GEOMETRY AND STYLE OF POST-OBDUCTION THRUSTING IN A PALEOZOIC OROGEN: THE TACONIC FRONTAL THRUST SYSTEM[1]

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ABSTRACT

The Taconic Frontal Thrust System, associated with the later stages of the medial Ordovician Taconic orogeny, a continental margin-volcanic arc collision, defines the present western boundary of the Taconic Allochthon in eastern New York and west-central Vermont. The Frontal Thrust emplaces regionally folded and foliated Taconic rocks over deformed, but essentially unmetamorphosed, flysch. The Frontal Thrust is temporally and kinematically related to the Champlain and Orwell faults to the north, that emplace variably deformed sections of Early Paleozoic shelf rocks over partially coeval sections of the Early Paleozoic platform. Major movement on these faults occurred after initial obduction of the Allochthon onto the Early Paleozoic North American continental shelf and prior to being unconformably overlapped by the Early Devonian. This fault system is considered to be part of the final phase of a continuum of thrusts that evolved during the Taconic Orogeny, and therefore records only the final emplacement geometry of the Allochthon. Detailed mapping has revealed a complex, fine-scale imbricate structure at and near the front of the Allochthon. The imbricate structure in front of the Allochthon is defined by slivers and small thrust sheets of Lower and Middle Ordovician shelf carbonate and overlying Middle Ordovician shales, flysch and wildflysch (debris flow deposits), and melange. These imbricates have dimensions of hundreds of meters to kilometers parallel with strike and a few to several hundred meters structural thickness across strike. Ramps and tear faults within the imbricate stack control the final geometry of the otherwise gently east-dipping Frontal Thrust surface. Complex superposed fold patterns occur locally within the overlying regionally folded Taconic sequence at these frontal structures. At Bald Mtn. and other localities to the north, the carbonate slivers have an internal duplex structure, with the Frontal Thrust forming the roof fault to the duplex. In some areas the Frontal Thrust appears to follow the earlier, pre-cleavage thrusts (e.g., Basal Taconic Thrust) along which initial obduction occurred. Microscopic and mesoscopic fault-related deformation associated with the Frontal Thrust appear to have developed in fully lithified sedimentary sequences. Deformation involving partially lithified rock is limited to the local incorporation of olistostromes into tectonic melange at the leading edge of the Allochthon. The pattern of essentially coeval thrusting, lithification, cleavage development, low-grade metamorphism deduced here may be generally representative of the final stages of continental margin-island arc collision.

INTRODUCTION

The western margin of the allochthonous clastic rocks of the Taconic Orogen has long been recognized as a fundamental tectonic and structural feature in the geology of eastern New York and western New England. Although first interpreted as the trace of a major unconformity between fossiliferous Cambrian and supposedly older and unfossiliferous "Taconic" rocks (Emmons 1844), it was later correctly identified as the trace of a surface of regional overthrusting (Logan 1861). In eastern New York, "Logan's Line" places earliest Cambrian through Ordovician deep-water "Taconic" sedimentary rocks above Late Cambrian and Ordovician shallow-water clastics and carbonates of the "standard" sequence of eastern New York (Zen 1961, 1967). The actual fault contact generally juxtaposes Taconic lithologies with medial Ordovician, syn-orogenic flysch consisting of graywacke, siltstone, and shale. The flysch-Allochthon contact is rarely exposed, resulting in considerable dispute concerning its nature. More commonly the western-bounding thrust of the Allochthon is exposed where it contacts Ordovician shelf carbonates. These masses of shelf carbonate are demonstrably transported, vary in size from kilometers to pebbles, and have been variously interpreted as olistostromal blocks (Zen 1961, 1967; Rodgers and Fisher 1969) and fault slivers (Walcott 1888; Ruedemann 1914; Zen 1967; Bosworth 1980; Bosworth and Vollmer 1981).

The lack of well exposed sections through

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the western Taconic thrusts has allowed varied interpretations and controversy to persist as to the emplacement mechanisms of the Allochthon as a whole. For example, Zen (1961, 1967, 1968), Rodgers and Fisher (1969), Fisher et al. (1970), Bird (1969), and Bird and Dewey (1970) and others who have interpreted these carbonate masses as olistostromal blocks caught up within black shales and olistostromal "melanges" in front of the moving allochthon have also tended to favor gravity-slide mechanisms of emplacement of unlithified, or at least incompletely lithified, allochthonous Taconic rocks. This interpretation is based on the view that these masses generally have a chaotic distribution with respect to neighboring carbonate sequences, that black shales and associated melanges envelope each of the carbonate blocks, and that contacts with associated syn-orogenic deposits and adjacent carbonate blocks are essentially sedimentary.

Recent work along the western front of the Allochthon in regions primarily to the north of Albany, New York brings many of these earlier suggestions into question. The observations and arguments put forth below are based on detailed maps (1:6,000 to 1:12,000 scales) along most of the western boundary of the Allochthon from Schaghticoke, New York, to its northern limits in west-central Vermont (fig. 1) (Bosworth 1980; Rowley 1983*a*; Selleck and Bosworth 1985; Bosworth, Rowley and Kidd unpub. maps). Our data favor a hard-rock emplacement history of the Allochthon and at least the larger carbonate blocks based on (1) structural characteristics of the Frontal Thrust fault zone (Ruedemann 1914; Bosworth 1980), (2) the internal structure and stratigraphy of the Allochthon and adjacent Taconic flysch (Rowley et al. 1979; Rowley and Kidd 1981; Bosworth and Vollmer 1981), (3) the relatively ordered, albeit structurally complex arrangement of stratigraphic sequences within the frontal carbonate and flysch terrane, and (4) analogy with modern convergent orogens (Rowley 1980, 1983*a*; Rowley and Kidd 1981). This interpretation views the Frontal Thrust as part of a large-scale imbricate thrust system, the Taconic Frontal Thrust System, that is continuous to the north with the Champlain-Orwell thrust system of north-central Vermont (Rowley 1983*a*, 1983*b*). The

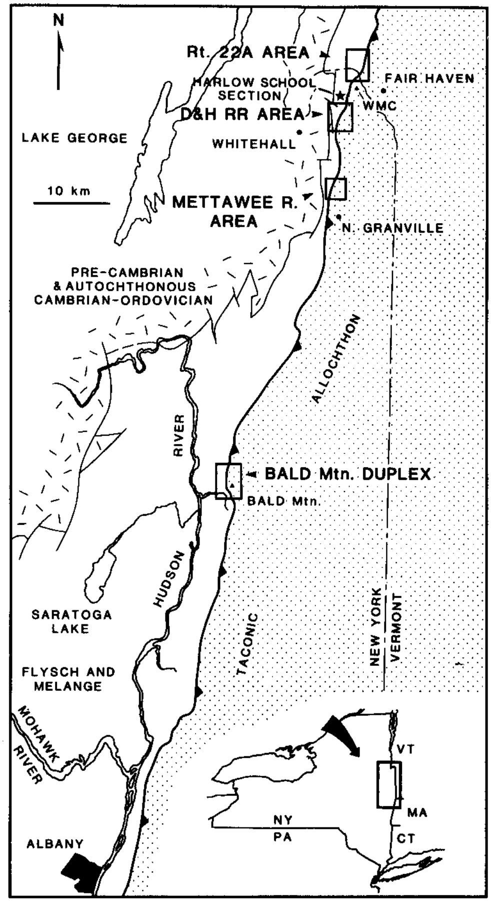

FIG. 1.—Location of areas described in the present study. Regional geology from Fisher et al. (1970). WMC—William Miller Chapel.

Taconic Frontal Thrust system is similar to those documented for other external fold-thrust belts (Bally et al. 1966; Dahlstrom 1970; Price and Mountjoy 1970) and is supported by recent geophysical studies in the Taconide Zone of Quebec (Seguin 1982) and western New England (Post and Taff 1985; Brown et al. 1983; Ando et al. 1984).

THRUST-RELATIONSHIPS BETWEEN THE TACONIC ALLOCHTHON AND SUBJACENT PARAUTOCHTHONOUS SEQUENCES

Mapping in the Taconic Allochthon in Vermont (Rowley 1983*a*, 1983*b*) has shown that an important distinction should be made between the thrust systems that define the present western and northern boundaries of the

Allochthon. The present western bounding thrust of the Taconics, referred to as the "Taconic Frontal Thrust" (Rowley and Kidd 1982*b*), is characterized by the truncation of regional folds and metamorphism within the Allochthon and emplaces the Allochthon on essentially unmetamorphosed and variably deformed and disrupted medial Ordovician parautochthonous flysch and, less commonly, Ordovician shelf carbonate assemblages. In marked contrast to this, the thrust bounding the northern end of the Allochthon, referred to as the "Taconic Basal Thrust" (Rowley and Kidd 1982*b*), juxtaposes allochthonous Taconic sequence rocks with comparably deformed and metamorphosed parautochthonous shelf and flysch assemblages along a regionally folded and metamorphosed thrust surface (Rowley 1983*a*, 1983*b*; see also Zen 1961, 1964, 1967 and Rodgers 1952, 1982). From their relative structural histories it is quite clear that the Basal Thrust must pre-date the Taconic Frontal Thrust and that the Basal Thrust and not the Frontal Thrust system represents the surface along which the Allochthon was initially emplaced onto the shelf.

The character of the Frontal Thrust System is documented here, using several key sections with relatively good exposures or significant single exposures. We focus primarily on some of the geometric details and rock fabrics that characterize the late-stage, west-directed thrusting of the Taconic Allochthon. These localities have been critical in producing a general emplacement scheme for the Taconics and in determining the mechanical state of the Taconic and underlying rocks at the time of this thrust-related deformation. Each of the key localities are described and interpreted individually, and then some generalizations are summarized. The details of the tectonic evolution of this region have been discussed elsewhere (Rowley and Kidd 1981) and are not reiterated here.

RAMPS AND FINE-SCALE IMBRICATION NEAR NORTH GRANVILLE

Exposures to the east of the Mettawee River between North Granville and East Whitehall, New York display both details within the Allochthon near the Frontal Thrust and the interaction between the Frontal Thrust and several large shelf carbonate slivers (fig. 1). To the east of the Frontal Thrust and within the Allochthon, stratigraphic relationships indicate the presence of a series of west-vergent regional D_2 folds that have been refolded by smaller scale folds and cross-cut by non-axial surface-parallel thrusts (figs. 2 and 3). These superposed deformations are not observed in adjacent regions immediately to the east, which suggests that they are the result of interactions with subjacent, shelf carbonate-bearing thrust sheets exposed to the west. The structurally subjacent carbonate sheets are comprised of Middle Ordovician shelf units of Trenton and Black River (D. W. Fisher pers. comm. 1983) age, with at least local occurrences of Chazyan in the southern mass (Selleck and Bosworth 1985). Both carbonate slivers are tightly folded internally, with steeply east-dipping axial surfaces and axial surface foliation. These folds appear to be truncated above by the Frontal Thrust and by melange beneath the carbonate slivers. This suggests that the folding in the slivers either pre-dates or developed synchronously with detachment from the carbonate platform during movement of the Allochthon across the shelf.

The two carbonate slivers are offset by about 400 m in an east-west direction along a transverse fault in a right-lateral sense (fig. 2). This transverse fault is inferred to be a right-lateral tear fault; it may alternatively be a lateral ramp (Boyer and Elliot 1982), but the data are not conclusive. The complexity of folding within the Allochthon increases greatly north of this transverse structure. The eastern contact of the northern sliver dips 40° to 50° E and defines a ramp in the Frontal Thrust. This appears to have induced fine-scale imbrication just east of the ramp. The small folds superimposed here on the regional fold trends have strongly attenuated limbs and variably curving hinge lines. The small imbricating thrust faults completely shear through folds near the tear fault and become bedding-parallel farther to the north where they appear to lose stratigraphic offset (fig. 2). In contrast, the eastern contact of the southern sliver is very shallowly dipping, more in accord with the regional dip of the Taconic Frontal Thrust (about 7°E; Bosworth 1980, p. 63; Brown et al. 1983; Post and Taff 1985), which may explain the apparent lack of

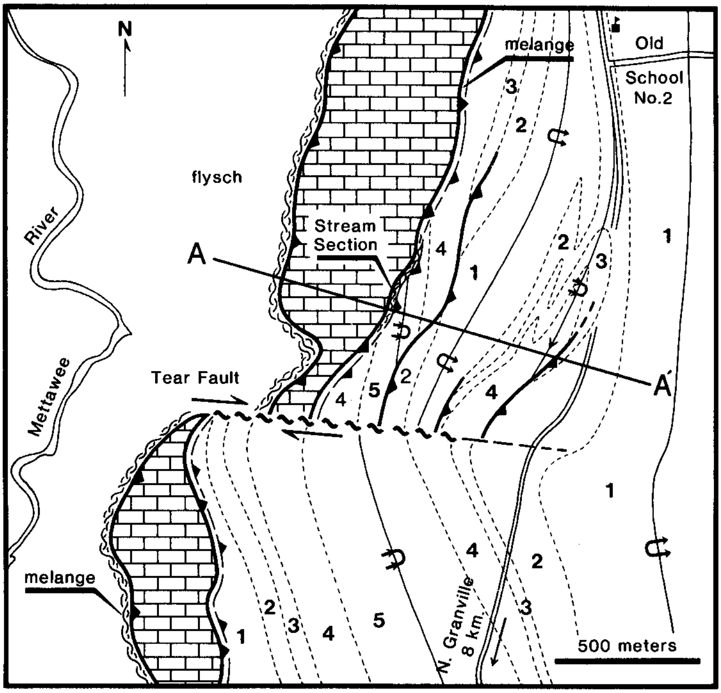

FIG. 2.—Geologic map of a portion of the Taconic Allochthon boundary (Frontal Thrust) east of the Mettawee River, Washington Co., NY (see fig. 1 for location). A tear fault apparently formed in association with break-up of the slivers of shelf carbonate attached to the base of the Allochthon. Complex folding and small-scale imbrication is superimposed on regional fold trends north of the tear fault, perhaps in part due to the presence of a ramp in the Frontal Thrust. 1 = Bomoseen Wacke and Truthville Slate; 2 = Browns Pond Fm.; 3 = Mettawee Slate; 4 = Hatch Hill Fm.; 5 = Poultney Fm. "Stream section" is illustrated in figure 4. Geology mapped by W. Bosworth, 1982; K. Klaski, W. Jackson, B. Doolan and W. Bosworth, 1983.

structural complexity within the Allochthon south of the tear fault.

In this same area the Taconic Frontal Thrust is exposed in an essentially continuous section along a small creek that flows through the northern carbonate sliver (fig. 4). This key section extends from shelf carbonate, through a melange zone containing clasts of shelf carbonate, to a melange containing blocks of Taconic rock, and finally to strongly deformed but stratigraphically and structurally intact Taconic allochthonous material in the east. Deformation in the entire section is dominated mesoscopically by the development of sets of shear fractures, in part anastomosing, merging to a strong

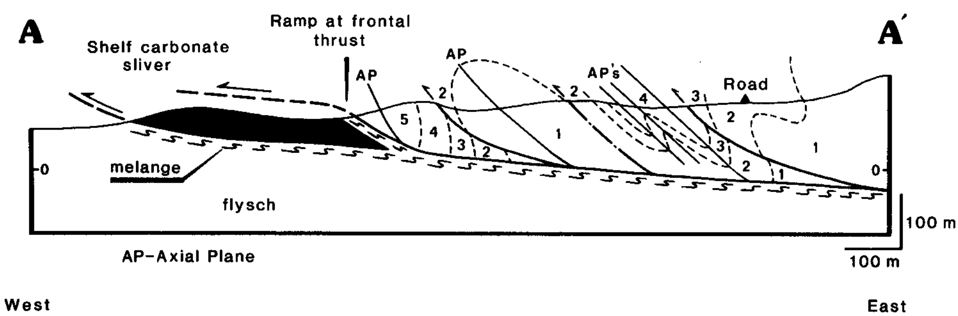

FIG. 3.—Interpretive cross-section through the Mettawee River area (fig. 2). Formation symbols are the same as in figure 2. No vertical exaggeration.

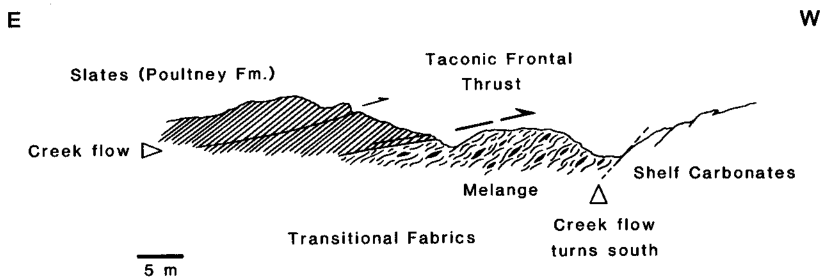

FIG. 4.—Detail of Frontal Thrust exposure east of the Mettawee River (see fig. 2 for location). Continuous creek bed outcrops illustrate the nature of the thin melange zone that follows the Taconic Frontal Thrust.

phacoidal cleavage at a smaller scale. Some of the shears are throughgoing, gently east-dipping, and mineralized with fibrous calcite and quartz. Clasts within the melange appear to have originated both through structural slicing (Bosworth, 1984) and from the incorporation of olistostromes into the melange matrix.

The critical observations and inferences derived from this locality are (1) that regional (D_2) folds within the Allochthon appear to be refolded, possibly in association with movement over a ramp in the Taconic Frontal Thrust system, (2) that the refolding must post-date the regional metamorphism which occurred synchronously with D_2 folding and slaty cleavage development within the Allochthon, and (3) that the style of deformation within the Taconic, flysch, and carbonate lithologies involves both brittle and brittle-ductile transition type behaviors that are not expected within soft, unlithified, or only partially lithified assemblages.

BALD MOUNTAIN SCHUPPEN OR FAULT DUPLEX

Bald Mountain has been a focal point of Taconic geology for the past 140 yrs (Emmons 1844). Lying at the western boundary of the Taconic Allochthon near Greenwich, New York (fig. 1), Bald Mountain exists as one of the few actual exposures of the Taconic Frontal Thrust. At the Bald Mountain quarry site, continuous exposure crosses from allochthonous Cambrian rocks through a zone of dark, phacoidally cleaved shale to massive Ordovician shelf limestones and dolostones. The base of the carbonate section is not exposed. Earlier workers have interpreted the shale/carbonate contact (or zone of phacoidally cleaved shale) as an unconformity (Emmons 1844; Sanders et al. 1961), a thrust fault above a fault sliver (Walcott 1888; Ruedemann 1914; Zen 1967, p. 32), or a thrust fault above olistostromal melange (Rodgers and Fisher 1969). Alternatively, Bosworth (1980), Bosworth and Vollmer (1981), and Rowley and Kidd (1982*b*) have suggested that the larger masses of Bald Mountain carbonate arose as hard-rock thrust imbricates. Sub-aqueous exposure of the upper plate sequences (e.g., Taconic, carbonates, and flysch) carried on these faults produced local olistostromes, subsequently overridden by the advancing thrust sheet in a manner analogous with that described for modern trench and trench-slope basin sequences (Karig and Moore 1975). This reworking produced some of the smaller carbonate pebbles and boulders found in the scaly shale associated with the carbonate masses in a fashion similar to that described from modern (Underwood and Bachman 1983) and ancient (Moore 1980) trench environments.

The details of the bedrock geology in the area adjacent to Bald Mountain have been mapped by Ruedemann (1914) and more recently by Platt (1960) and Bosworth (1980). Both later workers interpreted the western edge of the Allochthon as containing internal imbrication. One imbricating fault merges with or is truncated by the Frontal Thrust just north of the Bald Mountain quarry (fig. 5). The presence of scaly shale between individual blocks of carbonate beneath the Frontal Thrust has prompted some workers to call this entire section a deformed olistostrome (Rodgers and Fisher 1969). The overall geometry of the carbonate/shale mass is demonstrably sheet-like with lithologic units occur-

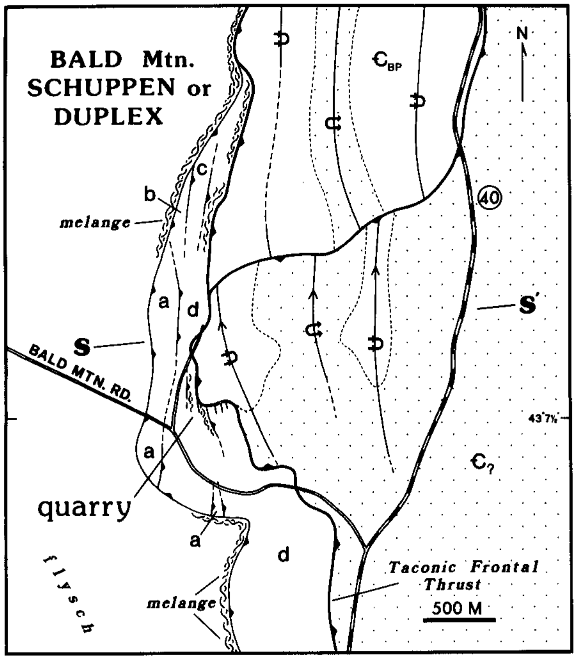

FIG. 5.—Geologic map of the Bald Mountain "schuppen" or fault duplex, Washington Co., NY (see fig. 1 for location). $C_?$ = Bomoseen Wacke and Truthville Slate; C_{BP} = Browns Pond Formation. Incomplete exposure prevents interpretation of the entire structure within the duplex itself. Location of cross-section S-S′ (fig. 6). Duplex lithologies are identified as: a—hard quartz arenites and mica-speckled quartz wackes (in part possibly Bomoseen lithologies; Elam 1960); b—limestone and dolostone pebble/cobble conglomerate with sandy dolomitic matrix (Rysedorph Hill Conglomerate; Ruedemann 1914); c—thin-bedded limestone and dark gray shale; d—undifferentiated limestones and lesser dolostones, often thick bedded or massive. Numerous melange zones are present within the duplex (anastomosing pattern) and phacoidally cleaved shale is present between most individual horses. Geology modified from Platt (1960) and Bosworth (1980).

ring in north-south aligned bands; some of the blocks are hundreds of meters in length (Bosworth 1980). Small-scale faults have similar north-south strikes. The outcrop pattern is suggestive of the small-scale shuppen or fault duplex structure found beneath many better-exposed thrust faults in other orogens (Peach and Horne 1914; Bailey 1938; Dahlstrom 1970; Elliott and Johnson 1980). The lengths of individual horses in this interpretation (fig. 5) are on the order of a few hundred meters to 1–2 km, with structural thicknesses measured in tens of meters (fig. 6). Locally, as at the Bald Mountain quarries, faulting results in stratigraphic replication on a scale of meters, and the true complexities of the thrust

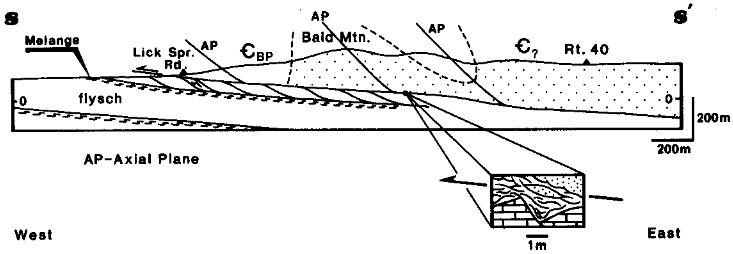

FIG. 6.—Interpretive cross-section through the Bald Mountain fault duplex (fig. 5). Formation symbols are the same as in figure 2. No vertical exaggeration.

geometry become apparent. This replication involves both the carbonate units and the stratigraphically younger black shale and olistostromal units within the duplexes which accounts for, and appears to provide an alternative explanation for, the earlier interpretations that favored an olistostromal origin for the entire assemblage.

The extent of deformation of the larger carbonate horses at and near Bald Mountain is quite variable. In many cases within the internal portions of large blocks, sedimentary and organic structures are well-preserved (e.g., Selleck and Bosworth 1985), with small-scale deformation limited to calcite twinning and the development of stylolitic cleavages. In general, the fabric of the block peripheries is in sharp contrast to that of the internal portions of larger blocks. The peripheries of the blocks are frequently brecciated or defined by discrete faults. Micro-fracturing of limestone and dolostone facilitated extensive dissolution and reprecipitation of carbonate. In many cases shear fractures terminate at thick, toothed stylolites in a complicated pattern of brecciation. These processes were accompanied by fracturing of individual calcite and dolomite grains (cataclasis) and probable grain boundary sliding. Intragranular twinning of calcite is pervasive. These deformation mechanisms suggest moderately low P-T conditions and/or relatively high strain rates. Locally, however, strongly foliated calci-mylonite (fig. 7) are observed within blocks, indicating earlier deformation under considerably different structural conditions.

The scaly melange seen at the Bald Mountain quarry between carbonate and Taconic rocks and between some of the carbonate slivers also exists as a zone beneath the Bald Mountain units. The fabric of this melange is identical to that described above for the Mettawee River area, consisting of an anastomosing network of shear fractures enclosing pebbles, cobbles, and angular clasts of slate, argillite, graywacke, and carbonate. At the Frontal Thrust the melange contains finely broken Taconic rock, referred to by Ruedemann (1914) as "mylonite." Ruedemann used this term to describe the intense "milling" of Taconic rocks in this zone; this fabric is now referred to as phacoidal cleavage. These observations again suggest that the melanges along the western front of the Allochthon evolved by complex superposition of tectonically disrupted assemblages that were at least partially derived from olistostromes.

FIG. 7.—Calci-mylonite within the Bald Mountain fault duplex (from quarry exposure of fig. 6; undifferentiated type "d" lithologies). Hammer handle is 60 cm long.

We infer from our observations in the Bald Mountain area that: (1) Carbonate slivers record a diachronous deformational history involving relatively early, but only locally developed mylonitic fabrics suggesting relatively higher P and T conditions, and/or slower strain rates that were succeeded by more brittle structures, including cataclasis and fracturing, suggesting a relatively lower P and T condition, and/or higher strain rates. We suggest that this transition records the progressive tectonic unroofing of the Bald Mountain carbonates, possibly in association with movement of the entire structural package over footwall ramps located somewhere to the east. (2) The intercalation of carbonate sheets and black shales with or without associated melanges reflects a duplex-type structure with the Taconic Frontal Thrust as the roof thrust of the duplex.

PRE-CLEAVAGE THRUST AND FRONTAL DEFORMATION NEAR WHITEHALL, NEW YORK

Several important exposures near the Taconic Frontal Thrust are found along Delaware and Hudson Railroad cuts between Whitehall, New York and Fair Haven, Vermont (fig. 1). The map area here (fig. 8) con-

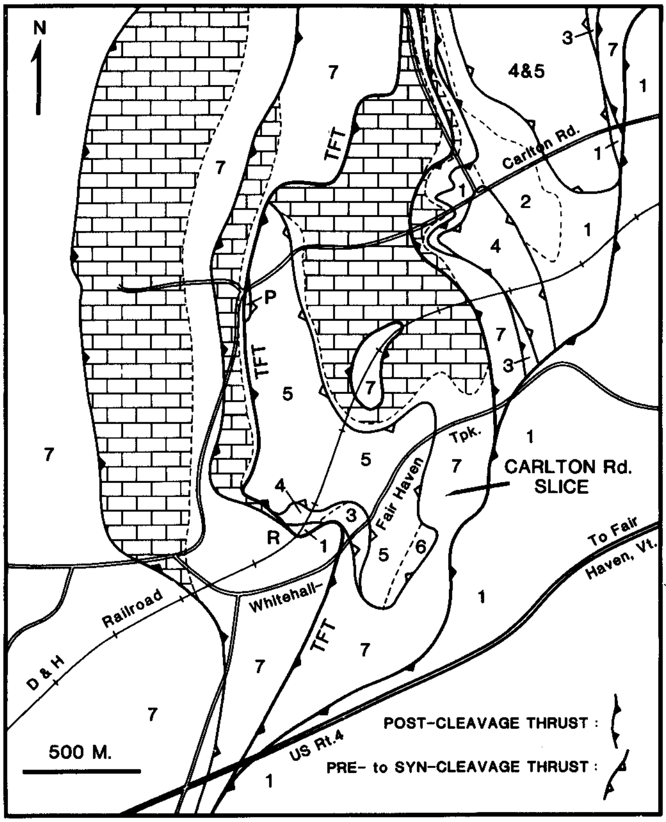

FIG. 8.—Preliminary geologic map of a portion of the Taconic Allochthon boundary (Frontal Thrust) between Whitehall, N.Y. and Fair Haven, Vt. (see fig. 1 for location). Formation symbols are 1 = Bomoseen Wacke and Truthville Slate; 2 = Browns Pond Fm.; 3 = Mettawee Slate; 4 = Hatch Hill Fm.; 5 = Poultney Fm.; 6 = Mt. Merino Fm.; 7 = flysch and melange; brick pattern = parautochthonous carbonates. A pre-slaty cleavage thrust surface is exposed at Plude's Quarry (fig. 11). The Frontal Thrust cuts below this surface. Geology mapped by C. Steinhardt, 1982, and by W. S. F. Kidd, M. Ross, J. Piedra, W. Bosworth and D. Wolf, 1983. P = Plude's Quarry (fig. 10); R = Delaware and Hudson RR cut (fig. 9).

tains several carbonate slivers and a complex imbricate pattern that in part pre-dates the Frontal Thrust generation of structures. An abandoned road metal quarry north of the railroad cuts presents one of the best exposures found to date of allochthonous sequence rocks thrust over parautochthonous flysch. This area illustrates both the geometric, map-pattern details of the Frontal Thrust and some of the smaller-scale deformation accompanying overthrusting.

The railroad cut near the intersection with the Whitehall-Fairhaven Turnpike (fig. 8) contains several large blocks and slivers of thin-bedded limestone, black shale, and rusty dolomitic arenite faulted against massive green-gray micaceous wacke. The thin-bedded units are probably from the Hatch Hill Formation (Cambrian), and the wacke is Bomoseen (?Cambrian). These are Taconic units, but they are not in their proper stratigraphic sequence being generally separated by several persistent Lower Cambrian formations (details of the Taconic stratigraphy of this area are discussed in Rowley et al. 1979). The fault contacts consist of steeply dipping broad zones of disruption (approx. 3 m wide) and discrete thrusts (fig. 9). At the western end of the exposure the massive wacke is in contact with either a shalier facies of the Bomoseen Formation or Hatch Hill shales. The rock is well-fractured and appears transitional to melange. A pebbly mudstone containing fist-sized lenses of limestone is pres-

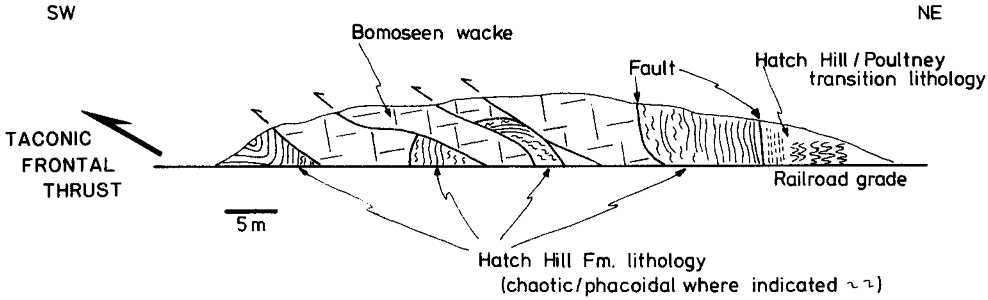

FIG. 9.—Delaware and Hudson Railroad (NE of Whitehall-Fairhaven Turnpike crossing) cut through the Frontal Thrust fault zone. Location of railroad is given in figure 8.

ent beneath the massive wacke on the southern side of the cuts. Following the ridge through which the cut was made farther north, more melange is found on its western flank, a good exposure being present at Carlton Road. Most of the ridge comprises a limestone sliver; a very small slice of Bomoseen wacke is preserved in the cut.

Traced to the north, the Bomoseen/Hatch Hill fault of figure 8 merges with a fault separating Poultney Formation thin-bedded arenites and gray-green slate (Lower Ordovician) of the Taconic Allochthon from gray slates of the flysch sequence. Without graptolites or other paleontologic control, it cannot be definitely determined whether this flysch is parautochthonous (Snake Hill) or truly allochthonous (Pawlet Formation). Lithologically it resembles much of the parautochthonous flysch of this area (Snake Hill Formation on New York State Geological Map, Fisher et al. 1970) in that graywackes are often absent. The fault contact is superbly exposed in the small road metal quarry (locally known as Plude's Quarry) at the intersection of Carlton and Lamphere Roads (fig. 8).

As at the railroad cut, the base of the quarry shows a gradation from undisrupted rock to melange. Lenses of cleaved slate and thin-bedded arenite are enclosed within a phacoidally cleaved, in part very black, matrix cut by numerous small thrust surfaces. This relationship of a superimposed phacoidal fabric on a pre-existing slaty cleavage is observed elsewhere (see below) and is critical to interpretations of mechanical state of the parautochthonous flysch at the time of Taconic Frontal Thrust motion. Moving up the face of the road cut, the number of shear surfaces decreases and the matrix is lost, giving way to coherent cleaved flysch and bedded arenites. This melange is again interpreted as the location of the Frontal Thrust.

The contact between the Poultney Formation and flysch is sketched in figure 10. The fault is cut by the regional slaty cleavage (dip-

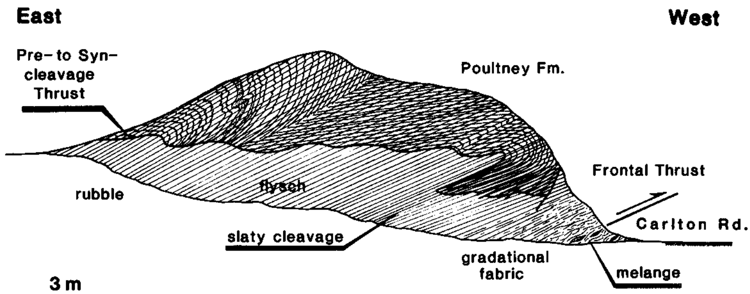

FIG. 10.—Exposed pre-slaty cleavage thrust in quarry face (Plude's Quarry; location given in fig. 8). Allochthonous Poultney Formation rocks were thrust over gray shales and then folded and cleaved. Thrusting and folding were apparently in part synchronous, as the amplitude of the fold in the thrust surface in the easternmost anticline is less than the amplitude in the folded Poultney. The gray slates most closely resemble a flysch lithology, although whether it is allochthonous or parautochthonous flysch cannot be demonstrated without biostratigraphic control.

ping approx. 42°E) and is in part folded by the structures present in the upper plate. As the amplitudes of the folds within the Poultney rocks are somewhat greater than those in the fault surface, the fault may in part be a syn-folding structure. These folds are the main, regional fold generation of the western Taconics (D_2). The lower limbs of the two anticlines seen at the quarry are strongly attenuated, which is suggestive of strong east-over-west movements at the time of their formation. The anticlines appear to be separated by a fault, but its exact nature is unclear due to difficulty of access. The structure at this quarry therefore supports the view that the allochthonous Taconic sequence was involved in westward directed thrusting prior to the development of the slaty cleavage fold generation, but that final emplacement post-dates slaty cleavage formation (Rowley and Kidd 1982*b*).

The melange and carbonate sliver define the Frontal Thrust at the Delaware and Hudson Railroad cut and farther north. Several hundred meters east, however, another limestone body outcrops within the allochthonous sequence. This shelf carbonate sliver appears either to be imbricated within Taconic rocks by the Frontal Thrust generation of structures or, more likely, was infolded during an earlier phase of deformation (fig. 8). A similar map pattern is present just to the northeast of figure 9 at the classic William Miller Chapel locality (fig. 1). Here a window through the Taconic Allochthon exposes upper Lower Ordovician shelf carbonates that display a more highly metamorphosed and extensively boudinaged (Voight 1965) character than that observed to west. The thrust contact that delineates the William Miller Chapel window was interpreted by Rowley (1983) as an exposure of the pre-cleavage, folded Taconic Basal Thrust. Thus, in this area it is possible to recognize fully the complex polyphase nature of the thrust boundaries that define the western front of the Allochthon.

The manner in which rocks adjacent to the Frontal Thrust are disrupted can be studied in some detail at these exposures. Deformation of the Bomoseen wacke at the railroad cut resembles that generally seen at the base or edge of thrust sheets composed of massive lithologies. The wacke is cut by two distinct sets of slickensided, striated fault surfaces

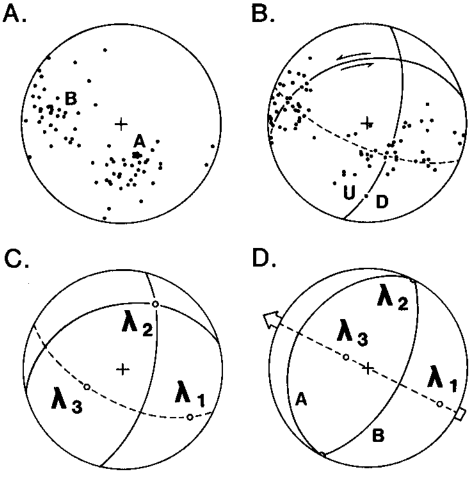

FIG. 11.—Stereograms of structural data collected in large wacke block at the Delaware and Hudson Railroad cut illustrated in figure 9. Lower hemisphere, equal area projections. *A*. Poles to small-scale faults (n = 76). Fault set "A" are north-dipping left lateral strike-slip faults, set "B" are east-dipping normal faults. *B*. Striations on small-scale faults (n = 83; a few faults possessed multiple slip directions). Great circles give average fault orientations. Fault striations cluster at points roughly 90° from the intersections of faults A and B, the case to be expected if plane strain is dominant. Dashed great circle is plane perpendicular to A-B intersection. *C*. Interpretation of principal extension and shortening directions given average fault orientations, slip directions, and slip senses of shear. *D*. Rotation of λ_2 direction to the horizontal. The trends of λ_1 and λ_3 now parallel the inferred west to west-northwest transport direction of the Taconic Allochthon. Fault set A corresponds to riedel shear orientations, and fault set B to anti-riedel orientations.

(fig. 11*a*), one dipping approximately 65° to the east, the other 35° to the north. The dihedral angle between these two shear sets is roughly 84°, and their intersection plunges 28° toward 027°. Multiple slip directions on a single fault surface are infrequently observed and it is assumed that fibrous, stepped mineralization on the faults can be used to infer each fault's slip direction and its relative sense of shear. Striations, mullions, and fibers plot within two groups, one for each fault set (fig. 11*b*). Motion on the moderately north-dipping faults (Set A) is predominately strike-slip, with upper blocks consistently moving west and slightly down-dip (left lateral faults). The steeply east-dipping faults (Set B) are frequently normal faults (east-side down), but a significant number of reverse faults are also present. Several through-going faults (fig. 9) are sub-parallel to Set A structures (fig. 11*a*) and have east-west trending slip directions.

The fact that only two sets of faults are present suggests that they initially formed under roughly plane strain conditions (Reches 1978). The variations in orientation of fault surfaces and slip directions, however, would allow for the accommodation of some three-dimensional strain later in the deformational history of the massive graywackes, analogous to the finite strains interpreted for the shale matrix in portions of the Taconic melange (Vollmer and Bosworth 1984). The coherence of the graywackes and the relatively simple distribution of fault orientations suggest that these rocks are in a fairly early stage of the fault zone deformational sequence. The bisectors of the acute and obtuse dihedral angles between fault sets A and B can then be reasonably interpreted as representing some approximate orientation of the principal extension and shortening directions (λ_1 and λ_3 respectively). Alternatively, λ_1 and λ_3 can be found as the bisectors of the average slip directions for each fault set, measured in the plane containing the two slip directions. λ_3 is found to plunge steeply to the west-southwest and λ_1 shallowly to the southeast (fig. 11*c*).

These interpretations can be accommodated within the overthrust mode of deformation in a simple model. A rotation of about 25–30° would bring the intersection of fault sets A and B back to the horizontal, the general orientation expected for the symmetry of a thrust deformation. λ_3 would now be subvertical, and λ_1 subhorizontal and east-southeast trending (fig. 11*d*). This agrees well with the general transport direction inferred for the allochthonous terrane. In a horizontal shear couple, λ_1 and λ_3 might be expected to plunge approximately 45° with trends paralleling the transport direction (remembering that these are referring to the initial stages of deformation only in the present context), and we must therefore envision some rotation of the graywacke blocks (counterclockwise when viewed from the south) following formation of the shear fractures (fig. 12). The observed dominant senses of shear on sets A and B are supportive of this model. The pres-

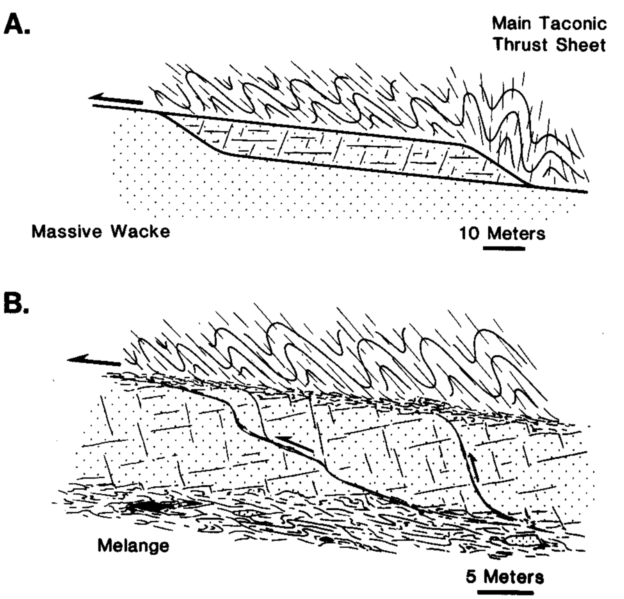

FIG. 12.—Schematic structural evolution inferred for a wacke block or sliver exposed in the Taconic Frontal Thrust fault zone at the Delaware and Hudson Railroad cut (figs. 8 and 9). *A*. Block disrupted from coherent allochthonous mass, overridden and attached to base of allochthon. Conjugate shear fractures initiated at 30° to 45° from incremental shortening direction. *B*. Rotation of fractures as block begins to break up and become incorporated into melange.

ence of several reverse faults in set B suggests that later in the deformational sequence, the early formed normal faults (or "anti-Riedels") are reactivated as east-over-west small-scale structures, in accord with the larger-scale sense of displacement.

STRATIGRAPHIC REPETITION IN SHELF CARBONATES ALONG ROUTE 22A, VERMONT

The structural and stratigraphic relationships within the shelf and flysch sequences are well displayed to the north and west of the Delaware and Hudson Railroad localities described above. We have chosen several key exposures in this area to illustrate the structural style and relationships critical to an assessment of the structural history of this region. The first outcrop is a roadcut along Route 22A approximately 3.4 km north of its intersection with Route 4 (fig. 13). Here a sequence of imbricates repeat the upper part of the Ordovician shelf and flysch stratigraphy, including massive limestone (Isle LaMotte) that grades stratigraphically upward into progressively more argillaceous limestones and finally interbedded limestones and dark carbonaceous shales (Glens Falls Formation). The Glens Falls in turn passes upward into dark shales (Hortonville or Snake Hill) overlain by pebbly mudstone in a black scaly shale matrix ("Forbes Hill Conglomerate" of Zen 1961). This stratigraphic sequence or various parts of it are structurally repeated at least four times, with thrusts commonly juxtaposing massive Isle LaMotte with either shales or pebbly mudstone lithologies. The carbonates within the sequence are pervasively fractured, veined with carbonate, and prominently slickensided. Thin laminated and slickensided carbonate veins are also prominent within the shales and pebbly mudstones. The thrusts that repeat the sequence dip moderately to the east and appear to represent an imbricate stack below the Frontal Thrust which is exposed only a hundred meters to the east.

The second road section is exposed approximately 1.2 km southwest of Harlow School in the Thorn Hill 7.5′ quadrangle along Washington Co. Route 11 (fig. 1). From east to west, the road cut exposes massive carbonate of the Isle LaMotte on top of dark low-rank slates and graywackes of the Snake Hill Formation (fig. 14). Just to the east, the Isle LaMotte is in stratigraphic contact with overlying Orwell, Glens Falls, and Snake Hill, which together represent a thrust sheet with a structural thickness of somewhat less than a couple of hundred meters. The structures exposed here are of particular interest for several reasons: (1) a clear relationship between slaty cleavage, thrusting, and phacoidal cleavage are displayed; (2) the thrust geometry within the hanging wall can be observed; and (3) this exposure is near the present northern extent of the purported "block-in-shale" shale sequence of Fisher et al. (1970).

The contact between the Isle LaMotte carbonate and Snake Hill is marked by a narrow (1–3 cm) veined and slickensided thrust surface with slickenside lineations plunging down dip to the east. Immediately below the thrust is a one to several meter thick zone of phacoidally cleaved slate, with rare angular fragments of Isle LaMotte carbonate and Snake Hill shales and graywackes. The phacoidally cleaved Snake Hill grades downward into slates and rare graywackes that have a well defined slaty cleavage that dips steeply east (~70°). The slaty cleavage is folded to more shallow eastward dips in the transition zone between the slaty cleaved and phacoidally cleaved argillites and becomes progressively superposed by the phacoidal cleavage up-section (fig. 14). These relationships demonstrate that (1) the Isle LaMotte and stratigraphically overlying units are not randomly disposed but occur as regular thrust packages (fig. 13), a relationship not expected in an olistostromal deposit; (2) thrusting not only post-dated lithification, but also the development of slaty cleavage within the flysch, and (3) at least in this exposure, phacoidal cleavage developed by the superposition of an anastomosing thrust-related fabric on a pre-existing axial surface foliation.

DISCUSSION

The suggestion has been made that at least the lower slices of the Taconic Allochthon were transported as a soft (or only partially lithified) sediment mass into a basin filled with likewise soft sediments in one or several large-scale gravity slides (Zen 1964, 1967, 1972; Bird and Dewey 1970; Potter 1972). Some workers have emphasized only the

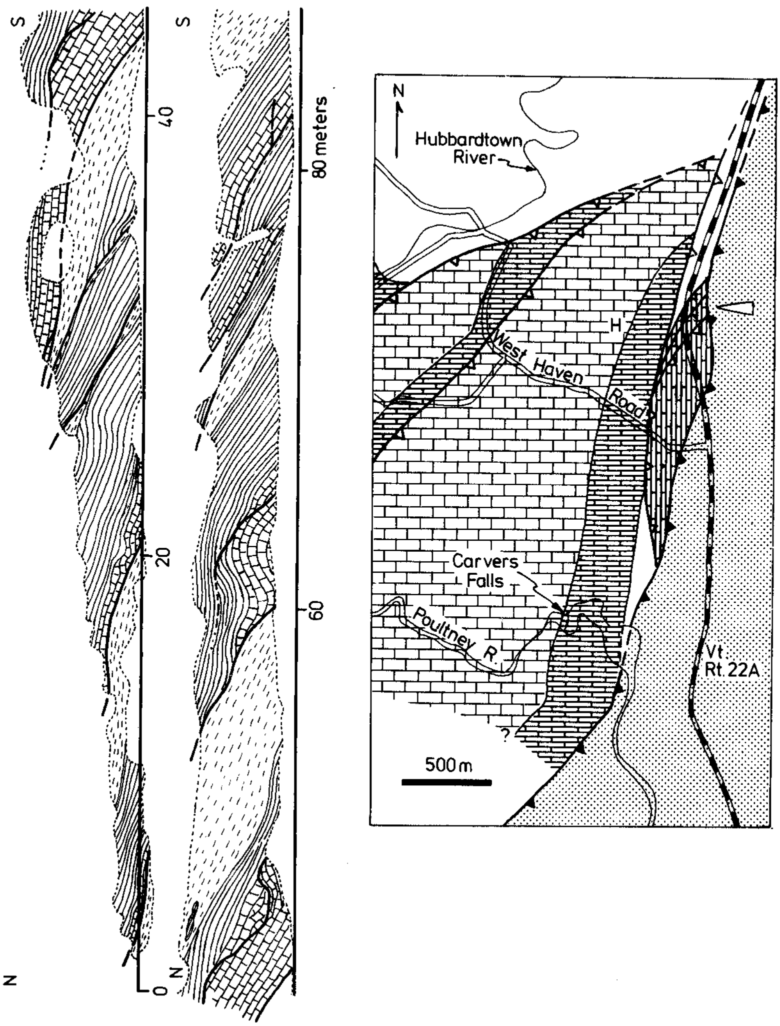

FIG. 13.—Map and profile of roadcut on east side of Vermont Route 22A 6.5 km north of Fair Haven, Vt. (see fig. 1 for location). Roadcut shows imbricated sequence of middle Ordovician Orwell Limestone (bricks), overlain by Glens Falls Limestone (lines), overlain by black shale and melange (Hortonville shale/Forbes Hill conglomerate)—two profiles shown overlap—the upper one continues to the right in the lower one. Major thrusts shown by thick lines; other faults not emphasized. Line with meter scale is road surface, which slopes to the north, and is not flat as implied by the diagram. Dips shown are those exposed at the outcrop surface—true dips are considerably steeper, typically 50–80°E. N-S cross-section along road in area indicated by arrow on map; the imbricated zone is shown schematically on the map. Map units: Stippled—Undifferentiated Taconic rocks; Coarse bricks—Providence Island Dolostone and Middlebury Limestone; Fine bricks—Orwell and Glens Falls Limestone; Blank—Hortonville shale and Forbes Hill conglomerate (melange). Taconic Frontal Thrust shown by black teeth; other thrusts with open teeth. Mapping by C. Steinhardt, C. Cooper, D. Rowley.

unlithified nature of the underthrust flysch sediments and proposed that the western Taconic regional slaty cleavage was imposed after emplacement (Steuer and Platt 1982). These interpretations were largely made based on relationships seen adjacent to the Frontal Thrust, particularly the role played by olistostromal deposition in the formation of the Taconic melanges. The observations reported here, however, show that the Frontal Thrust and related faults are hard-rock structures, that these faults cut the regional slaty cleavage, and that this fault system resembles geometrically and kinematically the

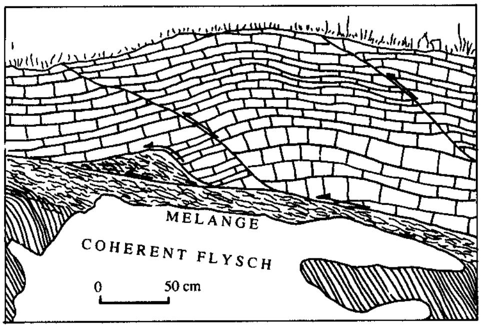

FIG. 14.—Field sketch of thrust relations along Washington Co. Route 11, ~1.2 km southwest of Harlow School along western margin of figure 13. Isle LaMotte (brick pattern) thrust over medial Ordovician flysch and melange (solid lines—where coherent with orientation parallel to the regional slaty cleavage and wavy lines—flysch with superimposed phacoidal (melange) fabric, orientation parallels superimposed fabric).

fault systems described from other well-studied convergent tectonic settings (Boyer and Elliott 1982). This hard-rock view was early and very adequately expounded by Ruedemann (1914). He clearly recognized that the slaty cleavage found both within the Allochthon and underlying flysch was cut by what is now recognized as the Frontal Thrust and that the fabrics seen at Bald Mountain are indicative of deformation of indurated, not "sloppy" materials. Formation of the Taconic melanges did involve at least local incorporation of olistostromes at subaqueous, emergent fault zones, but the rocks adjacent to the fault zones were well-lithified, and subsequent deformation of this material quickly progressed to a "hard-rock" character (Bosworth and Vollmer 1981; Vollmer and Bosworth 1984).

The presence of relatively shallow-level fault breccias, cataclasites, and shear and extensional fracture systems and deeper level calci-mylonites in the Bald Mountain fault zone and other thrusts in this region suggests either that movement on the Frontal Thrust was very extensive or that the Frontal Thrust has in part reactivated or cut through earlier shelf-ramping faults. In either case, this favors hard-rock, tectonic imbrication for the emplacement of the Allochthon onto the carbonate shelf sequence.

The characteristics of the Frontal Thrust System faults are schematically shown in figure 15, and can be summarized as follows: (1) they cut the regional slaty cleavage and all major fold generations of the western Taconics and underlying flysch; (2) they may be marked by a melange zone formed through both sedimentary and tectonic processes; (3) they may be decorated with horses of shelf carbonate or by imbricate stacks and duplexes of shelf lithologies interleaved with flysch and melange; and (4) the faults follow in detail a ramp-flat and imbricate geometry but are not otherwise folded by later deformation. Utilizing these characteristics, we have attempted to delineate some of the more

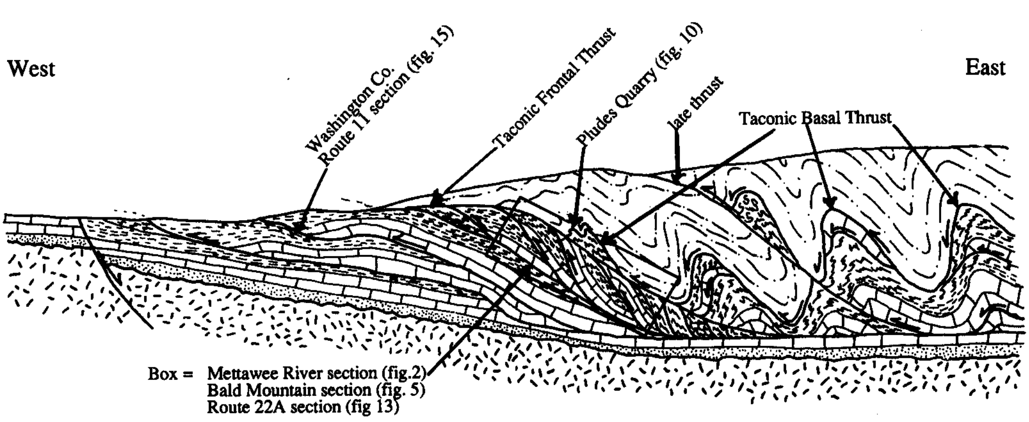

FIG. 15.—Schematic cross-section across the Taconic Frontal Thrust System. The section is synthetic and shows the geometry and structural environment of each of the locations described in the text. Random dashes—Grenville basement; Stipple—Potsdam sandstone; Brick—Late Cambrian-Early Middle Ordovician carbonates; dashes—Snake Hill/Hortonville Shale; wavy lines—melange; dash dot—Taconic Allochthon (showing characteristic fold geometry).

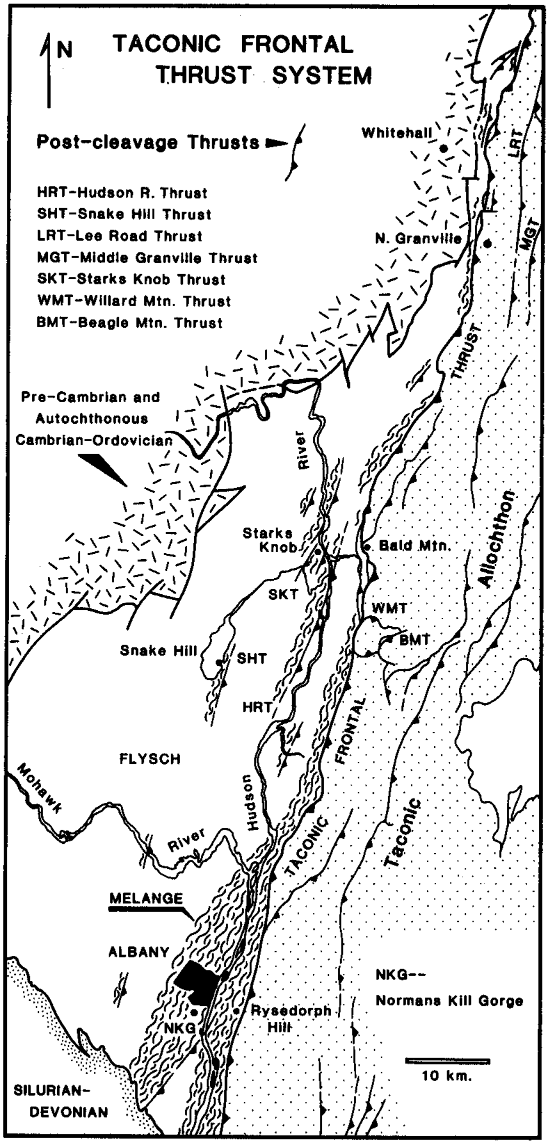

FIG. 16.—Compilation of faults believed to belong to the Taconic Frontal Thrust System. These faults accommodated late horizontal shortening of the Orogen and transport of the Allochthon across the orogen and transport of the Allochthon across the autochthonous continental shelf. Total displacement during this generation of thrusting for allochthonous rocks at the present surface trace of the Frontal Thrust is therefore on the order of 50+ km. Regional geology from Fisher et al. 1970. Melange terranes from Vollmer and Bosworth (1984).

important faults belonging to the Frontal Thrust System (fig. 16). Within the Giddings Brook Slice of the Allochthon (Zen 1967), these faults produce some internal rotation and deflection of large-scale fold axial planes and hinge lines. The relationships between this fault system and the actual slice boundaries as defined by Zen (1967) is a point of further investigation. The Giddings Brook Thrust itself was envisioned by Zen (1967) to place allochthonous continental rise rocks (Taconic Sequence) over parautochthonous and autochthonous flysch and shelf carbonates. Kinematically, the Giddings Brook Thrust therefore corresponds with the folded pre-cleavage Basal Taconic Thrust (Rowley and Kidd 1982*b*). In the present geometry, however, the boundary of the Giddings Brook Slice is in most places marked by the Taconic Frontal Thrust, which has cut through and only in part followed the original emplacement thrust. We therefore advocate retention of the term "Giddings Brook Slice" to denote the assemblage of thrust sheets with a common "low Taconic" stratigraphy and continental rise paleogeographic provenance, but replacement of "Giddings Brook Thrust" with Taconic Frontal Thrust and Taconic Basal Thrust, their local application dependent upon specific local structural relationships.

External to the Allochthon, several major faults within the Taconic flysch appear to be part of the same fault system as the Frontal Thrust. These follow the major melange zones of the Hudson River lowlands (fig. 16; Bosworth and Vollmer 1981, fig. 5; Bosworth 1982, figs. 3 and 4). The melange zone paralleling the Hudson River at Schuylerville contains a fault sliver of pillow basalt apparently imbricated from a subcrop in the underlying shelf sequence (Vollmer and Bosworth 1984). The melange zones can be traced south to the outcrops of Silurian and Devonian carbonate rocks at the Helderberg Escarpment (fig. 16). Here the melange fabric is truncated by the post-Taconian, pre-Acadian unconformity (see fig. 2 of Vollmer and Bosworth 1984), demonstrating a Taconic age for all movement in these melanges. This argues for Taconian limits to the movement recorded by the entire Frontal Thrust System in the northern Taconics. As this is the latest phase of significant deformation in the northern Taconics, all the structures observed here are reasonably assigned to the Taconic Orogeny (Rowley and Kidd 1982*a*). Acadian and Alleghanian overprinting apparently was restricted to the southern Taconics and did not significantly affect Taconian structures in the north.

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