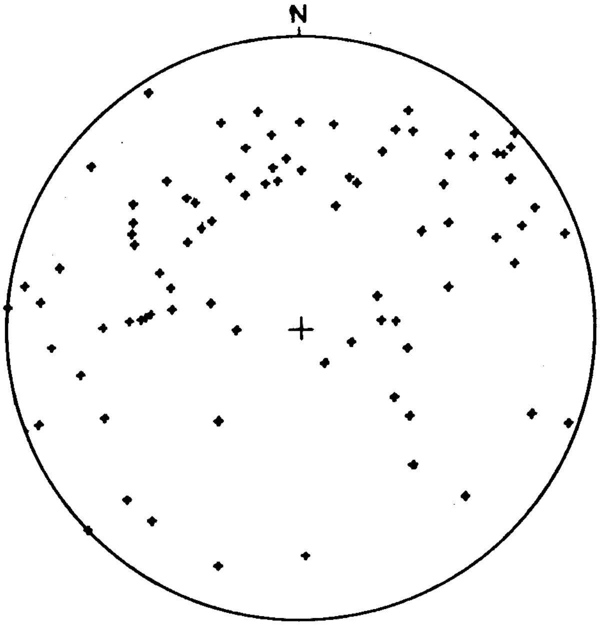


9 ⊥ faults
striation

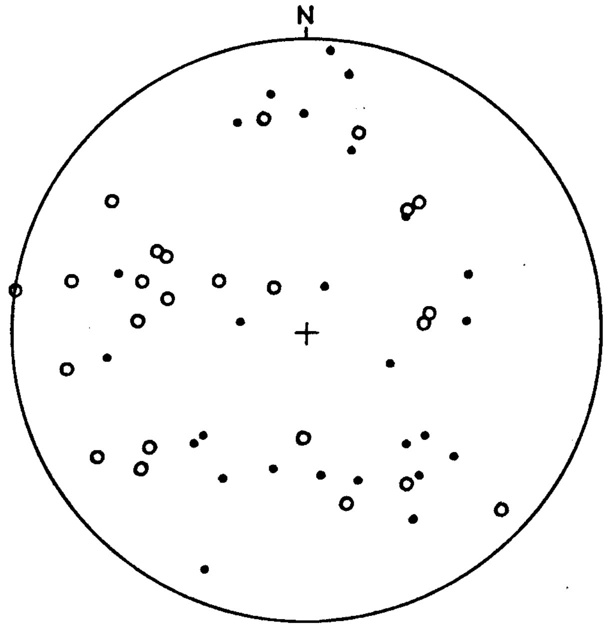


27 ⊥ cleavage
22 bedding / cleavage

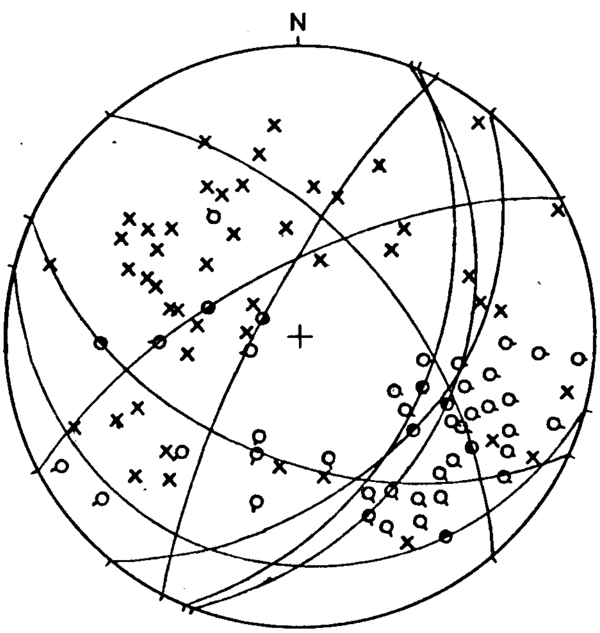
A6 - Austin Glen (?) Graywacke



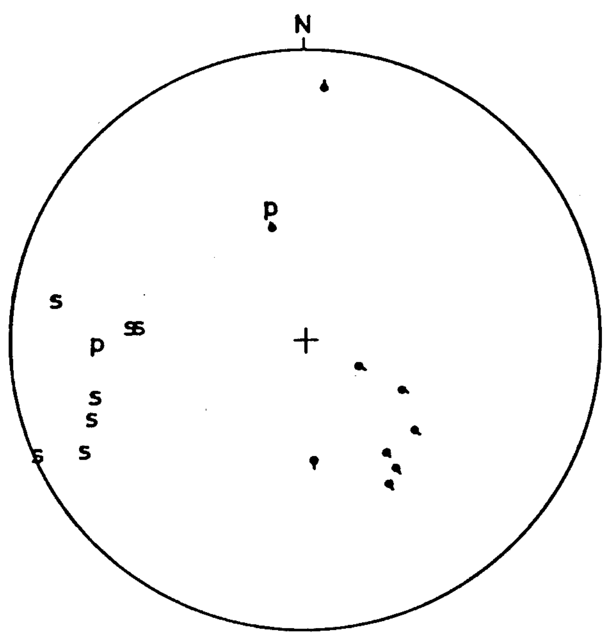
86 ⊥ bedding



26 fold axes
24 ⊥ axial planes



49 ⊥ faults
45 striations



9 ⊥ cleavage
8 bedding/cleavage

A7 - Glenmont (Mount Merino?)
Chert

APPENDIX B - FOSSIL LOCALITIES

Fossil names are given only where the locality is known; therefore many fauna, particularly in the Schenectady beds, may be lacking. Parentheses around a reference indicate a single fossil entry. Parentheses and a question mark following a fossil entry indicate a questionable identification, from Riva, 1974.

Locality	Reference	Fossil (graptolite, unless specified)
1 Kenwood (Normans Kill gorge)	Ruedemann, 1908, p. 13-15	*Amphigraptus divergens* (Hall)
		A. multifasciatus (Hall)
	(Riva, 1974, p.11)	*Amplexograptus sp.*
	(Ruedemann, 1930, p. 99-101)	*Azygograptus? simplex* Ruedemann
("from black shale in the lower part of the Austin Glen Graywacke left bank of Normans Kill, just above an abandoned bridge at Kenwood, NY" -Riva, 1974)	(also Riva, 1974, p. 7)	*Climacograptus bicornis* (Hall)
	(Riva, 1974, p. 19)	*C. brevis strictus* (Ruedemann)
	(also Riva, 1974, p. 25)	*C. parvus* Hall
	(Ruedemann, 1930)	*Corynoides curtis* Lapworth(?)
		Cryptograptus tricornis (Carruthers)
("Austin Glen Graywacke Member, approximately the middle part of it, in railroad cut in the north bank of the Normans Kill 1/8 mile northwest of the old Kenwood bridge and 2 miles S35°W from Albany, New York" -Berry, 1962)	(also Berry, 1962)	*Dicellograptus divaricatus* (Hall)
	(also Berry, 1962)	*D. divaricatus var. bicurvatus* Ruedemann
		D. divaricatus var. rectus Ruedemann
		D. divaricatus var. salopiensis Elles & Wood
		D. mensurans Ruedemann
		D. sextans (Hall)
		D. sextans var. tortus Ruedemann
		Dicranograptus cantortus Ruedemann
		D. furcatus (Hall)
		D. furcatus var. exilis Ruedemann
		D. ramosus Hall
		Didymograptus sagitticaulis (Hall) Gurley

Locality	Reference	Fossil (graptolite, unless specified)
1 continued		*D. serratulus* (Hall) *D. subtenuis* (Hall) *Diplograptus angustifolius* Hall *D. foliaceus var. acutus* Lapworth
	(Ruedemann, 1930)	*D. incisus* Lapworth *Glossograptus ciliatus* Emmons *G. Whitfieldi* (Hall) *Lasiograptus bimucronatus* Nicholson *L. mucronatus* (Hall) *Nemagraptus exilis var. linearis* Ruedemann *N. gracilis* (Hall) *N. gracilis var. approximatus* Ruedemann *N. gracilis, var. surcularis* Hall
	(Riva, 1974, p. 28)	*Pseudoclimacograptus scharenberg* (Lapworth)
	(Riva, 1974, p. 26)	*P. scharrenbergi stenostoma* (Bulman) *Retiograptus geinitzianus* Hall *Thamnograptus capillaris* (Emmons)
	(Ruedemann, 1942)	*Hughmillera prisca* Ruedemann (eurypterid)
	(Ruedemann, 1942)	*Pterygotus normanskillensis* Clarke & Ruedemann (eurypterid)
	(Ruedemann, 1901a)	*Leptobolus walcotti* (brachiopod)
2 Glenmont (mainly from railroad cut at State Route 144?)	Ruedemann, 1908	*Amphigraptus divergens* (Hall) *Azygograptus? simplex* Ruedemann *Climacograptus bicornis* Hall
	(Riva, 1974, p. 18)	*C. brevis strictus* (Ruedemann) *C. parvus* Hall (?) *C. putillus mut. eximus* Ruedemann (?) *C. scharenbergi* Lapworth (*pseudo-climacograptus scharenbergi?*) *Corynoides calicularis* Nicholson

Locality	Reference	Fossil (graptolite unless specified)
	(Ruedemann, 1930)	*C. curtus* Lapworth (?) *C. gracilis mut perungulatus* Ruedemann *Cryptograptus tricornis* (Carruthers) *Desmograptus tenuiramosus* Ruedemann *Dicellograptus divaricatus* (Hall) *D. divaricatus var. bicurvatus* Ruedemann *D. gurleyi* Lapworth *D. sextans* (Hall) *D. sextans var. exilis* Elles & Wood *Dicranograptus furcatus* Hall *D. nicholsoni var. diapason* Gurley *D. nicholsoni var. parvangulus* Gurley *D. ramosus* Hall *D. spinifer* Elles & Wood *D. spinifer var. geniculatus* Ruedemann *Dictyonema spiniferum* Ruedemann *Diplograptus angustifolius* Hall *D. euglyphus* Lapworth *D. foliaceus var. acutus* Lapworth *D. foliaceus var. incisus* Lapworth *Glossograptus ciliatus* Emmons *G. Whitfieldi* (Hall) *Lasiograptus bimucronatus* Nicholson *L. mucronatus* (Hall) *Leptograptus flaccidus mut. trentonesis* Ruedemann *L. flaccidus var. spinifer mut. trentonensis* Ruedemann *Nemagraptus exilis* Lapworth *N. exilis var. linearis* Ruedemann *N. gracilis* (Hall) *N. gracilis var. approximatus* Ruedemann *N. gracilis var. distans* Ruedemann

Locality	Reference	Fossil (graptolite, unless specified)
		N. gracilis var. *surcularis* Hall *Odontocaulis heptaticus* Ruedemann *Ptilograptus poctai* Ruedemann
	(Ruedemann, 1930)	*Retiograptus geinitzianus* (Hall) *Syndyograptus pecten* Ruedemann *Thamnograptus capillaris* (Emmons)
	(Ruedemann and Wilson, 1936)	*Acanthosphaera perspinosa* Ruedemann & Wilson (radiolaria) *Choenicosphaera brevispina* Ruedemann & Wilson (radiolaria) *Dorydictym magnum* Ruedemann & Wilson (radiolaria)
	(Ruedemann, 1901a)	*Leptobolus walcotti* (brachiopod)
3 "Siliceous mudstone in bed of Vloehie Kill, 125 feet west of highway and on southern outskirts of Castleton" -Berry, 1962 East side of Hudson River, ESE of Selkirk.	Berry, 1962, Table 4	*Climacograptus eximius* Ruedemann (?) *C. modestus* Ruedemann (?) *Corynoides calicularis* Nicholson *Cryptograptus tricornis* (Carruthers) *Dicellograptus gurleyi* Lapworth *D. intortus* Lapworth *D. sextans* (Hall) *Glossograptus ciliatus* Emmons *G. teretiusculus* (Hisinger) *Hallograptus mucronatus* (Hall) *Nemagraptus gracilis* (Hall) *Orthograptus calcaratus* var. *acutus* (Lapworth) *O. Whitfieldi* (Hall)
4 "The Penitentiary, Albany" -Ruedemann, 1901	Ruedemann, 1908, p. 37	*Climacograptus curtus* Lapworth *C. putillus* (Hall) (?)
	Ruedemann, 1901a, p. 530	*C. typicalis* Hall
Present site of Veterans Administration Hospital, Albany		*Corynoides curtis* Lapworth (?) *Diplograptus putillus* Hall *D. spinulosus* Ruedemann

Locality	Reference	Fossil (graptolite, unless specified)
	Ruedemann, 1908	*Glossograptus quadrimucronatus* (Hall) *G.? eucharis*
	Ruedemann, 1901a	*Leptobolus insignis* Hall (brachiopod) Undetermined brachiopod
5 "ravine in northern part of Beaver Park" -Ruedemann, 1901 Northwest corner of Lincoln Park, Albany	Ruedemann, 1901a, p. 530	*Diplograptus putillus* Hall
6 Normansville - "small outcrop of shale about a mile farther up" from old bridge	Ruedemann, 1901a, p. 530	*Climacograptus bicornis* Hall (?) *Corynoides curtis* Lapworth(?) *Diplograptus* cf. *foliaceus* Murchison fragments *D. quadrimucronatus* Hall *Leptobolus insignis* Hall (brachiopod)
7 "Ravine by Normans Kill 1/2 mile farther up the river (from 6) in the south bank" -Ruedemann, 1901a	Ruedemann, 1901a, p. 531	*Diplograptus putillus* Hall
8 Black Creek Voorheesville "a small southerly affluent, 4 miles farther up" (from 7) -Ruedemann, 1901a Font Grove Road	Ruedemann, 1901a, p. 531	*Climacograptus typicalis* Hall *Diplograptus putillus* Hall *Orthograptus quadrimucronatus* Hall sp. *Cameroceras protiforme* Hall sp. (cephalopod) *Sagenella ambigua* Walcott *Triarthrus becki* Green (trilobite)
9 Vly Creek, Voorheesville	Ruedemann, 1901, p. 532	*Climacograptus typicalis* Hall *Cameroceras protiforme* Hall sp. (cephalopod) *Sagenella ambigua* Walcott

Locality	Reference	Fossil (graptolite, unless specified)
10 South Bethlehem, Onesquethaw Creek	Ruedemann, 1942	*Eurypterus decipiens* Ruedemann (eurypterid)

Locality (see plate 1)	Tentative Graptolite Zone, Based on Lists of Riva, 1974
1	*N. gracilis*
2	*N. gracilis*
3	*N. gracilis*
4	*C. spiniferus?*
5	?
6	*D. multidens?*
7	?
8	*C. spiniferus*
9	*C. spiniferus*
10	?

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