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TACONIC PLATE KINEMATICS AS REVEALED BY FOREDEEP STRATIGRAPHY, APPALACHIAN OROGEN

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Abstract. Destruction of the Ordovician passive margin of eastern North America is recorded by an upward deepening succession of carbonates, shales, and flysch. A compilation of the age of shelf drowning (carbonate-to-shale transition) reveals the degree to which orogeny was diachronous both across and along strike. Shelf drowning occurred first at the northern end of the orogen in Newfoundland, then at the southern end of the orogen in Georgia, and finally in Quebec. Diachronism is attributed to oblique collision between an irregular passive margin, that had a deep embayment in Quebec, and at least one east dipping subduction complex. The rate of plate convergence during collision is estimated at 1 to 2 cm/yr, and the minimum width of the ocean that closed is estimated at 500 to 900 km. Far-traveled deepwater sequences in the thrust belt contain anomalously old Taconic flysch, related to early arrival of the continental slope/rise at a west advancing trench then located far to the east. The drowning isochron map provides a new basis for estimating tectonic transport distances of four of these allochthons (about 165 to 450 km), results not readily obtained by conventional structural analysis.

INTRODUCTION

Reconstruction of pre-Jurassic plate motions is hindered both by the fragmentary nature of the rock record and by the complexity of plate tectonics. One approach to this vast problem is the construction of global continental drift maps, which are based largely on paleomagnetism, biogeography, and paleoclimatology [e.g., Van der Voo, 1988]. To those specialized disciplines should be added regional geology, without which continental reconstructions would be as impossible as they would be pointless. Field-based regional geology provides the fundamental basis for recognizing ancient continents, oceans, magmatic arcs, and the former plate boundaries between them. On the other hand, regional geology has contributed little to the quantification of ancient plate motions. The primary objective of this paper is to demonstrate a new, quantitative method of plate kinematic analysis based on stratigraphy. The method is not subject to the longitudinal uncertainty that will inevitably limit paleomagnetism to the detection of about half of all plate motions, and it is applicable to a common class of orogeny.

Arc-passive margin collisions are one orogenic setting where the geologic corollaries of plate tectonics are not overly complex. Such collisions are readily recognized in the ancient record, and many related processes are orderly and well understood. In particular, arc-passive margin collisions produce flexural foredeeps that migrate through time in response to plate convergence. Cisne et al. [1982] and Bradley and Kusky [1986] used this property to estimate the rate of plate convergence during the Taconic Orogeny in New York. These studies related diachronous foredeep stratigraphy to plate convergence and concluded that the strike-normal rate of plate convergence was about 2 cm/yr. The present paper extends the concept from two to three dimensions (latitude, longitude, time), using data from the entire foredeep from Newfoundland to Alabama rather than a single transect. The results bear on the rate of plate convergence, the collisional plate geometry, the width of the Taconic ocean, and the transport distance of far-traveled slope/rise allochthons. Future applications will substantially enhance our understanding of past plate motions in many orogenic belts.

THE TACONIC OROGENY AND FOREDEEP

During Cambrian and Early Ordovician the eastern margin of North America (present coordinates) was the site of a carbonate platform [e.g., Rodgers, 1968; Bird and Dewey,

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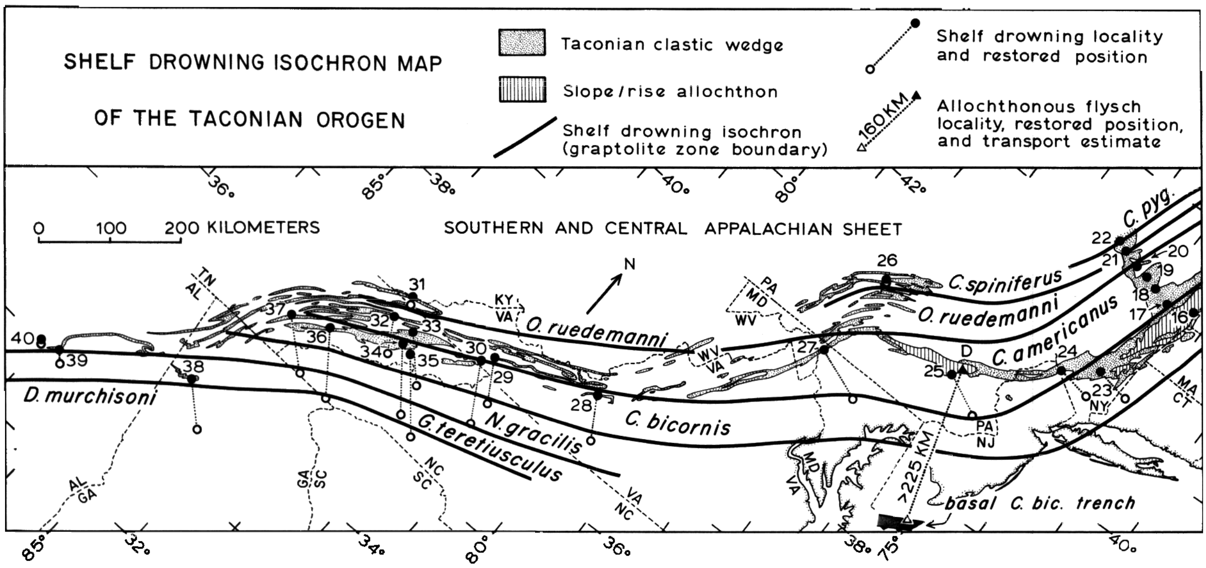

Fig. 1. Maps of (a) southern and central Appalachians and (b) northern Appalachians, showing the distribution of Ordovician shales and graywackes, far-traveled slope/rise allochthons, numbered locations (see Tables 1 and 2), and corresponding palinspastic positions. Isochron lines (graptolite zone boundaries) track shelf drowning through time; at a particular time represented by an isochron, shale was being deposited to the southeast of the line and carbonates to the northwest. Where drowning isochrons have been extrapolated outboard of the former carbonate platform they do not correspond to a particular geologic event but still provide a basis for estimating the position of the plate boundary.

1970] which faced an ocean, Iapetus. The platform is represented by an eastward thickening, shallow-water, mainly carbonate sequence in both the autochthon and parautochthon. The platform was flanked to the east by a continental slope and rise. Strata of the slope/rise sequence consist of "dominantly deep water argillaceous and arenaceous sediments, with lesser carbonates, carbonate conglomerates, cherts, and minor volcanics" [Rowley and Kidd, 1981, p. 201], preserved in far-traveled thrust sheets such as the Taconic Allochthon.

The irregular trace of the Appalachian fold-thrust belt (Figure 1) probably evolved from original irregularities along the passive margin [Bird and Dewey, 1970; Rankin, 1976; Thomas, 1977]. Major promontories along the continental margin were located in the Gulf of St. Lawrence and Alabama; lesser promontories probably existed in Virginia and near New York City. A deep embayment occupied western New England and southern Quebec; lesser embayments may have existed in western Pennsylvania and Tennessee.

The Taconic Orogeny resulted in drowning of the carbonate platform, followed by obduction of slope/rise allochthons and large ophiolite sheets. These events are widely interpreted as a result of collision with a convergent plate boundary, following easterly subduction of an oceanic tract. Whereas the arc-passive margin collision model is the most elegant rationale for the Ordovician geology of the Appalachians, it is only one of several interpretations proposed for the Taconic Orogeny during the first years of plate tectonics. The presently accepted model was first developed in Newfoundland by Stevens [1970] and has subsequently been applied, with modifications and different emphases, along the entire length of the Appalachians [Hiscott, 1978; Chapple, 1973; Stanley and Ratcliffe, 1985; Rowley and Kidd, 1981; Read, 1980; Shanmugam and Walker, 1980]. In Pennsylvania, Lash and Drake [1984] interpreted the colliding object to have been a microcontinent with Grenville basement rather than an allochthonous arc, but for present purposes this difference of opinion is a minor one. Understanding of Taconic events has greatly benefited from studies of analogous arc-passive margin collisions, including Timor [Veevers et al., 1978], Papua [Pigram et al., 1989], Oman [Gealey, 1977], Ouachita [Houseknecht, 1986], and several in the Canadian Shield [Hoffman, 1987].

Interaction between passive margin and convergent plate boundary began in Newfoundland. Arrival of the continental margin at the convergent boundary, which is presumed to have been the site of a trench analogous to Timor Trough, is recorded by an influx of orogen-derived flysch. The flysch overlies older slope/rise facies thought to have been derived from North America [Stevens, 1970]. Orogen-derived flysch also comprises the youngest facies preserved in the Gaspe (Quebec), Taconic (New York), and Hamburg (Pennsylvania) allochthons (Table 1). In each of these places the flysch is represented by a single graptolite zone. Sedimentation ended when strata of the slope/rise region were accreted to the overriding plate by footwall imbrication, then thrust onto and across the former shelf.

On the carbonate platform the first sign of an impending Taconic Orogeny was uplift and erosion, an event that many workers attribute to flexural loading (Figure 2) [Rowley and Kidd, 1981; Jacobi, 1981]. Passage of a carbonate platform through a forebulge is ideally recorded by shoaling upward sedimentation, then erosion, then deepening upward sedimentation. Ordovician unconformities which have been attributed to Taconic lithospheric flexure occur near the top of the carbonate succession from Newfoundland to Alabama. In

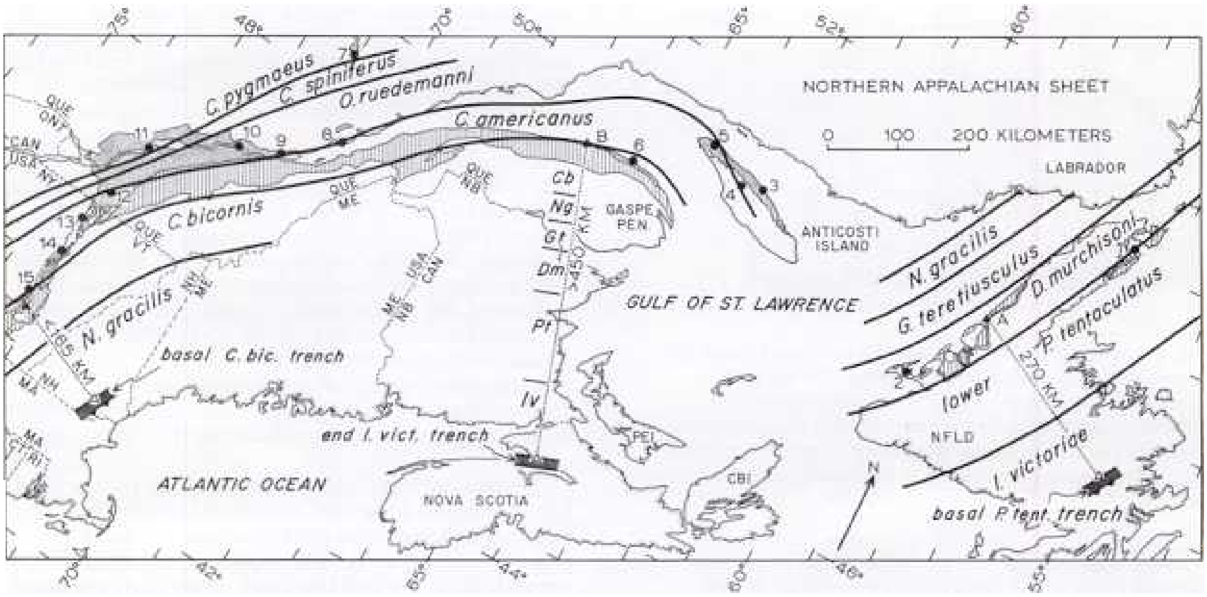

Fig. 1. (Continued)

Newfoundland, regionally discontinuous unconformities occur at or near the St. George-Table Head contact [Jacobi, 1981; Knight and James, 1987]. In New York [Rowley and Kidd, 1981; Bradley and Kusky, 1986] and Pennsylvania [Shanmugam and Lash, 1982], a comparable but younger interval of erosion followed deposition of the Beekmantown Group. In Virginia [Mussman and Read, 1986] and Tennessee [Shanmugam and Lash, 1982], the post-Knox unconformity occupies the analogous stratigraphic position. The unconformities of purported forebulge origin are complex, with multiple erosion surfaces of variable extent rather than a single surface (Figure 3). This might be expected from the geographic complexity of the present-day flexural arch in the subducting Australian shelf at Kepulauan Aru (an archipelago breached by antecedent drainages) and the Sahul Rise (a drowned submarine arch [Veevers and Van Andel, 1967]).

A diachronous shelf drowning sequence overlies the unconformity. Typically, shallow-water carbonates are succeeded by deepwater carbonates, then hemipelagic shales. Superimposed on this general pattern are local complications and variations. For example, the transition from shallow-water carbonates to deepwater shales varies from abrupt to gradational, perhaps reflecting the presence or absence of a pronounced shelf-slope break. Local carbonate buildups formed along the shelf edge in Tennessee and Virginia [Walker, 1977; Read, 1982]; these are probably analogous to Ashmore Reef along the Australian flank of Timor Trough. Figure 3 illustrates the diachronous shelf drowning sequence in the Taconic foredeep of New York. Comparable drowning sequences also exist in Newfoundland [Klappa et al., 1980], Quebec [Belt et al., 1979], Pennsylvania [Lash and Drake, 1984], Virginia [Read, 1980], and Tennessee [Shanmugam and Walker, 1980]. Table 2 summarizes the age of the carbonate-to-shale transition at 40 locations throughout the Appalachians.

TABLE 1. Age of Allochthonous Flysch in the Taconic Orogen

Letter in Figure 1	Allochthon	Location	Flysch Unit	Age of Oldest Flysch Derived from Orogen	Allochthon Transport, Kilometers	Reference
A	Humber Arm, Newfoundland	Lobster Cove Head	Lower Head	basal *P. tentaculatus*	270	James et al. [1987, p. 1203]
B	External Domain, Quebec	Gaspe Peninsula	Tourelle	*I. victoriae*	>450	Barnes et al. [1981]
C	Taconic, New York	Granville	Pawlet	early *C. bicornis*	<165	
D	Hamburg, Pennsylvania	Hamburg	Windsor Township	early *C. bicornis*	>225	

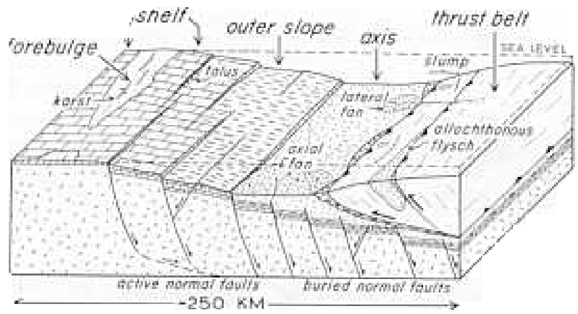

Fig. 2. Schematic block diagram of a collisional foredeep showing the distribution of facies belts. During plate convergence, collisional foredeeps are characterized by a submarine thrust belt, flysch sedimentation along the basin axis, and flexural extension on the outer slope. Facies belts migrate cratonward in response to continued plate convergence.

Shelf drowning was in part accommodated by eastward regional tilting and in part by motion on closely spaced normal growth faults (Figure 2). Faulting was induced by extension on the convex outer arc of the flexed plate [Bradley and Kusky, 1986]. Normal faults commonly have down-to-trench displacements of several hundred meters [Bradley and Kusky, 1986], and some are known to correspond to significant Middle Ordovician facies, thickness, and bathymetric changes [Cisne et al., 1982].

Shales of the outer slope grade eastward and upward into siliciclastic turbidites (flysch) deposited in coalescing submarine fans along the foredeep axis. Petrographic studies have revealed orogenic source areas for flysch in Newfoundland (Mainland Sandstone and Goose Tickle Formation [Stevens, 1970; Quinn, 1988]), Quebec (Cloridorme Formation [Hiscott, 1978, 1984]), New York (Austin Glen and Schenectady Formations [Rowley and Kidd, 1981]), Pennsylvania (Martinsburg Formation [Lash and Drake, 1984]), and Tennessee (Sevier Formation [Shanmugam and Walker, 1980]). Some local conglomeratic facies within the flysch (e.g., Fincastle Conglomerate Member, Virginia [Rader and Gathright, 1986]) contain clasts of platform carbonates, vein quartz, and granitic gneiss, suggesting that rocks that originated along the North American margin were exposed to erosion in the advancing thrust belt to the east. Autochthonous flysch overlying the former shelf is sedimentologically indistinguishable from slightly older flysch in the allochthonous slope/rise succession [Rowley and Kidd, 1981].

The foredeep was flanked on the east by the Taconic thrust belt. The frontal thrust zone is marked by wildflysch conglomerates, containing blocks shed from advancing submarine thrusts, set in a shale matrix. Clasts include slope/rise facies and shelf carbonates. Ordovician submarine emplacement of thrusts along the Taconic front (Logan's Line) in Quebec and New York is constrained by graptolites in matrix shales. Subsequent overthrusting transformed some olistostromes and turbidites into melanges [e.g., Bosworth and Vollmer, 1981]. Melanges are also present beneath Taconic thrusts within the mountain belt, where they are interpreted to mark earlier positions of the thrust front [e.g., St. Julien and Hubert, 1975].

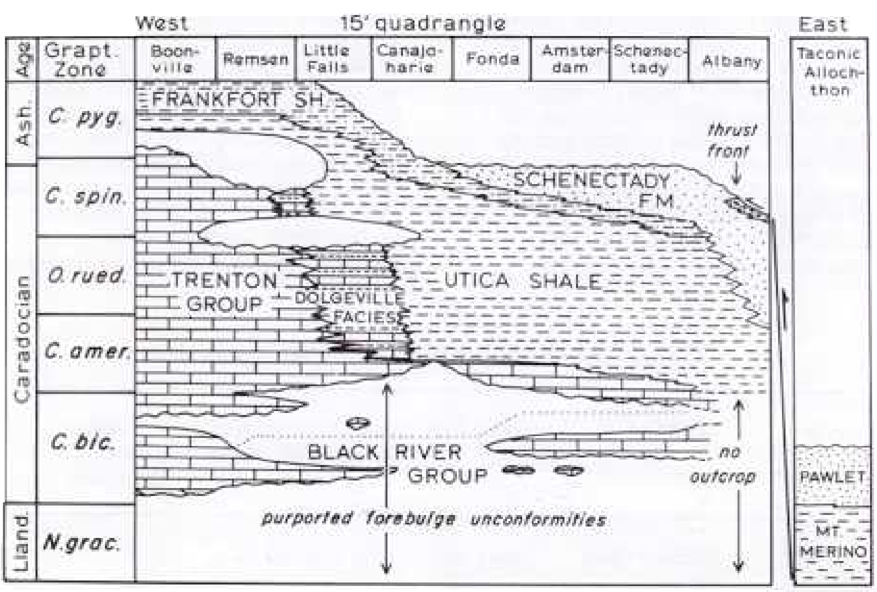

Fig. 3. Middle Ordovician stratigraphy of the Taconic foredeep and allochthonous slope/rise sequence in New York (Figure 1, locations 18 to 24), adapted from Fisher [1977, 1979] and Rowley [1983]. Foredeep transects in the southern, central, and Canadian Appalachians experienced similar stratigraphic evolution. Brick pattern, shallow-water carbonate; brick and dash pattern, deepwater carbonate with interbedded shale; dash pattern, shale; dash-dot pattern, siltstone; stipple, siliciclastic turbidites; conglomerate pattern, wildflysch. Graptolite zones are after Riva [1974], as modified by Finney [1986a]: *C. pyg.*, *C.pygmaeus* Zone; *C. spin.*, *C. spiniferus* Zone; *O. rued.*, *O. ruedemanni* Zone; *C. bic.*, *C. bicornis* Subzone; *N. grac.*, *N. gracilis* Subzone.

TABLE 2. Age of Ordovician Carbonate-to-Shale Transitions in the Taconic Foredeep.

Number in Fig. 1	Location	Shale-Bearing Unit	Age of Onset of Shale Deposition	Reference
1	Hare Bay, Nfld.	Goose Tickle	basal *D. murchisoni*	Barnes et al. [1981]
2	Port au Port Peninsula, Nfld.	Black Cove	*D. murchisoni*	Barnes et al. [1981]
3	LGCP Well, A.I.	Macasty	*O. ruedemanni*	Riva [1969, p. 540]
4	NACP Well, A.I.	Macasty	*O. ruedemanni*	Riva [1969, p. 539]
5	LGPL Well, A.I.	Macasty	*C. americanus*	Riva [1969, p. 534]
6	Gaspe N. shore, Que.	Cloridorme	base *C. americanus*[a]	Barnes et al. [1981]
7	Chute-aux-Galets, Que.	Macasty	*C. pygmaeus*	Riva [1969, p. 542]
8	Cap Martin, Que.	St. Irenee	base *O. ruedemanni*	Belt et al. [1979, p. 1470]
9	Montmorency Falls, Que.	Utica	*O. ruedemanni*	Belt et al. [1979, p. 1470]
10	Lotbiniere, Que.	Utica	*O. ruedemanni*	Belt et al. [1979, p. 1470]
11	Bald Mtn., Que.	Utica	base *C. pygmaeus*	Riva [1969, p. 523-5]
12	L. Joseph 2 Well, Que.	Iberville	*C. americanus*	Riva [1969, p. 517]
13	Rouses Point Quad., N.Y.	Cumberland Head[b]	*C. americanus* (E) *O. ruedemanni* (W)	Fisher [1977]
14	Port Henry Quad., N.Y.	Hortonville	*C. americanus*	Fisher [1977]
15	Ticonderoga Quad., N.Y.	Snake Hill	*C. americanus*	Fisher [1977]
16	Hoosick, N.Y.	Walloomsac	late *C. bicornis*	Rickard & Fisher [1973, p. 588]
17	Albany Quad., N.Y.	Snake Hill	base *C. americanus* [a]	Fisher [1977]
18	Amsterdam Quad., N.Y.	Utica	*C. americanus*	Fisher [1977]
19	Fonda Quad., N.Y.	Utica	*C. americanus*	Fisher [1977]
20	Canajoharie Quad., N.Y.	Utica	*C. americanus*	Fisher [1977]
21	Little Falls Quad., N.Y.	Dolgeville[b]	*C. americanus* (E) *C. spiniferus* (W)	Fisher [1977]
22	Utica Quad., N.Y.	Utica	*C. pygmaeus*	Fisher [1977]
23	Ellenville Quad., N.Y.	Martinsburg	*C. bicornis*	Fisher [1977]
24	Port Jervis Quad., N.Y.	Martinsburg	*C. bicornis*	Fisher [1977]
25	Leesport, Pa.	Martinsburg	*C. americanus*	Ross et al. [1982]
26	State College, Pa.	Antes	*C. spiniferus*	Ross et al. [1982]
27	Williamsport, Md.	Martinsburg	*C. bicornis*	Ross et al. [1982]
28	Catawba Valley, Va.	Liberty Hall[bc]	*N. gracilis*	Ross et al. [1982]
29	Saltville, Va.	Rich Valley[bc]	*N. gracilis*	Ross et al. [1982]
30	Abingdon, Va.	Paperville	early *N. gracilis*	Ross et al. [1982]
31	Hagan, Va.	Reedsville	*O. ruedemanni*	Ross et al. [1982]
32	Thorn Hill, Tenn.	Martinsburg	*C. bicornis*	Ross et al. [1982]
33	St. Clair, Tenn.	Blockhouse	late *N. gracilis*	Ross et al. [1982]
34	Mosheim, Tenn.	Blockhouse	*G. teretiusculus*	Bergstrom [1973, p. 278-279]
35	Greeneville, Tenn.	Blockhouse	*D. murchisoni*	Bergstrom [1973, p. 281]
36	Blockhouse, Tenn.	Blockhouse	late *D. murchisoni*	Bergstrom [1973, p. 282]
37	Athens, Tenn.	Athens	*G. teretiusculus*	Ross et al. [1982]
38	Polk County, Ga.	Rockmart	*D. murchisoni*	Ross et al. [1982]
39	Calera, Ala.	Athens	*G. teretiusculus*	Finney [1980, p. 1186]
40	Pratt Ferry, Ala.	Athens	*N. gracilis*	Finney [1980, p. 1186]

Nfld, Newfoundland; A.I., Anticosti Island; Que, Quebec; N.Y., New York; Pa, Pennsylvania; Md, Maryland; Va, Virginia; Tenn, Tennessee; Ga, Georgia; Ala., Albama.
a. Could be older because base of unit is not exposed.
b. Transitional facies including deep-water limestones.
c. Ignoring local carbonate buildups.

In the Northern Appalachian orogenic hinterland, Ordovician volcanic rocks are inferred to belong to one or more magmatic arcs that developed above one or more east dipping (present coordinates) subduction zones. Volcanism lasted from Tremadocian to Llandeilian in Newfoundland, Llanvirnian to Caradocian in New Brunswick, and Arenigian to Ashgillian in Maine [Neuman, 1984]. Siluro-Devonian magmatism along the same trends cannot be readily attributed to the Taconic Orogeny and is probably related to pre-Acadian plate convergence [Bradley, 1983].

SHELF-DROWNING ISOCHRON MAP

Foredeep facies isochron analysis is based on two precepts: (1) foredeep subsidence and migration are driven by plate convergence; and (2) at a given time, major facies transitions within a foredeep occur at set distances from the plate boundary. The primary data are the location and age of a given facies transition; contour lines connecting data of equivalent age are isochrons. In the Taconic foredeep, the transition from carbonate to shale is interpreted to mark the boundary between shelf and foredeep, trenchward of the flexural arch. By analogy with the Timor Trough [Veevers et al., 1978], the shelf break is interpreted to have been situated about 120 km from the plate boundary. The transition from shale to turbidites approximates the boundary between the outer slope and axis of the foredeep. The sediment-filled axial zone of the Timor Trough is about 15 km wide, that is, the turbidite front is about 15 km from the thrust front. Using the Timor Trough as a model foredeep, the position of the plate boundary at a given time can be predicted from the position of major facies belts in the Taconic foredeep.

Figure 4 shows a sequence of paleogeographic maps of a hypothetical foredeep and a facies isochron map tracking the migration of the carbonate-to-shale transition. The gradient in Figure 4d approximates the rate of relative plate motion.

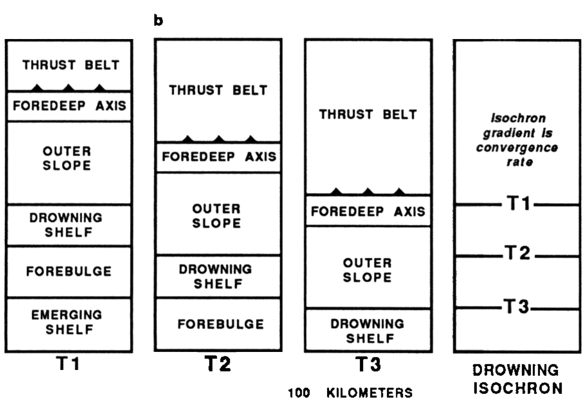

Fig. 4. (a)-(c) Sequential paleogeographic maps of a hypothetical foredeep, showing cratonward migration of facies boundaries through time. (d) Facies isochron map of the carbonate-to-shale transition. Gradient corresponds to the rate of migration of the facies front. If foredeep migration is driven primarily by plate convergence, then the gradient approximates the rate of relative plate motion.

Some factors that might influence an isochron pattern are shown in Figure 5. Figure 5a shows a highly unlikely, hypothetical collision between an irregular passive margin and an exactly matching magmatic arc, showing successive positions of the plate boundary. Overriding plate trajectory is perpendicular to the mean strike of both passive margin and arc, and the rotation pole is sufficiently distant that plate rotations can be approximated as translations. These ideal conditions result in synchronous collision at time 3. All real examples of arc-continent collision can be expected to be diachronous along strike. Figures 5b-5e show various arc and passive margin configurations that can lead to diachronous collisions. Factors include straightness of both arc and passive margin, angle between arc and passive margin, and trajectory of relative motion. In Figures 5d and 5e, convergence rate abruptly decreases during collision. Figure 5f shows a hypothetical collision proximal to a rotation pole; plate trajectories are small circles about the rotation pole, and convergence rates increase away from the pole.

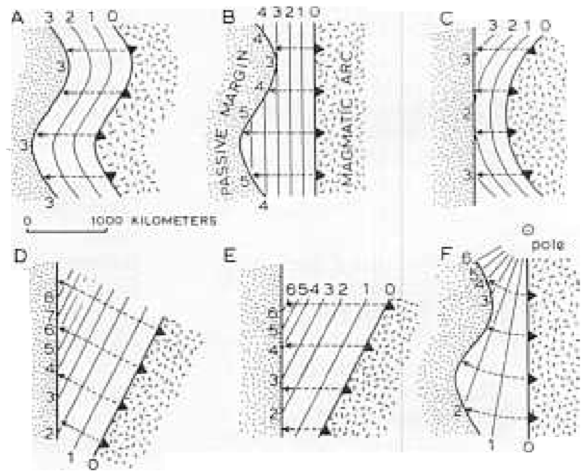

Fig. 5. Some combinations of variables that can lead to synchronous and diachronous collisions.

Procedures Followed in Isochron Map Construction

The shelf-drowning isochron lines in Figure 1 were constructed from stratigraphic data in Table 2. Paleontologic ages were keyed to graptolite and conodont zones, following the International Union of Geological Sciences correlation chart for the United States [Ross et al., 1982]. The drowning isochrons were labeled according to Riva's [1974] graptolite zonation scheme (Figure 6), subject to two minor modifications: (1) the *C. bicornis* Zone replaces the *D. Multidens* Zone, with a slightly older lower boundary defined at the first appearance of the name-giving species [Finney, 1986a]; and (2) for greater resolution the British *D. murchisoni* Zone was distinguished from the lower part of the North American *P. tentaculatus* Zone.

In cases where the carbonate-to-shale transition is gradational through an interval of interbedded deepwater carbonates and shales (e.g., Dolgeville Facies of New York; Figure 3) the transition was placed at the base of the gradational interval, based on the assumption that the shales represent ambient hemipelagic sedimentation, whereas the carbonates represent episodic, rapid influx of material from upslope. Isochrons in Figure 1 were drawn as smoothly as the data would allow, but isochron lines show considerable pinching and swelling. This could be due to variation in plate convergence rate, but more likely it is an artifact due to a combination of such factors as (1) eustatic sea level changes superimposed on flexurally induced subsidence of the shelf; (2) local water depth complications related to tilting of normal

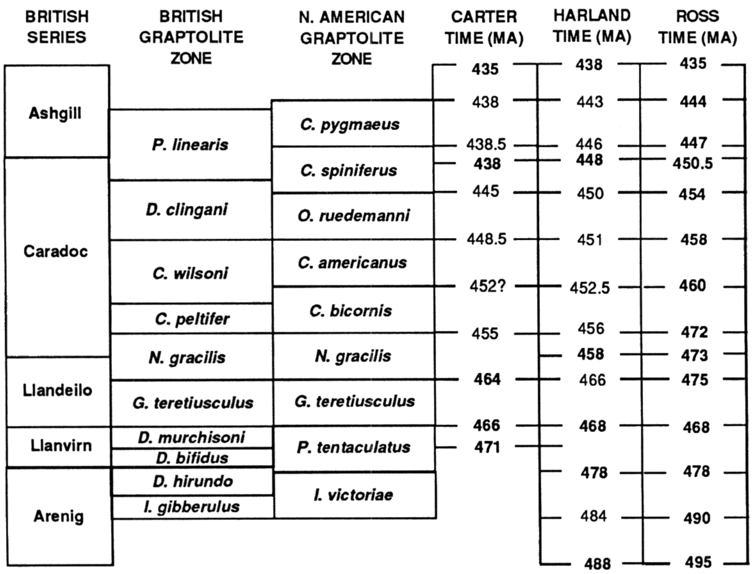

Fig. 6. Correlation chart relating Ordovician graptolite zones [Riva, 1974], British Series, and numerical time scales according to Harland et al. [1982], Carter et al. [1980], and Ross et al. [1982]. Ages in boldface were explicitly assigned in the original source; others were interpolated.

fault blocks; (3) erroneous fossil age assignments; (4) faulty biostratigraphic correlation schemes; and (5) erroneous structural restorations. Nonetheless, the drowning isochron lines never cross, suggesting that the overall pattern is qualitatively correct.

Contouring the sparse data for Newfoundland presented several problems. Both shelf drowning points (Figure 1, locations 1 and 2) occur in the *D. murchisoni* Zone, one at the very base and one somewhat higher. The *N. gracilis/C. bicornis* isochron was positioned 120 km cratonward of the thrust front, using the Timor Trough model foredeep. The end of the *N. gracilis* Zone is about when the Humber Arm allochthon reached its final position on the Port au Port Peninsula (near location 2), based on the age of postemplacement strata of the Long Point Group that overlie both allochthonous and authochtonous rocks [e.g., Lindholm and Casey, 1989]. The lower boundaries of the *N. gracilis* and *G. teretiusculus* Zones were interpolated. The lower boundary of the *P. tentaculatus* Zone was not directly constrained by shelf drowning data, but its location was estimated by assuming that the lower *P. tentaculatus* Zone had twice the duration of the *D. murchisoni* Zone, following Ross et al. [1982].

Parautochthonous Data Restoration

The Taconic foredeep is divisible into northern and southern sectors on the basis of the relative positions of the Ordovician and late Paleozoic deformation fronts. In the northern Appalachians (as far south as Albany, New York, location 17 in Figure 1) the Taconic thrust front corresponds to the cratonward limit of significant contractional deformation. Strata which lie cratonward of the Taconic thrust front are essentially autochthonous, subject only to minor folding within 10-20 km of the thrust front and high-angle normal faulting in a zone extending as far as 150 km from the thrust front. Accordingly, stratigraphic data from the Taconic foreland in the northern Appalachians did not require palinspastic correction in Figure 1. On the other hand, in the Valley and Ridge province of the central and southern Appalachians, late Paleozoic deformation extended far cratonward of the Taconic thrust front, displacing formerly autochthonous Ordovician foredeep strata. These parautochthonous rocks were restored as shown in Figure 1, based on published sources as follows. Locations 39 and 40 were repositioned according to restored sections by Thomas [1985]; locations 28 through 38 according to restored sections by Woodward and Gray [1985]; and locations 26 and 27 according to restored sections by Shumaker et al. [1985]. Locations 23 through 25 were restored using Pedlow's [1976] palinspastic base map (a distorted grid of 15 minute quadrangle outlines); however, 23 and 24 were slightly off Pedlow's [1976] map and had to be projected a short distance along strike. Despite uncertainties in all restorations, any errors introduced are unlikely to be as severe as errors that would have resulted from ignoring the shortening.

Implications for Plate Geometry

Shelf drowning was diachronous both across and along strike [e.g., Rodgers, 1971; Bergstrom, 1973; Finney, 1986b]. At any given foredeep transect, drowning occurred first at outboard locations and progressed cratonward with time. Across-strike diachronism is interpreted as the result of the normal component of plate convergence. The along-strike component of diachronism is more complex. The earliest drowning was in Newfoundland; curiously, the next well-dated shelf drowning occurred at three outboard locations in the southern Appalachians. In other words, shelf drowning jumped from the northern end of the continental margin to the southern, while the middle remained unscathed. Ignoring

Newfoundland, shelf drowning generally progressed from south to north, with the youngest drowning at the deepest embayment in the former margin in Quebec.

Because exotic terranes tend to be molded into parallelism with passive margins during collision, the original shape and orientation of the Taconic convergent boundary or boundaries is unknown. At a given sector of the orogen it is not obvious from present structure whether the convergent boundary originally paralleled the passive margin or was oriented at some angle to it.

It is unclear from the foredeep stratigraphy whether the passive margin interacted directly with one or more convergent boundaries. Figure 7 summarizes the timing of collision and illustrates two of many possible interpretations of the plate geometry. The shelf- drowning isochron pattern between Alabama and Quebec seems to track the migration of a single flexural foredeep, implying that this sector of the passive margin probably interacted with a single convergent boundary ("arc", below). However, earlier shelf drowning in Newfoundland can either be interpreted in terms of the same or a different arc. If collision involved two inboard arcs, a configuration like that in Figure 7a might have existed just prior to impact, with both arcs convex toward the continent. Alternatively, if a single arc collided directly with North America, the configuration might have resembled Figure 7b. The concave arc in Figure 7b would be reasonable if the Taconic Orogeny involved closure of a back arc basin like the Bering Sea.

Geologic, paleontologic, and paleomagnetic data from Ordovician volcanic rocks in the Northern Appalachians all support the notion that more than one Ordovician magmatic arc collided with North America. However, none of these data bear conclusively on the question raised by the drowning isochron pattern: How many arcs directly collided with the continent, as opposed to colliding with each other? On the basis of forearc basement type, Rowley [1983] suggested that two distinct arcs above east dipping subduction zones collided directly with the North American passive margin. According to Rowley's [1983] interpretation, a northerly arc (Rowley's Dunnage arc) collided with the Canadian sector of the passive margin and was characterized by an ophiolitic forearc; a southerly arc (Rowley's Grand Pitch arc) extended from near the U.S.-Canada border southward for some unspecified distance and was characterized by continental basement which had been deformed during the Penobscottian orogeny of Neuman and Max [1988]. This interpretation of two inboard arcs is debatable, since the forearc basement of some active magmatic arcs (e.g., Aleutian and Banda) varies along strike from continental to oceanic. Both Rowley [1983] and Williams et al. [1988] suggested that additional Ordovician arc terranes occur farther outboard in Newfoundland and New England; however, none of these outboard terranes have been interpreted to have collided directly with North America.

Paleontologic evidence suggests that Ordovician volcanic islands in Iapetus were distributed in at least two belts [Neuman, 1984]. Neuman's [1984] paleogeographic map did not show the locations of inferred plate boundaries, but at least two subduction zones of unspecified polarity seem to be required for the eventual closure of Iapetus. Similarly, recent paleomagnetic studies of Ordovician volcanic rocks in Newfoundland have revealed two paleomagnetically distinct tracts [Johnson et al., 1988]. North America's Appalachian margin lay at about 10°-15° S. Within Iapetus Ocean an inboard volcanic tract represented by the Moreton's Harbour Group was located at about 15°S; a second volcanic tract, represented by the Robert's Arm Group, lay outboard at about 30°S. In summary, while the paleontologic and paleomagnetic data support the concept of multiple Ordovician arc terranes in Iapetus, it remains unclear whether one or more interacted directly with North America.

Time Scale and Plate Convergence Rates

To obtain rates of plate motion from the drowning isochron map, it is necessary to calibrate fossil ages with isotopic ages (Figure 6). In our study of Caradocian plate motions in New York [Bradley and Kusky, 1986] we adopted the time scale of Harland et al. [1982] and concluded that the normal component of plate convergence was about 2 cm/yr. However, consideration of a single Ordovician series obscured a more fundamental problem. The Harland et al. [1982] time scale ascribed 10 Ma to each of the five post-Tremadocian stages of the Ordovician. This seems improbable. Alternatively, series in the Ordovician time scale of Carter et al. [1980] are quite variable in length, a conclusion based on

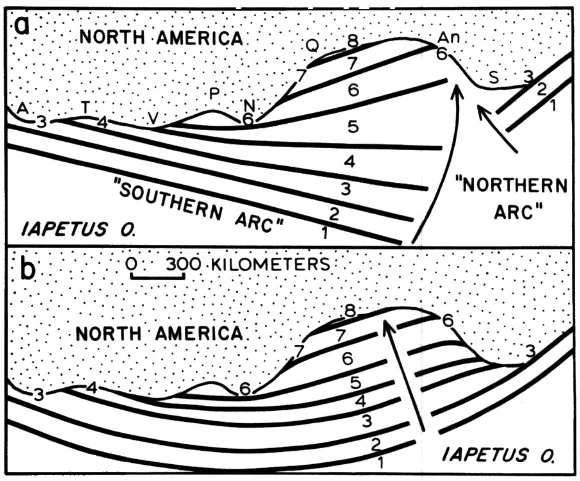

Fig. 7. Two possible plate geometries that could account for the drowning isochron pattern. Letters identify irregularities along the ancient passive margin of North America (stippled on landward side): A, Alabama Promontory; T, Tennessee Reentrant; V, Virginia Promontory; P, Pennsylvania Reentrant; N, New York Promontory; Q, Quebec Reentrant; An, Anticosti Reentrant; S, Saint Lawrence Promontory. Numbers along the continental margin indicate age of shelf drowning; where across-strike diachronism is evident for a given sector of the margin, only the time of earliest drowning is shown. Numbers correspond to graptolite zones in figure 1, beginning with 1 as *I. victoriae* Zone and ending with 8 as *O. ruedemanni* Zone. Bold isochron lines are positions about 120 km in advance of the plate boundary. (a) Model for the Taconic Orogeny involving collision between North America and two inboard arcs, a northern arc colliding with the Newfoundland sector of the passive margin and a southern arc colliding with the rest of the margin. The configuration of the implied plate boundary between the two postulated arcs cannot be specified. (b) Model for the Taconic Orogeny involving a single inboard arc, which must be concave to account for early collision in the extreme north and south.

the assumption that thicknesses of pelagites from widely distributed deep marine settings are proportional to the duration of deposition. The time scale adopted by Ross et al. [1982] also attributes unequal duration to the various Ordovician series but differs substantially from that of Carter et al. [1980].

Despite unresolved time scale disputes that are beyond the scope of this paper, the drowning isochron map (Figure 1) provides the basis for some conclusions about Taconic plate convergence rates. The migration of the shelf drowning line through time is assumed to have been a direct response to convergent plate motion [Bradley and Kusky, 1986]. Accordingly, the contour gradient should approximate the rate of plate convergence. Convergence rates were calculated for three foredeep transects, perpendicular to isochron lines through locations A, 22, and 31 (in Newfoundland, New York, and Tennessee, respectively). Gradients were calibrated according to the various proposed time scales to determine a range of convergence rates (Figure 8). In Tennessee and New York, calculated convergence rates were 1 to 2 cm/yr. In Newfoundland, a convergence rate of about 1 cm/yr was obtained using the Harland et al. [1982] and Carter et al. [1980] time scales, but a rate between 4 and 5 cm/yr was obtained from the Ross et al. [1982] time scale. This might mean either (1) that the Ross et al. [1982] time scale is accurate and convergence rate was significantly faster in Newfoundland than in New York or Tennessee, or (2) that the Harland et al. [1982] and Carter et al. [1980] time scales are accurate, and convergence rate was about the same at all three transects. Whichever the case, Taconic plate convergence rates appear to have been of the same order as present-day plate motions. While it is likely that convergence rates in arc-passive margin collisions decrease with time (as collision grinds to a halt), the facies isochron maps provide no compelling evidence of this.

Width of the Closed Ocean Basin

Taconic arc-passive margin collision is believed to have been preceded by subduction of an unknown amount of oceanic lithosphere. The width of the closed ocean can be estimated from the rate and duration of subduction. Convergence rate during collision is extrapolated back in time to the interval of oceanic subduction, the duration of which can be inferred from the duration of arc magmatism. The most appropriate transect for this analysis is in Maine, where the age of Ordovician volcanism is well constrained by fossils and where a more complete record of volcanism is present than in New Brunswick or Newfoundland. In Newfoundland, Ordovician volcanic rocks are separated from the foredeep by large Carboniferous strike-slip faults such as the Cabot, whereas in Maine the major Carboniferous wrench faults lie outboard of the Ordovician arc terranes. As noted earlier, magmatism that can be reasonably attributed to Taconic plate convergence lasted from late Arenigian to Ashgillian time in Maine. Applying the Carter et al. [1980] time scale, arc magmatism lasted about 44 Ma. At a convergence rate of about 1.1 cm/yr, this suggests that about 480 km of ocean floor was consumed prior to collision along the New England sector of the orogen. Applying the Harland et al. [1982] time scale, magmatism lasted about 39 Ma at a convergence rate of about 1.9 cm/yr, yielding an oceanic width of about 740 km. Applying the Ross et al. [1982] time scale, magmatism lasted about 41 Ma at a convergence rate of about 0.8 cm/yr, yielding an oceanic width of about 330 km. It is probably appropriate to add 150

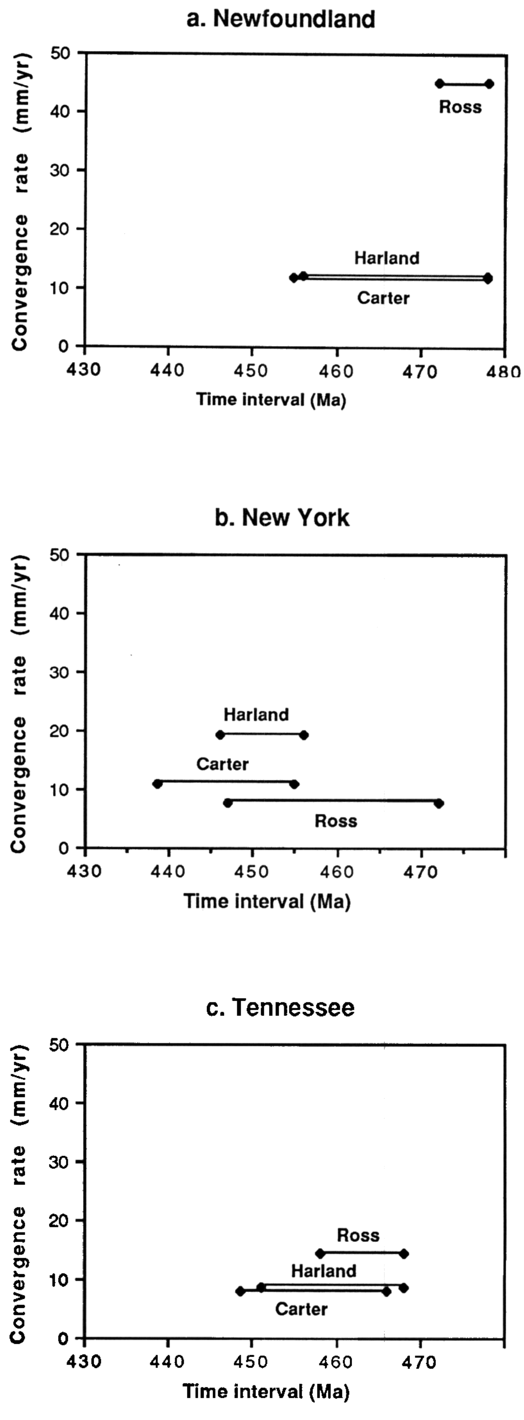

Fig. 8. Plots of plate convergence rate versus age for three transects: (a) Newfoundland, through location A in Figure 1; (b) New York, through location 22; and (c) Tennessee, through location 31. The bars represent the mean convergence rate for the time interval between the oldest and youngest isochrons crossed by each transect, according to the time scales of Harland et al. [1982], Carter et al. [1980], and Ross et al. [1982].

km to each result, corresponding to the minimum amount of ocean floor that must have been subducted before any magmatism could have occurred; this yields widths of 630, 890, and 480 km for the Carter, Harland, and Ross time scales, respectively. If convergence rates were decreasing during collision, the calculated ocean widths would be underestimations. It should be emphasized that these widths do not correspond to the width of the entire Iapetus Ocean but only to the oceanic part of the Laurentian plate that was subducted prior to the Taconic Orogeny. Pre-Taconic closure of a relatively narrow ocean is consistent with biogeographic data from carbonate-bearing conglomerates associated with volcanic rocks in the Buchans Group in central Newfoundland [Nowlan and Thurlow, 1984]. A late Arenigian to Llanvirnian conodont fauna belonging to the Toquima-Table Head Realm suggests that the Buchans magmatic arc was not far from North America.

Transport Distance of Slope/Rise Allochthons

Early influx of orogen-derived turbidites in transported slope/rise successions can be explained as a consequence of postdepositional tectonic transport. However, the amount of displacement cannot be readily obtained using standard section restoration techniques; hence these data are not useful in establishing facies isochron patterns or deriving plate convergence rates. Bradley and Kusky [1986] inverted the problem to calculate transport distance. In the autochthonous Taconic foreland of New York we suggested that the shale-to-turbidite transition migrated westward at a rate of about 3 cm/yr; while in the Taconic allochthon, the shale-to-turbidite transition is several million years older than would be expected for autochthonous rocks in that location. We concluded that transport of about 120 km would correct the age anomaly. In light of two new considerations discussed below this appears to have been an underestimation.

The shelf drowning isochron map (Figure 1) allows estimation of transport distances of slope/rise allochthons that do not happen to lie adjacent to well-exposed sectors of the foredeep (Table 1). Transport distances were estimated from the drowning isochron map, as follows. Using the Timor Trough as a model foredeep, the shelf drowning isochron line at a given time was considered to lie approximately 120 km cratonward of the thrust front and 105 km cratonward of the turbidite front (base of outer trench slope). Arrival of turbidites at the slope/rise was interpreted to have occurred about 15 km cratonward of the thrust front. The positions of the thrust front and turbidite front were then estimated for the time of the first flysch in a given allochthon. Finally, the map distance between present location and inferred initial position was measured perpendicular to strike. Results so obtained are subject to many possible sources of error, which include variations in widths of foredeep facies belts, age uncertainties, undetected plate kinematic complexities, and arbitrary contouring decisions. Nonetheless, the present transport estimates are based on quite different considerations than palinspastic structure sections [e.g., Stanley and Ratcliffe, 1985], which have yielded broadly comparable results.

Taconic Allochthon, New York. Transport distance of the Giddings Brook Slice of the Taconic Allochthon is estimated at a maximum of 165 km. It now appears that Pawlet Formation flysch in the Taconic Allochthon is slightly older than we previously indicated; this revision is minor in light of Finney's [1986a] modified graptolite zonation. A second error in our previous analysis was one of interpretation; the shale-to-turbidite transitions used to estimate convergence rate [Bradley and Kusky, 1986] included both trench fill in the east, and postconvergence foredeep fill in the west. The new transport estimate is based on extrapolation from Pennsylvania of the isochron representing drowning at the *N. gracilis/C. bicornis* Zone boundary. Since the base of the Pawlet Formation is probably slightly younger than the zonal boundary, 165 km is a maximum estimate. The allochthon was palinspastically restored perpendicular to strike, along an azimuth of 105°, which was the direction of tectonic transport during late-stage Taconic convergence [Bosworth and Vollmer, 1981].

Hamburg Klippe, Pennsylvania. Taconic flysch occurs in the Greenwich Slice, which is the lower of two thrust slices of the Hamburg Klippe of Pennsylvania [Lash and Drake, 1984]. Graywacke of the Windsor Township Formation can be assigned to the *C. bicornis* Zone, based on occurrence of the name-giving species [Wright et al., 1979]. However, the Greenwich slice contains no pre-flysch slope/rise strata (such rocks do occur in the Richmond Slice, but flysch does not). Therefore it is uncertain whether flysch sedimentation began in the slope/rise before or during *C. bicornis* Zone time. The latter interpretation is preferred here on the grounds that flysch sedimentation lasted no more than a whole graptolite zone in the other Taconic allochthons. As in the case of the Taconic Allochthon, tectonic transport was estimated from the position of the isochron line representing shelf drowning at the *N. gracilis/C. bicornis* Zone boundary. The allochthon was palinspastically restored perpendicular to strike, along an azimuth of 162°, that is, the direction of tectonic transport during Taconic convergence [Lash and Drake, 1984, p. 26] (note the discrepancy between this restoration direction and that inherent in Pedlow's [1976] palinspastic map). Transport of at least 225 km is inferred. Since the Windsor Township Formation is somewhat older than the zonal boundary, this is a minimum estimate.

Humber Arm Allochthon, Newfoundland. Allochthonous slope/rise facies in central western Newfoundland comprise the Humber Arm Allochthon, which structurally overlies the shelf and foredeep sequence. Late Arenigian arrival of the slope/rise region at the trench is recorded by turbidites of the Lower Head Formation [James et al., 1987]. Stevens [1970] considered the Blow-Me-Down Brook Formation to be part of the allochthonous flysch succession, but newly discovered fossils show that this unit is no younger than Early Cambrian [Lindholm and Casey, 1989]. The source of ophiolitic debris in the Ordovician flysch was the Bay of Islands ophiolite complex, which structurally overlies the transported slope/rise deposits. The Lower Head Formation represents one of the oldest obducted trench fill sequences that was deposited atop the former slope/rise of the Appalachian passive margin. Its great age is not surprising, insofar as Newfoundland is located near a promontory, and the Humber Arm Allochthon has clearly been transported a long distance from its depositional site. Transport distance of the Humber Arm Allochthon at Lobster Cove Head is estimated at 270 km, based on the poorly constrained position of the isochron line representing shelf drowning at the *P. tentaculatus/I. victoriae* Zone boundary. The allochthon was palinspastically restored perpendicular to strike.

External Domain, Gaspe Peninsula. The Tourelle Formation occurs at the top of a far-traveled slope/rise allochthon of St. Julien and Hubert's [1975] External Domain. Tourelle Formation flysch conformably overlies slope facies of the Cap des Rosiers Group [Hiscott, 1978, p. 1580].

Influx of ophiolitic flysch is interpreted to mark arrival at the trench. Transport distance appears to exceed that of the other slope-rise allochthons, but is impossible to estimate with confidence. The problem is that the Tourelle flysch is comparatively old, while shelf drowning along this sector of the continental margin was comparatively young. Five drowning isochron lines had to be located with very little to go on other than their mean spacing elsewhere along the orogen (Figure 1). The allochthon was palinspastically restored perpendicular to strike. On this basis the best estimate of transport distance is a minimum of 450 km.

CONCLUSIONS

Decades of regional tectonic studies have led to the definition, testing, and refinement of the arc-passive margin collision model for the Taconic Orogeny. This qualitative model has provided a unifying rationale for existing observations and has served admirably as a predictive basis for new observations, leading, for example, to the rejection of the dominant role of gravity sliding in the evolution of the orogen [e.g., Rowley and Kidd, 1981]. Considering the usual disagreements among geologists on interpretations of regional tectonics, the consensus regarding Taconic plate tectonics is indeed remarkable.

The present study represents a next logical step in regional tectonic analysis, toward the quantification of plate motions. While this attempt has not been entirely successful, some important new relationships and concepts have been revealed. Shelf-drowning isochron maps are introduced here as a new tool with a variety of applications in tectonic studies of arc-passive margin collisions. The pattern of Taconic shelf drowning clearly reveals the diachronous nature of the Taconic Orogeny, both along and across strike. The shelf-drowning pattern is not diagnostic of the number of arcs that collided directly with North America. The rate of plate convergence is interpreted to have been 1 to 2 cm/yr, and the minimum width of the ocean that closed was probably 500 to 900 km. These results are in no way subject to the latitudinal uncertainty which precludes paleomagnetic detection of east-west motions. An unexpected benefit of the analysis is a new technique for estimating tectonic transport distances of slope/rise allochthons. Such distances are not readily obtained by conventional structural analysis, but appear to have been in the range of 165 to 450 km for four Taconic allochthons. Foredeep facies isochron analysis shows enough promise that applications are warranted in analogous settings in the Urals, Ouachitas, Oman, Papua, and Brooks Range.

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