STRUCTURES OF THE MEDIAL ORDOVICIAN FLYSCH OF EASTERN NEW YORK: DEFORMATION OF SYNOROGENIC DEPOSITS IN AN OVERTHRUST ENVIRONMENT[1]

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ABSTRACT

Synchronous deposition and deformation of the flysch deposits of eastern New York occurred during the westward overthrusting of the Taconic Allochthon in medial Ordovician time. An observed spatial west to east increase in the intensity of deformation is believed to represent the progressive development of structures through time. Folding initiated as upright kinks and buckles with fold axes north-south and approximately horizontal. Fold axes then rotated towards an east-west shear direction with fold tightness and asymmetry increasing and fold axial planes rotating to the west. Shear zones with a phacoidally cleaved fabric and small thrust faults strengthened the east over west structural asymmetry. After attaining intermediate dips (roughly 45°) the fold axial planes began to rotate back toward vertical and lose asymmetry. Bulk flattening and shear competed in the microstructural development of the flysch with slaty cleavage and phacoidal cleavage the corresponding end-products. Shear zones and thrust faults evolved into master faults, producing a large-scale imbricate structure in the flysch. Melange originated both as tectonically broken formations and as disrupted olistostromic deposits. The dominant mechanism for melange formation appears to have been the disruption of interbedded graywacke and shale sequences under large strains. Imbrication of the original stratigraphic sequence has allowed the incorporation of older rocks, including shelf carbonate, into the melange as blocks and large slivers. The progressive sequence of structures observed within the flysch of eastern New York represents deformation within the leading edge of an accretionary prism developed over continental lithosphere.

INTRODUCTION

Graywacke and shale deposits of the Hudson River Valley are part of a nearly continuous medial Ordovician flysch sequence which extends along the Appalachian orogenic belt from Newfoundland to Alabama (Enos 1969; Williams 1978; fig. 1). These are westward transgressive synorogenic deposits and are associated with the emplacement of allochthonous terranes including the Hamburg klippe of Pennsylvania (Wright et al. 1979); the Taconic Allochthon of eastern New York, Massachusetts, Connecticut, and Vermont (Zen 1967); the nappes of Quebec (St. Julien and Hubert 1975); and the Humber Arm and Hare Bay Allochthons of western Newfoundland (Stevens 1970). In eastern New York the graywacke and shale sequences have been highly deformed adjacent to the Taconic Allochthon, locally forming melange, while their finer-grained westerly equivalents are undeformed. Thus it is possible to study the eastward increase in deformation and to infer the deformational history of synorogenic deposits deformed and overridden during the emplacement of allochthonous terranes.

Recently much attention has centered on deformational processes occurring within subduction-accretion zones (e.g., Cowan and Silling 1978; Moore and Karig 1980). Although the final products of accretionary processes have been widely studied (e.g., Cowan 1974; Moore and Wheeler 1978), the initiation of accretionary processes has only been investigated through geophysical methods, deep sea coring and limited submersible observations (e.g., White and Ross 1979; Heezen and Rawson 1977; Moore 1979). Recent tectonic models for the evolution of eastern North America have suggested that during medial Ordovician times an island arc

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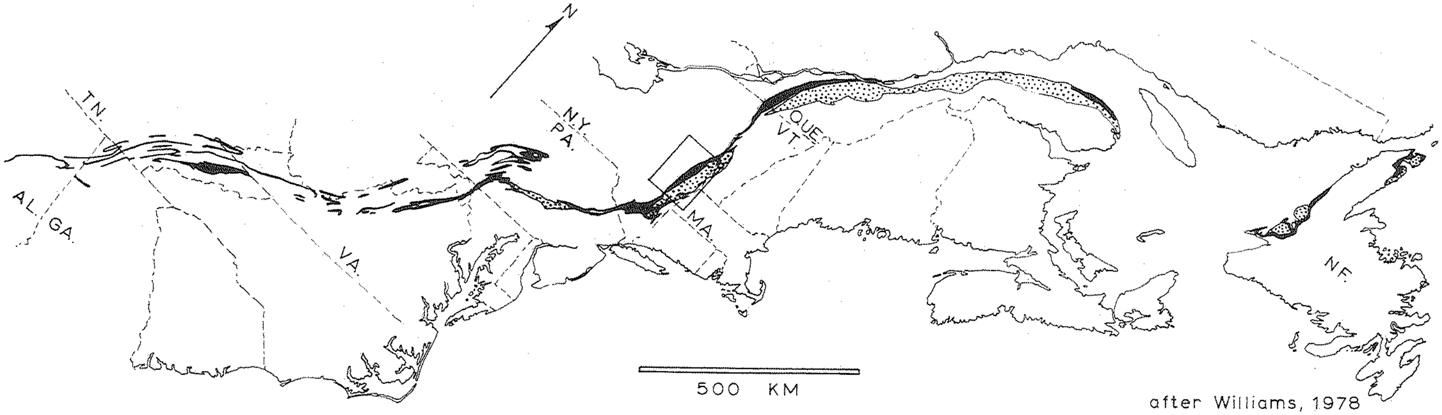

FIG. 1.—Areal distribution of medial Ordovician flysch facies and associated allochthonous terranes of the Appalachian orogenic belt, eastern North America. Solid black is mainly deformed, easterly derived and westerly transgressive medial Ordovician graywackes, siltstones and shales. Stippled pattern is mainly transported Cambrian(?) to medial Ordovician slope and rise sediments, including some ophiolites, emplaced during medial Ordovician times (after Williams 1978). Box indicates location of figure 2.

above an east dipping subduction zone approached and collided with the North American continental margin resulting in the attempted subduction of the North American continental lithosphere (Chapple 1973; Rowley and Kidd 1981). During this collision accretionary processes continued with synchronous deposition and deformation of flyschoid sediments in a "trench" created by the down-flexing of the loaded continental lithosphere. Eventually, buoyancy dominated over near-horizontal compression, and subduction ceased. The deformed medial Ordovician flysch deposits of the Hudson River Valley thus may represent the leading edge of a fossilized accretionary assemblage developed during the aborted subduction of continental lithosphere.

Past work within the Taconic flysch has focused on biostratigraphic correlations based on graptolite zonation (Ruedemann 1914, 1930; Berry 1962, 1963, 1973, 1977; Rickard and Fisher 1973; Riva 1974 and references therein). However, the time transgressive nature of the flysch and structural complications have led to the confusion of biostratigraphic, lithologic, and structural units by some workers resulting in, we believe, erroneous structural interpretations. In general, the paucity of outcrop and the absence of stratigraphic marker horizons impede interpretation by traditional stratigraphic mapping. Our work has focused mainly on detailed structural observations and mapping of lithologic variations. Two complementary field areas along the Taconic front have been studied (fig. 2). These two areas provide a broad view of the structures within the flysch and show a range of structural styles and deformation intensities. Lithologic variations were recorded at a scale of 1:12,000, while detailed structural mapping of selected outcrops was done at scales from 1:240 to 1:2400.

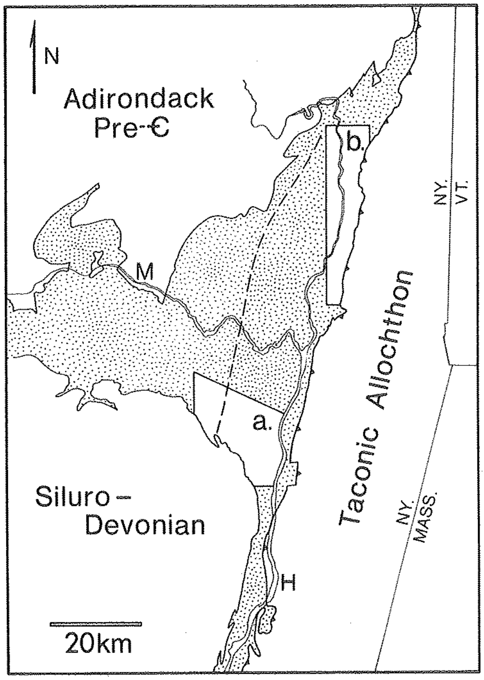

FIG. 2.—Location of field areas (a and b) mapped in the present study. Medial Ordovician flysch and fine-grained equivalents are shown in stipple. Dashed line indicates the western limit of distinct Taconic folding, after Ruedemann (1914, 1930). Outlines of regional tectonic units are from Fisher et al. (1970). Area of "Adirondack Precambrian" includes block-faulted Cambro-Ordovician shelf rocks. M = Mohawk River, H = Hudson River.

GEOLOGIC SETTING

The medial Ordovician Taconic flysch outcrops in an elongate belt along the Hudson River lowlands of eastern New York (fig. 2). Its eastern boundary is marked by the emergence of the basal Taconic thrust from the foothills of the Taconic Mountains, although flysch deposits are also found folded within and to the east of the rocks of the allochthon (Pawlet Formation of Zen 1961 and Austin Glen Graywacke of Ruedemann 1942). Bird and Dewey (1970) interpreted the Cambrian(?) to medial Ordovician argillaceous and arenaceous sedimentary rocks of the Taconic Allochthon as continental rise facies, transported to their present position as stacked thrust sheets during the Taconic Orogeny and now overlying the synorogenic Taconic flysch. Hard-rock thrusting (Walcott 1888; Keith 1912; Ruedemann 1914; Kay 1935, 1942; Fowler 1950; Rowley et al. 1979) and gravity sliding of incompletely lithified sediments (Zen 1961, 1967, 1972; Rodgers and Fisher 1969; Potter 1972) or overpressured strata (Cady 1968) have been variously suggested as mechanisms for emplacement of the allochthon.

The flysch units disconformably to unconformably overlie a Cambrian through medial Ordovician carbonate platform sequence of eastern New York (Rickard 1973; Fisher 1977). In the north and northwest the flysch exposures are terminated at high angle boundary faults of the Adirondack massif, which bring the shelf carbonates and underlying basement rocks to the surface (fig. 2). In the south, the flysch is unconformably overlain by Siluro-Devonian carbonates of the Helderberg Group. The flysch is highly deformed in the east, grading gradually into the undeformed black shales of the Mohawk Valley to the west and then progressively through interbedded limestones and shale to a dominantly carbonate medial Ordovician section of equivalent age. This distribution of facies arose when the shelf-slope boundary shifted from eastern to west-central New York during the medial Ordovician (Bird and Dewey 1970; Fisher 1977). Current structures and facies changes within this area, as to the south (McBride 1962), indicate that the depositional environment for the flysch is a north-south trending elongate trough. These sedimentary rocks were deposited by turbidity currents with an eastern source and dominant north-south transport.

LITHOFACIES

Three informal lithologic units have been recognized in the present work: Taconic melange; interbedded shales, siltstones, and wackes; and black shales. These are defined on the basis of lithologic criteria and have neither time nor stratigraphic connotations. The units are gradational in character and, where exposures are small, may be distinguished only by consideration of numerous outcrops.

The most complex unit is the Taconic melange (figs. 3, 4). The term "melange" is used here in the manner suggested at the recent Penrose Conference on melanges (Silver and Beutner 1980) and refers to a "mappable,

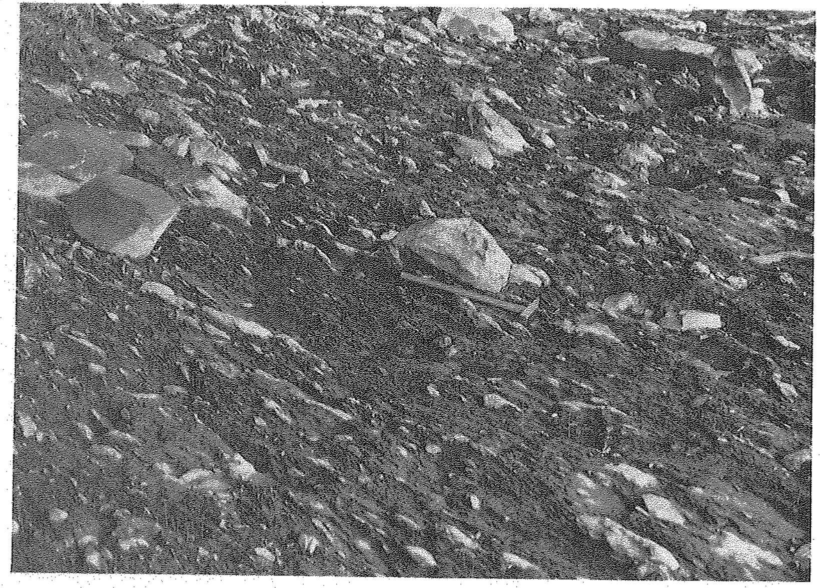

FIG. 3.—Taconic melange with blocks of arenite in phacoidally cleaved shale. Hammer handle length is 50 cm (Hoosic River bed below Schaghticoke, NY).

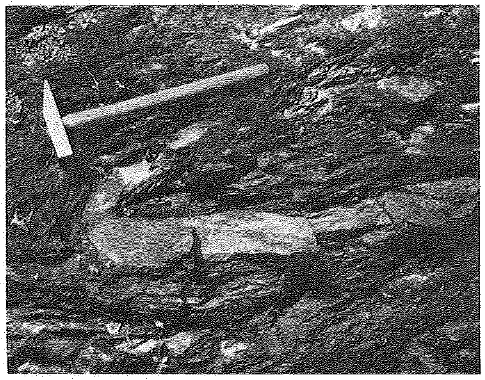

FIG. 4.—Isolated fold of arenite in melange. Viewed southeast. The axial plane strikes 039° and dips 71° east. Hinge line plunges 60° toward 183° (Kroma Kill above U.S. Route 4 in Saratoga National Historical Park).

internally fragmented, and mixed rock body containing a variety of blocks, commonly in a pervasively deformed matrix.'' Outcrops of the Taconic melange are commonly composed of phacoidally cleaved shales enclosing clasts and disrupted beds of graywacke. Large blocks or ''knockers'' of chert and other lithologies enclosed within the shale are also frequently observed (see also Bird 1969). Subdivisions of the Taconic melange are made principally on the basis of the nature of the enclosed blocks, the most important units being:

(1) Melange with no demonstrable exotic blocks (exotic indicating lithologies not found undisrupted in the flysch sequence; equivalent to ''broken formation'' of Hsü 1968). (2) Melange with exotic blocks: a. melange with blocks of Taconic lithologies; b. melange with blocks of shelf lithologies; and c. melange with exotic blocks of unknown affinity.

The melange includes the Rysedorph Hill Conglomerate (Ruedemann 1901) and Bald Mountain limestone of Ruedemann (1914, as reinterpreted by Rodgers 1952) and the Forbes Hill Conglomerate of Zen (1961) and is roughly equivalent to the ''blocks-in-shale unit'' of Berry (1962), the ''wildflysch-like conglomerate'' of Bird (1963), and the Poughkeepsie Melange of Fisher (1977). Previous interpretations of the Taconic melange (and its various synonyms) have, for the most part, considered this heterogeneous assemblage of rock types as a single unit, with a similarly singular tectonic significance (Zen 1961, 1967, 1972; Berry 1962; Bird 1963; Rodgers and Fisher 1969). We believe this simplification has led to misinterpretation of the position of some of the melange sections in the overall tectonic evolution of the Taconic Orogen.

The melange with no demonstrable exotic blocks appears to have been formed mainly through the progressive deformation and disruption of interbedded graywacke and shale. Isoclinal folding and boudinage due to high strains have lead to complete transposition and disruption in many areas. Near the Taconic Allochthon the sediments coarsen and in places cobbles and boulders of limestone, dolostone, and graywacke may be found within a pebbly mudstone matrix. These deposits are clearly of sedimentary origin and suggest that at least some of the smaller exotic blocks within the melange were derived from olistostromes. Imbrication of the original stratigraphic sequence has also lead to the incorporation of blocks or slivers of older rocks into the graywacke-shale melange. Of particular importance is the nature of the melange which occurs immediately to the west of the basal Taconic fault in the vicinity of Bald Mountain, New York. This melange contains blocks of early through medial Ordovician shelf rocks (Sanders et al. 1961; see fig. 5). Much of the block material can be seen to consist of brecciated, cataclasized and mylonitized carbonates and arenites (Bosworth 1980). Ruedemann (1914) believed the Bald Mountain unit to be principally a fault sliver, caught and carried beneath the overriding Taconic thrust sheet. Rodgers (1952) and later Taconic geologists reinterpreted the Bald Mountain rocks as olistostromic deposits overridden by advancing gravity slides of the Taconic Allochthon. As the structures of this portion of the melange are indicative of hardrock thrusting, we agree in principle with Ruedemann and interpret the Bald Mountain

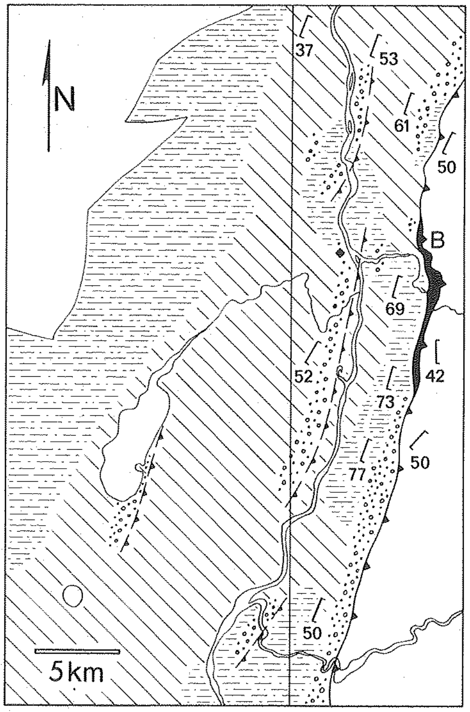

FIG. 5.—Generalized flysch lithofacies map of a portion of the upper Hudson River lowlands. Right-hand strip of the diagram corresponds to area "b" of figure 2, where detailed mapping has been completed. Rock types for the western area were determined from reconnaissance mapping and from the earlier works of Ruedemann (1914, 1930). Stippling = melange without demonstrable exotic blocks; solid black = melange with exotic blocks of Taconic and shelf affinities, interpreted to represent principally fault rock and slivers at the Bald Mountain locality; diamond symbol = melange with exotic blocks of uncertain origin, in this case, Stark's Knob pillow basalts; horizontal dashed lines = black shales and slates; diagonal lines = interbedded shales, siltstones and arenites. Structural symbols indicate average orientations of fold axial planes and slaty cleavage within the flysch and above the Taconic thrust. Interpreted positions of some thrust faults within the flysch are shown by broken lines, teeth on overthrust side. B = Bald Mountain.

unit as more likely to be fault slivers originating as the Taconic Allochthon ramped over the North American Cambro-Ordovician shelf during emplacement in the medial Ordovician, in accord with Rowley and Kidd's (1981) model for the Taconic Orogeny.

A final, enigmatic facies of the melange outcrops north of Schuylerville, New York at "Stark's Knob" (fig. 5). The knob consists principally of a large block of pillow basalt (Woodworth 1901; Ruedemann 1914), the longest dimension of which is about 100 m. It is entirely surrounded by phacoidally cleaved shales and slates, containing clasts of chert and arenite. It is not known whether the basalts are of ocean floor affinity, or originated in some other tectonic setting. Hence, their structural position and history are difficult to ascertain. Graptolite faunas described from this area (Ruedemann 1914; see also Fisher et al. 1970) suggest that the melange corresponds with a structural contact between flysch units of different medial Ordovician ages. Our present interpretation is that this melange with its exotic blocks delineates a master thrust fault, with significant horizontal displacement (fig. 5).

Flysch and distal equivalents not containing blocks have been divided into two units: a unit consisting of black shale and one comprised of interbedded shale, siltstone, and arenite (largely graywacke). These have previously been placed in formations according to their graptolite zone ages (Ruedemann 1914, 1942; Berry 1962; Rickard and Fisher 1973). As the lithofacies are demonstrably time transgressive (Rickard 1973; Fisher 1977), the previous bio-stratigraphic nomenclature was not deemed satisfactory for the construction of lithofacies maps. The black shale unit corresponds in part with the Utica, Canajoharie, and Snake Hill Formations of Rickard and Fisher (1973) and includes well-cleaved slates in the upper Hudson River Valley. Rickard and Fisher's (1973) coarse phases, the Normanskill graywackes (Austin Glen) and Schenectady sandstones and the coarse lithologies mapped by some workers as minor components of the Snake Hill (Ruedemann 1914), constitute our interbedded unit.

A lithofacies map of the portion of the upper Hudson River lowlands mapped in the present study is presented in figure 5. Pertinent conclusions derived from this data can be summarized as follows: (1) although melange in general is best developed close to the basal Taconic thrust, it is not confined to this position; (2) melange containing exotic blocks derived from the shelf or Taconic Allochthon *is* restricted to the basal Taconic thrust; (3) the flysch sequence shows a regional trend of fining to the west, as observed by previous workers (e.g., Fisher 1977), although lateral facies variations are common.

FOLDS

Folding occurs within the flysch sequence for a distance of 15 to 20 km west of the Taconic front; further west the rocks show gentle dips for several 10's of kilometers before becoming flat-lying (figs. 2, 6). In the absence of reliable stratigraphic marker horizons within monotonous sequences of graywacke and shale, fold observations were generally limited to those visible at the outcrop scale. The largest fold observed has a minimum half wavelength of 600 m; in many folds the half wavelength is 5 cm or less.

Style and Geometry.—Fold styles are varied and are dominantly controlled by lithology and amount of imposed strain. Homogeneously layered shale sequences often form kink or angular, similar style folds. Thicker bedded sequences of arenite tend to show more open folds with rounded hinges and a more parallel style. Interbedded sequences often show rounded folds in arenite becoming pinched angular folds in shales. The majority of folds cannot be traced farther than a single outcrop; many are structurally discontinuous with attenuated or disrupted limbs (fig. 4). Most folds in the west are open, with tight to isoclinal folds dominating in eastern areas.

Nearly all folds measured have axial planes dipping to the east (figs. 6, 7). The westernmost folds have steeply dipping axial planes and near horizontal hinge lines (figs. 6, 7*a*). These are found in relatively undeformed, gently dipping and well bedded, fine-grained arenite-shale sequences. One exception is a fold on the edge of a 20 m wide phacoidally cleaved shale zone on Vly Creek, below Voorheesville, New York, which plunges 28° (fig. 7*a*). This zone also contains anomalous steeply dipping disrupted beds and down dip striations and is the westernmost example of the phacoidally cleaved fabric which is well developed and widespread to the east. To the east folds have axial planes dipping moderately to the east or southeast with variably plunging hinge lines (figs. 6, 7*b*). Folds within the phacoidally cleaved melange are generally steeply inclined, whereas folds within slaty cleaved units are only moderately so. Hinge lines plot as a great circle within the average axial plane orientation (fig. 7). One outcrop example of a noncylindrical fold shows the steepening of a fold hinge line through 35° of arc as it approaches a small shear zone (fig. 7*c*). Folds exposed nearest the Taconic front have steeply to vertically dipping axial planes.

Fold Development.—Structures often associated with incoherent sedimentary deformation, such as convolute folds sandwiched between undeformed beds, sedimentary truncations of folds, and polyclinal or chaotic folds (Hobbs et al. 1976), are conspicuously absent or found only within typical Bouma C sequences near the top of individual graywacke beds. Features found in the study area suggestive of a tectonic fold origin include folded extensional fibrous calcite veins (fig. 8), axial planar cleavages, clastic dikes cut by axial planar cleavages, brittle failure of folds in hinge areas, and consistent axial plane orientations (fig. 7). Although perhaps individually inconclusive, taken as a whole these observations indicate that fold development proceeded as a tectonic process.

In discussing the fold development within this area an important assumption made is that the observed spatial west to east increase in deformation intensity represents the progressive development of structures through time. This is suggested by the gradational character of the structures from west to east; in particular, the initiation and tightening of folds, the progressive reorientation of fold hinge lines (fig. 6), the increased disruption and transposition of bedding, and the development of pervasive cleavages. Furthermore, as these flysch deposits are a trans-

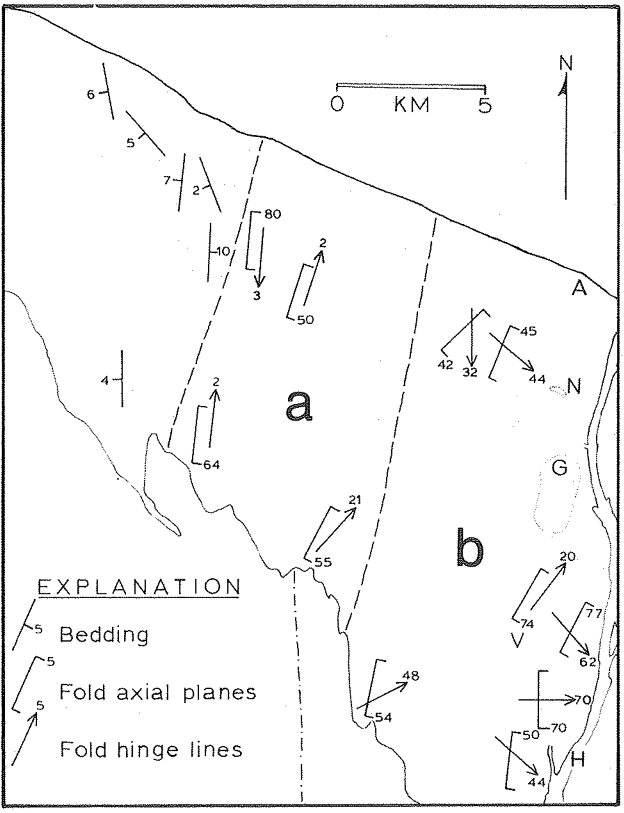

FIG. 6.—Generalized fold orientations in the Hudson River Valley flysch terrane; area "a" of figure 2. The southwestern boundary is the exposure of the unconformity with overlying Devonian carbonates. The dot-dashed line represents the western extent of obvious mesoscopic folding and faulting in the Devonian carbonates (after Ruedemann 1930). Fold orientations given represent the generalized fold orientation within small structural sub-domains from single outcrops or clusters of outcrop. Dashed lines indicate structural domain boundaries. The western domain contains essentially undeformed gently west-dipping strata. Domain a consists mainly of folded strata. Domain b is mainly folded and disrupted melange. Orientation data from domains a and b, with the exception of Normans Kill Gorge and Glenmont, are plotted in figure 6*a* and 6*b*, respectively. Letters represent locations: A = Albany, New York; N = Normans Kill Gorge; G = Glenmont; V = Vloman Kill Gorge; H = Hudson River.

gressive sequence deposited in front of the westerly advancing Taconic Allochthon (Bird 1969; Bird and Dewey 1970; Rowley and Kidd 1981) it is reasonable to assume that these sedimentary rocks were affected by a westerly migrating deformation front, with ever more westerly rocks being deformed by the approaching Allochthon. Thus, although the time of initiation of deformation may vary across strike, the sequence of events should remain uniform.

Fold orientation and tightness vary from west to east towards the allochthonous Taconic rocks. The westernmost folds are consistent with east-west layer parallel shortening leading to kinking and buckling of strata. The predominance of easterly dipping axial planes and westerly vergence, however, suggest a small horizontal component of east over west shear strain. Farther east fold hinge lines become progressively more easterly trending accompanied by an increase in fold

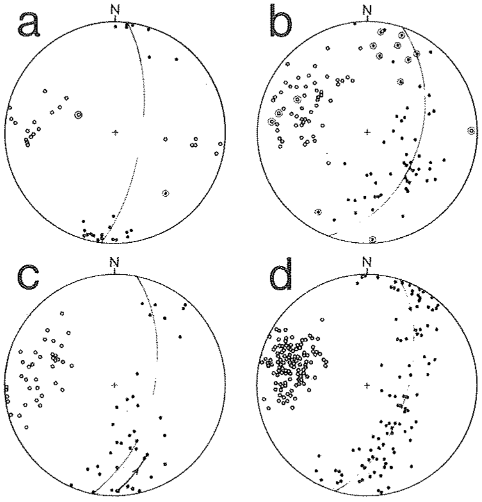

FIG. 7.—Schmidt net projections of structural elements from areas "a" and "b" of figure 2. In *a*, *b*, and *c* filled circles represent fold hinge lines and open circles represent poles to fold axial planes. Great circles are average fold axial planes. In *d* filled circles represent bedding/cleavage intersections, open circles represent poles to cleavage and the great circle is the average cleavage orientation. (*a*) Fold orientation data from domain "a" of figure 6. Concentric circles are data from a fold in a narrow phacoidally cleaved shear zone. (*b*) Fold orientation data from domain "b" of figure 6. These are mainly from discontinuous folds enclosed within phacoidally cleaved shales. Concentric circles are data from a thick bedded graywacke sequence in the Vloman Kill Gorge. (*c*) Fold orientation data from the total northern area, area "b" of figure 2. Curve segment with arrow represents a fold with a hinge line which is reoriented at a small shear zone. (*d*) Cleavage and bedding/cleavage orientations from the total northern area, area "b" of figure 2.

tightness and by an increase in the disruption of bedding. This suggests that fold hinge lines were rotated during increased straining (Vollmer 1980).

Although this progressive west to east change in structural style occurs on a large scale, local variations are common. Fold rotation appears to have occurred in the narrow zone of phacoidally cleaved shales mentioned above, probably due to local high shear strains (fig. 7*a*). In one area dominated by thick graywacke beds (Vloman Kill gorge, fig. 6), fold hinge lines show average plunges of 10 to 30° north-northeast, rather than 30 to 60° southeast as in the surrounding phacoidally cleaved shaly terrane (fig. 7*b*). This area correspondingly shows more open and less disrupted folds, suggesting that the total strain was less within the less ductile graywackes. A planar slaty cleavage is well developed within the siltstones of this area.

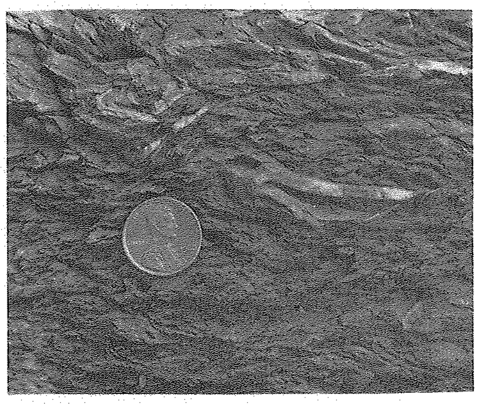

FIG. 8.—Isoclinically folded extensional calcite vein in phacoidally cleaved shale. Vein fibers are perpendicular to vein walls at all positions in fold. This suggests that brittle deformation of these rocks occurred prior to folding (Hill north of Vloman Kill at NY Route 144).

A number of authors have attributed the reorientation of fold hinge lines within high strain zones to the rotation of linear elements (such as hinge lines) into the principal elongation direction under homogeneous strain (e.g., Flinn 1962; Sanderson 1972; Escher and Watterson 1974). The development of strongly noncylindrical folds, or sheath folds, is common in shear zones (Minnigh 1979; and references therein). Along strike variations in strain within the flysch may have resulted initially in the formation of local fold culminations (e.g., Ramsay 1967, p. 436). Strain variations are common and may result from along strike variations in lithology or applied stresses. These culminations may then have been amplified during increased straining, with the rotation of hinge lines into the principal elongation direction accompanying boudinage.

The change in orientation of fold axial planes from west to east (figs. 5, 6) provides further constraints on the style of deformation. The initial change fom near vertical to approximately 45° east dipping axial planes implies a change in orientation of the strain ellipsoid, probably due to an increased component of horizontal simple shear related to the overthrusting of the Taconic Allochthon. The final step in fold formation appears to be a steepening of fold axial planes and a decrease in fold asymmetry. These developments occur nearest the Taconic front and generally in well-cleaved areas, suggesting a high bulk flattening. This steepening may also be due to the breaking through of listric master shears resulting in a package of rocks undergoing rigid-body rotation.

Two localities show some deviation from the generally coherent pattern of fold development seen elsewhere. Fold hinge data from these localities have not been incorporated into the orientation diagrams presented in figures 6 and 7*b*. The first locality comprises a number of outcrops of mostly black and green bedded chert and siliceous argillite near Glenmont, New York (fig. 6). Similar chert bodies are common throughout the melange. Although there is a greater amount of scatter in fold orientations here, they are generally consistent with the fold model presented above; the data does not suggest that the chert occurs as randomly oriented blocks. The chert is a slightly older facies (Ruedemann and Wilson 1936; Fisher 1977) which has apparently been intercalated into the graywacke-shale melange as thrust slivers. Cleavage orientations within the chert are uniform and show moderate easterly dips. Also within the cherts thrust faults with east plunging slickenside striations are common (fig. 9*b*). The second locality is within the Normans Kill gorge (fig. 6), a classic graptolite locality and the type section of the Normanskill "formation" (Ruedemann 1930). Here deformation is complex with large blocks and fold hinges of graywacke enclosed in a disrupted shaly matrix. Downward facing folds, wide scatter in fold orientations, and north plunging maxima of poles to bedding and fold axial planes (fig. 9*a*) are all features not observed in other areas. Our interpretation for the deformation within this outcrop is that a relatively localized slumping or refolding event has complicated the structural history, resulting in the formation of downward facing folds and weak and unusual orientations of structural elements.

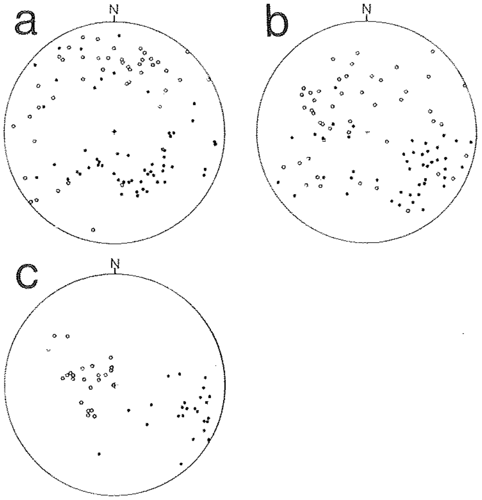

FIG. 9.—(*a*) Schmidt net projection of poles to fold axial planes (open circles) and fold hinge lines (filled circles) from Normans Kill Gorge (fig. 6). Scatter and unusual orientations of structural data are believed to have resulted from a refolding event. (*b*) Schmidt net projection of slickenside striations (filled circles) and poles to slickenside surfaces (open circles) from chert and siliceous argillite outcrops near Glenmont, New York (fig. 6). Eight of these faults show stepped slickenside fibers giving overthrust solutions. (*c*) Schmidt net projection of slickenside striations (filled circles) and poles to slickenside surfaces (open circles) from northern area "b" of figure 2.

CLEAVAGE

The microstructure of the flysch is dominated by the development of planar fabrics of which two end members can be recognized. A descriptive division between slaty cleavage and phacoidal cleavage is made in view of their widely differing morphologies and modes of occurrence, although intermediate or transitional forms are clearly present.

Slaty Cleavage.—The westernmost, upright folds of the Taconic flysch are not generally accompanied by any tectonic foliation that is distinguishable in the field. Rather, a bedding parallel fissility in the shaly units is well developed, which strongly affects later fabric changes. Farther to the east an increasing east-over-west fold asymmetry is seen and a closely-spaced cleavage becomes apparent in the dark shale beds. Its orientation here is roughly parallel to the western border of the Taconic Allochthon, striking 0–30° east of north and dipping 30–45° to the east. Approaching the Taconic front, the intensity of this foliation steadily increases, as does its dip (fig. 7*d*). In the northeasternmost exposures of flysch within the study area all lithologies are cleaved and the dip has become vertical or nearly so. Here the flysch has been locally quarried for slate.

The cleavage folia are essentially flat in hand specimen, their anastomosing nature becoming apparent only in thin section. Folia are composed of phyllosilicates and unidentified dark material (clay?) which are also present within the interfolial domains. No recognizable metamorphic minerals have been seen. This foliation is morphologically identical to the regional slaty cleavage seen in the westernmost units of the Taconic Allochthon, although its orientation is quite different. The slaty cleavage within the allochthon dips at approximately 45° to the east just east of the thrust boundary, and its strike does not generally parallel the present exposure of the fault line nor the strike of the cleavage in the underlying flysch (fig. 5).

In most observed mesoscopic folds and in a statistical sense the slaty cleavage in the flysch is axial planar. Notable exceptions do exist, with measured differences between cleavage and axial plane orientation of as great as 29°. The slaty cleavage is non-parallel with and refracted by clastic dikes observed in the flysch. The cleavage therefore clearly formed after injection of the dikes, in agreement with observations of Boulter (1974), Beutner et al. (1977), Beutner (1978, 1980), and Gregg (1979) concerning clastic dike-cleavage time relationships.

The foliation described above loses its "slaty" appearance in two distinct fashions. In the first, when passing from the limbs of some folds to their hinge regions, the slaty cleavage will gradually change to a crenulation cleavage easily recognized in hand specimen. The orientation of the cleavage remains unchanged and no evidence of refolded-folds in the areas of slaty cleavage development has ever been seen. The crenulated surface is therefore thought to represent a prefolding (sedimentary?) bedding-parallel fissility. In the second case, the slaty cleavage becomes anastomosing in hand specimen whenever the parent material consists of recognizable blocks or clasts of coarse material in a shaly matrix (by definition, "melange"). This cleavage then approaches the description which follows for phacoidal cleavage, with every transition between the two being represented in the field (although not all of the phacoidally cleaved rocks necessarily contain clasts or blocks).

Phacoidal Cleavage.—The term *phacoidal cleavage* is used here to describe the highly irregular anastomosing fabric characteristic of outcrops in the melange (fig. 10). This phacoidal cleavage also generally strikes

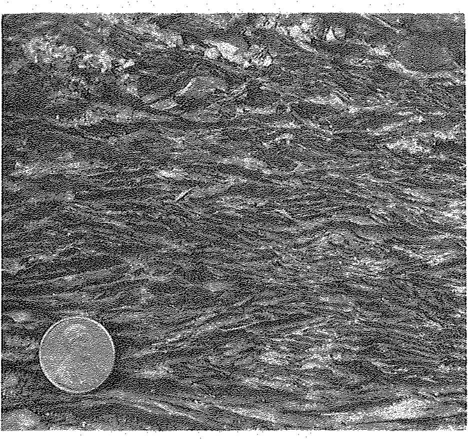

FIG. 10.—Phacoidally cleaved shale. Foliation is defined by aligned lenses and chips of argillite and fine-grained arenite, and dips approximately 45° east. East plunging striations can be seen on many of the phacoid surfaces (north bank of Normans Kill at Normansville, NY).

0–30° east of north, and dips 40–80° to the east. It is defined by lensoid chips, fragments, and blocks with long axes lying in a common plane and thin anastomosing films of dark argillaceous material. Characteristically, blocks of graywacke including fold hinges, and less commonly siliceous argillite, green and black chert, dolostone, and limestone are found within a shaly matrix. The matrix consists of shiny gray or black shale and siltstone chips usually 2 cm or less across, commonly with down-dip striations similar to non-fibrous slickenside striations. In some cases, disrupted graywacke beds can be traced discontinuously through the matrix. Isolated fold hinges found within the phacoidally cleaved matrix have axial planes parallel or sub-parallel to the foliation. These folds commonly show steeply southeast plunging hinge lines (fig. 4). In some areas gradations from deformed, but well-bedded graywackes and shales into phacoidally cleaved shales enclosing disrupted graywacke beds occur within several meters. Phacoidal cleavage is never observed within undisrupted strata. Although characteristically associated with blocks in a shaly matrix, phacoidal cleavage also occurs in shaly rocks where any effects of contrasting lithologies on material behavior should be minor. Identical lithologies commonly show well developed slaty cleavage in nearby units.

Microstructural examination of several thin sections of impregnated phacoidally cleaved shale shows the fabric to be defined by thin, anastomosing films of dark micaceous or argillaceous material. The films enclose lenses or phacoids of siltstone or other rock fragments (fig. 11). Siltstone phacoids commonly show truncated foliations along their boundaries. In some cases, the phacoids appear to have formed from broken layering. Asymmetric folds and offset calcite veins are also present.

This type of irregular fabric defined by alignment of phacoids and anastomosing films has been described from melange terranes in Wales (Greenly 1919 cited in Hsü 1968), California (Cowan 1974), Indonesia (Moore and Karig 1980), the Aleutians (Moore and

FIG. 11.—Transmitted light photomicrograph of phacoidal cleavage (negative image). Hand sample resembles the rock illustrated in figure 10. Scale bar equals 2 mm.

Wheeler 1978), Newfoundland (Stevens 1970), Norway (Horne 1979), and other areas (Hsü 1968; Silver and Beutner 1980). In most cases, these melanges are associated with the deformation of flysch in an overthrust environment and the fabric is often described as "highly sheared" or "sheared looking."

Cleavage Development.—Cleavage development in this area is viewed as the result of two competing processes. The first is the development of a regular, planar slaty cleavage through the processes of rotation and growth of phyllosilicates and diffusive mass transfer. The second is the development of a shear fabric through processes still poorly understood, but probably including microfaulting, diffusive mass transfer, and phyllosilicate growth and rotation. Slaty cleavage is best developed in the northeast and postdates at least some brittle behavior. Structural observations, as a whole, suggest a shear origin for the phacoidal cleavage. Down-dip striations are common on individual phacoids. Microstructural observations of asymmetric folds and offsets are in agreement with a shear origin. The consistent easterly dip of the cleavage, association with overturned asymmetric folds, east-plunging slickenside striations, and increasing areal extent of phacoidally cleaved zones towards an overthrust terrane also support this idea.

Several mechanisms, possibly acting together, are suggested that may explain the irregular nature of the phacoidal cleavage. In a piece of rock subjected to simple shear at high strain rates, the axes of the infinitesimal strain ellipsoid will rotate through material lines in the rock at correspondingly high rates. As cleavage is defined by material lines, the infinitesimal strain ellipsoid rotates with respect to the cleavage orientation, unless the cleavage lies in the shear plane. If the microstructural development of cleavage folia is controlled by processes related to the infinitesimal state of strain, perhaps through the state of stress (diffusive mass transfer and recrystallization are possible examples), then the rate of these processes relative to the rate of strain axis rotation becomes important. The simplest case to consider from the standpoint of cleavage morphology is the one where the microstructure of the rock changes through these processes at a rate fast enough to keep up with strain axis rotation. In this case, the cleavage maintains a constant orientation with respect to the infinitesimal strain ellipsoid. On the other hand, if the deformation processes are not fast enough, a given cleavage folium will assume a new orientation relative to each successive position of the infinitesimal strain ellipsoid.

A possible consequence of such a rate differential is that cleavage initially formed perpendicular to the maximum compressive stress (σ_1) (however, see Hobbs et al. 1976) will rotate to planes experiencing a shear stress as deformation proceeds. This introduces the possibility of cleavage-parallel shearing, a phenomenon supported by the presence of slickenside striations on much of the phacoidal cleavage. New folia may then develop perpendicular to successive σ_1 orientations, producing a number of cleavages. Older cleavage folia under shear stress could then slice through younger folia, or folia of various orientations could link to enclose phacoids. These features are also seen in the microstructure of the phacoidal cleavage.

FAULTS

The lack of lithostratigraphic marker horizons in the flysch prevents delineation of large scale faults, except where paleontologic control indicates their presence (Ruedemann 1914; Rickard and Fisher 1973). Areas of phacoidally cleaved melange, often containing exotic blocks, occur along many of these paleontologic discontinuities. We have interpreted these melange belts as the traces of major thrust faults or shear zones within the flysch (fig. 5). Numerous structural discontinuities can be seen in individual outcrops, and the most significant of these occur as low-angle thrust faults and narrow shear zones. High-angle faults are less frequently encountered and have not been studied in detail.

The thrust faults have a general north-south strike, dipping 0–30° to the east. Their morphology varies from that of a discrete surface to a zone up to one-half meter across. The faults are commonly mineralized with quartz and calcite, with slickenside striations plunging down dip (fig. 9*b*, *c*). An east-over-west displacement is established for many of the faults by the presence of a steep east-dipping foliation between their bounding surfaces, by flexure of beds and slaty cleavage toward the fault surface, and by stepped slickenside fibers. Fault breccias consisting of chert and argillite clasts and broken quartz-calcite veins in a shaly matrix are commonly present. These faults post-date at least a major portion of the slaty cleavage development and truncate mesoscopic fold axial planes.

A general west-to-east change in the character of the thrust faults is observed. In the moderately folded west-central portion of the flysch where long fold limbs dip at about 30° to the east, the faults are mostly bedding parallel, breaking across layering only in the hinges of folds. As easterly limbs steepen in approaching the allochthon, the faults are no longer bedding parallel and their frequency of occurrence and the thickness of the zone of shearing concurrently increase.

POST-TACONIC DEFORMATION

Southwest of Albany, the Taconic flysch is unconformably overlain by a sequence of folded and thrust faulted latest Silurian and Devonian shallow water limestones. Distinct mesoscopic folding within these limestones dies out 4 to 5 km east of the western extent of deformation in the Ordovician graywackes and shales (Ruedemann 1930; figs. 2, 6). Several exposures of this unconformity show shearing of the younger rocks along bedding parallel thrusts, suggesting that a significant percent of post-Taconic shortening may have been accommodated within Silurian and younger sediments. Although folding of the unconformity can be seen in outcrops to the south, the most significant deformation of the Ordovician flysch is believed to have occurred prior to the deposition of Silurian sediments. The unconformity is generally at a high angle to Ordovician bedding with truncation of Taconic axial planes and slaty cleavage observed at several localities. In at least one area, on Spruyt Creek near South Bethlehem, New York, phacoidally cleaved melange fabric is unconformably overlain by the carbonates. In general, the later deformation was roughly coaxial with Taconic deformation, and structural overprinting seems confined to the rare development of a weak crenulation cleavage, low amplitude warping of cleavage planes and tightening of earlier structures.

DISCUSSION

Interpretation of the structure and lithofacies of the Taconic flysch terrane leads to a model of progressive deformation of synorogenic deposits in an overthrust environment, associated with the westward directed emplacement of the Taconic Allochthon. The basic features of this model are presented in figure 12. Deposition of the flysch deposits occurred as turbidity currents shed off of the westerly advancing Taconic Allochthon into an elongate north-south trending trough. A west to east increase in deformation intensity suggests that the structural development began with kinking and folding of beds. Folds then became tighter and more asymmetric with axial planes inclined to the east. With increasing strain, disruption of the interbedded graywacke and shale sequences occurred due to high ductility contrasts, resulting in the formation of tectonic melange. Increased strains also reoriented fold hooks within the melange progressively towards the east-west overthrust direction of the Taconic Allochthon. Microstructural development within the melange appears to have been dominated by the formation of phacoidal cleavage, possibly related to a noncoaxial strain history. Slaty cleavage is well developed in the less disrupted units of the flysch. Locally, imbrication of the original stratigraphic sequence occurred, bringing slivers of older rocks to the surface. Relief along fault scarps then allowed erosion and reincorporation of portions of these rocks into the sediments. Slumping was active, although not dominant

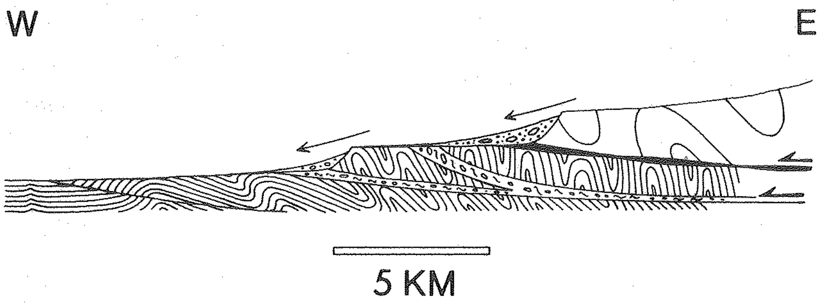

FIG. 12.—Schematic cross section illustrating the basic deformational and depositional processes inferred to have occurred in the Taconic flysch terrane during the medial Ordovician. Overthrusting from the east of Taconic rocks (thick bedding symbol) occurred along a master thrust (half arrow) with carbonate slivers (solid black) derived from the shelf. This lead to the progressive development of asymmetric folds and rotation of fold axial planes and hinge lines within the flysch (thin bedding symbol). Below and in front of the allochthon tectonic melange (coarse debris symbol with dashes) formed in areas of high shear strain. Adjacent to major fault scarps olistostromes (coarse debris symbol with stippling) were deposited and subsequently incorporated into the melange.

as a deformational process. Final steepening of structures directly beneath the Taconic thrust occurred due to rotation above listric thrusts or increased horizontal shortening.

This model is similar in some respects to those proposed by Seely et al. (1974) and Karig and Sharman (1975) for accretionary prism complexes (and as modified by Homewood 1977 for the formation of North-Penninic melange). Although the depositional environment might be referred to as a "foreland basin" (e.g., Dickinson 1977), structurally the environment is equivalent to a subduction zone in which continental lithosphere is being underthrust. The buoyancy and stiffness of the continental lithosphere results in a braking of the subduction which has in effect "fossilized" the deformation. Studies of the structures within the Cretaceous accretionary terrane of the Kodiak Islands, Alaska by Moore (1973) and Moore and Wheeler (1978) provide an interesting comparison with our findings. A thick turbidite sequence, the Kodiak formation, is pervasively folded with fold hinges parallel to the Aleutian trench, folds overturned seaward and axial planes dipping landward. An older melange terrane occurs landwards which contains blocks of various lithologies within an argillaceous matrix characterized by an anastomosing fabric defined by lensoid fragments. Folds within the melange have hinge line orientations which plot on great circles within an average steeply landward dipping fold axial plane. The last structural event within the Kodiak Islands appears to be a further steepening of structures. Although the formation of these terranes in Alaska occurred over a longer time and at a larger scale, this does suggest that similar processes may have been operating (Vollmer 1981). In the Hudson River Valley, however, a more continuous structural sequence from undeformed sediments into highly deformed and complex rock units exists.

Previous models relating to the emplacement of the Taconic Allochthon (Zen 1967; Bird 1969; Bird and Dewey 1970) have assumed that emplacement of the westernmost (Giddings Brook and Sunset Lake) slices involved gravity sliding into a basin of unlithified flysch. We maintain that the coherent nature of the deformation within the flysch does not allow this interpretation. Other evidence including the coherent structure and stratigraphy within the lower Taconic slices, truncation of fold axial planes by the Taconic thrust, and the presence of slate clasts within the flysch has been presented by Rowley et al. (1979) and Rowley and Kidd (1981). Fisher and Rickard (1973) have presented biostratigraphic data (but see Berry 1973, 1977) that led them to propose an earlier (pre-Giddings Brook) gravity slide within the Taconic flysch. Flysch deposited to the east (Austin Glen Graywackes) was thought to have been uplifted and slid onto younger flysch in the vicinity of the present Hudson lowlands prior to emplacement of the Taconic Allochthon. The Austin Glen Graywackes are supposedly preserved as klippen lying on autochthonous flysch terrane in this model (see Fisher et al. 1970). We believe that their biostratigraphic data (see also Ruedemann 1914, 1930; Berry 1962, 1963, 1973, 1977; Riva 1974) is compatible with our interpretation of imbricate thrusting and does not require a pre-Giddings Brook gravity slide event.

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