GEOLOGIC EVIDENCE FOR RATE OF PLATE CONVERGENCE DURING THE TACONIC ARC-CONTINENT COLLISION[1]

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ABSTRACT

The rate of plate convergence during arc-continent collision can be estimated from the rate at which the secondary effects of subduction move across the underriding plate in advance of the plate boundary. The following sequence of events is typical: (1) shoaling and/or emergence of the continental shelf, presumably caused by lithospheric flexure; (2) rapid subsidence, by a combination of normal faulting and trenchward tilting; and (3) a change from platformal to flysch sedimentation. Such a sequence has been recognized in the Taconic foreland basin in eastern New York and interpreted as being the result of collision between the ancient passive margin of North America and an island arc terrane at an east-dipping subduction zone during Medial Ordovician times. A plot of age versus distance across strike shows that the diachronous migration of these phenomena across the foreland proceeded at rates of 2 to 3 cm/yr; we regard this as the plate convergence rate during the latter part of the Taconic Orogeny. Our result is comparable with modern rates of plate motion and also agrees with an earlier estimate for the Taconic, which was based on the rate at which a series of locations on the outer trench slope passed through fossil-defined isobaths.

INTRODUCTION

One of the rewards of working with the present plate mosaic is that contemporary tectonic motions can be quantified; but unfortunately, this is not the case for the older Paleozoic. If ancient plate motions could be quantified so as to yield estimates of the rates, directions, and duration of relative motion, then such data could be used to find poles of rotation among the preserved remnants of the ancient plates, greatly facilitating the construction of palinspastic maps, estimation of the width of closed ocean basins and, perhaps, understanding of the diachroneity of orogenesis. Quantification of ancient plate motions in this way also has implications for the general understanding of the evolution of the plate mosaic.

Most geologists now agree that the Taconic Orogeny was the result of an arc-continent collision (Chapple 1973; Robinson and Hall 1978; Rowley and Kidd 1981; Stanley and Ratcliffe 1983). Despite the success of this model in rationalizing the Ordovician geology of eastern New York and western New England, however, it has still provided only a qualitative idea of the geometry and location of Ordovician plate boundaries, and of the timing, directions, and rates of relative plate motions. Paleomagnetism, which has been so important in unravelling the accretionary history of allochthonous terranes in western North America, is unlikely to provide any quantitative information on the relative motions between North America and the Ammonoosuc Arc which resulted in the Taconic collision: the arc was so badly damaged during the Devonian Acadian Orogeny that its earlier paleomagnetic history is inherently suspect, if not lost.

Recently, information on the rate of plate convergence during the Taconic Orogeny has come to light as one result of a long-term paleontologic study in the Mohawk Valley of New York (Cisne et al. 1982). Cisne and his colleagues estimated plate convergence based on the rate to which outer trench slope locations passed through fossil-defined isobaths. Their elegant method, unfortunately, requires the collection of a vast body of fossil data. The present paper describes a somewhat simpler way of approximating convergence rates during arc-continent collisions such as the Taconic (Bradley et al. 1985*a*). Our approach uses nothing more than the stratigraphic and structural data that have been collected routinely by survey geologists for generations; hence it can be readily applied to many Phanerozoic arc-continent collisions without the need for a major field effort.

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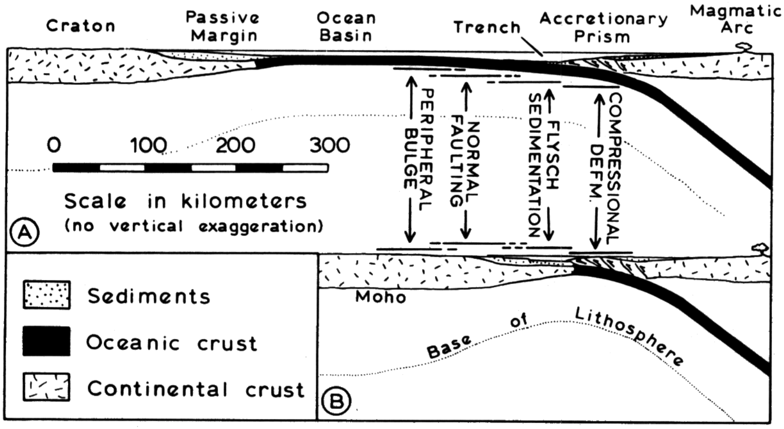

FIG. 1.—*A*. True scale cross section of an impending collision between a passive continental margin and a magmatic arc. Note the locations of peripheral bulge, normal faulting, flysch sedimentation, and compressional deformation. *B*. After 350 km of additional plate convergence, the arc continent collision is in progress. The former shelf has moved into the region of peripheral uplift and normal faulting, the former continental slope is buried by trench fill, and continental rise sediments are being scraped off and incorporated into the accretionary prism.

THEORETICAL BASIS FOR DETERMINING CONVERGENCE RATES DURING COLLISION BETWEEN AN ARC AND A PASSIVE CONTINENTAL MARGIN

The fate of most ancient Atlantic-type margins has been to collide with a magmatic arc. Studies of Phanerozoic examples (e.g., Timor, Taiwan, Oman, Antler, Brooks Range, Ouachita, and Taconic; Burke et al. 1984) have revealed a readily recognized progression of events during collision.

Subduction of ocean floor leads to the development of several features that become important in determining convergence rates when subduction ultimately leads to collision (fig. 1*a*). On the oceanward side of the trench axis, normal ocean floor is commonly deformed by a broad, gentle peripheral swell that forms as an elastic response to flexure of the downgoing slab (Turcotte et al. 1978; Bodine and Watts 1979). Typical flexural bulges in oceanic lithosphere have crests located 100–200 km from the trench line, and amplitudes of a few hundred meters (hence, even the crest of the bulge is still at abyssal depths). The outer slope of a typical deep sea trench is cut by down-to-trench normal faults, which are also considered to form in response to bending of the subducting slab (e.g., Hanks 1979). Being lower than its surroundings, the trench floor is often the site of rapid turbidite sedimentation, resulting in burial of the block-faulted basement. The base of the inner trench slope is a seaward-verging thrust (or blind thrust) along which trench-fill sediments are scraped off into an accretionary prism (Karig and Sharman 1975). These zones of (1) flexural uplift, (2) normal faulting of a regionally tilted and trenchward deepening surface, (3) flysch sedimentation, and (4) compressional deformation overlap to some extent (fig. 1*a*).

When plate convergence brings a passive continental margin into this steady-state arrangement, these phenomena move in sequence onto the continent. Ideally, each secondary effect should move at a rate comparable to convergence rate between the arc and continent. However, if the flexural strength of the transitional and continental lithosphere is significantly greater than that of the oceanic lithosphere, these features could conceivably migrate at a rate faster than the convergence during passage of the arc onto the continent. Figure 1*b* shows the distribution of these features during an early stage of collision. The continental shelf has become the site of the peripheral bulge, and because it was already near sea level, uplift of 100 or 200 m results in shoaling and/or emergence of the shelf. The continental slope (now the outer trench slope) has become an area of normal faulting, while the former continental rise has

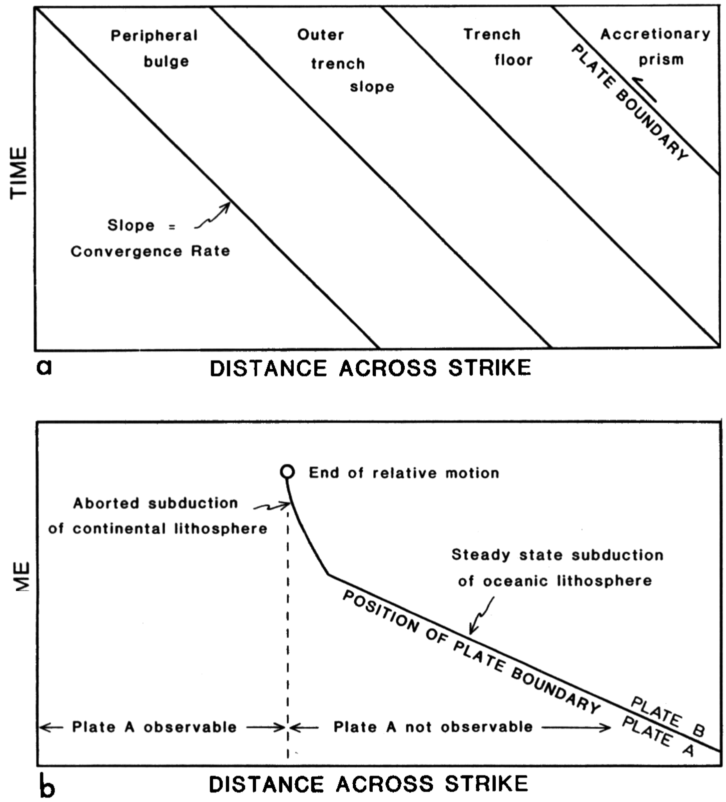

FIG. 2.—*A*. Idealized plot showing the diachronous nature of geologic phenomena which move in advance of the overriding plate which is responsible for them. The vertical axis is time and the horizontal axis is distance measured perpendicular to strike on the underriding plate. The slope of "contacts" between regimes gives the convergence rate. *B*. An idealized convergence curve with relatively fast subduction of oceanic lithosphere at a constant rate, followed by continental collision, during which plate convergence slows to a stop. Because of this effect, convergence rate calculations from collisional forelands such as the Taconic are probably minimum values.

been buried by younger sediments in the trench axis, and the more distal rise sediments have been scraped off and incorporated into the lower part of the accretionary prism. Continued plate convergence would result in the displacement of each of the above phenomena toward the craton.

The normal component of the rate of plate convergence can be obtained if the peripheral bulge, outer trench slope, trench floor, and accretionary prism are recognizable, steady-state environments which migrate across a collisional foreland in advance of the arc (fig. 2*a*). Figure 2*b* shows a likely shape of a plate convergence curve, with the convergence rate decreasing with time, as might be expected when an arc-continent collision "grinds to a halt." It follows from figure 2 that the amount of convergence during a given interval can be determined if the rate is known. If the duration of arc magmatism can also be determined, it should then be possible to make a reasonable estimate of the minimum width of the ocean.

PREVIOUS AND RELATED WORKS

Several workers have used aspects of the rock record as indirect measures of the rate of relative plate motion, each tracking the diachronous migration of some geologic phenomenon in advance of a convergent plate boundary. Dubois et al. (1975, 1977) computed convergence rates between the Pacific and Australian plates at the Tonga and New Hebrides trenches from the history of uplift of island chains that are obliquely passing over flexural bulges and are soon to be subducted. Their results (90 and 120 mm/yr, respectively) are close to the 98 mm/yr calculated from Minster et al.'s (1974) pole and rotation rate. In the Timor Trough, where the passive margin of northwestern Australia is being subducted beneath the Banda Arc, Veevers et al. (1978) used sediment cores and seismic reflection profiles to trace the migration of a "topographic wave" (corresponding to flexural uplift of the shelf, rapid subsidence into the trench, and uplift in the accretionary prism). They concluded that this wave migrated southward at a rate of about 53 mm/yr from 3.0 to 1.8 Ma, and at a much slower rate of about 5 mm/yr since then. It seems likely that the rate of southward migration corresponds to a rapidly decreasing rate of plate convergence between the Banda arc and the Australian continent. The calculated convergence rate between Australia and Eurasia (77 mm/yr, from Minster and Jordan 1978) agrees reasonably well with the Pliocene rate, and since then, most relative motion has evidently been accommodated at the incipient subduction zone north of the Banda arc. In the ancient record, Johnson and Pendergast (1981) determined a convergence rate of 6 mm/yr during the Antler Orogeny (western U.S.), from the cratonward migration of sedimentary facies belts in front of the Roberts Mountains Allochthon. This result cannot be confirmed, but equally slow rates of relative motion are known in the present-day plate mosaic. Lyon-Caen and Molnar (1985) inferred from similar evidence that the Himalayan front is advancing southward at 10–15 mm/yr. Since the Indian and Eurasian plates are converging at about 50 mm/yr, some relative motion must be taken up between Tibet and Eurasia. In the Alpine System, Van Houten (1974) noted that the depositional axis of the Flysch migrated to the northwest at a rate of 20 mm/yr, although he did not explicitly interpret this as a rate of plate convergence. Ettensohn (personal comm. 1986) has recently shown that the strike-parallel component of the rate of relative motion during the Acadian Orogeny can be obtained from the southward migration of black shale depocenters in the foreland basin. Estimates of convergence rates based on palinspastic restorations have been made by Hsu and Schlanger (1971) in the Alps and by Dickinson et al. (1983) in the Antler.

In essence, Cisne et al. (1982) based their estimate of the convergence rate during the Taconic Orogeny (about 2 cm/yr) on the time it took a series of localities on the outer trench slope to pass through a sequence of paleontologically identified depth zones. Numerous volcanic ash horizons allowed precise time correlation from one measured section to the next, thereby eliminating any potential chronologic error due to facies control of fossil distribution. It was their remarkable study which led us to recognize a general approach to determining convergence rates during arc-continent collision (Bradley et al. 1985*a*) combining the approaches used in the various works cited above. Our result for the Taconic compares favorably with that determined by Cisne et al. (1982).

APPLICATION OF THE METHOD TO THE TACONIC OROGENY

Geologic Setting.—Effects of the Taconic Orogeny can be recognized from Newfoundland to Alabama. Virtually all recent workers have interpreted it as the product of a collision between the east-facing (present direction) passive margin of North America with a magmatic arc or arcs over an east-dipping subduction zone (Stevens 1970; Chapple 1973; Hiscott 1978; Rowley and Kidd 1981; Hatch 1982; Shanmugam and Lash 1982; Stanley and Ratcliffe 1985). In the type area of New York and western New England, the principal features of the orogen can be appreciated with reference to eight Precambrian through Ordovician rock units (figs. 3 and 4).

Metamorphic and plutonic rocks of the Grenville Province form the Precambrian basement of what by Cambrian time had become the continental margin of North America. Grenville basement is exposed in the area of figure 3 along the southern flank of the Adirondack Mountains, and in a few erosional windows through the lower Paleozoic cover. The Grenville is overlain by a shallow marine sequence consisting of westward-transgressing, basal siliciclastics (Potsdam Sandstone) overlain by carbonates (Beekmantown Group). Since the work of Zen (1967), Rodgers (1968), and Bird and Dewey (1970), this sequence has come to be universally regarded as having been deposited on a thermally subsiding passive margin. The Beekmantown carbonates extend into the Lower Ordovician, and are truncated by a

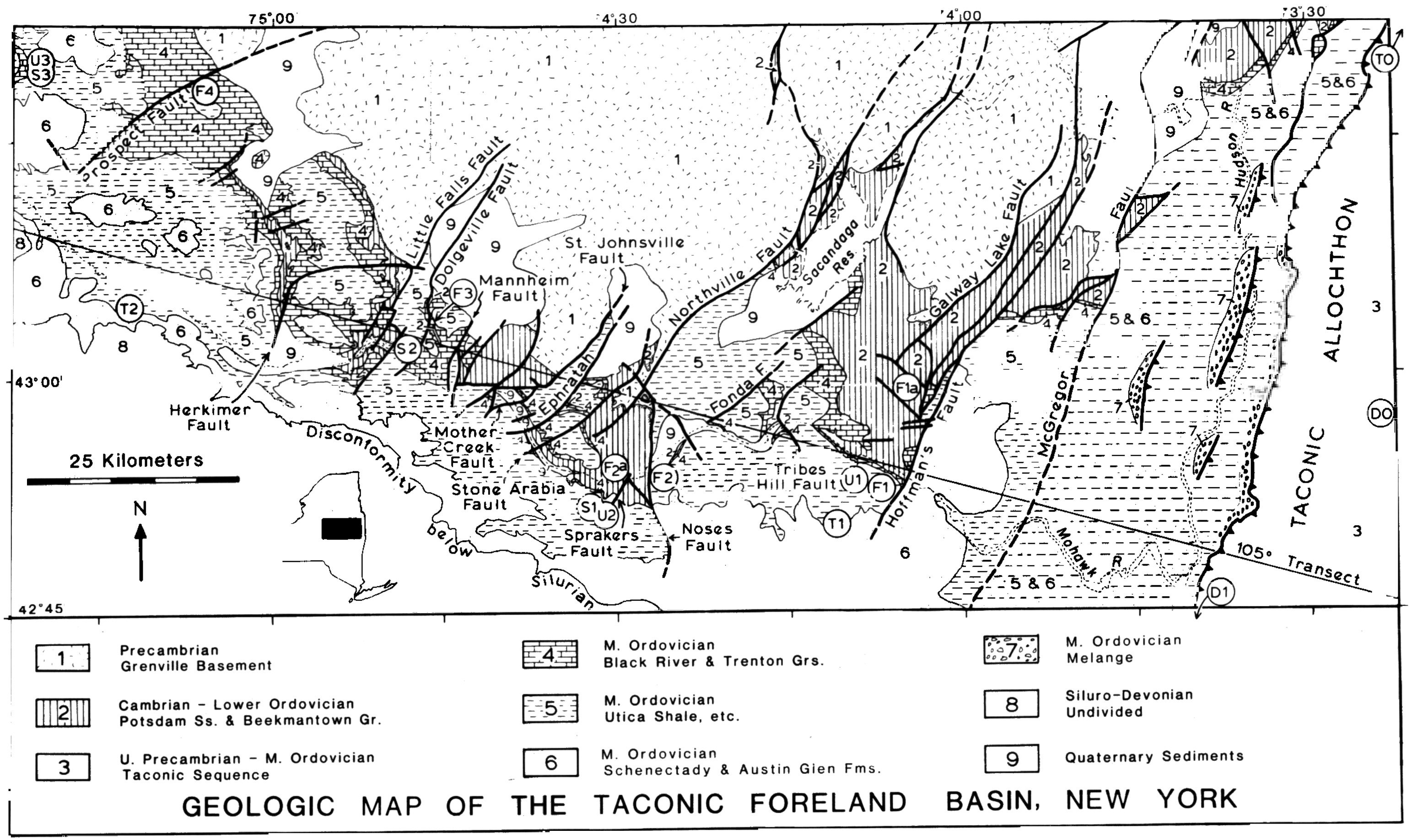

Fig. 3.—Geologic map of the Taconic foreland basin in New York showing the distribution of rock units and the locations of structures and localities mentioned in the text. Unit 5 includes the Canajoharie Shale; Unit 6 includes the Austin Glen Greywacke and the Frankfort Formation. Units 5 and 6 have been left undivided in the area of little outcrop and mild deformation to the east of the McGregor Fault. Unit 9 is only shown where the distribution of covered bedrock units cannot be reasonably inferred. Adapted from Fisher et al. (1970), Fisher (1980), and Bosworth and Vollmer (1981).

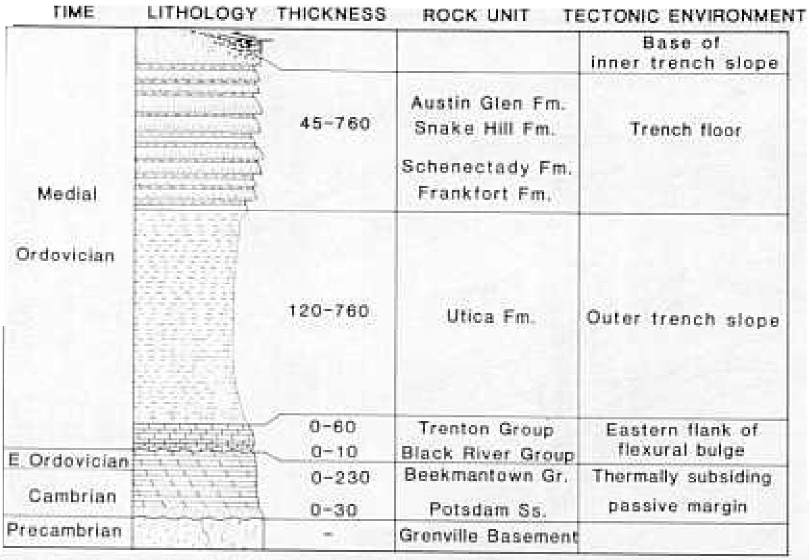

FIG. 4.—Generalized stratigraphic section of the Taconic foreland basin, New York. Thicknesses shown in the lithology column are averages of the ranges given in meters in the thickness column (from Fisher 1977). Exact ages are not shown because the rock units are markedly diachronous.

Middle Ordovician disconformity discussed below under the heading "Peripheral Bulge."

Above this surface lies a second sequence of marine carbonates, the Black River and Trenton Groups, which deepen upward and eastward into black, marine shale of the Utica Shale and lithologic equivalents (e.g., Canajoharie). Each of these units was deposited during a time when the former continental shelf was being cut by high-angle faults (described below under the heading "Normal Faulting") which Chadwick (1917) first suggested were genetically related to Taconic thrusting. The Utica coarsens upward into turbiditic siltstones and sandstones which are assigned to the Frankfort and Schenectady Formations in the west and to the Snake Hill and Austin Glen Formation in the east (see discussion under the heading "Flysch Sedimentation"). Uppermost Ordovician molasse facies (Quassaic Formation) succeed the flysch to the south of the area of figure 3. Shallow marine strata of Silurian age overlie the Ordovician disconformably in the western part of figure 3; this contact becomes one of angular unconformity to the east (see discussion under the heading "Compressional Deformation").

Geologic relations from the Ordovician thrust front eastward provide the main basis for regarding the Taconic Orogeny as an arc-continent collision. According to this interpretation, the Taconic foreland basin is what remained of the topographic trench when convergence ceased (fig. 5), the Taconic thrust belt is the accretionary complex, and the Bronson Hill Anticlinorium, containing the Ammonoosuc Volcanics, is the magmatic arc. The succession described in the preceding paragraph can be traced well to the east of the Taconic deformation front, where it is exposed in windows through the Taconic and related thrust sheets. The Medial Ordovician history is strikingly similar to that of the Mohawk Valley: following platformal deposition during Cambrian and early Ordovician times, the shelf was uplifted and block-faulted (the Tinmouth Phase of the Taconic Orogeny; Rodgers 1971; Zen 1967, p. 10; Rowley 1982), then buried beneath black shales and turbidites (Walloomsac, Ira Formations) and ultimately, in places, by olistostromes (Whipstock Breccia of Potter and Lane 1969).

Structurally overlying these rocks in the Taconic Allochthon, a package of thrust slices of deep-water Cambro-Ordovician sediments that were deposited in a continental slope and/or rise setting (Zen 1967; Bird and Dewey 1970). The uppermost unit in the al-

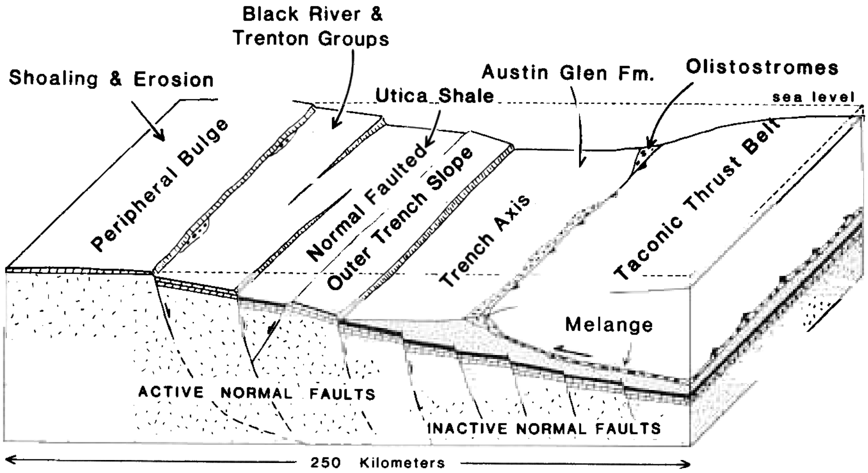

FIG. 5.—Schematic paleogeographic block diagram of the Taconic foreland basin, New York, near the close of the Taconic Orogeny. Stratigraphic units are represented on the front face as follows: dolostone pattern = Cambrian and Lower Ordovician; limestone pattern = Black River and Trenton Groups; black = Utica Shale; stipple = Austin Glen Greywacke; conglomerate pattern = melange and/or olistostromes.

lochthon is the east-derived Pawlet Formation, a lithologic correlative of the Austin Glen Formation. Rowley and Kidd (1981) interpreted it as recording the arrival of the continental rise at the trench.

The Taconic Allochthon is but one of an imbricate stack of thrust sheets that extend across strike into east-central Vermont, where the first-formed slices consist of strongly deformed metasediments and dismembered ophiolites. This serpentine belt has been interpreted as that part of the accretionary complex that formed before the arrival of North America at the trench (Rowley and Kidd 1981; Stanley and Ratcliffe 1985). Still farther east, much obscured beneath Siluro-Devonian strata and modified by the effects of the Acadian Orogeny, is a belt generally interpreted as the Ordovician magmatic arc (the Ammonoosuc Arc as shown by Rowley and Kidd 1981) which was presumably responsible for the Taconic collision. In western New Hampshire, its axis corresponds to the Bronson Hill Anticlinorium. This is well to the east of the most easterly exposures of Grenville basement and is probably about where the Taconic sequence was deposited.

Peripheral Uplift. — Subduction-related drowning of the passive margin was preceded by development of a widespread unconformity in the shelf sequence. In the Mohawk Valley, Lower Ordovician carbonates of the upper part of the Beekmantown Group are overlain disconformably by carbonates of the Black River and Trenton Groups. The gap in the record is thought to span about 5 Ma (Fisher 1980, p. 6), during which time considerable erosion took place in some areas. For example, in the northwestern corner of the area of figure 3, erosion was sufficient to remove the Beekmantown entirely, so that Black River-Trenton carbonates rest directly on basement. Several writers have speculated that the principal Medial Ordovician disconformity records uplift of the shelf in response to its passage over a flexural bulge (Bird and Dewey 1970; Chapple 1973; Rowley and Kidd 1981; Jacobi 1981). However, Cisne et al. (1982) pointed out that a flexural bulge is not obviously present on the northwestern margin of Australia, and hence it is not clear whether one should be expected in the Taconic foreland. Alternatively, this surface might instead be attributed to a major eustatic event, as discussed by Mussman and Read (1986, p. 292). Minor erosion surfaces of local extent are also reported higher in the Black River-Trenton sequence (Fisher 1977; Cisne et al. 1982).

In question is whether or not the cratonward migration of some phenomenon associated with a peripheral bulge can be used to help establish a convergence rate. Whatever its origin, the sub-Black River conformity is not demonstrably diachronous, and therefore cannot be used for this purpose. We suggest, however, that the youngest medial Ordovician disconformity of inferred subaerial origin can be used to date the final emergence of each section along the transect. What sets these surfaces of erosion/non-deposition apart from all older ones is that abrupt deepening of the continental margin immediately followed.

In figure 6, the age of the horizon immediately above the last unconformity is plotted against location across strike. Each of the three occurrences is younger than the one to its east. In the Amsterdam Quadrangle (fig. 3, location U1), the Larrabee Limestone (Lower Trenton Group; Kirkfieldian Stage of Kay 1968) lies above this surface (Fisher 1977, his plate 4). Just west of the Sprakers Fault (location U2), Utica Shale in the *Corynoides americanus* zone directly overlies Lower Ordovician strata (Fisher 1980; Riva 1969, p. 13-5). Considerably farther west, at Frenchville (location U3), Utica also overlies the youngest disconformity but is three graptolite zones younger (*Climacograptus pygmaeus*; Riva 1969, p. 13-7) than at Sprakers. A visual best-fit line through these three points implies a convergence rate of about 2 cm/yr (fig. 6).

Normal Faulting on the Outer Trench Slope.—As described above, the Black River and Trenton Groups form a deepening upward carbonate sequence that passes east-

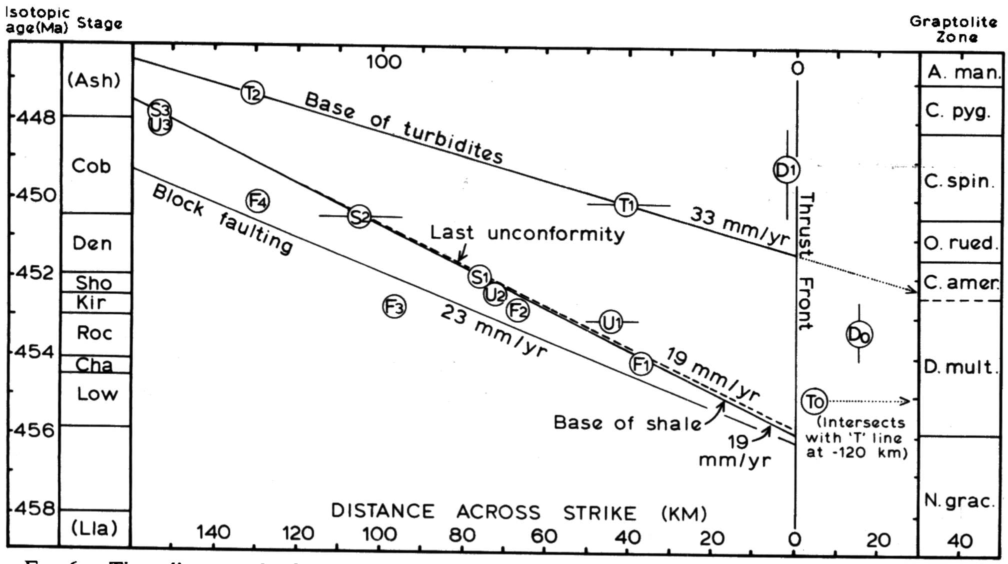

FIG. 6.—Time-distance plot for the Taconic foreland basin (left of $X = 0$) and the area immediately to the east which was overthrust by the Taconic Allochthon. The horizontal axis is distance measured along a transect with an azimuth of 105°. This value is perpendicular to the strike of foliations near the Taconic thrust front (from Bosworth and Vollmer 1981), and is nearly parallel with the trend of outer trench slope paleocurrents, which Cisne et al. (1982) used to define a transect azimuth of 103°. The vertical axis (time) has been calibrated by interpolation between the base and top of the Caradocian Stage (as given by Harland et al. 1982). Data used as a basis for various estimates of convergence rate are from table 1 and the text. Horizontal error bars correspond to uncertainties as to the exact location of measured sections or key fossil occurrences. Vertical error bars correspond to age spans permitted by fossil evidence. The absence of error bars around many points does not imply that these are necessarily that well constrained, but only that we have no way of evaluating the potential error without additional information. Best-fit lines connect points which represent diachronous phenomena, and these are visually best-fit because many potential sources of uncertainty cannot be quantified (e.g., the uncertainty due to assigning isotopic ages to North American faunal zones based on correlation with the British Caradocian). Slopes are shown in mm/yr, but the last digit is not considered significant. The line fitting "F" points omits F1a and F2a (fig. 3) because the purpose is to date the earliest Middle Ordovician conglomerates related to a given fault. Abbreviations for stages: Lla = Llandeilian; Low = Lowvillian; Cha = Chaumontian; Roc = Rocklandian; Kir = Kirkfieldian; Sho = Shorehamian; Den = Denmarkian; Cob = Cobourgian; Ash = Ashgillian. Graptolite zones are from Riva (1974).

ward and upsection into black shales. These carbonates are interpreted as having been deposited during (as suggested by local unconformities within the Black River and lower Trenton) and immediately after (as revealed by deepening upward) the local passage of a peripheral bulge (fig. 5). It is along this bathymetric gradient that Cisne et al. (1982) determined a convergence rate of about 2 cm/yr.

Regional eastward tilting was accompanied by motion on northeast-trending normal faults which dominate the map pattern in the Mohawk Valley (fig. 3; Megathlin 1938). Several types of evidence indicate that these faults were active during Medial Ordovician times (Cisne et al. 1982): (1) the presence of conglomerates (grading laterally into carbonates and/or shales) immediately adjacent to high-angle faults; (2) the presence of thicker stratigraphic sections (as indicated by the distance between ash beds) within graben than on adjacent horsts; (3) the presence of deeper water facies within these graben; and (4) thinning, pinchout, and/or absence of stratigraphic units across the tops of horsts, indicating syndepositional tilting of fault blocks. While these observations provide evidence for motion on particular faults at particular times (Cisne et al. 1982, p. 241–243), not all can be utilized readily in the rate calculation because the zone of active normal faulting had considerable width and duration. Those Medial Ordovician faults in figure 3 which can be dated appear to have first been active during Black River and/or Trenton deposition. While some of these faults cut rocks as young as the Utica Shale and Schenectady and Frankfort turbidites, all significant motion clearly predated deposition of the Silurian and Devonian (note the post-faulting disconformity in the southwestern corner of fig. 3), except perhaps a small amount of Neogene slip on the McGregor fault near Saratoga (e.g., Willems et al. 1983). We therefore infer that motion on an individual fault began before the shelf was drowned, and that displacement continued as the shelf passed down the outer trench slope and was buried by flysch in the trench floor (Bradley et al. 1985*b*). Hence, faults in the east have greater displacement (fig. 7) because they were active longer. A rate calculation based on the timing of all known fault motions would be less accurate than one based, for example, on the earliest motion on each fault. Accordingly, in figure 6, we have used only those points that correspond to the first conglomerates deposited near faults. These could only have been deposited when the upthrown fault block was above sea level; hence they can be interpreted to record an early phase of normal faulting.

In a rough way conglomerate occurrences show that the normal faulting front advanced from east to west. At locality F1 (figs. 3 and 6), evidence that the Hoffmans fault was active during deposition of the Amsterdam (Black River Group) is provided by clasts (up to 1 m across) of Beekmantown carbonates in conglomeratic horizons near the fault (Fisher 1980, p. 18 and 38). Conglomeratic horizons in the overlying Larrabee Formation (lower Trenton Group) here and along strike to the north (locality F1a) contain Black River clasts (Park and Fisher 1969), suggesting that displacement on the Hoffmans fault continued for some time. Farther west, Cisne et al. (1982, p. 235) noted clasts of Potsdam-type sandstone and Beekmantown-type dolostone at the base of the Trenton limestone just east of the Noses Fault (fig. 3, locality F2); but this far west there is no evidence of motion as early as Black River time. In nearby Sprakers (fig. 3, locality F2a), Sherman Fall-age limestones of the Trenton Group contain boulders of Beekmantown dolostone up to 60 cm in diameter (Kay 1937, p. 264), constraining the age of early motion on the Sprakers Fault. Point F3 represents the Kings Falls Limestone (Kay 1968), a member of the lower Trenton Group containing clasts of older Trenton, Black River, and Beekmantown near the Dolgeville fault at Inghams Mills (Kay 1937, p. 264) (fig. 3). We discovered clasts of Grenville basement gneiss at this locality in 1983. Point F4 represents the lower of two conglomeratic, slump-folded horizons in the upper Trenton at the type section at Trenton Falls (Kay 1953, p. 59), just east of the Prospect Fault. The above relationships together suggest that the convergence rate was around 2 cm/yr.

Black Shale and Flysch Sedimentation.— Shallow marine carbonates of the Trenton Group are replaced eastward and upward by deeper water, slump-folded limestones interbedded with graptolitic shale (Dolgeville facies of Fisher 1979), which in turn give way

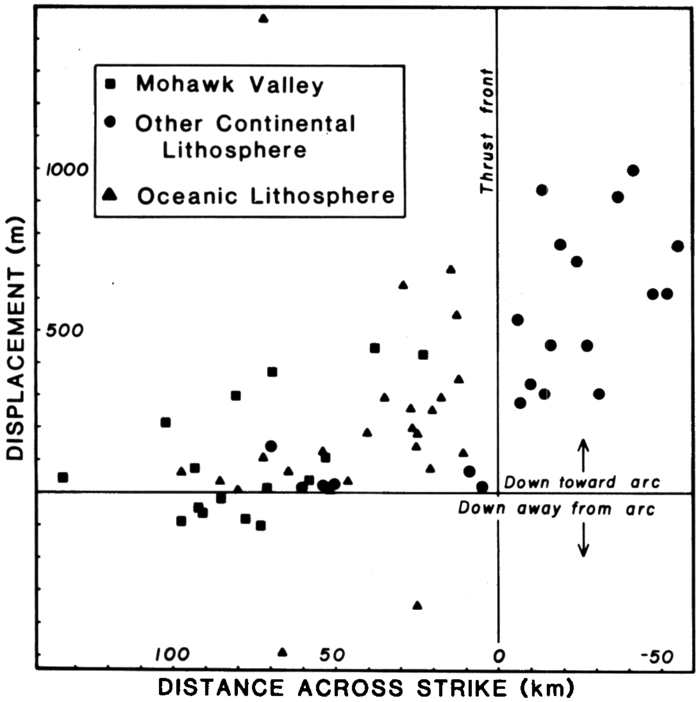

FIG. 7.—Dip slip on high angle faults in various convergent settings, plotted against distance across strike. Note that slip increases toward the arc, and that the displacement on most faults is down toward the arc. Faults in the Mohawk Valley plot in the same field as those along strike in the Taconic foreland in Quebec and Newfoundland, as well as those in modern subduction systems. Data are from Fisher (1980), Kay (1953), Willems et al. (1983), St. Julien et al. (1983), Cumming (1983), Ludwig et al. (1966), and Moore et al. (1980).

to hemipelagic black shales of the Utica Formation. Previous workers (Chapple 1973; Rowley and Kidd 1981) have inferred that the Utica transgression was a result, at least in part, of plate convergence. The additional inference implicit in Cisne's work and adopted here is that the rate of transgression reflects the rate of plate convergence.

It has long been recognized (Ruedemann 1912; Fisher 1977) that the base of the Utica and its lithologic equivalents is time-transgressive, younger to the west. Thus, at Canajoharie (fig. 3, locality S1), the base of the Utica is in the *Corynoides americanus* zone of Riva (1969, p. 13-5; 1974); while at Frenchville (locality S3), this lithologic contact lies about three graptolite zones higher, within the *Climacograptus pygmaeus* zone (Riva 1969, p. 13-7). The age of this contact at various locations, summarized in table 1 and plotted in figure 6, defines a line (visual best-fit) with a slope of about 2 cm/yr, similar to the rates obtained from the youngest disconformity and the earliest motion on normal faults. Possible problems with graptolite zonation are discussed under "Limitations of the Method."

Higher in the section is a second useful lithologic transition, the contact between shales of the Utica Formation and overlying turbidites, which we interpret as the transition from outer trench slope to trench floor environments. Graptolites show that it too is somewhat time-transgressive, younger to the west (Ruedemann 1912; Fisher 1977). In the Amsterdam area (locality T1), this contact occurs within the *C. spiniferus* zone, but near Utica (locality T2) it is within the *C. pygmaeus* zone (Fisher 1977). More data on the precise age of this contact at various locations are clearly needed, but the slope of the line defined by the two available points in

TABLE 1

DATA PLOTTED IN FIGURE 6

No.	Age	Location
U = Youngest Unconformity in Medial Ordovician Section		
U1[a]	453	Amsterdam Q.
U2[b]	452	Sprakers
U3[c]	448	Frenchville
S = Base of Utica and Equivalent Shales		
S1[d]	452	Canajoharie
S2[a]	450.5	Little Falls Q.
S3[c]	448	Frenchville
T = Base of Schenectady and Equivalent Turbidites		
T0[e]	455	Granville
T1[a]	450	Amsterdam Q.
T2[a]	447.5	Utica
D = Compressional Deformation as Dated by Olistostromes		
D0[f]	453	Whipstock Hill
D1[g]	449	Moordener Kill

NOTE.—T0 is from the Giddings Brook Slice of the Taconic Allochthon, and D0 is from parautochthonous (?) rocks beneath the Taconic Allochthon.
[a] Fisher 1977, pl. 4.
[b] Fisher 1980.
[c] Riva 1969, p. 13-7.
[d] Riva 1969, p. 13-5.
[e] Rowley and Kidd 1981.
[f] Rickard and Fisher 1973, p. 588.
[g] Zen 1967, p. 40.

figure 6 implies a convergence rate around 3 cm/yr.

Compressional Deformation.—Next in the sequence of events in the foreland of an arc-continent collision is compressional deformation. Our analysis thus far has been limited to the region extending westward from the thrust front. Hence, deformation can be dated at only one location along the transect, and a convergence rate cannot be derived from this indicator. However, knowledge of the age of deformation at $x = 0$ on the transect (fig. 6) is important for reasons discussed under "Additional Applications."

Deformation at the Taconic front is dated by fossils in both clasts and the matrix of olistostromes and related melanges of the Forbes Hill Conglomerate (Wildflysch-type conglomerate of Zen 1967). These rocks outcrop immediately in front of and beneath the Taconic Allochthon and contain clasts belonging to the Taconic, shelf carbonate, and flysch sequences. Ruedemann (1930) noted the presence of clasts which themselves are olistostromes; Bosworth and Vollmer (1981) described both turbidites and olistostromes that have become so strongly deformed that they are more properly termed melanges. At Moordener Kill (fig. 3, loc. D1), the matrix shale has yielded graptolites assigned by Berry (*in* Zen 1967, p. 40) to his Zone 13 (zone of *Orthograptus truncatus var. intermedius,* corresponding to Riva's *Climacograptus spiniferus* zone (1974, p. 3)). At nearby Rysedorph Hill, olistostrome blocks contain graptolites assigned to the same zone (see discussion in Zen 1967, p. 40).

ADDITIONAL APPLICATIONS TO THE TACONIC OROGENY

Transport Distance of Allochthons.—An unexpected and potentially useful benefit of time-space plots such as figure 6 is a means of estimating thrust transport distance independent of palinspastic reconstructions. The data in figure 6 are barely sufficient to allow a crude estimate of the transport distance of the Taconic Allochthon, which we will describe for illustrative purposes. If the base of the Pawlet Formation records the arrival of the depositional site of the Taconic sequence at the trench during the zone of *Diplograptus multidens* (Rowley and Kidd 1981), the place where this occurred can be approximated by assuming a constant rate of convergence and projecting onto the rate line defined by the base of the flysch (Point T0 in fig. 6). On this basis, it could be concluded that the Giddings Brook Slice of the Taconic Allochthon was deposited some 120 km east of its present location, or somewhat less if the 2 cm/yr slope is used. We suspect that the actual transport distance was significantly greater, and that the low estimate is due to a decreasing convergence rate during Caradocian times.

Point D0 in figure 6 represents melange exposed beneath the Taconic Allochthon at Whipstock Hill (fig. 3., loc. D0). If this locality is autochthonous or at least parautochthonous, it can be concluded that the deformation front did not move toward the craton at the same rate as the peripheral bulge, the normal faulting front, or the limestone-shale or shale-turbidite transitions. Such a relationship would be consistent with the idea that the last phase of convergence between North America and the Ammonoosuc Arc was taken up on out-of-sequence thrusts to the east of the thrust front, such as those faults which bring up slivers of shelf carbonates and cut the Taconic Allochthon into several slices (Rowley and Kidd 1981). On the other hand, it is equally plausible that the Whipstock Hill olistostromes are not essentially in place, as is commonly supposed, but instead have been thrust several tens of kilometers westward (W. S. F. Kidd, personal comm. 1984). Figure 6 would then provide a basis for estimating the transport distance.

Oblique Convergence and the Location of the Taconic Euler Pole.—Because subduction and convergence between the North American Craton and the Ammonoosuc Arc may have been oblique rather than head-on, our calculated rate is necessarily that of the normal component of the relative motion vector. However, a time-space plot like figure 6 using distance along rather than across strike could help resolve the component of relative motion parallel to the orogen. Furthermore, once these quantities are known for a significant distance along strike, the location of the Euler pole could be estimated.

LIMITATIONS OF THE METHOD

Effects of Decreasing Convergence Rate.—Because we have only examined the area from the craton to the thrust front, our calculated convergence rate is probably a minimum: it is based on features dating from the final stages of collision. We suspect that those data plotted in figure 6 and best-fit to lines actually fall on the steep segments of curves which have "dog-leg" patterns like that in figure 2*b*.

Chronologic Errors.—A detailed analysis of the biostratigraphic framework of the Taconic foreland is beyond the scope of this study, but it is obvious that the rate calculation is founded on a knowledge of the fossil ages of the various phenomena of interest. In this paper, all age assignments are based on Fisher's (1977) recent correlation chart, and thus on Kay's (1968) shelly fossil zonation for the Black River and Trenton carbonates and Riva's (1974) graptolite zonation for the Utica shales, Schenectady turbidites, and their equivalents. Rabe and Cisne (1980) showed by cross-correlation techniques that their age assignments in the Trenton Group have an accuracy within about 50,000 yrs (neglecting any uncertainties in isotopic ages of the boundaries of the Caradocian Stage). Even if Fisher's age assignments (which are based on more traditional biostratigraphic correlation techniques) are less accurate by an order of magnitude, this is probably not the greatest source of chronologic error. One possible problem not addressed in this study has been raised by Cisne and Chandlee's (1982) reexamination of Caradocian graptolites in the Mohawk Valley. They showed that the distribution of some major graptolite genera was partly dependent on water depth, and not controlled solely by evolution, a tacit assumption in Riva's (1974) zonation. In particular, *Corynoides, Climacograptus,* and *Orthograptus ssp.* appear to have populated deeper to shallower waters in the order given. From the standpoint of our results, Cisne and Chandlee's (1982) findings are probably not critical. Only one point (T1) in figure 6 was assigned an age on the basis of graptolites in the critical zones from *C. Americanus* to *C. Spiniferus,* and T1 seems anomalously young.

Probably the greatest source of chronological error is in assigning isotopic ages to the fossil ages of these rocks. No isotopic determinations have been made on strata in the Taconic foreland, although a series of volcanic ash beds in the Trenton and Utica (Kay 1935; Cisne et al. 1982) may ultimately allow more precise dating of the paleontologic divisions used in the present study. We have used values of 458 ± 8 and 448 ± 6 for the base and top of the Caradocian, respectively (Harland et al. 1982), but it is possible that the Caradocian spanned an interval as long as 24 m.y. or as short as a few million. Because of these uncertainties, our rate calculation could easily have inherited an error of greater than 50%. Given these uncertainties and the shortage of data in figure 6, lines were visually best-fit to determine convergence rates.

Effects of Sea Level Variation.—The convergence rate calculation is based on the assumption that changes in eustatic sea level during the Taconic collision were relatively minor, an assumption also made by Cisne et al. (1982). Their graphical treatment of time-depth relations across the Taconic foreland is indeed sensitive enough to show one short rise and fall of sea level (interpreted as a eustatic event) superimposed on the longer-term relative rise (interpreted as tectonically induced). Possibly, some of this longer-term rise was partly eustatic: based on the record from both sides of the Iapetus ocean and on Gondwana tillites, McKerrow (1979) concluded that a rise in global sea level began at the end of Llandeilian and continued into Caradocian times. However, comparison of thicknesses of Mohawk Valley and coeval midcontinent limestones (e.g., Cook and Bally 1975) indicates that any eustatic effects were minor compared to the tectonically induced subsidence.

DISCUSSION

The method of estimation of plate convergence presented here yields results for the Taconic (about 2 cm/yr for the last unconformity, the limestone/shale transition, and the normal faulting front, and about 3 cm/yr for the shale/turbidite transition) which are comparable to the 2 cm/yr determined by Cisne et al. (1982). While Cisne et al.'s method is almost certainly more accurate than the one described here, it cannot readily be used in other areas without a major research effort involving intensive sampling and counting of fossil populations.

Since our method is based entirely on published data that for years have been collected by survey geologists in connection with quadrangle mapping, it should be immediately useful in the foreland of many Phanerozoic arc-continent collisions (e.g., the Antler and Ouachita) with reasonably good paleontological age control. If this method can be applied successfully in a number of such collisions, it may be possible to investigate relationships between convergence rate and the flexural behavior of the lithosphere as manifested in foreland basin width and subsidence history.

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