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STRATIGRAPHIC RELATIONSHIPS AND DETRITAL COMPOSITION OF THE MEDIAL ORDOVICIAN FLYSCH OF WESTERN NEW ENGLAND: IMPLICATIONS FOR THE TECTONIC EVOLUTION OF THE TACONIC OROGENY[1]

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ABSTRACT

We present new stratigraphic and petrographic data on the easterly-derived medial Ordovician flysch sequence of western New England and eastern New York State. A conformable relationship exists between the flysch and underlying early Paleozoic continental rise sediments within the western Taconic Allochthon. Farther east in the Allochthon we observe a possibly disconformable relationship. Contrary to previous interpretations, these facts suggest that at any place within this paleogeographic realm the sediments were undeformed and untransported at the initiation of flysch deposition. At least three sources contributed detritus to the flysch: (1) Taconic Sequence sediments; (2) deformed and metamorphosed pelitic, psammitic, and volcanic lithologies; and (3) igneous rocks of dominantly mafic-ultramafic affinities. These three sources are respectively interpretable as: continental rise, accretionary prism, and ophiolitic-volcanic arc assemblages, which are recognized in the regional geology of western New England. There is a progressive decrease in the age of the basal flysch from that within the allochthonous Taconic rocks to that deposited on top of the parautochthonous and autochthonous early Paleozoic carbonate shelf sequence. This indicates westerly progradation of the flysch synchronous with westward transport of allochthonous realms. Truncation of regional folds in Taconic rocks by shelf carbonate slivers on the basal thrust of the Allochthon shows that Taconic rocks were consolidated and strongly deformed well before the end of their westerly transport. The stratigraphic and petrographic data indicate progressive and diachronous east to west thrust stacking, deformation, and metamorphism of paleographic realms during the Taconic orogeny, a medial Ordovician continental margin-volcanic arc collision. They are evidence against emplacement of the Taconic Allochthon as one or several gravity slides detached from their origin.

INTRODUCTION

The stacking sequence of large allochthonous thrust sheets formed during the medial Ordovician Taconic Orogeny has been worked out in western Newfoundland and the Quebec Appalachians, in part through careful study of the stratigraphic and petrographic character of the flysch sequences associated with these allochthons (Stevens 1970; Williams 1975; Hiscott 1978; St. Julien and Hubert 1975). In both cases, the stacking of slices from ocean toward the continental margin has been demonstrated to be a relatively orderly sequence. This stacking geometry gives rise to an arrangement in which the farthest travelled slices are on top and less far travelled slices lie below. The Taconic Allochthon of western New England constitutes a southerly continuation of this belt, but here the stacking sequence is commonly argued to have a diverticulated (tectonic inversion of stratigraphic sequences deposited on top of one another) order (Zen 1961, 1967; Ratcliffe 1975; Fisher 1969, 1979) or a structural arrangement in which less far travelled slices occur in the highest structural position (Ratcliffe and Hatch 1979; Ratcliffe 1979; Stanley and Ratcliffe 1980).

This paper presents new data bearing on the stratigraphic and petrographic character of the flysch sequence of the Taconic Allochthon (Pawlet Formation/Austin Glen Greywacke) and surrounding parautochthonous and autochthonous flysch (Austin Glen Greywacke). These data support the view that the well understood stacking order of allochthonous sequences of western Newfoundland and Quebec apply equally well in New England, deny the possibility of a diverticulated stacking sequence, and strongly argue against a more complex arrangement. Our data, in conjunction with

[1] Manuscript received May 20, 1980; revised August 18, 1980.

[Journal of Geology, 1981, vol. 89, p. 199–218]

0022–1376/81/8902–004 $1.00

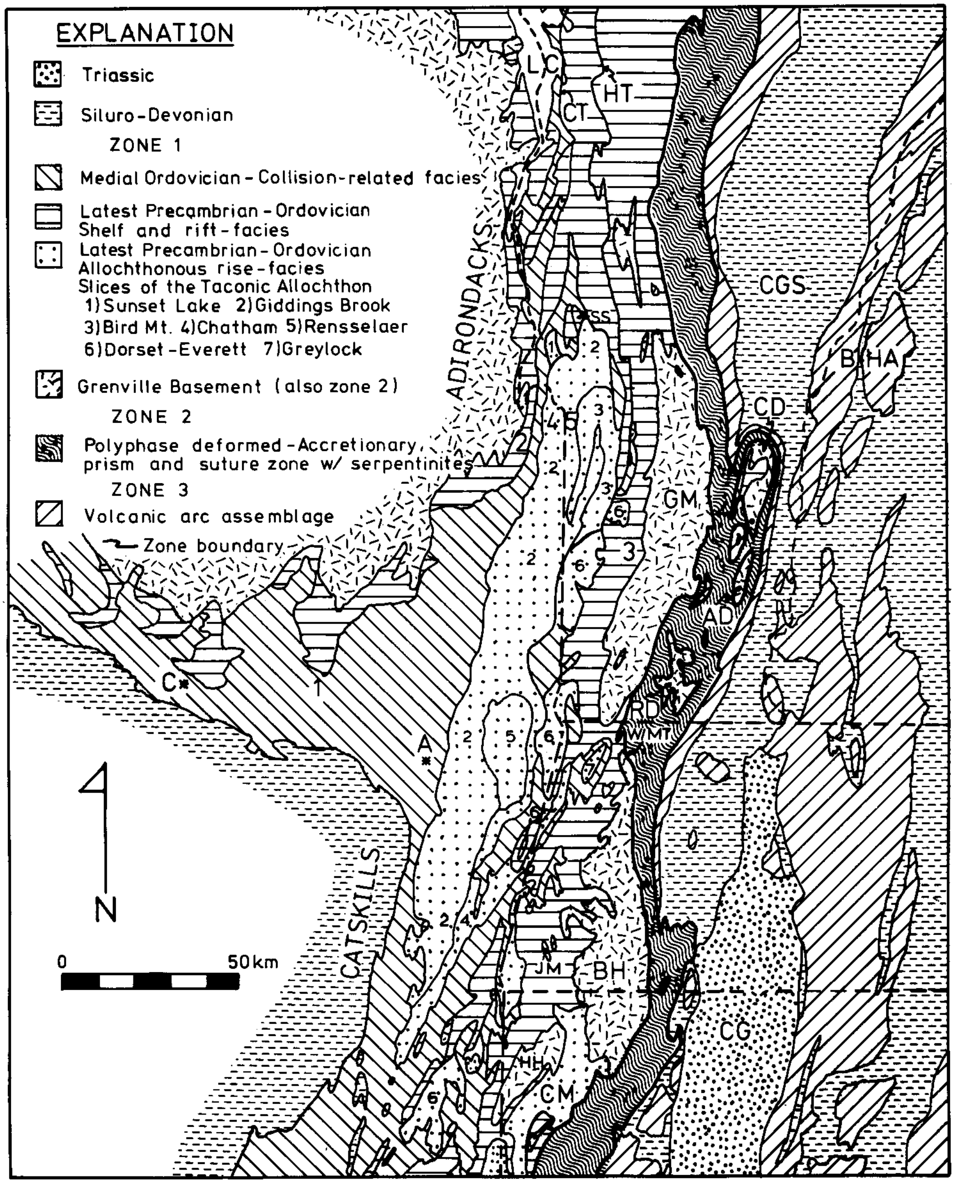

Fig. 1.—Generalized geologic map of western New England and eastern New York. Map redrawn from Williams (1978) and Bird and Dewey (1970). Zone boundaries are structural contacts. Larrge numbers indicate the location of stratigraphic columns of figure 2. Small numbers distinguish the various Taconic slices (key on figure). Abbreviations: A – Albany; AD – Athens Dome; BH – Berkshire Highlands; BHA – Bronson Hill Anticlinorium; C – Canajoharie; CM – Canaan Mountain Slice of the Taconic Allochthon; CD – Chester Dome; CGS – Connecticut-Gaspe Synclinorium; CG – Connecticut Graben; GM – Green Mountains; HT – Hinesburg Thrust; HH – Housatonic Highlands; JM – June Mountain Slice of the Taconic Allochthon; LC – Lake Champlain; RD – Ray Pond Dome; SS – Suddbury Nappe; W/MT – Whitcomb Summit/Middlefield Thrust Zone.

the regional geology of New England, suggests an arc-continental margin collision for the Taconic Orogeny in New England as has been previously argued for western Newfoundland and the Quebec Appalachians (Church and Stevens 1971; Williams 1975; Nelson and Casey 1979; Hiscott 1978).

REGIONAL GEOLOGY OF WESTERN NEW ENGLAND

Three pre-Silurian geologic provinces may be distinguished in the western New England segment of the northern Appalachians (fig. 1). These are, from external (west) to internal (east): zone 1, a Cambro-Ordovician rifted continental margin; zone 2, a medial Ordovician suture zone; zone 3, a volcanic arc terrain.

Zone 1.—The Cambro-Ordovician continental margin was established on Grenville age (approximately 1.0 b.y. and older) crystalline basement, which is locally intruded by latest Precambrian diabase dikes (Fisher 1977). This basement is locally overlain by immature arkosic and feldspathic sandstones and conglomerates of Cambrian(?) age. An eastward thickening sequence (Rickard 1973) of earliest Cambrian to late early Ordovician shallow-water carbonates and less abundant orthoquartzites (the carbonate platform) unconformably overlies the basement everywhere else. Late early Ordovician carbonates at the top of this sequence are disconformably to unconformably overlain by a succession of medial Ordovician limestones and dark, relatively deep-water argillites, followed conformably upward by greywackes and slates (flysch) locally containing olistostromic horizons (so-called 'wildflysch' of Zen 1967; Bird 1969) near the top. West of the longitude of Albany, the flysch grades upward into relatively shallow-water southeasterly-derived deltaic sediments (molasse) of late medial to late Ordovician age (Zerrahn 1978).

The basal part of the medial Ordovician section is oldest in the east and becomes progressively younger to the west to about the vicinity of Canajoharie, New York (Rickard 1973; Fisher 1977). The internal contacts of this medial Ordovician succession also become progressively younger to the west, suggesting a westward progradation of the medial Ordovician flysch and associated sediments over the underlying Cambrian to late early Ordovician carbonate platform sequence. To the east of Albany, flysch sedimentation was diachronously terminated by overriding of the Taconic Allochthon, being earliest in the east (*D. multidens* zones of Riva 1974) and later (*O. ruedemanni* zone) in the west (fig. 2).

Structurally overlying this dominantly shallow water carbonate platform and flysch sequence is a coeval, Cambrian(?) to medial Ordovician sequence of allochthonous, dominantly deep water argillaceous and arenaceous sediments, with lesser carbonates, carbonate conglomerates, cherts and minor volcanics (Zen 1967; Rowley et al. 1979) exposed in the slices of the Taconic Allochthon. Bird and Dewey (1970) interpreted these sediments as the off-shelf, continental rise facies equivalents of the carbonate platform; some of the oldest sediments they interpreted as having been deposited during rifting and the initial formation of the continental margin.

The Allochthon has been traditionally divided into seven or so major imbricate and partially nested thrust slices (Zen 1967). These are, from structurally lowest (west) to highest (east) the Sunset Lake, Giddings Brook, Bird Mountatin, Chatham, Rensselaer, Dorset/Everett, and Greylock slices (fig. 1). Recent mapping has identified several other high Taconic slices farther to the south, including the June Mountain and Canaan Mountain slices (Harwood 1975), which are correlated with the Greylock slice. Comparable stratigraphies are observed in the different slices although the most complete and the only fossil-controlled stratigraphies are observed in the Giddings Brook and Sunset Lake slices (Zen 1967). The Giddings Brook slice is by far the largest of all the slices and is the only one that has the younger units of the stratigraphic section widely preserved within it. Complex, polyphase deformation is observed in all slices (Zen 1972; Potter

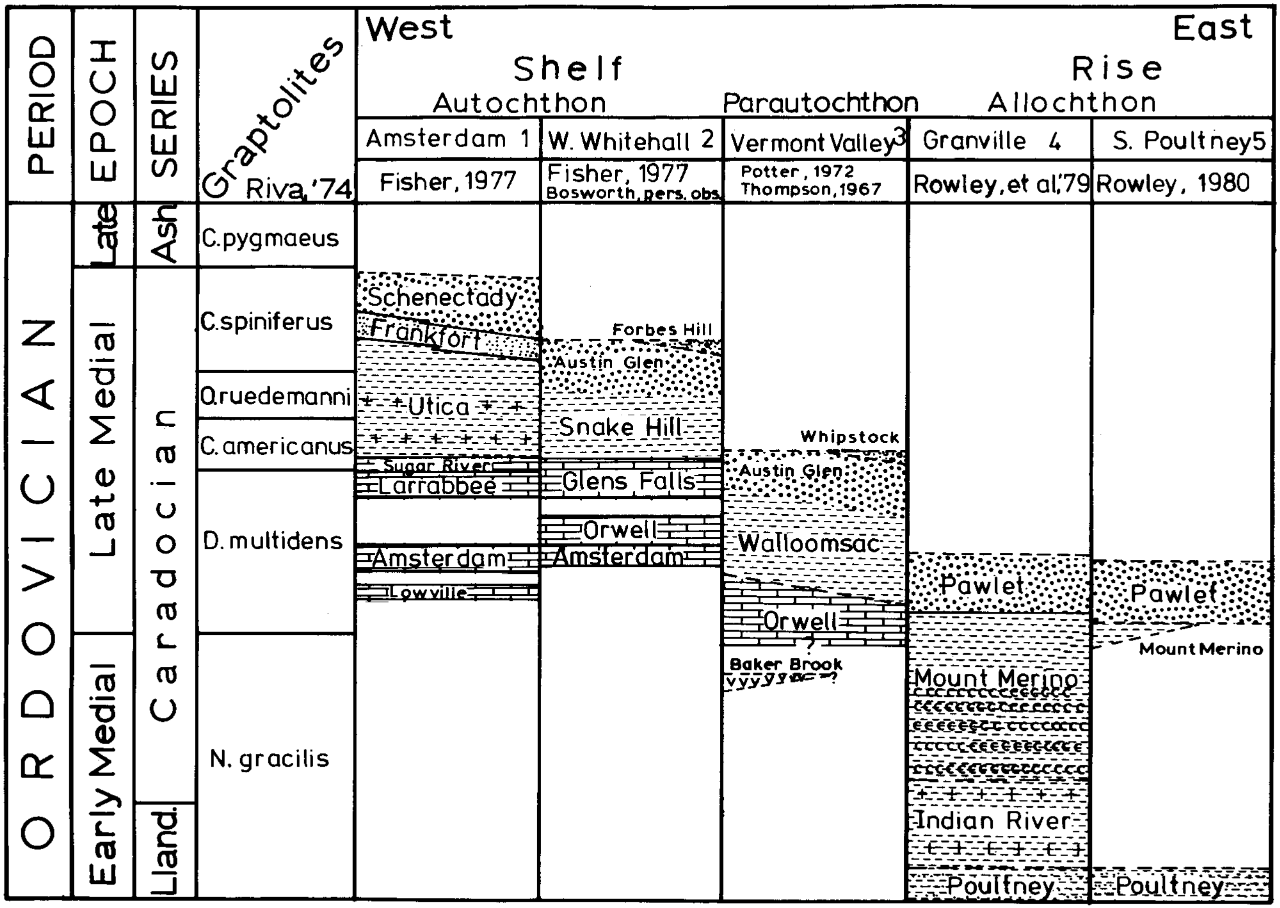

Fig. 2.–Medial Ordovician stratigraphy of western New England. Brick pattern-carbonates; horizontal dash pattern-argillites; coarse stippling-flysch; fine stippling-siltstone and silty quartzites; t – tuff beds; c – chert; v – volcanics; stippling with O – olistostromic boulder conglomerates. Graptolite zones after Riva (1974). Abbreviations Lland-Llandeilian; Ash – Ashgillian. Geographic location of columns shown on figure 1. Fossil control given by references cited on figure.

1972; Rowley et al. 1979; Rowley 1980*a* and in prep.), with deformational complexity and metamorphic grade generally increasing to the east (Zen 1967). Traditionally defined slice boundaries typically coincide with topographic breaks and are locally marked by slivers of shelf-derived carbonate rocks (Zen 1967) and, rarely, Grenvelle basement (Ratcliffe and Bahrami 1976). Relatively large allochthonous or parautochthonous slices of shelf carbonate are present in many places at the base of the Taconic Allochthon, for example, in the Dorset Slice (Thompson 1967), Sudbury Nappe (Voight 1965, 1972), Florence Nappe (Zen 1972) and Butternut Hill slice of Potter (1979). Large carbonate slivers are also well known along the western front of the northern Giddings Brook slice, including the so-called Bald Mountain carbonates (Ruedemann 1914; Zen 1967; Bosworth 1980).

Grenville age basement is generally exposed along the eastern edge of zone 1 as in the Green Mountains, Berkshire Highlands, and Housatonic Highlands, forming part of the Blue-Green-Long line of Rankin (1976). Remnants of the autochthonous shelf sequence cover are preserved on these massifs (Ratcliffe 1979). These basement massifs are internally complexly deformed and are allochthonous to parautochthonous (Ratcliffe and Zartman 1976; Ratcliffe and Hatch 1979). Westward-directed thrusting of these basement massifs occurred primarily during the Taconic Orogeny (Ratcliffe 1979).

Grenville age basement is also exposed as a series of domal inliers within Zone 2, including the Chester, Ray Pond, and Athens Domes (Doll et al. 1961). In these domes Grenville age gneisses (Faul et al. 1963) are overlain by quartzose and feldspathic psammitic metasedimentary gneisses and quartzites which are believed to represent autochthonous(?) Cambrian(?) cover. Basement and cover are almost indistinguishable in these domes due to complex, polyphase, basement-involved infolding, thrusting, and associated metamorphism (Nisbet 1976; Downey and Thompson 1980). The easternmost limit of the North American early Paleozoic continent is unknown, but is interpreted to have lain somewhere to the east of these basement domes. How far to the east is at present indeterminable due to the large magnitudes of both Taconic and Acadian age shortening and possible Taconic and younger large-scale transcurrent faulting along the strike of the orogen.

Zone 2.—The medial Ordovician accretionary prism and suture zone lies along the west flank of the Gaspe-Connecticut River "synclinorium" and consists of an unknown thickness of polyphase deformed and metamorphosed pelitic, psammitic and volcanic schists and phyllites, locally grading into gneisses (Doll et al. 1961). These are associated with slivers of serpentinized ultramafics and mafics interpreted to be dismembered ophiolites (Merguerian 1979) which are discontinuously exposed along strike with unequivocable ophiolites to the north (Laurent 1977; Williams and Talkington 1977) and to the south (Morgan 1977). Locally, glaucophane and omphacite-bearing amphibolites (Laird and Albee 1975) that resemble the basal aureoles of ophiolites exposed to the north (Doolan pers. comm. 1979) are also observed. Large-scale thrust zones separate Grenville age basement and associated presumed autochthonous cover from Zone 2 lithologies; these include the Middlefield Thrust, Whitcomb Summit Thrust, and Camerons Line (Ratcliffe and Hatch 1979; Williams 1978). Isotopically-dated (Rb/Sr) granitic dikes cross-cutting the Middlefield Thrust yield a 463 m.y. age demonstrating Taconic movement (Ratcliffe and Mose 1978). Detailed mapping in northern New England has shown that the suture zone consists of a myriad of complex thrust faults and polyphase folds (Stanley pers. comm. 1979). Such structures have not yet been commonly mapped within it farther south, in part owing to increased metamorphic grade and intensity of Acadian deformation.

Zone 3.—The volcanic arc terrain is exposed along the eastern edge of Zone 2 and as domes in the Bronson Hill "anticlinorium" (Thompson et al. 1968; Robinson et al. 1979). The volcanic arc terrain consists of variably metamorphosed mafic and lesser felsic volcanics, volcaniclastics, and associated dominantly intermediate plutonics that yield zircon, K-Ar and Rb/Sr ages ranging from 490 to 440 m.y. (Naylor 1976; Aleinikoff et al 1979). These volcanic arc rocks intrude and overlie deformed and metamorphosed igneous and metasedimentary gneisses of late Precambrian age (620 to 600 m.y.) (Robinson et al. 1979; Besancon et al. 1977; Aleinikoff et al. 1979) and latest Precambrian to earliest Cambrian (590 to 560 m.y.) metasedimentary cover (Naylor 1976; Robinson et al. 1979). Stratigraphically overlying the volcanic arc sequence are black sulfidic schists (Partridge Formation) of presumed medial Ordovician (Caradocian) age (Thompson et al. 1968).

These three zones form essentially continuous belts that extend to the north at least as far as Newfoundland (Bird and Dewey 1970; Williams 1978). The volcanic arc and Atlantic-type continental margin were juxtaposed during the medial Ordovician Taconic Orogeny. Analogy with young plate tectonic environments indicates that a volcanic arc-continental margin collision was responsible for this orogenic event (Chapple 1973; Stevens 1976; Hiscott 1978; Nelson and Casey 1979; Rowley et al. 1979; Rowley 1980*b*). The obduction of large allochthonous sheets of North American continental rise and slope sediments, and locally ophiolites, resulted from the partial subduction of the North American Atlantic-type margin in an east-dipping subduction zone. Imbrication, deformation and metamorphism of continental basement and cover are also associated with this collision (Rowley et al. 1979; Chapple 1979; Rowley 1980*b*).

In modern examples of arc-continental margin collision such as New Guinea and Timor (Hamilton 1979), and in well-documented ancient analogs, such as Oman (Gealey 1977) and western Newfoundland (Stevens 1970; Church and Stevens 1971; Williams 1975, 1979; Nelson and Casey 1979), stacking of thrust slices and their contained paleogeographic realms occurs from the oceanic to the continental side, with highest structural slices being the farthest travelled. Similar relationships are well known from other collisional belts (Dewey and Bird 1970; Sengör 1977; Dewey 1976, 1977). Major deformation and metamorphism also pre-date final emplacement of the allochthons (Hamilton 1979). Stevens (1970) demonstrated such a stacking sequence in western Newfoundland on the basis of the detrital composition and age variation of the Blow-Me-Down and Goose Tickle flysch and Hiscott (1978) documented a similar stacking sequence in Quebec from his study of the allochthonous Tourelle flysch. In both cases, the earliest flysch sequences contain ophiolitic detritus, indicating that ophiolites which now constitute the highest slices were uplifted and moving at the time of flysch deposition on still undeformed and untransported rocks which soon after became parts of the lower slices.

In the Taconics, however, the generally held view (Zen 1967; Fisher 1979) has been that stacking occurred from structurally lowest to higher slices, opposite to that since documented to the north. This interpretation is based on the following arguments: the lower slices are interpreted to have been emplaced as relatively soft sediments and not to have been penetratively deformed or metamorphosed at their time of emplacement (Zen 1960, 1961, 1967, 1976; Potter 1972). Higher slices are proposed to have been emplaced, however, as hard rock thrust slices (Zen and Ratcliffe 1966) and some of the higher slices, e.g. Greylock, Canaan Mountain, and June Mountain, are interpreted to have experienced preemplacement deformation and metamorphism (Prindle and Knopf 1932; Ratcliffe 1979). Emplacement of the higher slices has been interpreted as the cause of the major deformation and low-grade metamorphism of the already emplaced lower Taconic slices (Zen 1967, 1972; Ratcliffe and Harwood 1975). The general increase in complexity of deformation and metamorphic grade of higher Taconic slices is supposed to have been due to deeper and more prolonged exposure to orogenesis in the root zone (commonly held to have been over the site of the Green Mountains; Zen 1967, 1976), prior to being thrust to the west (Zen 1967). The presence of slivers of shelf-derived carbonate (and locally Grenville basement) along slice boundaries is supposed to have required sequential emplacement of slices so that shelf rocks could be intercalated along these thrusts (Zen and Ratcliffe 1966; Zen 1967). Many of the competing hypotheses outlined above can be tested with information reported in this paper on the allochthonous flysch within the northern Taconic Allochthon and parautochthonous to autochthonous flysch deposited in front of the Allochthon during the later stages of its emplacement.

ALLOCHTHONOUS FLYSCH

A flysch sequence consisting of greywackes and slates constitutes the uppermost stratigraphic unit within the Taconic Allochthon (Zen 1961, 1967; Dale 1899). This flysch is presently ascribed to the Pawlet Formation (Zen 1961) in the northern Taconics and to the Austin Glen Greywacke in the central and southern Taconics (Fisher 1977). The contact between the flysch and the underlying Taconic sequence has been generally considered to be an unconformity (Zen 1961, 1967; Shumaker 1967; Potter 1972; Bird 1969). This unconformable relationship led Bird (1969) to suggest that the flysch was epikinallochthonous (parallochthonous in present usage). Recent detailed mapping within the Giddings Brook Slice in the northern Taconics, in the vicinity of Middle Granville, New York (Jacobi 1977; Rowley 1980*a*; Rowley et al. 1979) shows that, along the western side of the Allochthon, a completely conformable early and medial Ordovician section is present through the Poultney, Indian River, Mount Merino, and Pawlet Formations (fig. 2). In this area and nearby, the Pawlet and underlying Mount Merino contain graptolites (Berry 1962) indicative of the same zone (Zone 12 of Berry 1962), ascribable to the *N. gracilis* and *D. multidens* zones of Riva (1974). The contact between the Mount Merino and Pawlet Formations is gradational in this area of the western Giddings Brook Slice and is marked by the appearance of thin (less than 1–2 cm) silty to fine sandy greywackes, in black graptoliferous slates also characteristic of the upper part of the Mount Merino. The rocks above and below this contact have an identical deformation history (Rowley et al. 1979; Rowley in prep.). Upward in the Pawlet the greywacke beds become thicker and coarser-grained and constitute approximately 50% of the unit in this area, the remainder being dark grey slates. These stratigraphic and structural relationships require that the underlying Taconic sequence was undeformed at the time of the initiation of flysch deposition and suggests that the underlying Taconic sequence was untransported at this time. We therefore propose that this flysch is now completely allochthonous and not parallochthonous as Bird (1969) suggested.

Farther to the east, but still lying within what has been traditionally defined as the Giddings Brook slice (Zen 1967), Pawlet greywackes directly overlie the Poultney Formation, with only local thin lenses of Mount Merino-like black graptoliferous slates intervening along the contact (Rowley 1980*a*; Shumaker 1967). Features diagnostic of pre-Pawlet erosion and angular unconformity are not observed anywhere along this contact; this led Rowley et al. (1979) to suggest that the contact between Poultney and Pawlet, where it is stratigraphically intact, is at most a disconformity. Zen (1964) and Shumaker (1967) reported that Pawlet locally overlies with angular unconformity units as low as the early Cambrian(?) Mettawee Slate Facies of the Bull Formation (Shumaker's St. Catharine Formation). Our mapping shows that all contacts where a lithostratigraphic excision occurs are tectonic in nature, that is they are thrust faults (Rowley 1980*a*; Rowley et al. 1979). The same structural history is observed in both the Poultney and Pawlet, as well as in all underlying units, supporting the conclusion that their original contact was no more than disconformable. As disconformable relationship in this more eastern part of the Giddings

Brook slice has the same implications as the conformable relationship observed to the west, i.e. that this section of the continental rise remained undeformed and untransported at the time of flysch deposition on it.

Stratigraphic and facies comparisons between western and eastern regions of this northern part of the Giddings Brook slice suggests that the rocks of the western region lay closer to the continental shelf source of detritus in pre-flysch times than did those of the eastern region (Rowley 1980*a*, in prep.). The eastern region now structurally overlies the western region along a complex, transitional boundary of imbricate thrusts (Rowley 1980*a*, Rowley et al. 1979). These relationships suggest that an east to west stacking sequence can be demonstrated on a small scale within the Giddings Brook slice (Rowley and Delano, 1979).

It is generally accepted that the Pawlet/Austin Glen greywackes were derived, broadly speaking, from the east (Zen 1961, 1967; Bird 1969) from orogenic lands on the present site of the Appalachians and not from the stable North American continent to the west. Evidence supporting an easterly derivation includes: 1) the dominant lithic debris within the greywackes (see below) has Taconic affinities; in contrast, coeval rocks on the carbonate platform (fig. 2) are hemipelagic shales (Walloomsac Formation) in the east grading into limestones farther west (Orwell Formation) (Fisher 1977). 2) The more easterly sequence of allochthonous flysch in the northern Giddings Brook slice contains generally thicker, coarser, and more abundant beds of greywacke (Rowley 1980*a*). This may be interpreted to mean that the easterly sequence consists of more 'proximally' deposited turbidites, but more complex arrangements of facies are alternatively quite possible. Paleocurrent data are not abundant and usually indicate axial (north-south) transport, a feature common to many flysch sequences (Reading 1978 and references therein).

Petrographic analysis of the greywackes indicate that they are lithic wackes in the usage of Pettijohn (1975). Quartz, plagioclase, potash feldspar, carbonate, muscovite, and chlorite are the dominant detrital mineral phases. Minor amounts of epidote, hornblende, zircon, tourmaline, sphene, staurolite, biotite, magnetite, and pyrite are also observed.

Detrital chromite has been found locally by J. M. Bird (pers. comm. 1978, 1980) and B. Baldwin (pers. comm. 1979). Interestingly, the detrital quartz displays considerable variation in degree of internal strain, much of which is demonstrably predepositional. Features such as deformation lamallae, polygonalization and recrystallization, suturing, and fine mylonitic-like ribboning of the quartz grains are fairly commonly observed.

Lithic clasts are abundant. They include shale, quartzite, chert, and argillaceous and arenaceous limestone. Pre-depositionally deformed and metamorphosed clasts are also common and consist dominantly of low grade slates, phyllites and other metapelites and metapsammites (fig. 3*a*). The following metamorphic mineral assemblages have been recognized in these low-grade lithic fragments: quartz-muscovite; quartz-muscovite-chlorite; quartz muscovite-chlorite-biotite; and quartz-feldspar-muscovite-chlorite-biotite. These assemblages, together with the foliation in many clasts, indicate low-greenschist facies metamorphism and penetrative deformation of the source rocks prior to erosion and incorporation within the flysch.

Clasts of devitrified volcanic glass showing pilotaxitic textures, fine-grained plagioclase-phyric basalts with intersertal textures, as well as somewhat coarser-grained diabase clasts are also present within the flysch (fig. 3*b*). Most of the volcanic fragments are somewhat altered and chloritized and consist of chlorite + plagioclase + opaques ± greenish-brown alteration material ± hornblende. Weber and Middleton (1961) found that 'Normanskill' greywackes (Austin Glen in present usage, Fisher 1977) are relatively enriched in Mg, Ni, V, Cr, Ti and Sc. Enrichment in these elements is suggestive of a mafic-ultramafic component within the source terrain, supporting the inferences made from the petrographic data.

Fig. 3*a*—Pre-depositionally deformed and metamorphosed muscovite-chlorite-quartz schist. Pre-depositional cleavage is crenulated by 'regional' slaty cleavage of the greywacke. Field of view 0.7 mm, 10X magnification. Pawlet Formation.

The detrital constituents of the allochthonous Pawlet/Austin Glen greywackes clearly indicate a source terrain consisting of a variety of lithologies having experienced different degrees of metamorphism and deformation. This source lay to the east of their site of deposition on the continental rise of the ancient North American continental margin. The clasts showing no apparent or slight metamorphism are identical to lithologies in the Taconic sequence stratigraphically underlying the flysch. The silty quartzites are identical to thin silty quartzites in the Poultney; cherts occur in the Mount Merino, Indian River, and locally within the Poultney; argillaceous and fine sandy carbonates occur in the White Creek Member (Potter 1972) of the lower Poultney Formation, and in the West Castleton and Browns Pond Formations; rounded quartz, zircon, tourmaline, some plagioclase, potash feldspar and sphene occur within quartzites and wackes of the Hatch Hill, Browns Pond, and Bomoseen Formation (Rowley et al. 1979) and arkosic arenites of the Rensselaer 'Grit' (Potter 1972). The clasts of pre-depositionally deformed and metamorphosed metapelite, metapsammite, and highly strained quartz might be correlated with phyllites and low-grade, fine-grained schists of higher Taconic slices such as the Dorset/Everett and Greylock slices and/or with metapelitic and metapsammitic schists lying to the east of the Green Mountains in Zone 2. The mafic volcanic, diabase, serpentinite, detrital chromite, epidote, hormblende, sphene and magnetite, and probably some of the plagioclase, are compatible with derivation from an ophiolitic source and/or a volcanic arc source, both of which are recognized to the east in Zones 2 and 3.

PARAUTOCHTHONOUS AND AUTOCHTHONOUS FLYSCH

The uppermost medial Ordovician stratigraphic units of the continental margin east

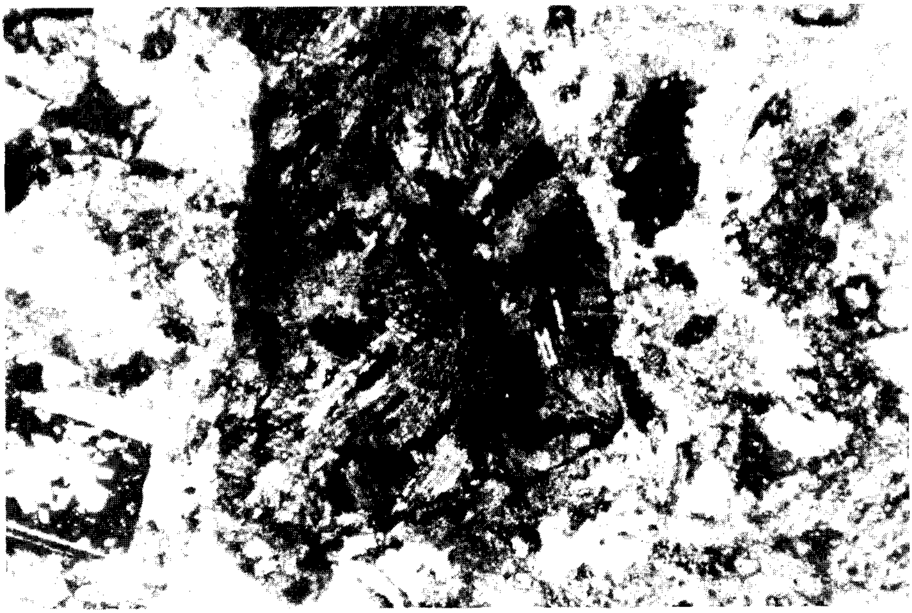

Fig. 3*b*–Subrounded volcanic fragment. Clast consists of altered volcanic glass, plagioclase and chlorite with a pilotaxitic texture. Altered plagioclase grain is adjacent to volcanic fragment. 0.7 mm field of view, 10X magnification. Pawlet Formation.

of the longitude of Canajoharie, New York are flysch consisting of interbedded argillites, greywackes, and pebbly mudstones, together with some lesser boulder conglomerates. This flysch stratigraphically overlies the carbonate platform and is ascribed to the Austin Glen Formation (Fisher 1977) in eastern exposures and to the Schenectady Formation farther to the west. The boulder conglomerate facies and some of the pebbly mudstone facies, commonly referred to as wildflysch (Bird 1969) are ascribed to the Whipstock Conglomerate (Potter 1972) and Forbes Hill Conglomerate (Zen 1961) along the east and west edges of the Taconic Allochthon, respectively. The age of the basal part of the flysch decreases progressively from east to west suggesting westerly progradation of the flysch associated with progressive subsidence of the carbonate platform to 'abyssal' depths. The decrease in age of the upper part of the flysch sequence to the east of the longitude of Albany can be correlated with progressive east to west truncation of sedimentation by overriding of the Allochthon (Chapple 1973). The small amount of paleocurrent evidence now available from these greywackes is indicative of easterly derivation.

At present, only preliminary petrographic observations of parauthochthonous and autochthonous greywackes have been completed. These observations indicate that the detrital composition of these greywackes is very similar to that of the allochthonous flysch. Major minerals include quartz, plagioclase, carbonate, muscovite, chlorite, potash feldspar and opaques. Pre-depositionally strained quartz is common. Minor phases include epidote, zircon, tourmaline, sphene, biotite, and hornblende. Lithic clasts include argillite, quartzite, chert, carbonate, and volcanic clasts. Some of the carbonate may have been derived from shelf carbonates, as well as from Taconic carbonates, as has been described for the carbonate boulders within the Forbes Hill (Bird and Dewey 1975). Pre-depositionally deformed and metamorphosed slate, phyllite and schist clasts are quite common (fig. 3*c*).

The source terrain for these greywackes appears to be essentially similar to that of the allochthonous flysch. The presence of

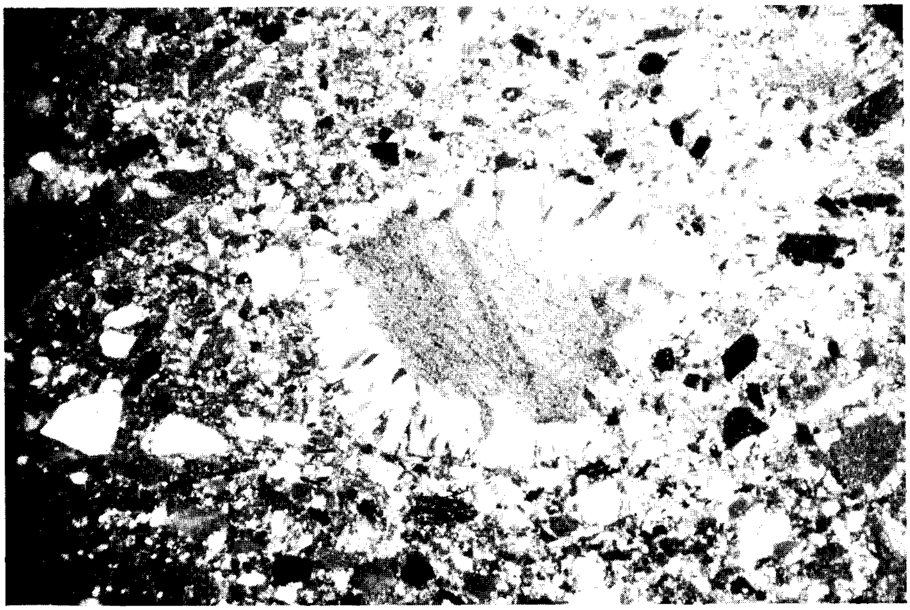

Fig. 3c–Pre-depositionally deformed and slightly metamorphosed clast from parauthochthonous conglomeratic greywacke with diagenetic rim of carbonate. Several sand and silt-size lithic fragments are within the field of view along with quartz, feldspar, muscovite, chlorite and opaques. Texture is typical of the greywackes. 1.8 mm field of view; 4X magnification. Austin Glen Greywacke.

slate clasts, particularly red Indian River-like slate, within this flysch has important implications for the timing of slaty cleavage development within the low Taconic slices. Indian River slates are essentially confined to the low Taconic Giddings Brook slice (Zen 1967). The presence of clasts of predepositionally deformed red slate within the parautochthonous flysch suggests that slaty cleavage developed within the rocks of these low Taconic slices during the medial Ordovician. Previously, many workers, notably Zen (1967, 1972), had speculated that the 'regional' slaty cleavage was developed in the late Ordovician or early Silurian. Medial Ordovician 440 m.y. K-Ar isotopic ages have been reported for muscovites lying in this cleavage by Harper (1968) and Ratcliffe (1979). This observation lends further support to structural observations indicating that the major folds and associated slaty cleavage observed within the Allochthon predate its emplacement (Rowley and Delano 1979; Rowlet et al. 1979; Ruedemann 1914).

CONCLUSIONS AND DISCUSSION

The stratigraphic and petrographic data supports the following primary conclusions:

(1) At the time of initiation of flysch deposition on the continental rise sequence now preserved in the western side of the Allochthon, during approximately *D. multidens* zone time, this portion of the continental rise remained undeformed and untransported and lay some distance to the east (present direction) of the coeval continental shelf.

(2) A source area lying to the east and including variably deformed and metamorphosed pelitic, psammitic, mafic, and ultramafic lithologies was being eroded and was shedding flysch to the west onto the sediments of the continental rise. At the same time deep-water hemi-pelagic clays and, farther west, shallow-water limestones were being deposited on the subsided carbonate shelf.

(3) Subsequently, this remaining continental rise terrain was itself incorporated

into the overriding, moving allochthonous assemblage of continental rise sediments, accretionary prism materials and ophiolitic lithologies. This continental rise terrain was then itself penetratively deformed and subjected to low grade metamorphism (chlorite grade or lower, Zen 1960) prior to and during emplacement onto the shelf.

These three conclusions require that stacking of the allochthon, deformation, and metamorphism must have occurred diachronously and progressively from east to west mostly or wholly before the obduction of the continental rise onto the shelf. Therefore, the Taconic Allochthon as a whole must have initially been part of a pre-assembled thrust stack and obducted in a way similar to that demonstrated in other collisional belts (Stevens 1970; Glennie et al. 1974; Dewey 1976; Sengör 1977).

Some detritus in the Pawlet can only be matched by Taconic lithologies (in particular, Bull or Poultney silty quartzites); we suspect that a considerable volume of the Pawlet had a Taconic source, but it is hard to prove this conclusively. This derivation requires cannibalism of the continental rise sediments, with some being thrust-accreted, deformed, uplifted, and eroded while deposition continued on top of another part (farther to the west and/or along strike) that was not yet tectonically disturbed. This more westerly part is now preserved in the Giddings Brook slice where a conformable sequence exists up into the Pawlet flysch. In present-day thrust-accretion piles, deformation (folding, cleavage development) begins immediately after the material starts to be incorporated into the stack (J.C. Moore and Karig 1976), and presumably continues for some time as the material moves into the accretionary prism, except perhaps for the most near-surface part of the accreted stack. We suggest that deformation of the rocks of the Taconic Allochthon similarly began as soon as they started to move and that they were already as strongly cleaved and folded as they are today by the time they crossed the carbonate shelf edge and thin slivers of the carbonates were attached to the basal thrust surface, because these carbonates can now be seen truncating fold structures in the Giddings Brook slice (Rowley et al. 1979). The pre-depositionally foliated clasts within the Pawlet and Austin Glen are supporting evidence for this claim.

We emphasize that there is no evidence supporting the idea that *Taconic* rocks were soft sediments during their transport. The greywacke-shale mélange and olistostromic breccias developed particularly at the western margin of the Taconic Allochthon (Forbes Hill and related units) have been pointed to in the past (Zen 1967; Bird 1969) as evidence for gravity sliding emplacement of the Taconics, particularly of the low Taconic Giddings Brook slice. It is our contention that the mélange and olistostromes are evidence only for local relatively steep submarine slopes, produced by outcropping submarine thrust faults. The overriding of recently deposited, poorly consolidated muds, turbidites, and olistostromes by the assembled Taconic thrust sheet probably contributed to the disruption seen in the mélange. As an expression of submarine thrust faulting, this mélange is no more evidence for gravity sliding at any stage in allochthon emplacement than similar mélange in known thrust-accretion prisms produced by subduction (e.g., , G. F. Moore and Karig 1980).

The occurrence of slivers of shelf carbonate and related rocks at the sole of several slices is most easily interpretable as the product of later large-scale imbrication of a *single* initial thrust surface, with carbonates attached to the sole thrust from the shelf. Interpretation as successive detached slices travelling over the carbonate shelf with gaps developed behind them (and hence travelling by gravity sliding) is, we suggest, a mechanically unattractive hypothesis by comparison. Proponents of gravity sliding for all or even just the last portion of movement must explain how the slices moved up the regional palaeoslope on the North American continental margin so clearly expressed by the facies change from autochthonous and parautochthonous deep water shales and greywacke turbidites in the east to the medial Ordovician carbonate bank edge in the west. The westward migration of the coarser flysch turbidites of the Pawlet and Austin Glen with time requires their deposition in a westward-moving trench-like feature which we interpret to have lain close to the edge of the moving allochthon, in the same way that coarse turbidite sedimentation in present-day trenches (Piper et al. 1973) is confined to the area near the trench axis. Similarly, the axial transport of turbidites is a feature of this environment and is well documented for the coeval Martinsburg of Pennsylvania (McBride 1962) although less well established for the Austin Glen and Pawlet flysch.

The present stacking order and slice divisions of the Taconic Allochthon are, in part, a product of large-scale imbrication during the last stages of the collision. The thin shelf carbonate slivers found at the base of most of the Taconic slices, including the northern Giddings Brook slice, are the signposts of this event. The carbonate slivers (in one place, including Grenville basement) occur along thrust faults between successive slices of the Taconic Allochthon where there are little or no associated flysch-type sediments. Examples include those between the Chatham and Giddings Brook slices and the Rensselaer and Giddings Brook slices. Apart from sequential emplacement over the carbonate shelf with gaps between moving slices, an hypothesis rejected for reasons given above, the only other hypothesis we find plausible to explain these slivers is that of large-scale imbrication of a single thrust surface. This is the thrust surface on which Taconic rocks were moving as they crossed the outer carbonate shelf and small pieces of carbonate (and rarely basement) were attached in places to the sole of the moving thrust. Subsequently, more easterly parts of this thrust sheet overrode more westerly parts using the same surface of movement (at the base of the carbonate slivers) as before, leading to the present relationship. We do not accept the interpretation of Ratcliffe and Bahrami (1976) regarding the mechanism of emplacement of the Ghent Block (carbonates and Grenville basement) between the Chatham and Giddings Brook slice, and by implication the other carbonate slivers at slice boundaries.

It will be noted that our hypothesis does not preclude the existence of earlier thrusts within the Taconic rocks, generated during initial thrust-accretion and truncated by the movement surface with attached carbonates. In particular, such early thrusts are known within the present northern Giddings Brook Slice (Rowley 1980*a*). It also does not preclude the existence of later imbricate thrust faults that cut the carbonate sliver-bearing thrust surface(s) at oblique angles, but these also cut significant thicknesses of the parautochthonous shelf carbonates and flysch and, in some cases, the Grenville basement.

Despite the late, large-scale imbrication into the present, separate slices, Taconic rocks that may have initially been either in thrust relationship or in their original lateral stratigraphic arrangement in a single thrust sheet even now remain stacked in their correct east-to-west order. Thus the farthest-travelled slices are on top and less far-travelled slices are below, even though the relative difference in distance travelled may not be very great. We propose that the Allochthon therefore does not display a diverticulated sequence (Zen 1967; Fisher 1979) or other stacking arrangement (Ratcliffe 1979) in which less far-travelled slices occur in higher structural positions. The shelf carbonate slivers attached to allochthonous thrust slices are not unique to the Taconics, also occurring in Newfoundland (Riley 1957; Williams and Godfrey 1980), where we suggest that they have the same implications as in the Taconics.

TECTONICS OF THE TACONIC OROGENY

The regional geology of western New England and the along strike continuity of the major tectonic zones to the north are explicable by a general plate tectonic model involving the collision of the ancient North American Atlantic-type continental margin and a volcanic arc, with eastward-directed

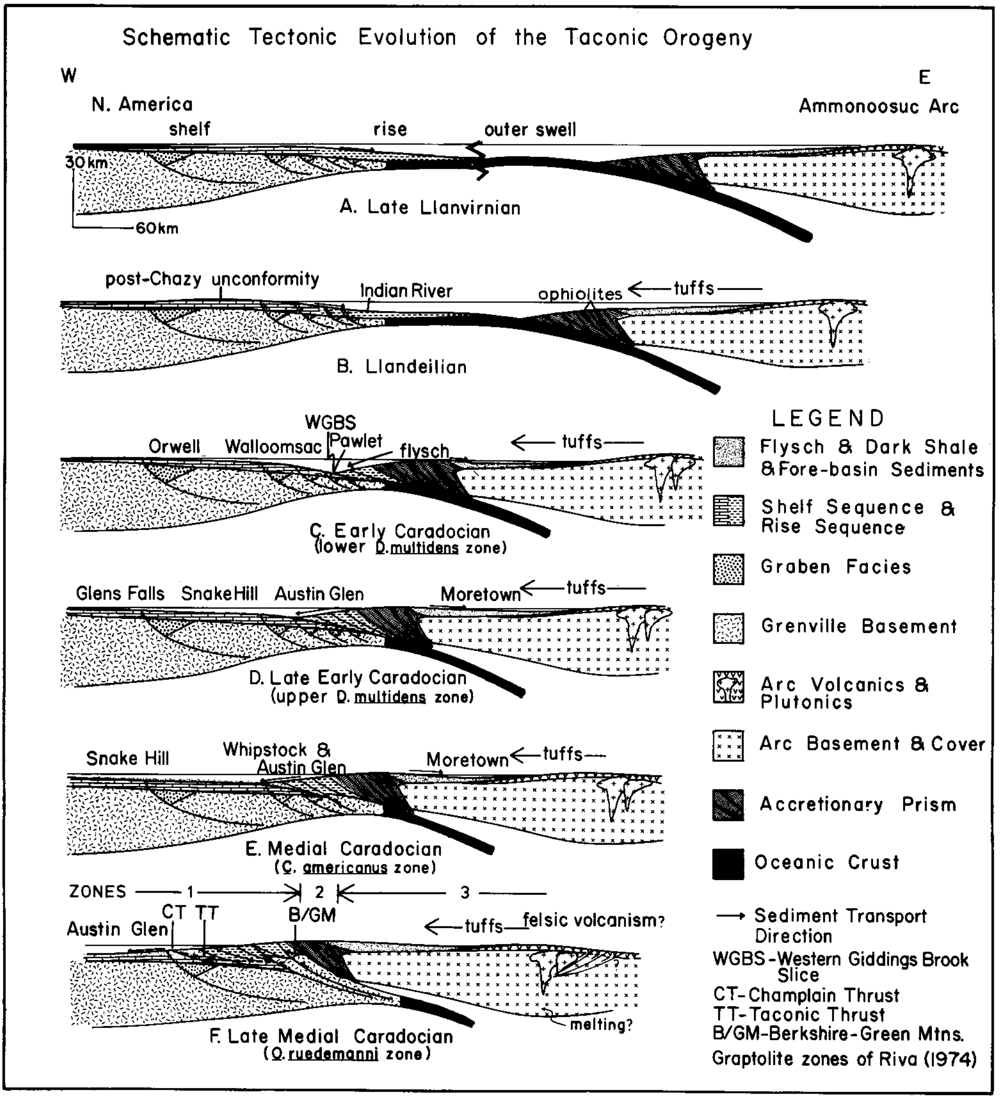

Fig. 4.—Sequential tectonic cross-sections for the Taconic Orogeny in New England. See text for further discussion.

subduction of intervening ocean floor. Our model for this collision (fig. 4) described below is similar to the general model described by Dewey and Bird (1970) and to those proposed by Gealey (1977) for Oman by Hamilton (1979) for New Guinea and Timor and by Stevens (1976) and Nelson and Casey (1979) for western Newfoundland.

During the late Llanvirnian (fig. 4*a*), deposition on the North American Atlantic-type continental margin shelf and rise was characterized on the rise by hemipelagic argillites interbedded with thin silty quartzites (Poultney Formation), interpreted to be contourites (Rowley et al. 1979) and on the shelf by shallow water carbonates. Eastward-directed subduction and volcanic arc activity were presumably occurring somewhere to the east, but these rocks show no signs of such activity in the form of identifiable bentonites or tuff beds.

An unconformity is observed on the carbonate platform (fig. 4*b*) in post-Chazy time (Llandeilian), associated with the development of east-dipping normal faults on the shelf (Thompson 1967; Zen 1967), constituting the Tinmouth phase of the Taconic Orogeny (Rodgers 1970). Chapple (1973) argued that this tectonic activity was associated with the passage of the eastern part of the continental shelf through the outer arc swell to the west of the trench. Deposition on the continental rise at this time was characterized by red hemipelagic argillites of the Indian River Formation. Bird and Dewey (1970) suggested that the red coloration is due to erosion of a terra rosa soil developed from the carbonates on the post-Chazy unconformity. Thin silicic tuff beds interbedded with the red argillites presumably come from the volcanic arc then approaching from the east (Rowley et al. 1979).

An interesting implication of the continued depostion of hemipelagics on the continental rise during the period of the post-Chazy unconformity is that there is no influx of coarse, shelf-derived detritus at this time. Thompson (1967), Zen (1967) and Ratcliffe (1979), among others, argue that erosion during this time cut deeply into the eastern part of the shelf sequence and at least locally exposed Grenville basement. During the Cambrian, periods of regression on the shelf are marked by the influx onto the continental rise of shelf-derived coarse detritus including sandstones, wackes and carbonate boulder conglomerates (Rowley 1979; 1980*a*). The lack of such coarse detritus during the Llandeilian within the Taconic sequence argues strongly against models invoking deep erosion of the shelf at this time.

Depostion on the shelf during the later Llandeilian and early Caradocian was characterized by an east to west facies change from relatively deep-water dark argillites of the Walloomsac through deep water argillaceous limestones of the Orwell to shallow water limestones of the Amsterdam in the west (fig. 2). This facies pattern suggests a progressive eastward deepening to abyssal depths of the formerly shallow-water carbonate platform. We correlate this with the downflexing of the shelf into the trench to the east. The progressive westward migration of these facies belts through the late medial Ordovician is indicative of continuous 'flow' of the shelf into this subduction zone.

In the late Llandeilian to early Caradocian, sedimentation on the rise changes from red argillite to deposition of black and dark green cherts and siliceous argillites of the Mount Merino Formation. Radiolaria tests are quite abundant in these cherts, but the presence of exotic minerals such as sodic plagioclase, chlorite, augite, hypersthene, garnet and biotite along with felted and matted textures of some quartz is suggestive of a significant volcanogenic component (Lang 1969; Bird and Dewey 1975). Bentonite horizons are known to be interlayered with coeval shelf carbonates to the west (Rickard 1973; Brun and Chagnon 1979), supporting the presence of a nearby volcanic arc source to the east.

The upper part of the Mount Merino Formation consists of sooty black, graptoliferous silty argillites of early to early medial Caradocian age (fig. 4*c*). These argillites pass gradationally and conformably upward into the Pawlet flysch. The composition of this easterly-derived flysch suggests a source terrain consisting of ophiolitic, metapelitic, and metapsammitic, and Taconic lithologies. We propose that the ophiolitic and metapelitic and metapsammitic lithologies were derived from an accretionary prism now represented by lithologies in tectonic Zone 2 (fig. 4*c*). The presence of Taconic lithologies indicates that North American continental rise sediments were now being incorporated into the overriding accretionary prism. An unconformity reported at the base of the Moretown and/or Umbrella Hill lithologies of Zone 2 in northern Vermont (Doolan and Stanley pers. comm. 1979) implies that the upper, more eastern part of the accretionary prims may have been extensively subaerially exposed at this time (fig. 4*d*).

The late early to medial Caradocian (figs. 4*d* and 4*e*) is marked by continued convergence and subduction of the continental margin. The previous continental rise had been entirely overridden and part, presently represented by the Taconic Allochthon, incorporated into the overriding accretionary complex. Deformation and metamorphism of this material was occurring giving rise to the major folds and associated slaty cleavage of the western Giddings Brook slice that predate final emplacement (Rowley and Delano 1979; Rowley et al. 1979). Flysch deposition (Austin Glen) continued in the 'trench' in front of the overriding allochthonous accretionary complex. Deposition of dark argillites (Snake Hill) and, farther to the west, progressively shallower water limestone (Glens Falls, Larrabbee) occurred on the previous shelf (fig. 4*d*). The carbonate bank edge migrated progressively to the west during this time (Fisher 1977).

The presence of carbonate platform-derived blocks within the olistostromic Whipstock Breccia (Potter 1972) and similar occurrences elsewhere indicates that slivers of the outer shelf had been attached to the moving allochthon and were exposed to erosion (probably entirely submarine) at this time. The olistostromes were deposited within the parautochthonous flysch in front of the advancing thrust pile and the presence of apparently predepositional deformation features within some of these blocks (Potter 1972) supports this interpretation.

During the late medial Caradocian (fig. 4*f*), attempted subduction of the Grenville basement and collision with basement of the volcanic arc resulted in the shortening and thickening of the North American continental basement. Buoyancy effects associated with the attempted subduction of the basement gave rise to the development of basement-involved folding (Chester Dome) and westward-directed, basement-cored nappes of the Berkshire Massif, Housatonic Highlands (Ratcliffe 1975, 1979; Harwood 1975) and other "allochthonous" basement complexes to the south. The Green Mountains are in our view almost certainly also transported to some extent, possibly along the Pine Hill thrust. Imbrication of basement resulted in complex deformational and metamorphic overprinting relationships in both its shelf cover and the structurally overlying, by now emplaced continental rise sediments of the Taconic Allochthon. Such features as the tight folds of the basal Taconic Thrust and associated development of slaty cleavage cross-cutting the faults, particularly as observed along the eastern edge of the Allochthon (Ratcliffe 1969, 1975, 1979; Potter 1972) are associated with these later phases of the collision. Overthrusting along the Champlain Thrust is probably also associated with this stage. Austin Glen and Schenectady greywackes continued to be deposited to the west, possibly recording some of the isostatically related uplift in the core of the orogen to the east.

Local anatexis of sediments within the suture (Zone 2) during collision gave rise to the granite pegmatite stringers observed to cross-cut early thrusts, such as the Middlefield Thrust (Ratcliffe and Mose 1978). Felsic volcanics dominate the upper part of the Ammonoosuc sequence in Zone 3 (Robinson et al. 1979). These volcanics may be related to anatectic melting of the basement of the volcanic arc due to shortening and thickening of the crust during collision in a manner similar to that proposed by Dewey and Burke (1973) for Tibet.

The model drawn here for the Taconic Orogeny of western New England differs in one important aspect from those commonly drawn for more northern parts of the Orogen in Quebec and western Newfoundland (Williams 1979; Nelson and Casey 1979). This difference is the lack of a wide ophiolite-floored fore-arc region before the collision. Rowley (in press; in prep.) argued that the along-strike change in the nature of the basement of the volcanic arc, from late Precambrian continental basement in New England to ophiolitic farther north, is reflected as well in the nature of the basement of the fore-arc region. In Newfoundland a wide fore-arc ophiolite was present that upon collision was obducted onto the continental margin along with the continental rise and slope sediments of the Humber Arm Allochthon. To the south the extent of the ophiolite floored fore-arc region may have decreased giving rise to a narrower belt of ophiolites upon collison, such as observed in Quebec. Farther south, subduction was initiated adjacent to a continental margin, and no fore-arc ophiolite is present. Collision here resulted only in the obduction of the fore-arc accretionary prism and western continental margin rise and slope sediments of the Taconic Allochthon without an overlying ophiolite. This along strike variation in the nature of the fore-arc region gives rise to a marked change in the geologic relationships associated with the suture zone. Where ophiolites floored the fore-arc region, such as Newfoundland, recognizable ophiolites are present along the suture, as along the Baie Verte Lineament. Where continental basement floored the fore-arc region recognizable ophiolites are not present, but only highly dismembered remnants are preserved.

ACKNOWLEDGMENTS.—We particularly wish to thank Louise Delano (formerly L. Jacobi) for discussions of Pawlet-Mount Merino relationships and for providing the starting point for this study in her accurate, detailed mapping of the area northwest of Granville, New York. We also thank B. Idleman and J. F. Casey for comments on early drafts of the manuscript and B. Idleman and G. W. Putman for assistance in petrographic identifications. Discussions with them and A. M. C. Sengör and J. F. Dewey, among many others, are gratefully acknowledged. We thank Barry Doolan, Ed Belt, Susan Anderson, and reviewer #1 for helpful criticisms of the manuscript, and we thank Donna Kelly for typing and retyping it.

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