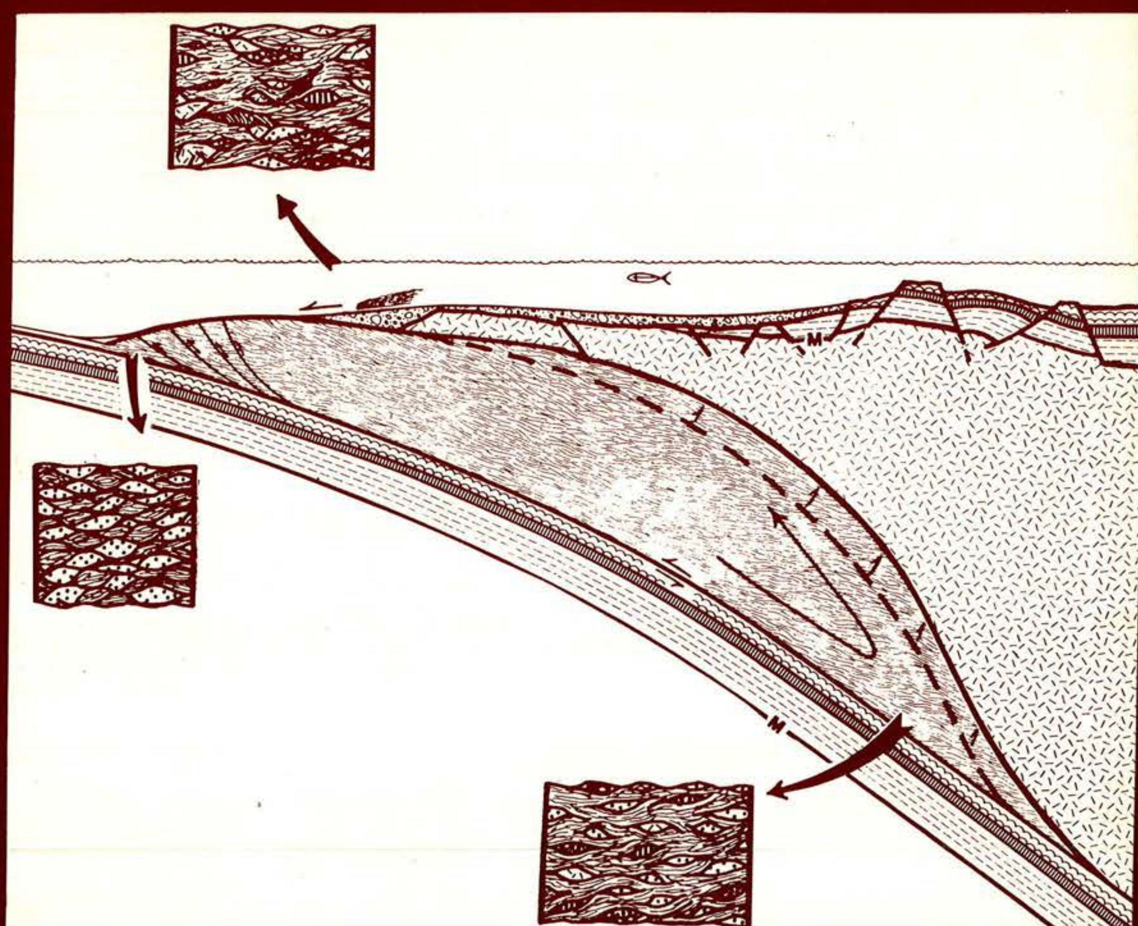
Melanges:
Their Nature, Origin, and Significance

Edited by Loren A. Raymond



THE GEOLOGICAL SOCIETY OF AMERICA · 1888 ·

SPECIAL PAPER

198

Printed in U.S.A.

Geological Society of America
Special Paper 198
1984

Formation of melange in a foreland basin overthrust setting: Example from the Taconic Orogen

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ABSTRACT

The Taconic melanges of eastern New York developed through the progressive deformation of a synorogenic flysch sequence deposited within a N-S elongate foreland basin. This basin formed in front of the Taconic Allochthon as it was emplaced onto the North American continental shelf during the medial Ordovician Taconic Orogeny. The flysch was derived from, and was subsequently overridden by the allochthon, resulting in the formation of belts of tectonic melange. An east to west decrease in deformation intensity allows interpretation of the structural history of the melange and study of the flysch-melange transition. The formation of the melange involved: isoclinal folding, boudinage and disruption of graywacke-shale sequences due to ductility contrasts; subaqueous slumping and deposition of olistoliths which were subsequently tectonized and incorporated into the melange; and imbrication of the overthrust and underthrust sedimentary sections into the melange. The characteristic microstructure of the melange is a phacoidal conjugate-shear cleavage, which is intimately associated with high strains and bedding disruption. Rootless isoclines within the melange have apparently been rotated into an east-west shear direction, consistent with fault, fold, and cleavage orientations within the flysch. The melange zones are best modeled as zones of high shear strain developed during the emplacement of the Taconic Allochthon. Total displacement across these melange zones is estimated to be in excess of 60 kilometers.

INTRODUCTION

The association of melanges with subduction zone deformational processes and accretionary prisms is now widely accepted, although this is clearly not the only tectonic environment for melange formation (e.g., Saleeby, 1979; Page and Suppe, 1981; Jacobi, this volume). The basic phenomena involved in the formation of melanges in subduction zones include the formation of a sedimentary trough in the overthrust zone, infilling of this basin with sediments (flysch), and subsequent progressive deformation of the sediment pile. Additional complications result from the imbrication and incorporation of portions of the overthrust and underthrust sheets into the accretionary complex. Olistostromes may occur in association with the flysch deposits and in some cases appear to play an important role in the formation of melange (e.g., Robertson, 1977). Complex deformational histories, including strike-slip deformation and accretion of exotic terranes, may be expected along convergent plate boundaries (Hamilton, 1980; Karig, 1980). Several problems exist in studying melange formation in this environment. Initial deformation in a trench environment can be studied only through geophysical methods, coring, or submersible observation (e.g., White and Ross, 1970; Moore, 1979; Heezen and Rawson, 1977). Most melanges currently exposed on land have been through a protracted history that may have involved several episodes of deformation not directly related to the initial formation of the melange (e.g., Aalto,

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1981). Additionally, melange contacts are commonly faulted and do not preserve the transition from undeformed rock units into melange (e.g., Moore and Wheeler, 1978; Moore and Karig, 1980).

Melanges may also form, however, in other tectonic regimes involving thrusting. Ophiolitic melanges commonly form during the obduction of ophiolites onto continental margins, although this may not necessarily involve the incorporation of large amounts of flysch into the melange (Gannser, 1974; Williams, 1977; Cohen and others, 1981). Melange may also form through syndepositional deformation of flysch in front of non-ophiolitic thrust nappes, such as the North Penninic Melange of the Prealps (Homewood, 1977). Similarly, during the medial Ordovician Taconic Orogeny, a series of thrust nappes, the Taconic allochthons, were emplaced onto the North American continental shelf. In front of these nappes were deposited transgressive flysch sequences subsequently overridden by the nappes. The interaction of sedimentation and overthrust deformation produced melanges along the western margins of many of these nappes (Williams, 1979; St. Julian and Hubert, 1975; Bosworth and Vollmer, 1981). The Taconic Allochthon of eastern New York, Vermont, Massachusetts, and Connecticut is believed to have been emplaced during the attempted subduction of the North American continental margin into an east-dipping island arc subduction zone, with subsequent migration of the accretionary environment onto the continental shelf (Rowley and Kidd, 1981). The resulting external flysch basin, or foreland basin (Dickinson, 1977), has preserved the transition from undeformed flysch into highly disrupted melange.

Mapping has been done within several subareas in the Hudson Valley lowlands of eastern New York (Fig. 1). This mapping has mainly involved detailed structural analysis and the study of facies distributions. Subareas were chosen to include deformation intensities varying from undeformed flysch to highly disrupted melange. Key localities along the front of the Taconic Allochthon have also been mapped in detail. If we assume that spatial sequences showing increasing deformation intensity, in equivalent rock types, represent the increasing deformation of a rock body through time, we may infer the deformation history of these rocks. This paper discusses the evolution of folds and fabric in the Taconic melange, and the relative roles of tectonic dismemberment, imbricate thrusting, and olistostrome deposition in its formation.

REGIONAL GEOLOGIC SETTING AND STRUCTURAL POSITION OF THE MELANGE

The Taconic Orogen can be divided into three geologic zones or provinces (Rowley and Kidd, 1981), from west to east: 1) Cambro-Ordovician rifted continental margin, including transported sediments of the continental rise sequence (eastern New York and western Vermont, Massachusetts, and Connecticut); 2) suture zone of medial Ordovician age (west side of the Connecticut River synclinorium); and 3) Ordovician volcanic arc terrane (exposed along the eastern edge of Zone 2 and within the Bronson Hill anticlinorium). These correspond approximately to the Humber, Dunnage, and western edge of the Gander zones of Williams (1978). The Taconic Allochthon and associated medial Ordovician flysch lie within Zone 1 (Fig. 1). The allochthon is composed of slightly to moderately metamorphosed argillites and lesser silty or shaly sandstones and limestones, interpreted to represent a transported continental rise sedimentary sequence (Bird and Dewey, 1970). The graywackes, siltstones and shales of the Taconic flysch are found as the youngest unit of the allochthonous terrane, and to the west of and beneath the allochthon. These flysch units were deposited prior to and during emplacement of the Taconic Allochthon onto the North American Cambro-Ordovician shelf (Zen, 1961). Shelf carbonate rocks and sandstones are currently visible in windows through the flysch and on the perimeter of the Adirondack Grenville basement dome northwest of the Taconic Allochthon (Fig. 1).

The central suture zone of the orogen is composed of metamorphosed and highly deformed schists, phyllites and lesser gneisses, with included slivers of serpentinized mafic and ultramafic rocks (Doll and others, 1961; Merguerian, 1979; Merguerian and others, 1982). Glaucophane and omphacite-bearing amphibolites have been found locally within this terrane (Laird and Albee, 1975; Laird, 1981). The boundaries and many internal lithologic contacts of this zone are complex thrust faults or major thrust zones (Ratcliffe and Hatch, 1979; R. Stanley, mapping progress) some with demonstrable Taconic movement (Ratcliffe and Mose, 1978). This amphibolite schist assemblage is interpreted to represent a Taconian suture zone, with shards of dismembered ophiolite as remnants of the early Paleozoic Iapetus Ocean (Merguerian, 1979; Rowley and Kidd, 1981).

The eastern zone of the Taconic Orogen is a volcanic terrane consisting of metamorphosed mafic and felsic volcanic rocks, tuffs, and intermediate composition plutonic rocks (Thompson and others, 1968; Robinson and others, 1979). The basement of this complex is Precambrian gneiss dated at 620 to 600 m.y. (Besancon and others, 1977; Aleinikoff and others, 1979; Robinson and others, 1979) and therefore distinctly younger than the 1.1 billion-year-old Grenville basement of Zone 1 (Hills and Gast, 1964; Silver, 1968; Bickford and Turner, 1971). This eastern terrane is interpreted to represent a volcanic island arc that became sutured to the Paleozoic North American plate in medial Ordovician times (Rowley and others, 1979; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1980).

Analogy with modern convergent plate boundary settings provides a tectonic interpretation for the Taconian geologic provinces. The polarity of the orogen (passive margin in the west, arc in the east) and location of the Taconian suture (central zone) suggest collision above an east-dipping subduction zone (Chapple, 1973), with westward-directed obduction of continental rise sediments and fragmented ophiolite onto the North American continental shelf. This scenario is supported by the westward transgressive nature of the Taconic flysch (Rickard, 1973; Fisher, 1977), which marks the migration of the trench environment

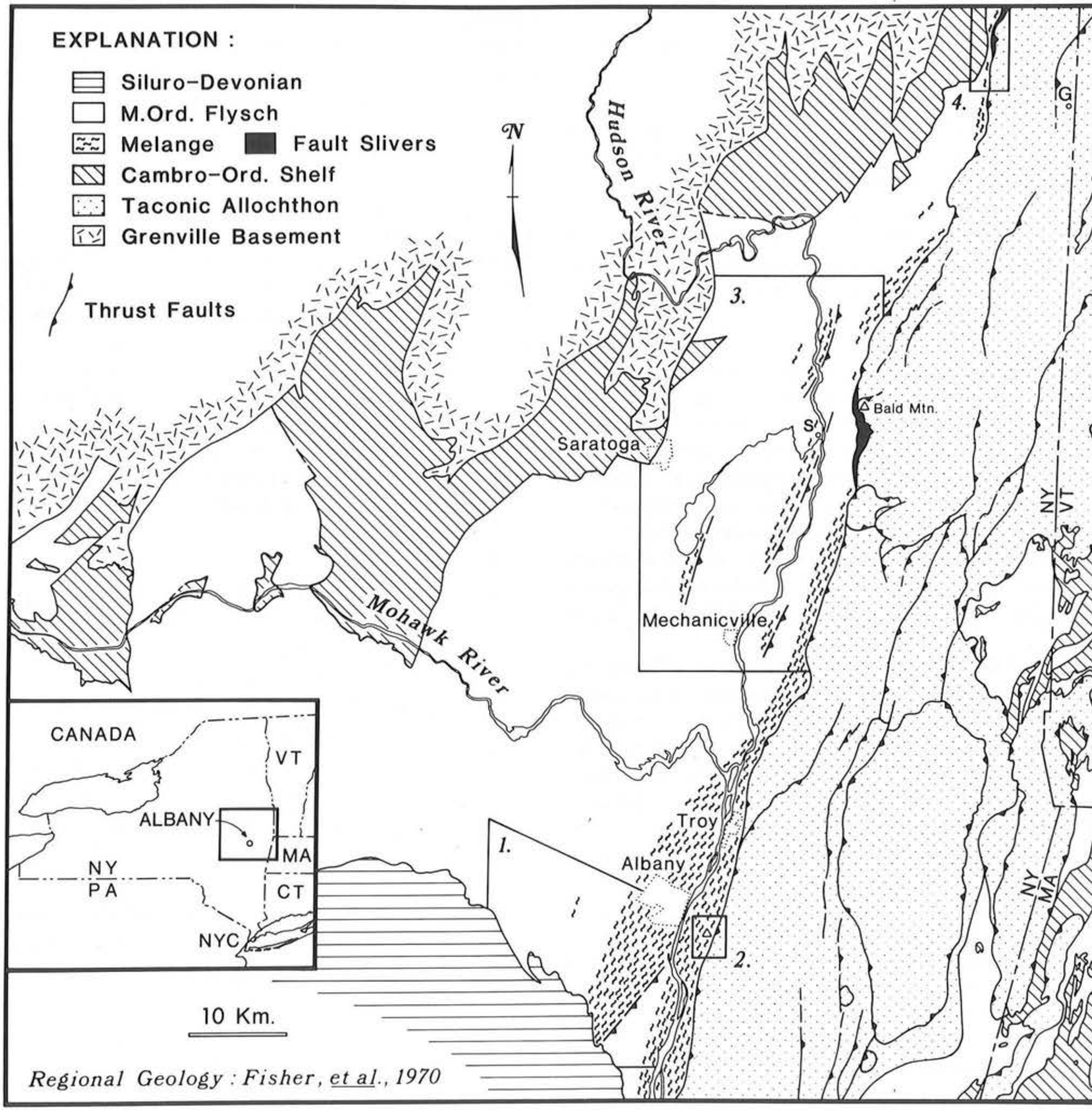

Figure 1. Regional geology of eastern New York. Numbered boxes indicate areas mapped for the present study (1 = Albany area, 2 = vicinity of Rysedorph Hill, 3 = Schuylerville area, 4 = Mettawee River section). Numerous thrust faults suggest internal imbrication of the Taconic Allochthon (stipple pattern). The fold-thrust mode of deformation continues into the flysch (unornamented), where major fault zones are delineated by melange (curl pattern). Modified from Fisher et al., 1970. (S = Schuylerville, G = Granville).

onto the downwarped passive continental margin, a depositional/structural setting that may best be referred to as a "foreland basin" (Dickinson, 1977). Detailed stratigraphic relationships of the Taconic flysch and their bearing on the Taconian arc-continent collision can be found in Rowley and Kidd (1981).

The Taconic flysch can be subdivided into three informal lithologic units: a sequence of interbedded shales, siltstones, and graywackes, with pebbly and rarely bouldery mudstone horizons; a dominantly shaly section, with local thin-bedded siltstones and fine-grained sandstones; and finally, melange (Bosworth and Vollmer, 1981; Vollmer, 1981a; Bosworth, 1980). The interbedded sequence represents the flysch "proper"; sediments deposited by turbidity currents in a longitudinal north-south elongate basin, derived from the arc terrane and advancing allochthons in the east (Rowley and Kidd, 1981, and references therein). Once sediments reached this basin, their transport direction changed to follow its north-south strike (Vollmer, 1981a; similarly observed for the Martinsburg Fm. by McBride, 1962). The dominantly shale unit is probably transitional to the interbedded unit, and corresponds to the more distal, fine-grained deposits of the turbidity flows. This unit is present to some extent within the deformed section of the flysch (Bosworth and Vollmer, 1981, Fig. 5) but becomes dominant farther west, where it is largely unaffected by Taconian deformation.

The final unit, melange, is restricted to flysch structurally beneath the allochthonous terrane or near its western edge. Known occurrences of Taconic melange and areas mapped by the authors are shown in Figure 1. The term *melange* is used in the manner suggested at the 1978 Penrose Conference on melanges (Silver and Beutner, 1980) and refers to a "mappable, internally fragmented, and mixed rock body containing a variety of blocks, commonly in a pervasively deformed matrix." A variety of melange types can be recognized in the Taconic flysch, and it is important that they each be distinguished in any discussion of the evolution or structural significance of melange in the Taconic Orogeny.

Most of the Taconic melange is composed of blocks and clasts of graywacke, siltstone, slate, and argillite in a phacoidally cleaved matrix (discussed below). This lithofacies is equivalent to the "broken formation" of Hsü (1968). This melange type occurs as much as 15 kilometers west of the present allochthon boundary (Fig. 1; Bosworth and Vollmer, 1981, Fig. 5; see also Berry, 1962). Other melange lithofacies of the Taconic flysch are distinguished by the presence of blocks of an exotic nature. Near the allochthon, the melange commonly contains pebble- to boulder-size clasts of quartzite, limestone, dolostone, limestone conglomerate, and chert. These lithologies can be correlated with units of the allochthonous Taconic sequence and with portions of the autochthonous carbonate shelf (Zen, 1967; Bird and Dewey, 1975). In less deformed outcrops, the exotic clasts are generally rounded and occur within an uncleaved mudstone matrix. These deposits are interpreted to have originated as olistostromes, as the most proximal sedimentary facies of the flysch depositional environment.

Some exotic blocks in the flysch are of an unknown affinity. This is particularly true for the melange just south of Schuylerville, New York, at Stark's Knob. Here a single knocker of pillow basalt (~100 m × 30 m × ?) sits within highly contorted shale, accompanied only by blocks of argillite and wacke, and rare clasts of chert. An additional complication arises in that graptolites obtained from shale near Stark's Knob are of early Ordovician age (Ruedemann, 1914; Berry, 1962); these shales are also interpreted to be caught up within the melange as exotic blocks, as flysch deposition in all other preserved parts of the orogen occurred in medial Ordovician times. Further discussion of the structural relationships observed at Stark's Knob can be found in Ruedemann (1914) and Bosworth (1982). The basalts were probably extruded onto the continental shelf in early Ordovician times, and subsequently imbricated into the flysch-melange structural sequence during the Taconian collisional event.

ALBANY QUADRANGLE

Exposures of the Ordovician rocks within the Albany 15 minute quadrangle (Fig. 1, area 1 and Fig. 2) exhibit a wide range of deformation intensities, generally increasing from west to east, within a sequence of shale, siltstone, and graywacke (Vollmer, 1981a). This range of deformation intensities provides an opportunity to study the response of these rock types to increasing strains, and the effect of lithologic variations on deformational style. The rocks of this area have been separated into seven structural domains, shown in Figure 2. Stereograms for these seven structural domains are given in Figure 3. The western flysch domain (domain 1, Figs. 2, 3) comprises mainly near-horizontal sequences of graywacke, siltstone, and shale. Shear zones are rare

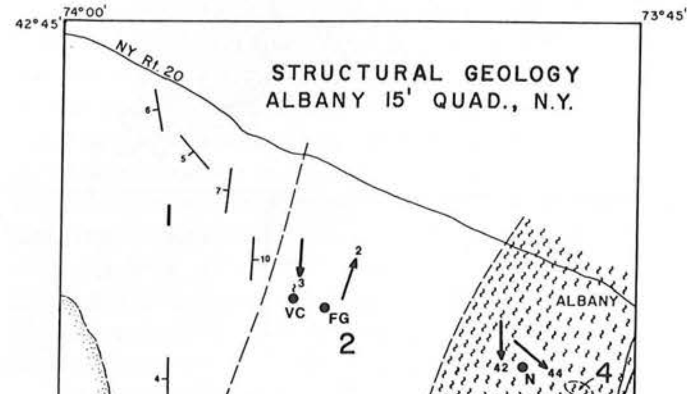

Figure 2. Structural geology of the Albany 15 minute quadrangle, eastern New York. Location is given in Figure 1. Structural symbols represent mean orientations for outcrop areas. Strike and dip symbols represent bedding; arrows signify fold hinge lines with plunges. Curl pattern = melange; no pattern = bedded flysch; stipple pattern = edge of Siluro-Devonian unconformity. Structural domains indicated: 1 = western flysch, 2 = eastern flysch, 3 = Normansville melange, 4 = Normans Kill gorge melange, 5 = eastern melange, 6 = Vloman Kill graywacke slice, 7 = Glenmont chert block. FG = Font Grove Creek, N = Normansville, SB = South Bethlehem, SP = Staats Point, VC = Vly Creek, VK = Vloman Kill.

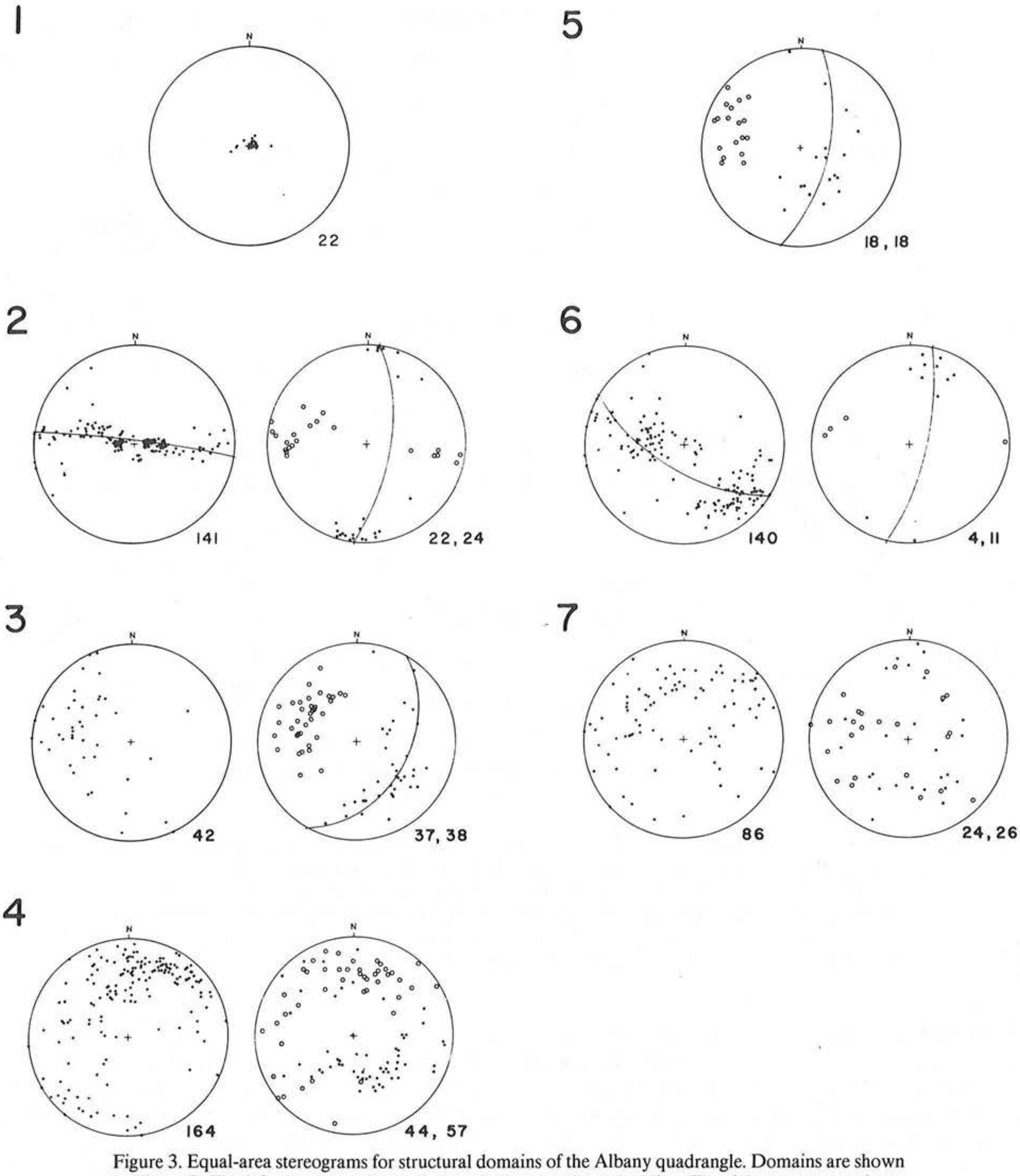

Figure 3. Equal-area stereograms for structural domains of the Albany quadrangle. Domains are shown in Figure 2. The left stereogram for each domain shows poles to bedding. The right stereogram shows poles to fold axial planes (open circles) and fold hinge lines (closed circles). Note change in fabric, particularly from domain 1 to 3.

in this sequence; however, fibrous slickenside steps (Durney and Ramsay, 1973) and a southeast-dipping internal cleavage within a one-centimeter-wide subhorizontal shear zone show northwest-directed thrusting. Gentle bedding dips here suggest long wavelength, low-amplitude folding. The eastern flysch domain (domain 2, Figs. 2, 3) also comprises interbedded graywacke, siltstone, and shale; however, the strata here form asymmetric folds predominantly with east-dipping axial planes and subhorizontal hinge lines (Fig. 4). The folds are mainly open, although several moderately plunging isoclinal folds occur near the eastern boundary of this domain. Half-wavelengths of the folds range from over 400 meters to one meter. Kink folds occur in some

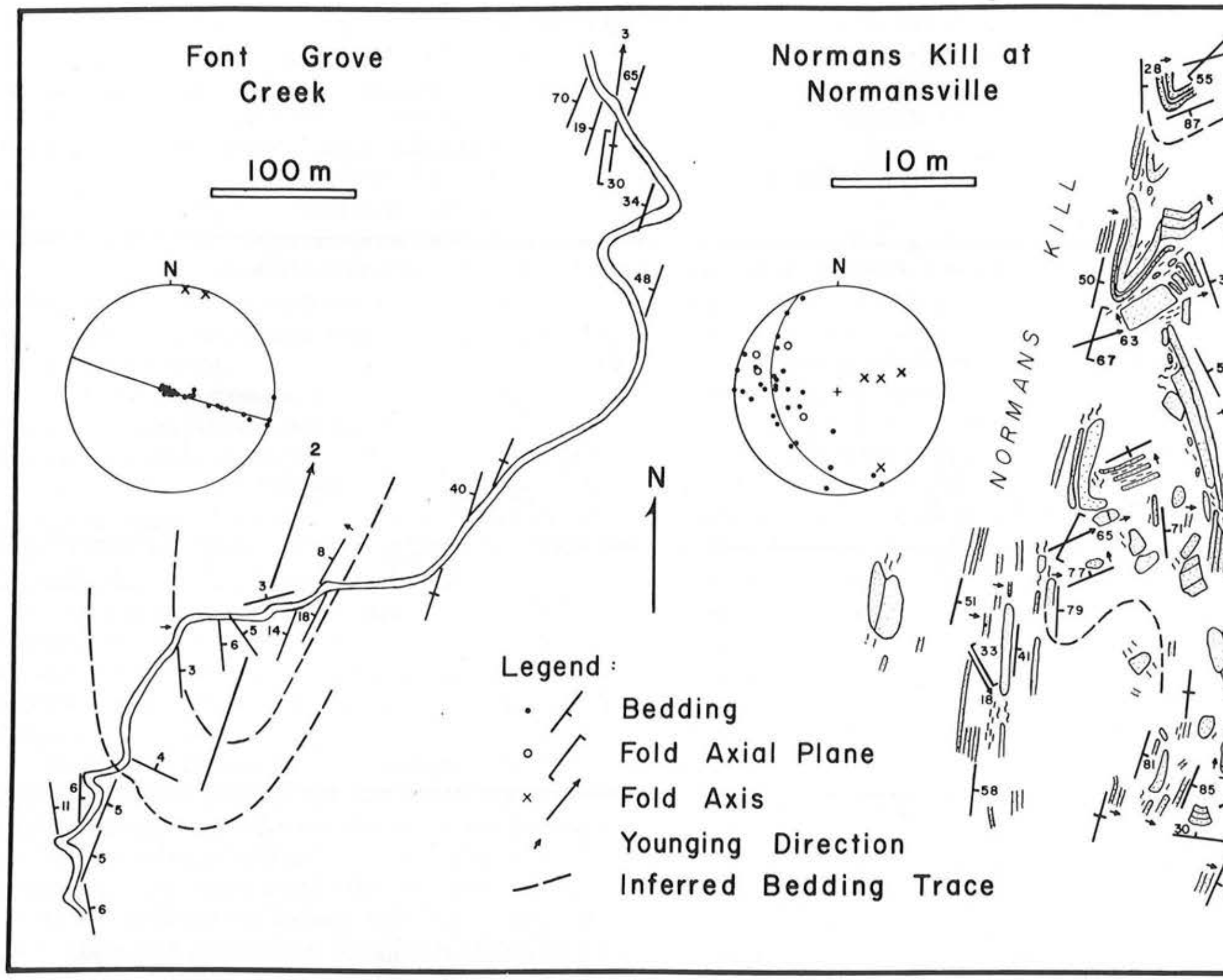

Figure 4. Structural maps of two outcrop areas within the Albany Quadrangle (Fig. 2) illustrating structural styles found in the eastern flysch (domain 2) and Normansville melange (domain 3). Outcrops at Font Grove define a large syncline with a horizontal axis, and an east-dipping axial plane. At Normansville, mapping has shown a series of dismembered asymmetric folds with steeply SE-plunging axes. Shaly sections in Normansville area show well-developed phacoidal cleavage.

outcrops, generally associated with north-northeast-striking thrust faults. These faults have moderate dips to the east and west and are narrow with minor offsets. The sense of relative motion can be determined from offsets and bedding flexures. One final, important structural feature of the eastern flysch is an approximately 20-meter-wide high strain zone exposed along Vly Creek (Fig. 2). This zone lies within otherwise only moderately folded strata, which steepen abruptly near the margins of the zone. The zone consists of dismembered arenite beds within phacoidally cleaved argillite. One small fold measured within this zone plunges 28 degrees southeast (domain 2, Fig. 3). This is the westernmost-known occurrence of the structural fabric characterizing the melange zones to the east.

The Normansville melange zone (domain 3, Figs. 2, 3) is characterized by rootless isoclinal folds, disrupted bedding, and phacoidally cleaved argillite. Rootless folds here show a variety of hinge line orientations, although they mainly plunge southeast and have moderately southeast-dipping axial planes (domain 3, Figs. 3, 4). The phacoidal cleavage also dips moderately southeast, subparallel to fold axial planes. Narrow faults commonly dip southeast with southeast or east-southeast-trending striations (Fig. 5). The eastern melange zone (domain 5, Figs. 2, 3) has a similar structural fabric, although bedding is seldom present. Here, blocks within the phacoidally cleaved argillite, normally less than 30 centimeters across, include dolomitic sandstone and some limestone, as well as abundant graywacke. Less deformed portions of this domain, particularly on the east side of the Hudson River at Staats Point and along Route 9J, are clearly olistostromic pebbly mudstones. These outcrops are characterized by rounded clasts within an uncleaved mudstone matrix (see Bird and Dewey, 1975, Fig. 6; Fisher, 1977, Figs. 65-67).

Included within our study are exposures of melange on the east side of the Hudson River in the vicinity of Rysedorph Hill (Fig. 1, area 2). This locality is particularly noted for the occur-

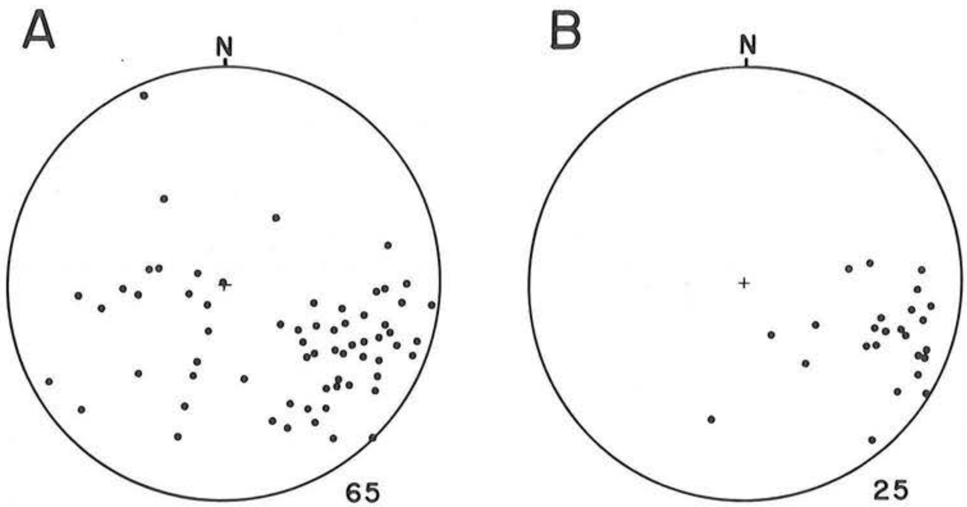

Figure 5. Equal-area stereograms of slickenside striations. Stereogram A shows data from the Albany Quadrangle (Fig. 1, area 1); stereogram B shows data from the Schuylerville area (Fig. 1, area 3). Overthrusting can be demonstrated on many of the fault surfaces by offset, bedding flexure, or stepped fibrous slickensides.

rence of large blocks of shelf-derived carbonate lying within phacoidally cleaved shales and siliceous argillites. Of particular importance is the presence of blocks, some greater than 10 meters in length, of a sand-matrix, limestone-pebble conglomerate, the "Rysedorph Hill Conglomerate" of Ruedeman (1901, 1914, 1930). The fauna of the matrix dates the conglomerate as Mohawkian (medial Ordovician), whereas the limestone pebbles span from Mohawkian to Champlainian (Chazyan), and purportedly through the Canadian (early Ordovician) (Ruedemann, 1901). Chazyan carbonates are not known from eastern New York, south of Ticonderoga, New York (Fisher and others, 1970; Fisher, 1977), and the Rysedorph Hill Conglomerate lithology has currently been identified only as slivers within the melange. We interpret the conglomerate as an outer shelf deposit that may have been transported considerable distance to its present position.

The Vloman Kill slice (domain 6, Figs. 2, 3) comprises interbedded graywackes, siltstones, and shales. Here the proportion of graywacke is substantially greater than in the surrounding melange. These rocks have been referred to the Austin Glen graywacke and are correlative with similar rocks extending south to the type locality. In this area, folds are again fairly open and hinge lines plunge gently to the north-northeast. Bedding is generally continuous, although often complexly broken and faulted. A moderately well-developed slaty cleavage forms divergent fans in the siltstones. Shortening associated with this cleavage development has apparently resulted in the buckling and thrusting of early bedding-parallel extensional fibrous veins, suggesting lithification prior to cleavage development.

Structurally, the most complex area comprises outcrops in and around the Normans Kill gorge (domain 4, Figs. 2, 3), a classic graptolite locality (Hall, 1847; Ruedemann, 1930; Riva, 1974) and the type locality of the Normanskill shale and the *Nemagraptus gracilis* graptolite zone (Ruedemann, 1930). These rocks are now ascribed to the Austin Glen Formation of the Normanskill Group (Fisher, 1977). Downward-facing folds, bedding-slaty cleavage relationships, and folded axial planes show that at least two phases of folding have occurred here. The second event apparently refolded early folds about a southeast-plunging axis. Detailed mapping at this locality has shown extensive dismemberment, with large structurally coherent blocks of folded strata juxtaposed along fault zones and dispersed within a disrupted shaly matrix. Rarely, an east-dipping slaty cleavage can be found in siltstone beds.

The final structural domain, the Glenmont block (domain 7, Figs. 2, 3), consists of folded and faulted green and black interbedded siliceous argillite and chert, structurally discontinuous from the graywacke-shale sequences. This large area of outcrop in the vicinity of Glenmont, New York, forms a block or klippe within the melange. The deformation within this block is characterized by at least two phases of folding. Apparently a late set of folds with an east-dipping axial planar cleavage was superimposed upon an early set of folds with variable orientations. Abundant faults have southeast plunging, fibrous, stepped slickensides, showing a southeast over northwest thrust sense (Fig. 5). This area is also a classic graptolite locality (Ruedemann, 1930; Riva, 1974), and the rocks may be assigned to the Mount Merino Formation. Another smaller block or sliver of chert occurs within graywacke-shale melange just west of Normansville on the Normans Kill. The Mount Merino Formation occurs within the upper portion of the Taconic sequence, directly below the Austin Glen (Pawlet of the northern Taconics) graywacke, and is also common as blocks or klippen within the Taconic melange. The type locality at Mount Merino is apparently such a block (Bird,

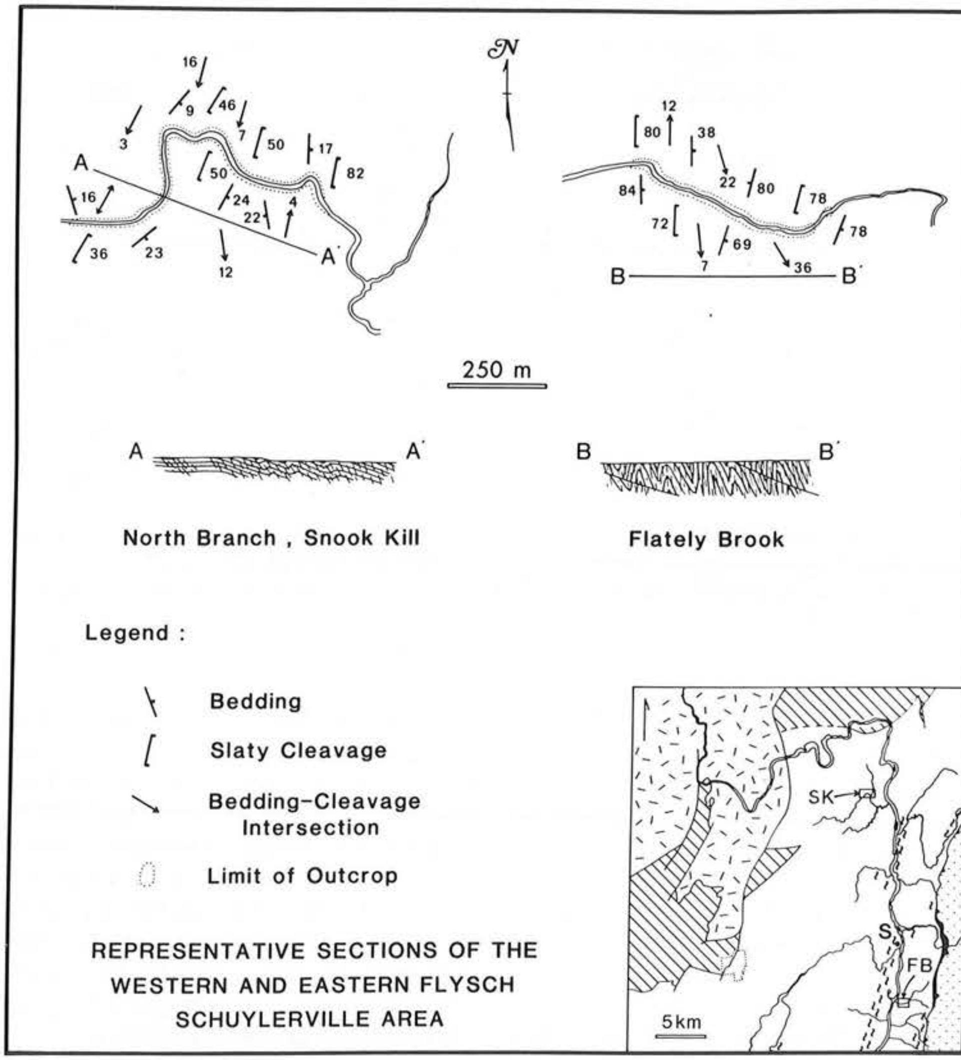

Figure 6. Structural measurements and interpreted cross section for representative areas of the western and eastern flysch, Schuylerville area (Fig. 1, area 3). Numbers with bedding and cleavage symbols give dip; those with bedding-cleavage intersection give plunge. Patterns used in location inset are same as in Figure 1. S = Schuylerville, SK = Snook Kill, FB = Flately Brook.

1969). Clasts of this lithology are common within the graywackes, and some cobble-sized fragments are found within the melange.

SCHUYLERVILLE AREA

Structures observed in the Taconic flysch of the Schuylerville area north of Albany, New York (Fig. 1, area 3), are similar in form and areal arrangement to those described above. A general increase in the intensity of deformation occurs from west to east, progressing from a gently folded section of bedded shales, siltstones, and graywackes; through a terrane composed of tightly folded strata cut by numerous zones of disrupted bedding within contorted and phacoidally cleaved shales; to a complex zone of melange and fault zones at the base of the allochthon (Bosworth, 1980). An important characteristic of the Schuylerville area is that the melange is not confined to the zone at the base of the allochthon, but is present as major structural and stratigraphic discontinuities within the flysch for as much as 15 kilometers west of the allochthon boundary (Bosworth and Vollmer, 1981).

Lesser degrees of deformation within the flysch are well illustrated by the river section on the north branch of the Snook Kill (Fig. 6). Over a distance (west to east) of less than one kilometer, bedding planes change from nearly flat-lying to involvement in gentle to open folds with moderately east-dipping axial planes and approximately horizontal hinge lines. Wavelengths are typically a few tens to one to two hundred meters, and amplitudes are generally no more than 10 to 20 meters. Weak slaty cleavage is present in the shale beds at the western edge of the section, dipping roughly 35° to the east. This slaty cleavage increases in strength to the east, being developed in siltstone and silty arenite as well, its dip increasing to 45-50° east and then becoming very steep at the east end of the section. No disrupted beds are found in this section, and the slaty cleavage is the only recognized tectonic foliation. Minor thrust faults are found parallel to the long east-dipping limbs of anticlines and cutting across section in the hinge zones of folds. On thick wacke beds, these commonly appear as grooved and stepped fibrous slickenside surfaces with east-over-west displacement.

East of the Snook Kill section, isolated outcrops commonly contain boudinaged wacke beds, isolated fold hooks, or simply lens-shaped pods of siltstone, wacke, and chert. Where outcrops are continuous or closely spaced, melange zones have been mapped (Fig. 1; see also Bosworth and Vollmer, 1981, Fig. 5), but many narrow or discontinuous zones have undoubtedly been missed. Figure 1 should be construed to represent only some of the most important melange zones and is a simplification of the actual geometry of the flysch-melange section. Structures of the melange are similar to those observed in domains three and five in the Albany Quadrangle. The fabric of the matrix is an anastomosing, east-dipping cleavage with numerous down-dip striations and commonly a polished or "glazed" appearance. Blocks and clasts within the melange are dominantly of "non-exotic" origin (found as bedded components of the flysch), except where previously noted.

The two most extensive melange zones lie in north-south elongate belts west of the Hudson River and at the base of the allochthon (Figs. 1, 7). In the vicinity of Bald Mtn. (Fig. 1), the melange is observed only locally. Here the boundary fault is marked by large slivers of shelf carbonate surrounded by lesser amounts of poorly exposed, phacoidally cleaved shale (Ruedemann, 1914; Rodgers and Fisher, 1969). These Bald Mtn. carbonates and the enclosing shale satisfy the definition of melange as used in this paper, and are referred to as fault slivers simply because of their sheet-like geometry (Bosworth, 1980) and obvious association with the frontal thrust of the Taconic Allochthon. The lithologies present in these slivers are also found as pebbles and cobbles within olistostromic horizons of the flysch near the allochthon. The large slivers are interpreted to be the source of the smaller cobbles in the depositional environment of the flysch (see further discussion in Rowley and Kidd, 1982). Although the margins of individual blocks are tectonized, primary sedimentary features are easily recognized in their interiors and on this basis and from the enclosed faunas, the carbonates have been dated as medial Mohawkian and late Canadian (early and medial Ordovician) in age (Ruedemann, 1914; Grabau, 1936; Chisick and Bosworth, 1984). Blocks of Rysedorph Hill Conglomerate are also present at Bald Mtn. (Ruedemann, 1914).

The section of flysch between the Schuylerville and Bald Mtn. melanges provides a good example of the flysch in a highly deformed state, yet not completely disrupted. The outcrops along Flately Brook have been chosen as an example of this terrane (Fig. 6), which is not well represented in the Albany area. Here hinge lines of folds have shallow to moderate plunges (7 to 36°), whereas axial planes and slaty cleavage dip steeply east (70° east to vertical). Fold asymmetry is less pronounced than in the western flysch, and fold tightness and amplitude have increased markedly. Numerous small thrust faults cut across bedding in this section, with east-over-west displacements dominating. Narrow zones of phacoidally cleaved shale containing small (generally <1 m) clasts of arenite crop out along strike and farther east from the Flately Brook section. Clasts of well-cleaved slate, similar to the adjacent undisrupted slates, are also found within these narrow melange zones.

METTAWEE RIVER SECTION

Exposures along the Mettawee River in northern Washington County (Fig. 1, area 4) provide an opportunity to observe shelf carbonate lithologies imbricated within the flysch section. The largest carbonate slivers occur in a belt at the base of the allochthon (Fisher and others, 1970), similar in form to the Bald Mtn. terrane described above. Lithologically and faunally, the slivers studied thus far are equivalent to autochthonous Chazyan (early medial Ordovician) rocks exposed farther north along the shores of Lake Champlain (Selleck and Bosworth, 1984). Bedding within the slivers is tightly folded, an easily recognized anticline being exposed at the Mettawee River. Whether this folding pre-dates, is synchronous with, or post-dates final emplacement of the allochthon cannot be determined at the Mettawee locality.

Beneath the frontal slivers, there occurs a melange terrane containing smaller blocks of carbonate rock, quartz arenite, wacke, and abundant pebbly mudstones. Some of the pebbles are lithologies found in the larger blocks and slivers. The melange becomes more discontinuous and is replaced by bedded flysch to the west, away from the allochthon boundary. Structurally, the flysch is quite complicated here, with some refolding of early folds and slaty cleavage. At several narrow disrupted zones within the flysch, small slivers of hard limestone and calcareous arenite are caught up within a phacoidally cleaved matrix. Fold and small-scale fault orientation data are generally similar to those observed in the Schuylerville area and domains 2 (flysch) and 3 and 5 (melange) in the Albany Quadrangle.

MICROSTRUCTURES OF THE MELANGE MATRIX

A characteristic feature of the Taconic melanges is the pervasive, sub-planar fabric developed within the shaly matrix. This fabric is defined in hand specimen by the parallel alignment of lens or phacoid-shaped shale and siltstone clasts, which commonly have striated and polished surfaces. In thin section, these surfaces appear as narrow, anastomosing cleavage lamellae. X-ray diffraction studies indicate that the cleavage lamellae are composed mainly of illite and chlorite. This fabric is here referred to as "phacoidal" cleavage, reflecting the presence of lens or phaciod-shaped domains between cleavage folia. Observations made thus far have not suggested any major differences in the microstructure of the different melange lithofacies, although the cleavage formed within olistostromal horizons appears to be complicated by an early primary deformation. This preliminary

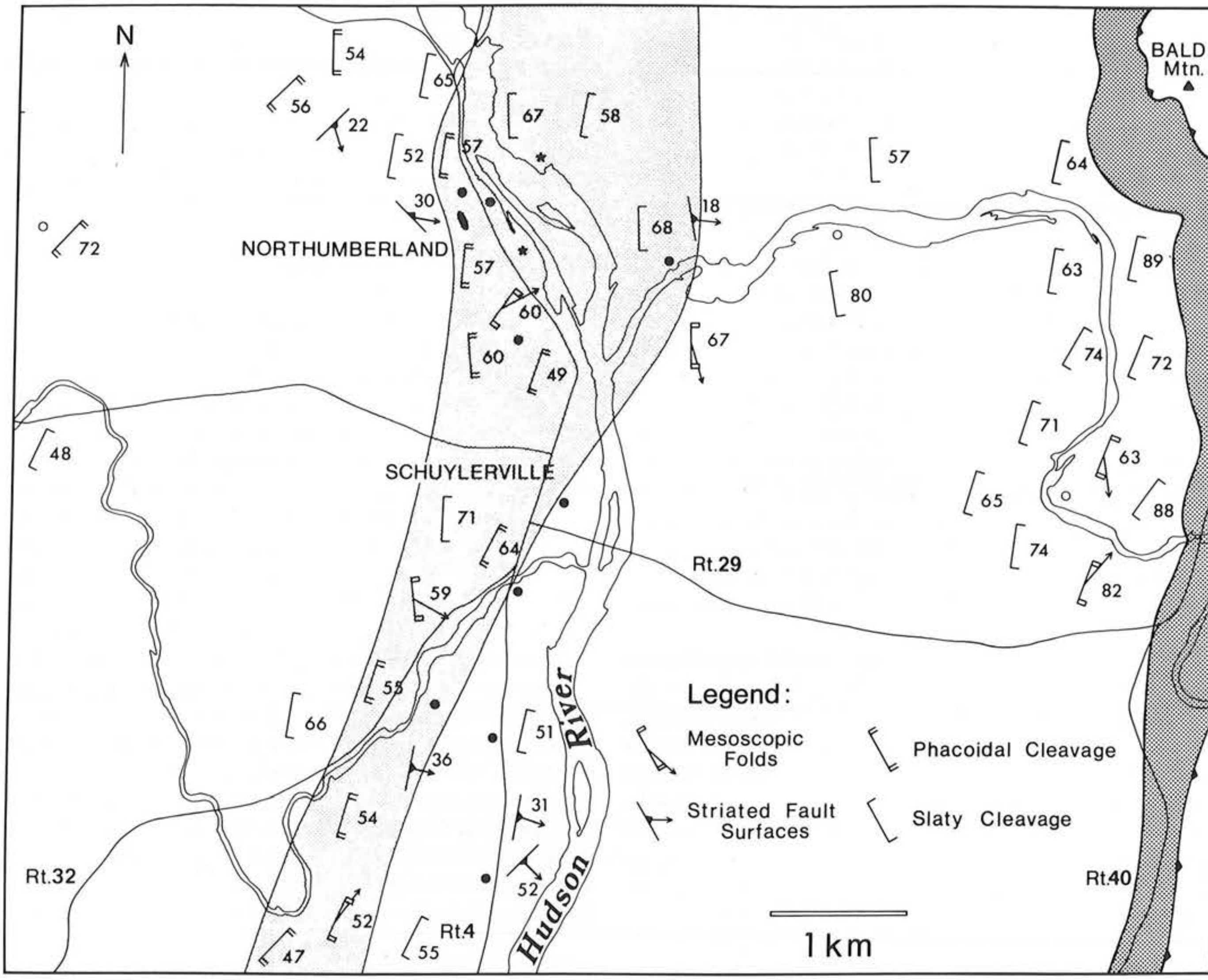

Figure 7. Structural data from the Schuylerville melange zone and adjacent flysch. Numbers with each symbol give dip of structural element, arrows indicate orientation of fold hinge lines on axial planes and striations on fault surfaces. Light stipple patterns = melange; heavy stipple pattern = fault rocks at base of Taconic Alochthon (Bald Mtn. Terrane carbonates); flysch is unornamented. Elliptical black body at Northumberland is Stark's Knob (pillow basalts). Graptolite fossil localities from Ruedemann (1914) are depicted as follows: asterisk = early Ordovician; solid circle = older medial Ordovician (probable *Nemagraptus gracilis* zone of Riva, 1974); open circle = younger medial Ordovician (probable *Diplograptus multidens* zone of Riva, 1974). From Bosworth, 1982. Used with permission of Vermont Geology.

account attempts only to relate the general results obtained from a number of melange localities chosen for their particularly good exposure or structural significance. We have looked mainly at the matrix of the graywacke-shale melange to avoid the effects of complex primary fabric.

Several dominant folia orientations are readily observed in outcrop, dipping moderately or steeply to the east. Significant populations of lamellae with other orientations, however, are also present. Lamellae can be measured in oriented hand samples to produce a three-dimensional statistical picture of the anastomosing cleavage network, or measurements can be taken from thin sections cut in various orientations to construct a number of two-dimensional pictures (Fig. 8). The phacoids enclosed by the cleavage lamellae are composed of shale, argillite, siltstone, wacke, or chert, depending on the melange lithofacies considered.

In hand specimen, shale phacoids are commonly crudely polyhedral and many appear rhombohedral in cross section, particularly where observed parallel to strike. The phacoid surfaces are polished and exhibit fine striations generally well developed on east-dipping surfaces, but also common in other orientations.

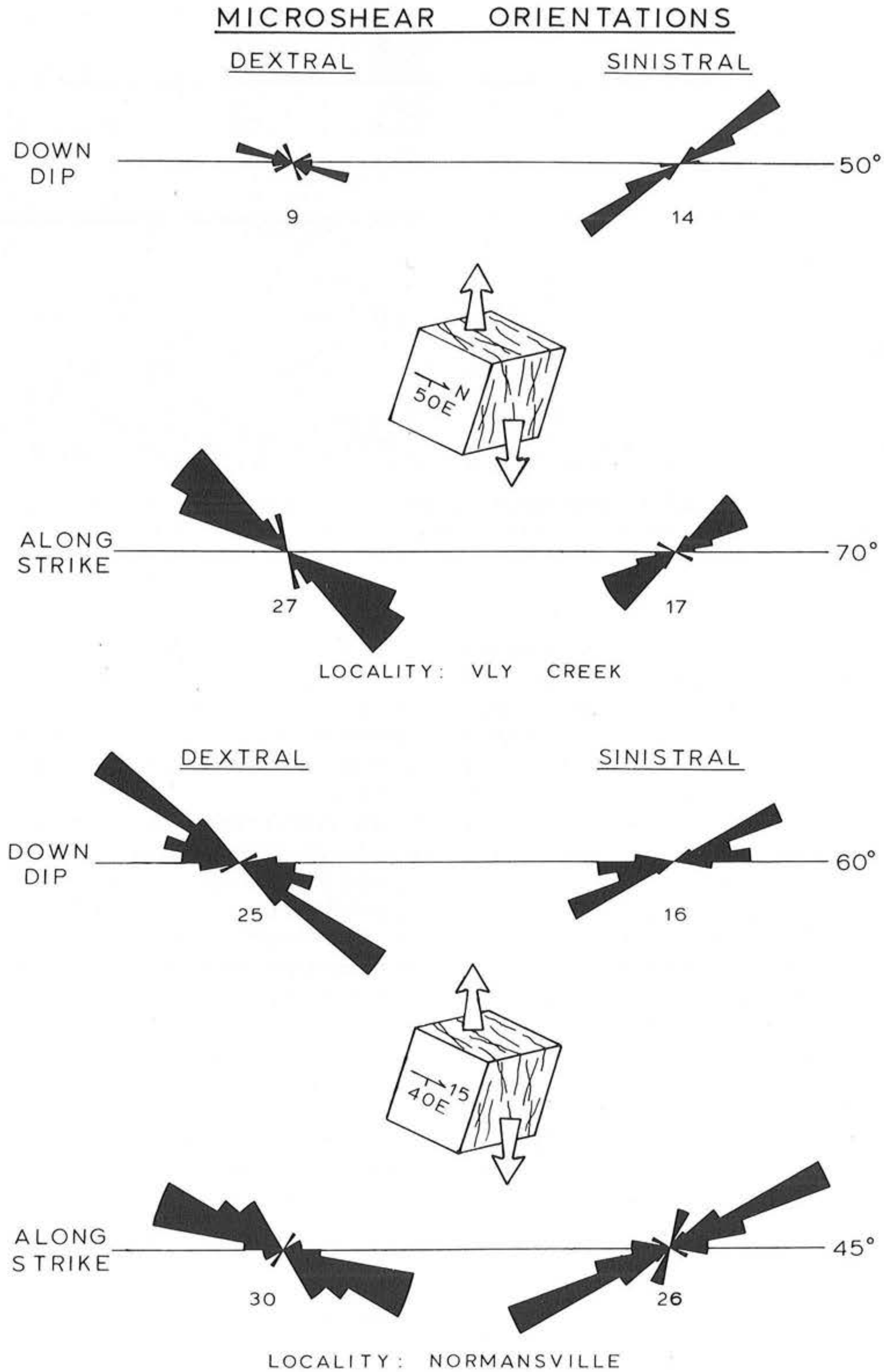

Figure 8. Microshear orientations from two localities within the Albany Quadrangle; see Figure 2 for locations. Microshear orientations were measured in thin section only where sense of shear could be determined from offset or flexure of primary phyllosilicate fabric. Horizontal lines represent approximate traces of mesoscopic foliation. Approximate angles between the two sets are given at right.

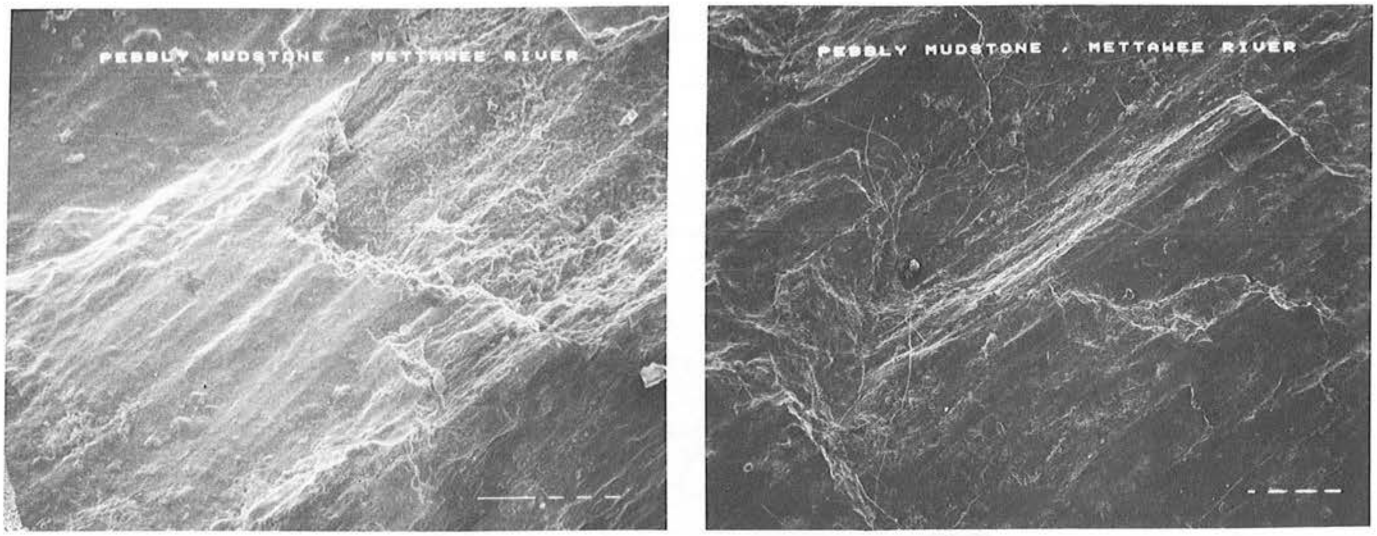

Figure 9. Scanning electron micrographs of phacoidal cleavage lamellae surfaces. Scale bar is bar farthest to the left in series and equals 100μ. Samples from pebbly mudstone horizon in melange on Mettawee River section (Fig. 1, area 4).

Scanning electron microscopy of the lamellae surfaces reveals a micromorphology corresponding to that observed in hand specimen, with microsteps, tracks of asparities that project from adjacent phacoids, and abundant striations (Fig. 9). In thin section, the phacoid boundaries appear as thin lamellae across which offsets are observed. They vary in character from crenulations to sharp, narrow shears (Bosworth and Vollmer, 1981, Fig. 11; Fig. 10). Measurable offsets across the shears are up to several millimeters, although more commonly no lithologic correlation can be made at the scale of the thin section. Sense of offset can be determined in most cases by the displacement of markers and by the bending of the pre-cleavage fissility into the zone. Measurement of the orientations of these microshears in sections cut perpendicular to the cleavage, both parallel and perpendicular to strike, shows two discrete populations in each section. The sense of shear on these surfaces indicates that these populations form conjugate normal sets of microshears (Fig. 8). The obtuse angles of intersecting sets are bisected by the normal to the mesoscopic cleavage. Although it is difficult to determine the relative orientations of the microshear planes in three dimensions, it is apparent from hand sample observations that the phacoids are bounded on all sides by shear surfaces, and that a minimum of four shear sets is required to define their crudely polyhedral shapes. Mutual cross-cutting relationships suggest that the conjugate microshears form coevally. Also, many of the microshear surfaces are distinctly non-planar, and in some cases curvature of a single surface may result in the opposite sense of shear along the same surface.

Orientations of these microshears are shown in Figure 8 for two samples from the Albany Quadrangle. The first is from the narrow, high strain zone at the Vly Creek locality; the second is from the Normansville locality within the main belt of tectonic melange. The angle between conjugate microshears varies between 45 and 70 degrees, but shows no consistent change from one locality to the other. A further important observation is from samples taken near the edge of the Vly Creek high strain zone (Fig. 10). The microshears in these specimens again have similar orientations and are distinguished only by their wider spacing and small offsets.

The origin of phacoidal cleavage through the progressive development and continued offset of conjugate microshears is suggested by the presence of widely spaced, small offset shear crenulations in the margins of the Vly Creek high strain zone (Fig. 10). Farther into the zone, a similar but more intense penetrative fabric defines the phacoidal cleavage. The relative orientations of the microshears remain relatively constant, although the total deformation, as shown by the disruption of bedding, increases significantly. The fabric of this zone appears identical to that typical of the main melange zones. This cleavage is also characterized by at least four distinct microshear orientations. It can be shown that eight slip systems, corresponding to four fault surfaces, are sufficient to accommodate a general, constant volume, three-dimensional deformation (Reches, 1978). It is suggested, then, that the formation of these microshear sets allows the melange matrix to accommodate a general, constant volume, three-dimensional state of strain. Deformation may then occur analogously to plastic flow by glide on crystal slip systems. Disruption of layering is caused by repeated offsets on the conjugate microshears. The relatively constant angle between microshear sets indicates that the largest component of strain is most likely taken up by slip along the phacoid boundaries, with a lesser component of internal deformation. This state of strain most likely corresponds to a flattened elongate ellipsoid ($\lambda_1 >> \lambda_2 > 1 > \lambda_3$), as shown by the alignment of fold axes and by the extensional character of the microshear sets in the plane of

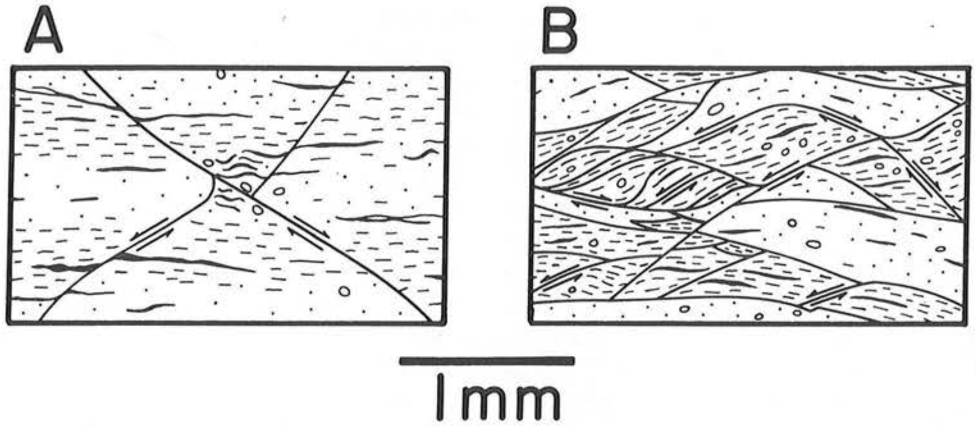

Figure 10. Line drawings from photomicrographs of thin sections from the Vly Creek high strain zone. A is from the margin of the zone; B is from the center of the zone. The fabric in B appears identical to that found within the main melange zones. Shear sense on many surfaces can be determined by flexure or offset of the primary fabric. Planar fabric is mainly clay, argillaceous fragments or fine-grained micas. Stipple represents siltier domains with quartz grains and lithic fragments in addition to argillaceous material.

the average foliation (Vollmer, 1981b). Phacoidal cleavage may develop preferentially in areas where strain rates are sufficiently high so that brittle failure is favored over diffusional processes.

As few constraints on the bulk strain history of these rocks are currently available, the possible significance of a non-coaxial (versus coaxial) deformation history in the formation of phacoidal cleavage currently cannot be properly assessed. However, it is clear from regional relationships that a deformation model approaching progressive simple shear is more reasonable than one invoking largely pure shear (a history of coaxial two- or three-dimensional strains). In particular, it is difficult to explain the emplacement of the Taconic alloththon onto the flysch sequence without the occurrence of large sub-horizontal shear displacements.

STRUCTURAL INTERPRETATION

Interpretation of the structures within the study area relies on across-strike variations in deformation style, and estimation of relative strains based on fold tightness, degree of bedding disruption, and microstructural interpretation of the melange matrix. Structures observed in the west, in the western and eastern flsych, suggest a component of horizontal shortening increasing to the east. Asymmetry of the folds and overthrust sense suggest a horizontal east-over-west (in the north) or southeast-over-northwest (in the south) shear component. Towards the east and into the melange, folds plunge more steeply east and southeast (Figs. 2, 3, 4, 6, 7). This change is associated with an increase in fold tightness and degree of boudinage, suggesting reorientation of the folds with increasing strain. This progression is shown in Figures 2 and 3 as a general change in fold orientation from west to east associated with a change from open to isoclinal folds. Folded extensional fibrous veins observed at several localities within the melange demonstrate some degree of lithification prior to folding (Bosworth and Vollmer, 1981, Fig. 8). It is suggested that this change in fold orientations towards the Taconic Allochthon indicates the rotation of fold hinge lines into a shear direction, and that this was related to the west-northwest-directed emplacement of the Taconic Allochthon during medial Ordovician times. This is consistent with thrust fault, fold, and cleavage orientations and the orientation of foliations in narrow east-dipping shear zones. The most intense deformation of the flysch is recorded in the extreme east, where bedding is completely disrupted to form the melange. Melange occurs first as narrow shear zones, as at Vly Creek, and then as broad belts just to the west of and along the front of the Taconic Allochthon.

Graptolite faunas found within this area also provide some insight into the deformational history. Most of the eastern rocks, including those of the Normans Kill gorge area, the Glenmont block (Mount Merino chert), the Austin Glen graywacke, and large sections of the Schuylerville melange are of *Nemagraptus gracilis* zone age (Riva, 1974; Riva, 1982, personal communication; also Berry, 1962; Fisher and others, 1970), corresponding to the late Llandeilian to early Caradocian (early medial Ordovician to earliest late medial Ordovician). However, several localities within the Normansville melange zone of the Albany Quadrangle give graptolites indicative of the younger *Corynoides americanus* zone (Riva, 1982, personal communication). One locality is within the city of Albany north of the Normans Kill gorge; the other is just west of Normansville on the Normans Kill. Farther west, at Vly Creek and in the vicinity, collections give *Climacograptus spiniferus* zone age graptolites, the youngest known within the deformed rocks (latest Caradocian; latest medial Ordovician). A similar younging in the age of the flysch is also observed west of the Schuylerville melange, although both the older and younger flysch crop out to the east (Fig. 7, and discussion in Bosworth, 1982). This suggests that, in general, older rocks progressively surface to the east, and the imbrication has resulted in the juxtaposition of rock units of various ages (see also Rickard and Fisher, 1973). Similar relationships have been observed along the Mohawk River gorge and near Quebec City, where Austin Glen and Mount Merino correlative units have been thrust over, and imbricated into, the younger flysch (Riva, 1982, personal communication).

Paleogeographic reconstructions (Rodgers, 1970; Fisher, 1977; Rowley and Kidd, 1981) suggest that carbonate deposition continued on the Paleozoic continental shelf during *N. gracilis* zone age, while deposition of flysch from an approaching eastern source had just begun on the continental rise sequence far to the east. This suggests that the cherts and graywackes of *N. gracilis* zone age, at least, have been thrust a minimum of 60 kilometers, the distance east-southeast to the present eastern extent of the Cambro-Ordovician carbonate sequence. It is suggested then, that the depositional-deformational environment associated with melange formation migrated across the slope-shelf boundary and continued, albeit weakly, until *C. spiniferus* zone age, or late Caradocian times. Although Ordovician units younger than this age are apparently undeformed, these units occur only farther west, beyond the limit of major deformation. An upper age limit for the formation of the melange in this area, however, is demonstrated by the unconformity exposed along the Spryt Creek, near South Bethlehem. Here thick beds of Austin Glen graywacke grade westward into highly deformed melange. The melange contains blocks of graywacke, some siliceous argillite, and steeply plunging rootless folds. Unconformably overlying the phacoidally cleaved melange fabric are Helderberg Group dolostones and limestones of latest Silurian to early Devonian ages (Ruedemann, 1930; Rickard, 1975). The carbonates are gently folded with some bedding plane thrusts, but are clearly unaffected by the fabric of the melange.

DISCUSSION

The structures and lithofacies of the Taconic flysch are interpreted in a model invoking progressive deformation of synorogenic deposits in a foreland basin overthrust environment. The central premise of this model is that the observed west-to-east spatial increase in intensity of deformation represents, as well, the temporal increase in deformation that occurred at any given locality within the flysch terrane. The more advanced stages of deformation resulted in the disruption of the bedded flysch sequence and the formation of melange. Final steepening of structures through time is suggested by the steepening of structures toward the allochthon. This steepening may have occurred through rigid body rotation along curved fault planes, or through an increased component of horizontal shortening (Bosworth and Vollmer, 1981).

Three processes are believed to have contributed to the formation of the Taconic melange: boudinage and general disruption of alternating graywacke-shale sequence; sub-aqueous slumping and deposition of olistostromic horizons that were subsequently tectonized and incorporated into the melange; and imbrication of the overthrust and underthrust sedimentary sections. The progressive disruption of the bedded flysch sequence can be readily inferred in the field. Attenuation and fracturing of less ductile wacke and siltstone beds leads to boudinage and the initial breakup of the sedimentary sequence. This can be observed at numerous localities in the flysch, and particularly at the margins of the mappable melange zones and on perimeters of some larger blocks already enclosed within melange. The sedimentary order is further destroyed and beds become untraceable as those boudins experience greater separation and rotation, the surrounding shales or slates taking on the characteristics of phacoidally cleaved melange matrix.

The sedimentary origin of some blocks within the melange is also apparent. The occurrence of well-rounded blocks of limestone and other lithologies within some melange outcrops suggests mechanical abrasion in the sedimentary environment. Pebbly mudstone horizons within the relatively undeformed sections of the flysch demonstrate that very coarse sedimentation took place at least locally within the flysch depositional environment. Tectonized olistoliths, for example in the eastern melange of the Albany Quadrangle, are generally distinguished in the field by their diversity of clast lithologies, and by the rarity or absence of disrupted bedding. A reasonable interpretation for the structural significance of the olistoliths is that they were generated by slope instabilities at active, emergent faults in the flysch basin (Bosworth and Vollmer, 1981; see also Zen, 1967, and Bird, 1969). The olistostromes would then be overridden by the upper thrust slice (or underthrust with the lower sheet) and incorporated into the fault zone. Finally, imbrication has led to the juxtaposition of rock units of various ages resulting in a general west to east stacking of progressively older units. Imbrication of the underlying shelf sequence has also occurred, leading to the incorporation of slivers of carbonate rock. The interplay of sedimentary and tectonic processes envisioned for the Taconic foreland basin is summarized in Figure 11.

The melange zones of the Hudson River Valley, then, occur as high strain zones across and within which rock units of various ages and lithologies have been imbricated and interspersed. In particular, regional relationships suggest that these melange belts represent shear zones associated with the emplacement of the Taconic Allochthon during medial Ordovician times (Bosworth and Vollmer, 1981; Bosworth, 1982). Displacements in excess of 60 kilometers across portions of the melange are indicated by paleogeographic reconstructions and the juxtaposition of various age units. These melange zones may have initiated as narrow high strain zones similar to that observed at Vly Creek. The fabric within the melange is dominated by boudinage, plunging rootless isoclines, and a phacoidal microshear cleavage. The pervasive microshear fabric demonstrates large shortening strains perpendicular to the fabric, and to the axial planes of the isoclines. This shortening was accommodated by movement on conjugate slip systems, analogous to bulk plastic flow. Deformation apparently progressed beyond the stage of isoclinal folding to that of extreme attenuation of isoclinal folds. The plunging fold axes are best

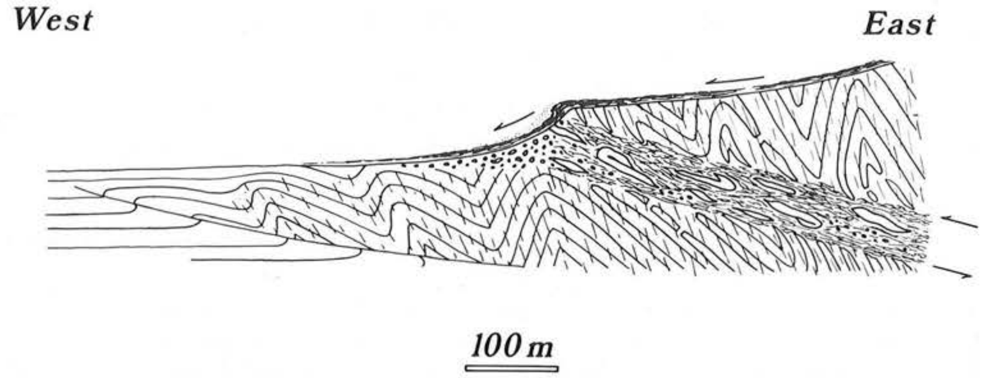

Figure 11. Model for the origin of melange in a foreland overthrust setting. Turbidity flows and slumping (single arrows) deliver sediments to the foreland basin, where they may be carried laterally along the basin axis. Coarse material (pebbly and bouldery mudstones—stipple pattern) is deposited near active fault scarps, where it is incorporated into evolving melange zones. Shearing across the melange zones (paired arrows) results in progressive boudinage and eventual disruption of the bedded flysch sequence, producing the bulk of the melange blocks and clasts and the anastomosing melange fabric. Slaty and phacoidal cleavage is interpreted to form coevally, in differing deformational environments.

explained through the rotation of initially horizontal hinge lines. In general, plunges of fold axes increase with increasing strain, as indicated by fold tightness and degree of boudinage. Within the melange zones, these axes form a mesoscopic fabric plunging moderately to the east or east-southeast, parallel to slickenside striations on fault surfaces. The direction of this linear fabric is interpreted to be the direction of maximum elongation in the melange. Although late horizontal shortening and further imbrication is believed to have subsequently rotated this fabric to steeper orientations, its trend is reasonably interpreted to represent the direction of transport of the Taconic Allochthon.

The amount of strain required to rotate the fold axes cannot be directly calculated without a more complete knowledge of the deformation path. Theoretical and experimental modeling of fold axes rotation within a body undergoing progressive bulk simple shear show that significant alignment of axes near the shear direction does not occur below shear strains of 10 or 20 (Skjernaa, 1980; Cobbold and Quinquis, 1980). Any additional component of extension in the intermediate strain direction should decrease the amount of rotation for a given shear strain. Therefore, if we assume a deformation approximating simple shear, plus some amounts of flattening, as a reasonable model, shear strains on the order of $\gamma = 10$ may be regarded as a conservative estimate for the melange zones. Although the thicknesses of the individual melange zones are poorly constrained, their cumulative outcrop width (w) (Fig. 1) is approximately 5 to 10 kilometers. The melange fabric commonly dips 45° or more to the east, and with high shear strains this fabric should be sub-parallel to the boundaries of the zones. The cumulative melange zone thickness should then be $w \cdot \cos 45°$, or 3½ to 7 kilometers. With a shear strain (γ) of 10, displacements of 35 to 70 kilometers could be accommodated across the melange high strain zones. In its original, more nearly horizontal attitude, this magnitude of lateral transport is in good agreement with that estimated from previous paleogeographic arguments.

CONCLUSIONS

The Taconic melanges were formed in a foreland basin environment through the deformation of a synorogenic flysch sequence. This flysch sequence was deposited in a north-south elongate basin in front of the Taconic Allochthon as it was emplaced onto the North American continental margin during the medial Ordovician Taconic orogeny. The flysch was derived from, and was subsequently overridden by the allochthon, resulting in the formation of belts of tectonic melange. The flysch sequence comprises three main lithologic units: a distal, dominantly shale unit; an interbedded graywacke and shale unit; and proximal pebbly mudstones. All of these units have locally been tectonized into melange. Tectonization of pebbly mudstone horizons has resulted in the formation of melange with "exotic" blocks. These blocks may be correlated with sedimentary units found within the allochthon and the underlying carbonate shelf, and were probably derived from exposed fault scarps formed during overthrusting.

An east to west increase in deformation intensity as well as local variations in deformation intensity have been used to infer the structural history of the melanges and to study the flysch-melange transition. Formation of melange from the three main lithologic units involved initial folding and thrusting, followed by tightening of the folds to form isoclines. This main phase of folding occurred after some degree of lithification of the sediments. Continuing deformation resulted in boudinage due to lithologic ductility contrasts, and the formation of a phacoidal conjugate-shear cleavage. The formation of this cleavage is believed to allow accommodation of a general deformation. Original layering within the matrix is disrupted through repeated slicing on conjugate microshear planes. A final process that contributes to the observed disruption in the melange is large-scale imbricate thrusting. This has resulted in the incorporation of larger blocks, slivers, and klippen of chert, carbonate rock, and several exotic rock types of unknown origin into the melange terrane.

High strains are indicated within the melange by isoclinal folding, boudinage, and pervasive extensional microfaulting. Transitions from flysch into melange show a progressive change in fold orientation, from horizontal north-northeast to steeply southeast plunging. This reorientation is suggested to be due to rotation of fold axes into the shear direction with increasing strains. This interpretation is consistent with the vengence of cleavage, folds, and faults throughout the area. The melange zones, then, are best explained as zones of high shear strain associated with the emplacement of the Taconic Allochthon. Total displacement across these melange zones is estimated to be in excess of 60 kilometers.

ACKNOWLEDGMENTS

The authors would like especially to thank W. D. Means, W.S.F. Kidd, and D. B. Rowley for their kind assistance in this study. Discussions with P. Hudleston, J. Riva, S. Chisick, and B. Selleck helped to clarify various aspects of the study. P. Hudleston critically reviewed an early draft of this work. The authors would also like to thank M. Cloos, B. E. Lorenz, and an anonymous reviewer for comments. Bosworth was funded through NSF graduate fellowship, a Penrose Grant from the Geological Society of America, and a William and Flora Hewlett Foundation Grant of Research Corporation. Vollmer received support through NSF Grant EAR 8007812 to Means. Field support was provided by the State University of New York at Albany. The staff of Colgate University and the University of Minnesota kindly assisted in the preparation of the present work.

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MANUSCRIPT ACCEPTED BY THE SOCIETY JULY 12, 1984

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ISBN 0-8137-2198-9