TECTONICS OF THE ACADIAN OROGENY IN NEW ENGLAND AND ADJACENT CANADA[1]

DWIGHT C. BRADLEY

Department of Geological Sciences, State University of New York at Albany, Albany, New York 12222

ABSTRACT

Paleogeographic analysis of post-Taconian rocks in New England and adjacent parts of Canada has revealed the existence of two volcanic arcs which shut off at the time of the Acadian Orogeny. One was built on arc basement previously accreted to North America during the Taconic Orogeny, the other on Precambrian continental basement of Avalonia. In the intervening Merrimack-Fredericton Trough, metamorphosed and polydeformed turbidites and black shales record deep water conditions in Silurian. Following McKerrow and Ziegler (1971), this tract is interpreted as the site of an ocean which closed in Siluro-Devonian by simultaneous subduction beneath both continental margins. In the Molucca Sea in Indonesia, a comparable arc-arc collision is in an early stage of development; Moore et al. (1982) suggested that an accretionary prism built against one arc is overthrusting its counterpart, which developed on the other side of the ocean. An identical geometry, with an Avalonian accretionary prism overriding the convergent North American margin, is proposed for the Acadian Orogeny in New England to explain these aspects of the regional geology: (1) early west vergent structures in the Merrimack Trough in Maine and New Hampshire, related here to subduction beneath Avalonia; (2) east vergent structures at a deeper structural level in the trough in Connecticut, related to subduction beneath North America (Rodgers 1981); (3) rapid subsidence of the Piscataquis Volcanic Arc beneath a thick pile of east-derived flysch in Devonian; (4) subsequent deep tectonic burial and high grade metamorphism of parts of this belt beneath west-vergent nappes; and (5) only minor Acadian deformation and metamorphism on the Avalonian side of the trough.

INTRODUCTION

Since Wilson's (1966) first application of plate tectonics to the Northern Appalachians, interpretations of the tectonic framework of the Acadian Orogeny have become so numerous that most of the possibilities have now been covered. Recent investigators have agreed on little more than the idea that orogeny resulted from convergent plate motion, as is shown in figure 1. While some discrepancies between conflicting models can be traced to regional biases, more fundamental controversies have arisen from the following interrelated problems: (1) the origin and nature of the basement of the major pre-Acadian basins, the Merrimack-Fredericton, Aroostook-Matapedia, and Connecticut Valley-Gaspe Troughs (fig. 2); (2) the existence, location, and vergence of Siluro-Devonian subduction zones beneath North America, the Miramichi Massif, and Avalonia; and (3) the degree to which post-Acadian strike slip invalidates across-strike reconstructions such as those illustrated in figure 1.

A review of geologic evidence and plate tectonic concepts now available shows that the early model of McKerrow and Ziegler (1971), of a pre-collision plate geometry with subduction zones dipping beneath both margins of the Merrimack-Fredericton Trough, is most successful in explaining the distribution of Silurian sedimentary and volcanic rocks (figs. 1 and 2).

Less obvious is the ability of this model to also account for Acadian synorogenic sedimentation, deformation, and metamorphism, particularly in the zone mapped in figure 2 as the Piscataquis Volcanic Arc. In Silurian, this linear belt of shallow marine sedimentation was dotted with andesitic volcanoes; it is regarded as an arc over a subduction zone dipping to the west or northwest beneath North America (McKerrow and Ziegler 1971; Rodgers 1981; Hon and Roy 1981). In the Devonian, following burial beneath many kilometers of east-derived flysch, the volcanic belt was overthrust from the east by a stack of nappes. Thus, the vergence of shallower level structures above the arc appears to have been opposite that of the subduction zone beneath it.

McKerrow and Ziegler (1971) did not pursue such questions, as they were concerned primarily with Silurian paleogeography and not with the collision itself. The purpose of

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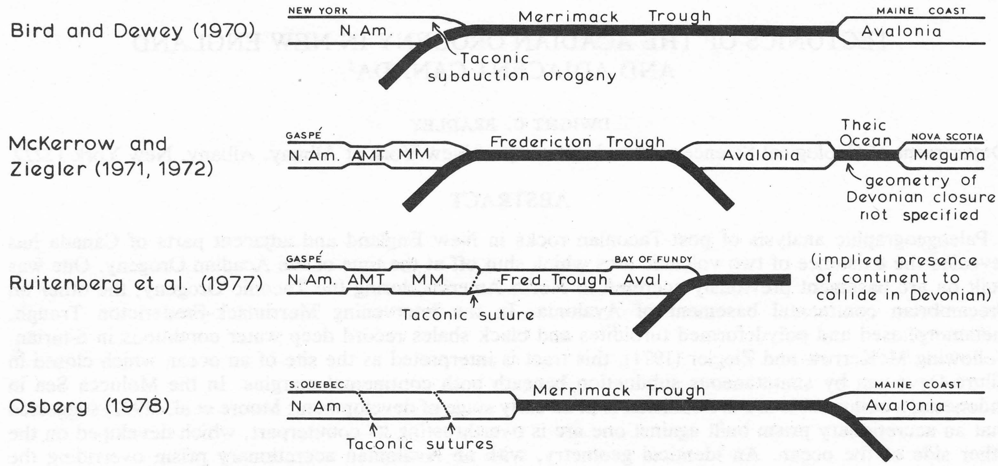


FIG. 1.—Plate tectonics of the Northern Appalachians as visualized by various workers. Cross sections show plate boundary conditions leading up to the Acadian Orogeny; geographic names at left and right locate ends of sections. Other models, not illustrated, include those of Rast and Stringer (1980), Poole (1976), Williams (1978), Robinson and Hall (1979), and Ludman (1981).

this paper is to extend their model into the Devonian, and demonstrate its success with the aid of a modern analog in the Molucca Sea in Indonesia, where accretionary prisms are colliding today.

MID-PALEOZOIC TECTONIC ELEMENTS

The area under consideration extends from Connecticut to the Gulf of St. Lawrence, where Paleozoic rocks form a nearly continuous 1000 by 300 km belt of strike-parallel paleogeographic realms that were deformed, metamorphosed, and intruded in Devonian. A Devonian orogeny also occurred in Nova Scotia and Newfoundland, but attempts to link tectonic elements across Carboniferous strike-slip faults and the Gulf of St. Lawrence have been unsuccessful. South of New York, Acadian tectonic elements have not been identified in the region of strong late Paleozoic shortening east of the Appalachian Basin. The present discussion will therefore be restricted to the contiguous Acadian foldbelt in New England, Quebec, and New Brunswick.

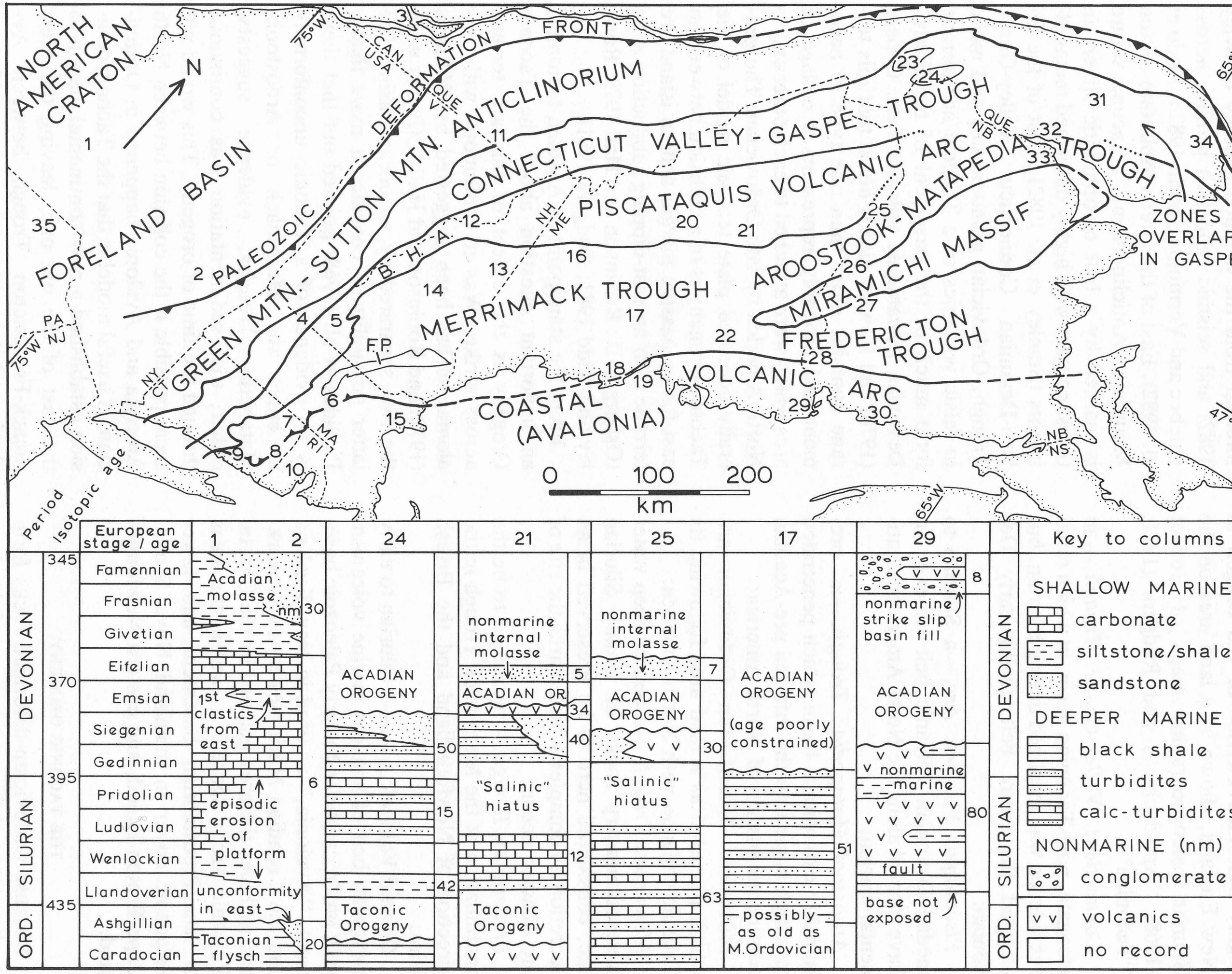
Here it is helpful to divide the orogen, as previous workers have, into zones with distinctive late Ordovician to Devonian histories of subsidence and tectonism. Some of these correspond to the major anticlinoria and synclinoria used by such earlier workers as Billings (1956) and Cady (1969), who believed that the elongate parallel belts of older and younger rocks were essentially large scale folds. Naylor and Boucot (1965), Boucot and Johnson (1967), Boucot (1968), Thompson et al. (1968), and Rodgers (1970) demonstrated that some of these structures were also ancestral pre-Acadian topographic features. Accordingly, in the present subdivision, "trough" replaces "synclinorium" where appropriate. From west and northwest to east and southeast, the following tectonic elements are recognized (figure 2):

North American Craton.—underlain by Precambrian Grenville basement and a lower Paleozoic cover sequence;

Foreland Basin.—filled with a thick wedge of Devonian synorogenic clastics which coarsen and thicken toward the mountain belt;

Green Mountain-Sutton Mountain "Anticlinorium".—a basement thrust slice interposed between the molasse basin and the

FIG. 2.—Zonal subdivision of the Northern Appalachians. Numbered localities referred to in text and in stratigraphic columns below are arranged numerically from west to east. FP is the Fitchburg "Pluton" (Massabesic Gneiss); B.H.A. is the Bronson Hill Anticlinorium. Numbers in the stratigraphic columns refer to thicknesses in hundreds of meters. Key references: columns 1 and 2—Rickard (1975); column 24—Lajoie et al. (1968); column 21—Rankin (1968), Boucot and Heath (1969), and Hall et al. (1976); column 25—Roy and Mencher (1976), Pavlides et al. (1964); column 17—Ludman (1976); column 29—Gates (1978).



NORTH AMERICAN CRATON
N
1
FORELAND BASIN
35
2
PALEOZOIC
DEFORMATION
FRONT
3
CAN USA
QUE VT
75°W
GREEN MTN.- SUTTON MTN. ANTICLINORIUM
CONNECTICUT VALLEY - GASPE TROUGH
PISCATAQUIS VOLCANIC ARC
B. H. A.
MERRIMACK TROUGH
AROOSTOOK-MATAPEDIA TROUGH
MIRAMICHI MASSIF
FREDERICTON TROUGH
COASTAL VOLCANIC ARC
(AVALONIA)
ZONES OVERLAP IN GASPE'
QUE NB
NH ME
NY CT
PA NJ
MA RI
NB NS
F.P.
65°W
47°N
0 100 200
km
Period
Isotopic age
European stage / age
1
2
24
21
25
17
29
Key to columns
DEVONIAN
SILURIAN
ORD.
345
370
395
435
Famennian
Frasnian
Givetian
Eifelian
Emsian
Siegenian
Gedinnian
Pridolian
Ludlovian
Wenlockian
Llandoverian
Ashgillian
Caradocian
Acadian molasse
nm
30
1st clastics from east
6
episodic erosion of platform
unconformity in east
Taconian flysch
20
ACADIAN OROGENY
50
15
42
Taconic Orogeny
nonmarine internal molasse
5
ACADIAN OR.
34
40
"Salinic" hiatus
12
Taconic Orogeny
7
30
63
(age poorly constrained)
possibly as old as M.Ordovician
51
nonmarine strike slip basin fill
8
nonmarine
marine
80
fault
base not exposed
SHALLOW MARINE
carbonate
siltstone/shale
sandstone
DEEPER MARINE
black shale
turbidites
calc-turbidites
NONMARINE (nm)
conglomerate
volcanics
no record

highly deformed interior of the orogen in New England, shown as a land area on the Silurian paleogeographic maps of Boucot (1968; "Appalachia") and Rodgers (1971; "Taconica");

Connecticut Valley-Gaspe Trough.—an elongate, post-Taconian basin, in which rapid subsidence was localized during Silurian, but affected the entire belt during early Devonian:

Piscataquis Volcanic Arc.—a Silurian to medial Devonian volcanic belt believed to have formed along the North American continental margin;

Aroostook-Matapedia Trough.—a presumably extensional basin which penetrated at a high angle into the inferred pre-Acadian continental margin of North America;

Miramichi Massif.—an Ordovician arc which persisted as a land area following its Taconic collision with North America;

Merrimack Trough.—a belt of deep water metasedimentary rocks of mainly Silurian age, considered here to be preserved in an accretionary complex which marks the site of the Acadian ocean;

Fredericton Trough.—presumed to be the continuation of the Merrimack Trough in the direction of Newfoundland and the British Isles;

Coastal Volcanic Arc.—a Silurian to early Devonian belt of shallow marine volcanism built on Precambrian to early Paleozoic basement. "Avalonia," as used in New England and the Canadian Maritimes by most workers, includes the area mapped as the Coastal Volcanic Arc in figure 2, as well as the areas of late Precambrian basement and lower Paleozoic cover in mainland Nova Scotia, Cape Breton Island, and eastern Newfoundland.

THE TACONIC OROGENY

Because Ordovician-deformed rocks form the basement of the western part of the Acadian orogen, a brief overview of Taconic relations is first presented as a basis for discussion of the younger geology. The western part of the Taconic Orogen consists of a Cambro-Ordovician continental margin sequence (rift, shelf, slope, and rise facies) now preserved, along with Ordovician flysch, in a westward imbricated fold-thrust belt (Rowley and Kidd 1981). Shortening of several hundred kilometers on subhorizontal thrusts is inferred from the mapped geology (Rowley 1982) and seismic reflection profiles across Quebec and Vermont (Seguin 1982*a*; Ando et al. 1982). East of the Green Mountain-Sutton Mountain "Anticlinorium," a Taconic suture is marked by a belt of ophiolitic slivers in thrust contact with highly deformed metasediments (Stanley et al. 1982). East of the Siluro-Devonian Connecticut Valley-Gaspe Trough, Ordovician granodiorites and mafic to felsic volcanics of a Taconic arc terrane form much of the basement of the Siluro-Devonian Piscataquis volcanic belt. Osberg (1978) and Rowley (1983) noted that this terrane contains more than one type of basement and probably represents a collage of arcs which were attached to each other and to North America by late Ordovician. The generally accepted plate tectonic model of the Taconic Orogeny is of a collision between an east-facing passive margin and an island arc terrane over an east-dipping subduction zone (Osberg 1978; Robinson and Hall 1979; Rowley and Kidd 1981; Rodgers 1981).

From the standpoint of Acadian tectonics, an important question about the Taconic Orogeny is the extent of this arc terrane across strike. Was it continuous with Avalonia, as has been suggested by Williams (1978) and Robinson and Hall (1979), or were the two separated by an ocean basin? The latter possibility is considered more likely. Pavlides et al. (1968) pointed out that there is no evidence of a Taconic unconformity in either the Merrimack or Aroostook-Matapedia Troughs; evidence suggests, rather, that sedimentation was continuous through the time of orogeny. This would not seem possible if the collision between North America and Avalonia happened in Ordovician. A useful model is that the Taconic collision established a new continental margin to the east of the old one, leaving the Merrimack-Fredericton Trough between Avalonia and the collided arc terranes (Osberg 1978; Roy 1980; Rodgers 1981; Hon and Roy 1981).

THE ACADIAN OROGEN

North American Craton and Foreland Basin.—The North American craton lies to the west and north of the Acadian deformation front and consists of Precambrian (1000 m.y.) basement overlain by thin early Paleozoic platform sediments (Fisher 1977). Towards the east, these cover rocks thicken into the continental margin sequence which was deformed during the Taconic Orogeny (Bird and Dewey 1970; Rodgers 1971). Following Silurian and early Devonian shallow water deposition, the region was rapidly buried beneath thick clastics of an Acadian molasse basin (fig. 2, cols. 1 and 2). Subsidence, presumably, was due to thrust loading. The molasse is best preserved in the Catskill Mountains of New York and in adjacent parts of Pennsylvania, where 3 or more kilometers of fluvial and shallow marine strata were deposited during about 20 m.y. The source of these sediments has long been recognized as a mountain belt to the east, because the sediments coarsen and thicken in that direction, and paleocurrents flowed to the west (Allen and Friend 1969; Rickard 1975). In northern Pennsylvania (fig. 2, loc. 35), Woodrow (1968) demonstrated the growth of anticlines during Upper Devonian sedimentation, a syntectonic environment typical of flexural molasse basins in orogenic forelands (Dickinson 1974).

To the north of the Catskills, much of the Acadian molasse, if once existent, has now been lost to erosion that resulted from Neogene uplift of the Adirondack Mountains (K. Burke, pers. comm. 1980). A molasse cover must have once existed as far north as Montreal, as is indicated by a xenolith of medial Devonian mudstone (equivalent to that of the Hamilton Group in the Catskills) in a Cretaceous intrusion (Boucot and Johnson 1967) (fig. 2, loc. 3).

In the Gaspe Peninsula, early and medial Devonian shallow marine and nonmarine sandstone is thick and widespread (Beland 1969). These strata fill a pre-Acadian basin (the Connecticut Valley-Gaspe Trough), and hence were deposited in a slightly different tectonic environment from the Catskill molasse facies, which they resemble lithologically.

Connecticut Valley-Gaspe Trough.—The Connecticut Valley-Gaspe Trough marks a belt of complex subsidence which developed through Silurian and early Devonian over the Taconic suture zone. The oldest post-Ordovician rocks are a widely distributed, generally thin (less than a kilometer is typical), diachronous sequence of Silurian quartz conglomerates, sandstones, limestones, and calcareous mudstones. They rest unconformably on polydeformed graywackes which locally contain dismembered ultramafic rocks, as well as on the less deformed arc terrane to the east. For 30 to 40 m.y., shallow marine conditions and relatively slow subsidence prevailed across much of the Taconic orogen. A reasonable inference is that the underlying basement must have achieved the thickness of normal continental crust by the onset of Silurian deposition; there seems little doubt that the Connecticut Valley-Gaspe Trough is a post-Taconian feature.

The first pulse of rapid subsidence in the trough occurred locally in the Mistigougueche subbasin (Roy 1980) (fig. 2) in late Llandoverian. Silurian isopach maps drawn by Lajoie et al. (1968) show a northeast-trending basin about 30 by 10 km, flanked on the southeast by a line of volcanoes, filled with about 4 km of Lower Silurian clastics (fig. 2, col. 24). A second basin of about the same size, the Lac des Baies subbasin, subsequently developed about 30 km to the northwest and received about 5 km of Ludlovian strata (Lajoie et al. 1968) (fig. 2, loc. 23). Such rapid but localized subsidence suggests an environment of extension. Comparable subsidence rates might also be possible under a tectonic load (i.e., a stack of nappes or thick pile of volcanics), but because neither voluminous accumulations of Silurian volcanics nor Silurian compressional deformation are known in Quebec, this hypothesis is unlikely. If the subsidence was a result of rifting, it remains to be explained why it was localized, and why depocenters shifted position. A tectonic environment which would account for these observations is one of oblique strike-slip (Reading 1980), with the Mistigougueche and Lac des Baies subbasins originating as pull-aparts. The coincidental onset of volcanism in the Piscataquis belt with rapid subsidence in southwestern Gaspe suggests a genetic relationship that would place the Connecticut Valley-Gaspe Trough in a backarc setting, as suggested by Rodgers (1981) and Hon and Roy (1981). A possible modern analog is the Andaman Sea between the Malasian Peninsula and the island of Sumatra, where backarc spreading has a strong strike slip component (Hamilton 1978).

Whereas rapid subsidence in the Connecticut Valley-Gaspe Trough was localized in Silurian, in Devonian it affected the entire belt as well as the Piscataquis Volcanic Arc to the east. Turbidites and calcareous turbidites are the dominant lithologies, with minor interbedded volcanics. As detailed by Boucot (1970), this monotonous slate-graywacke sequence goes by a variety of formational names (Gile Mountain Fm., Vermont; Littleton Fm., New Hampshire; Seboomook Fm., Maine; Frontenac Fm., southeastern Quebec; Temiscouata and Fortin Fms., Gaspe). Thicknesses as great as 6 km have been reported (Boucot and Heath 1969). Hall et al. (1976) demonstrated an easterly source of the Seboomook Fm. and more proximal Matagamon Sandstone in central Maine. This conclusion is based on paleocurrents and on the observation that from west to east, coeval rocks grade from limestones to turbidites to deltaic, plant-bearing sandstones (Boucot 1970). Rapid subsidence west of the Merrimack Trough immediately preceded Acadian deformation and was most likely an early response to collision between North America and Avalonia (Osberg 1978).

In the Gaspe Peninsula, the youngest pre-Acadian strata (nonmarine fluvial sandstones assigned to the Gaspe Sandstone) (Beland 1969) gradationally overlie turbidites, suggesting that the trough had filled to sea level by the onset of deformation.

Piscataquis Volcanic Arc.—Rankin (1968) first recognized the Devonian Piscataquis Volcanic Arc in north central Maine (fig. 2, locs. 20 to 21), where four distinct volcanic centers are aligned in a northeast-southwest direction. Although Rankin only traced the volcanic belt about 160 km along strike, similar rocks extend to the northeast as far as the Gaspe Peninsula and Chaleur Bay. Siluro-Devonian volcanics have also been recognized along strike to the south as far as north-central Massachusetts (Thompson et al. 1968), and probably continue still farther along strike to southern New England. In this region of poor fossil control and severe Acadian deformation south of Maine, the area mapped in figure 2 as the Piscataquis Volcanic Arc is roughly coextensive with Ordovician arc basement of the Bronson Hill Anticlinorium (Billings 1956).

Associated shallow marine sediments indicate that volcanism varied from time to time along the arc from early Silurian to medial Devonian, spanning a considerably longer interval than at the type area in Maine. In the Temiscouata region (fig. 2, loc. 24), volcanics within the late Llandoverian Point aux Trembles Formation (Lajoie et al. 1968) are the first record of post-Taconian magmatism. Igneous activity was sporadic through Silurian, with most reported occurrences in the Ludlovian-Pridolian interval (Naylor and Boucot 1965). A marked increase in magmatism came in early Devonian with eruption of thick volcanic piles from New England to Gaspe: the volcanic member of the Erving Formation, Massachusetts (Thompson et al. 1968); the volcanic member of the Littleton Fm., New Hampshire (Billings 1956); volcanic members of the Kidderville and Seboomook Fms., southeastern Quebec (Green and Guidotti 1968); the type Piscataquis volcanics and the Dockendorf Group in Maine (Pavlides 1968; Sargent et al. 1981); the Dalhousie volcanics in Chaleur Bay, New Brunswick (Alcock 1935); and the Mont Alexandre volcanics in Gaspe, where the youngest volcanics are interbedded with Middle Devonian molasse (Beland 1969) (fig. 2, loc. 31).

The volcanics are a varied suite of basalts, andesites, dacites, and rhyolites. Many were erupted subaerially, as is indicated by welded tuffs, volcanic breccias, and interbedded nonmarine sedimentary rocks (Rankin 1968). Pillow lavas are important in the upper parts of some sections, interbedded with lower Devonian turbidites (Billings 1937) (fig. 2, loc. 12). Until the recent initiation of trace element studies, geochemical work outside the type area in Maine had been restricted to a few whole rock analyses performed in the course of quadrangle mapping (e.g., Billings 1937). In Maine, Hon (1980) and Hon et al. (1981) found that the gabbroic to granitic rocks of the Greenville plutonic belt (comagmatic with the Piscataquis volcanics) show calc-alkaline differentiation trends and REE patterns typical of subduction related magmas in modern arc environments. The REE patterns of the penecontemporaneous, peraluminous Traveler Rhyolite (fig. 2, col. 21) (strongly fractionated LREE with a negative europium anomaly) are compatible with melting of continental crust with the composition of graywacke (arc basement?), above the subducted slab. The geochemistry of these rocks thus supports the idea of a pre-Acadian subduction zone beneath the Piscataquis Volcanic Arc.

Working farther south in Vermont, Hepburne (1981) concluded from his study of the possibly correlative Standing Pond Volcanics that the protoliths were LREE-depleted tholeiites. These pillowed and pyroclastic amphibolites occur within the Devonian turbidite sequence in the eastern part of the Connecticut Valley-Gaspe Trough. Hepburne (1981) suggested an extensional (backarc?) origin. Oblique backarc extension in Connecticut Valley-Gaspe Trough in Silurian has already been suggested on stratigraphic grounds, and it may have continued into Devonian. Alternately, the Standing Pond Volcanics may be Piscataquis arc tholeiites interbedded with Devonian flysch derived from the east.

Aroostook-Matapedia Trough.—The Aroostook-Matapedia Trough (fig. 2) is a problematical belt of Ordovician through Silurian turbidite deposition. From central Maine, where it merges with the presumably oceanic Merrimack Trough, it trends north and penetrates at a relatively high angle into the arc basement inferred to have collided with North America during the Taconic Orogeny. In northern New Brunswick and Gaspe, it trends more easterly, parallel with Taconic structures (Rast and Stringer 1980). The center of this elongate basin is distinguished by a sequence of calcareous and noncalcareous turbidites, flanked on either side by progressively more proximal, then shallower water facies (McKerrow and Ziegler 1971; Roy 1980). The oldest strata in the trough (Carys Mills Fm. in Maine; Grog Brook Group in New Brunswick; Matapedia Group in Gaspe) are Ordovician and possibly as old as Caradocian (Pavlides 1968; St. Peter 1977; Roy 1980). The trough probably originated during and as a consequence of the Taconic Orogeny (Rast and Stringer 1980). In Gaspe, the Matapedia Group is inferred to rest unconformably on rocks deformed in the Taconic Orogeny (Alcock 1935). Along strike in Maine, the nature of the basement is not as well established; it has been regarded as nonoceanic by McKerrow and Ziegler (1971), and oceanic by Roy (1980), Hon and Roy (1981), and Rowley (1983). The presence of a dismembered ophiolite (Spruce Top Greenstone of Pavlides 1965) stratigraphically below proximal facies of the Aroostook-Matapedia Trough in the Bridgewater Quadrangle (fig. 2, loc. 25) suggests that the latter is the case (Rowley 1983). In northeastern Maine, 3.6 km of Lower Devonian shallow marine to nonmarine andesites and associated sediments of the Dockendorf Group overlie the Silurian turbidite section (Pavlides et al. 1964). The contact has been inferred to be a disconformity on the basis of a faunal gap spanning latest Silurian and earliest Devonian (Pavlides et al. 1964). However, there is no angular unconformity which would indicate that shoaling was a result of shortening; instead, the basin appears to have filled to sea level well before medial Devonian regional deformation.

These observations suggest that the Aroostook-Matapedia Trough was an oceanic basin which lacked sufficient width to generate a volcanic arc when it closed. This interpretation leads to the simplest model of Acadian tectonics in the area. Accordingly, the Lower Devonian Dockendorf Group, the correlative Dalhousie volcanics in New Brunswick (Alcock 1935) (fig. 2, loc. 33), and the Siluro-Devonian volcanics of the Piscataquis belt, are all considered to be products of the subduction of oceanic basement of the Merrimack-Fredericton Trough beneath the North American continental margin. More elaborate tectonic models involving one or two Aroostook-Metapedia subduction zones (e.g., Hon and Roy 1981) are required if the trough was more than about 150 km wide.

Miramichi Massif.—The Miramichi massif is a belt of mainly Ordovician arc rocks and Acadian plutons occupying much of north central New Brunswick. Following Ordovician penetrative deformation and ophiolite obduction that are believed to mark its collision with North American during the Taconic Orogeny (Rast and Stringer 1980), the massif persisted through Silurian as an area of high ground between the Aroostook-Matapedia and Fredericton Troughs (Boucot 1968; McKerrow and Ziegler 1971; Roy 1980). The Silurian (?) Pocowogamis Conglomerate is a coarse clastic unit which fringes the massif on the south (Venugopal 1979) (fig. 2, loc. 27). On its north side, the massif was flanked by the Silurian Bathurst subbasin of the Aroostook-Matapedia Trough (Roy 1980) (fig. 2, loc. 33), the subsidence of which was probably fault controlled (Noble 1976). Widespread Silurian to Lower Devonian volcanics on the massif are compatible with the interpretation that it was part of the Piscataquis Volcanic Arc on the North American continental margin.

Coastal Volcanic Arc.—A second belt of Silurian to early Devonian volcanics has been traced discontinuously from eastern Massachusetts to southern New Brunswick for about 600 km. These rocks are best known from the mapping of Gates (1969, 1978) in the area aroung Eastport, Maine (fig. 2, col. 29), where an apparent thickness of 8 km of basalts, andesites, rhyolites, and interbedded fossiliferous sedimentary rocks were deposited in deep marine to nonmarine environments. Considerably thinner sequences of correlative volcanics are also known in Penobscot Bay (Gates 1969) (fig. 2, loc. 19), eastern Massachusetts (Shride 1976) (fig. 2, loc. 15), and Long Reach, southern New Brunswick (Gates 1969) (fig. 2, loc. 30). These volcanics occur within a belt of post-Acadian strike slip faults which bound blocks of late Precambrian basement (Webb 1969). Essentially unmetamorphosed Cambro-Ordovician platformal sediments bearing an Acado-Baltic fauna locally overlie Precambrian basement in this belt and constitute an important line of evidence cited by Wilson (1966) in support of the concept of a Paleozoic proto-Atlantic. Silurian volcanics are nowhere in normal stratigraphic contact with the fossiliferous Cambro-Ordovician, and so the identification of the Silurian volcanic belt as "Avalonian" may ultimately be subject to revision.

Gates (1969) originally believed these volcanics erupted in an island arc, and most plate tectonic interpretations by workers less familiar than he with the local geology have shown a subduction zone dipping beneath Avalonia either from the north or the south. More recently, Gates (1978) reassessed the case for an arc environment and concluded instead that an extensional environment was indicated. The evidence cited included: (1) syn-volcanic normal faulting; (2) bimodal volcanic compositions; and (3) late Acadian mafic to ultramafic plutons in the same belt as the slightly older volcanics. When also taken into account, the following evidence argues more strongly for retention of the original arc interpretation: (1) Volcanism in the Eastport area lasted from Wenlockian to Gedinnian, about 30 m.y. During this interval, predominantly submarine volcanics were gradually replaced by nonmarine volcanics, as 8 km of strata accumulated (Gates 1978). The Siluro-Devonian interval was thus a time of shoaling, not, as the rifting model would require, a time of deepening. Because the end result of extension is the generation of an ocean ridge 2.7 km below sea level, protracted rifting is not likely to generate a chain of volcanic islands. (2) Although Gates (1978) recently reported that the volcanics are a bimodal (basalt-rhyolite) suite, earlier descriptions (Gates 1969, p. 490) state that andesite is the dominant lithology at Penobscot Bay, and that intermediate rocks are also important in the volcanic sections at Eastport and southern New Brunswick. Shride (1976) noted that andesites dominate the volcanic pile in eastern Massachusetts. Moreover, bimodal volcanism is probably a poor criterion for rifting, because some modern arcs over Benioff Zones, such as the Tonga and Kermadec, show a pronounced silica gap (Miyashiro 1974). Conversely, volcanics in the Triassic-Jurassic rifts of eastern North America are all basaltic.

Merrimack-Frederiction Trough.—The Merrimack Trough is the most likely of the pre-Acadian basins to have been the site of an ocean. Across its present width of about 100 km, polydeformed, metamorphosed tubidites and lesser black shales record deep water sedimentation (Rodgers 1981) during an interval at least spanning the Silurian. A regional northward plunge has resulted in the exposure of deeper structural levels of the trough toward the south (Moench and Zartman 1976). Thus, sparsely fossiliferous, chlorite grade turbidites in central Maine give way to migmatites in New Hampshire, where metamorphism occurred at depths in excess of 15 km. (Thompson and Norton (1968) based this conclusion on the distribution of coexisting alumino-silicates.) Polyphase deformation is widely recognized in rocks of all metamorphic grades in the trough.

Certainly the most convincing evidence that the Merrimack Trough was underlain by oceanic basement would be the presence of slivers of ophiolite preserved within the sequence of deformed Silurian turbidites. Those who have balked at an oceanic origin have pointed to a virtual lack of such rocks

(Robinson and Hall 1979; Williams 1978). Compared with the abundant ophiolites obducted during the Taconic Orogeny, Acadian ophiolites are notably scarce. However, in two areas, dismembered ultramafic rocks have been recognized which might represent post-Taconian ocean floor.

In east-central Massachusetts, undated ophiolitic rocks occur in the Wachusett-Marlborough Tunnel where it crosses the mylonitized Clinton-Newbury Fault zone (Skehan and Abu-Moustafa 1976) (fig. 2, loc. 6). There, highly tectonized serpentinite, amphibolite, and metachert occur in fault slices bounded on the west by the deformed turbidites of the Merrimack Trough and on the east by Precambrian continental basement.

Another possible occurrence of post-Taconian ocean floor has been reported from coastal Maine (Gaudette 1981) (fig. 2, loc. 18), where a series of small ultramafic bodies, together known as the Union ultramafic complex, occur in a 30 by 5 km belt. These bodies lack contact aureoles and are concordant with structural trends in the enclosing metasedimentary rocks; Gaudette (1981) interpreted the contacts as tectonic. A U-Pb zircon age of 410 ± 7 m.y. from associated intermediate rocks may represent the age of formation of this presumed ocean floor (Gaudette 1981); if so, the Merrimack Trough is at least partly Silurian. On the other hand, at least some bodies in the complex may be intrusive, related to coeval ultramafic and mafic plutons nearly along strike in eastern Maine and adjacent New Brunswick.

The great thickness of deep water metasedimentary rocks in the trough is consistent with the interpretation that its basement was originally oceanic. In Waterville, Maine (fig. 2, col. 17), where fossils are abundant enough for a generalized stratigraphy to be recognized, more than 5 km of turbidites and graptolitic shales were deposited at least through the Silurian (Ludman 1976). The upper and lower ends of this section can be fleshed out by correlation with rocks exposed near the margin of the trough to the northwest (Moench and Zartman 1976) (fig. 2, loc. 16). The time of deep water sedimentation in the trough probably lasted from medial or late Ordovician into earliest Devonian, an interval of perhaps 60 m.y. These data are compatible with oceanic basement, but may not preclude stretched continental or immature (thin) arc basement as alternate possibilities.

The belt of turbidites which marks the Merrimack Trough bifurcates in east-central Maine. The southern fork, known as the Fredericton Trough, extends northeastward into New Brunswick where it is obscured beneath the cover of Carboniferous rocks. Like the sedimentary fill of the Merrimack Trough, the Fredericton turbidites are dominantly noncalcareous (McKerrow and Ziegler 1971) and are considered to be mainly Silurian, although fossil control is yet not good (Ludman 1981). Following Bird and Dewey (1970) and McKerrow and Ziegler (1971), the Fredericton Trough has been regarded by some later workers (e.g., Osberg 1978) as the continuation of the oceanic Merrimack Trough in the direction of Newfoundland and the British Isles, where oceans closed in the mid-Paleozoic (Phillips et al. 1976; McKerrow and Cocks 1977). The two troughs are juxtaposed across the Norumbega fault zone (Ludman 1981), on which post-Acadian dextral displacement appears to have been in the range of 30 km (D. Wones, in Ludman 1981). Displacements far in excess of this figure (as have been suggested by paleomagnetic data of Kent and Opdyke 1978) are improbable because turbidites have been mapped as the same formation, occur at the same metamorphic grade, and have the same history of Devonian deformation on both sides of the fault (Ludman 1981).

Volcanic belts on both margins of the Merrimack-Fredericton Trough have been interpreted as originating over oppositely-dipping subduction zones. If this interpretation is correct, the great duration of subduction (as long as 50 m.y.) argues strongly for oceanic crust in the original Merrimack Trough. A simple calculation allows a rough estimation of the original width (w) of the now-subducted plate (fig. 3). The parameters are the average rate of convergence (r_1 and r_2) and duration of subduction (t_1 and t_2) at each plate boundary, the dip of each slab (θ_1 and θ_2), and the depth of the slab beneath the locus of volcanism (h). The assumption is made that magmas generated at depth are erupted at the surface without a geologically resolvable delay (John Bender, pers. comm. 1982). The relationship,

$$w = r_1t_1 + r_2t_2 + h(\sin\theta_1 + \sin\theta_2) \quad (1)$$

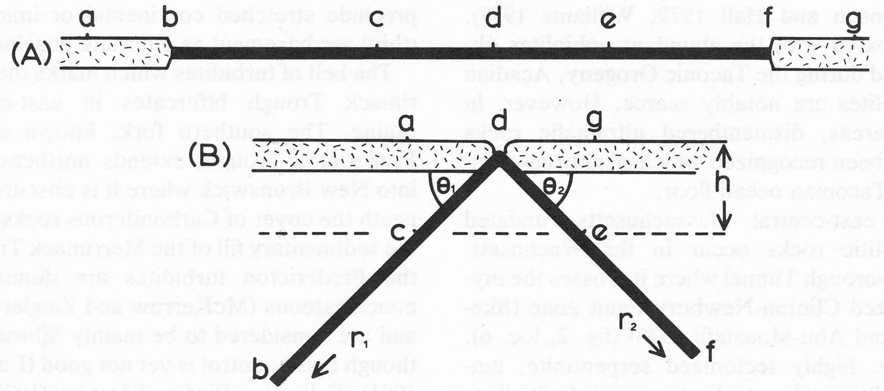


FIG. 3.—Method of estimating the original width of the Merrimack Trough (A), from the geometry and duration of subduction (B) inferred from geologic data. Terms in Equation 1 (see text) are equated with lengths in figure as follows: bf = w; bc = r_1t_1; cd = $h\sin\theta_1$; de = $h\sin\theta_2$; ef = r_2t_2. Points a and g are loci of arc volcanism.

then gives the width of the consumed oceanic plate. For the Merrimack Trough, h is taken to be 100 km, and 45° is estimated for θ_1 and θ_2. Based on the duration of volcanism, subduction beneath the Piscataquis Volcanic Arc lasted for about $t_1 = 50$ m.y.; beneath the Coastal Volcanic Arc for about $t_2 = 30$ m.y. Rates of convergence are not known. However, even at the very slow rates of $r_1 = r_2 = 0.5$ cm/yr, the pre-Silurian width of the trough is estimated at 680 km, and faster rates more typical of present day convergent plate boundaries would yield an even greater width. Thus, if the volcanics in the Piscataquis and Coastal belts are a record of subduction, the original width of the intervening area must have been substantial. Subduction of that amount of non-oceanic material seems unlikely.

Structure and Metamorphism.—If the Merrimack Trough closed by subduction beneath flanking arcs, some predictions can be made about early, pre-collisional structures. Folds and faults related to west-dipping subduction should verge to the east, while structures related to east dipping subduction should verge west. Such deformation might be accompanied by greenschist-facies metamorphism, but would most likely precede regional high grade metamorphism and anatexis.

A number of possible accretionary structures have been recognized in the Merrimack Trough. Probably most spectacular is a wedge of metamorphosed turbidites cut by west-dipping thrusts in northeastern Connecticut and adjacent Massachusetts (Rodgers 1981) (fig. 2, loc. 7). This belt, which measures about 30 km across strike, was related by Rodgers to post-Taconic, west-dipping subduction on the basis of its location and vergence.

Along strike in New Hampshire, the Merrimack Trough is dominated by subhorizontal, west vergent, synkinematic granite sheets (Nielson et al. 1976). Within the enclosing turbidite sequence, the presence of early recumbent folds is revealed by downward facing F2 isoclines, as at Mt. Kearsarge (Lyons 1979) (fig. 2, loc. 14). In southern Maine, Hussey (1978) reported west facing F1 recumbent folds, and farther along strike into lower grade rocks, Osberg (1980) demonstrated that upright F2 isoclines, which dominate the regional map pattern, refold an older generation of recumbent folds. These too may be west vergent (Osberg 1980), but it should be noted that the opposite vergence would be a corollary of a plausible alternate interpretation of the stratigraphy of central Maine. These early structures are probably more common in the trough than has generally been recognized. Early recumbent folds have also been noted locally in the southeastern Aroostook-Matapedia Trough near the Miramichi Massif (Rast et al. 1980), but these may be soft sediment structures, and in any case do not appear to be significant elsewhere in that belt. Moench and Zartman (1976) summarized evidence for pre-metamorphic fault-bounded fold packages of turbidites along the flank of the Merrimack Trough in northwestern Maine (fig. 2, loc. 16). Although Moench and Zartman (1976) interpreted the structures as syn sedimentary normal faults, they might instead be thrusts developed during subduction-accretion.

On a regional scale, it is evident that west vergent recumbent folds dominate the early structure of the Merrimack Trough in New Hampshire and Maine, while the structure is east vergent in southern Massachusetts and Connecticut. Rodgers (1981) noted that the regional northward plunge of the orogen allows the map to be viewed as an oblique cross section. This exercise suggests that the west vergent deformed turbidites of the Merrimack Trough structurally overlie the east vergent package.

Thompson et al. (1968) and Thompson and Rosenfeld (1979) have documented early Acadian tectonic transport of fold nappes westward from the Merrimack Synclinorium over the Bronson Hill Anticlinorium in western New Hampshire and north-central Massachusetts (fig. 2, loc. 5). The nappes are formed from Ordovician arc volcanics (Ammonoosuc) and black shale (Partridge), Silurian quartzite (Clough) and limestone (Fitch), and Devonian turbidites (Littleton). Based on the amplitudes of these recumbent folds, Thompson et al. (1968) estimated shortening of about 40 km took place in the cover sequence. This stratal shortening must have been accompanied by a comparable amount of eastward A-type subduction (Bally 1975) of arc basement from which the cover was removed.

In the Connecticut Valley-Gaspe Trough and at the eastern side of the foreland basin in New York, Acadian structures also verge toward the craton (Beland 1969). West and northwest of the Merrimack Trough, the only exception to this as a general direction of Acadian tectonic transport is in the Connecticut Valley-Gaspe Trough in southern Vermont and adjacent Massachusetts, where early structures verge east (Doll et al. 1961; Osberg 1975).

In the Merrimack Trough, Piscataquis Volcanic Arc, and Connecticut Valley-Gaspe Trough, initial recumbent folding was followed by a later phase of upright folding that accentuated the ancestral anticlinoria and synclinoria to generate the regional map pattern (Rodgers 1970). Acadian-reactivated basement forms the cores of the Oliverian gneiss domes in western New Hampshire (Naylor 1969) (fig. 2, area between locs. 5 and 12) which refolded the early west vergent nappes described by Thompson et al. (1968). Beneath the Connecticut Valley-Gaspe Trough in southeastern Vermont, the Taconic suture zone was folded to produce its complex map pattern around the Chester Dome (Rowley 1983) (fig. 2, loc. 4).

Acadian deformation was comparatively minor in the Coastal Volcanic Arc. Although folded, many lithologies lack penetrative deformation (Gates 1978; Shride 1976). The Silurian volcanic section in eastern Massachusetts is overturned but unmetamorphosed (Shride 1976) (fig. 2, loc. 15), and possibly even escaped deformation until the Carboniferous.

Acadian metamorphism and deformation were thus asymmetric across the strike of the orogen, with Avalonia escaping much of the damage suffered by rocks of the Merrimack-Fredericton Trough, Piscataquis Volcanic Arc and Connecticut Valley-Gaspe Trough.

Acadian Plutonism.—The same is not true of magmatism. Acadian plutons intruded every belt from the Gaspe Peninsula (Beland 1969) to southern Nova Scotia (Rodgers 1970), and were particularly abundant in the Piscataquis and Coastal Volcanic Arcs and in the Merrimack Trough. In the two belts identified as arcs on the basis of pre-Acadian volcanism, many of the Acadian melts were gabbroic and presumably of mantle derivation. Ultramafic to granophyric plutons comprising the Bays-of-Maine igneous complex (Chapman 1962) are coextensive with the slightly older Coastal Volcanic Arc. Likewise, in north central Maine, the gabbroic to granitic Greenville plutonic belt (Hon et al. 1981) is nearly coextensive with the Piscataquis Volcanic Arc.

In the Merrimack Trough, the main Acadian intrusives, assigned to the New Hampshire Plutonic Series (Billings 1956; Page 1968), are syn- and post-kinematic S-type granites (Loiselle and Ayuso 1979). These minimum melting granites are attributed to crustal thickening and partial melting during collision (Dewey and Kidd 1974).

POST-ACADIAN STRIKE-SLIP

Implicit in the cross sectional approach of most previous Acadian late tectonic models is the assumption that collision was followed by little, if any, later strike-slip. Carboniferous strike-slip faults are nonetheless prominent structures in southeastern New England and the Atlantic Provinces of Canada (Webb 1969), so it is evident that some post-orogenic lateral motion took place. It is important to determine whether this had a significant effect on the regional geology.

Paleomagnetic data are now widely interpreted to indicate about 2000 km of sinistral strike-slip, such that the Precambrian (i.e., Avalonian) rocks of eastern Massachusetts began the Carboniferous at about the latitude of Florida (with respect to North America), and came to rest opposite western Massachusetts some 25 m.y. later (Kent and Opdyke 1978; Van der Voo et al. 1979). If this hypothesis is correct, models of Acadian tectonics involving head-on collision (fig. 1) are probably not very useful.

Geologic evidence, on the other hand, has been interpreted to indicate the opposite sense of motion, and only about 300 km of displacement (Webb 1969). Strike-slip of this magnitude is much less likely to discredit Acadian tectonic models based on the rocks in their present positions. From the standpoint of the older geology, a resolution of this conflicting interpretation of late Paleozoic tectonics is clearly desirable.

The geologic evidence against large scale left lateral Carboniferous strike slip has been discussed recently (Bradley 1982*a*) and will only be summarized here.

Mapped Offsets.—Measurable strike-slip offsets of post-Acadian age are known for 12 faults in the Northern Appalachians, 11 of which are dextral. The lone sinistral fault (16 km on the Harvey-Hopewell Fault in New Brunswick) is probably a late reversal on an older dextral fault (Webb 1969); the sinistral motion post-dated that suggested by the paleomagnetic data.

Orientation of Pull-Apart Basins.—Strike-slip along a network of faults resulted in the development of a variety of extensional Carboniferous basins. Of the three most easily interpreted as simple rhomboidal pull-aparts (Magdalen Basin in the Gulf of St. Lawrence, Stellarton Subbasin in Nova Scotia, and southern Bay St. George Basin in Newfoundland), the geometry and orientation are consistent with right lateral motion.

Related Structures.—The orientations of *en echelon* folds in pull-apart strata in the Moncton Basin (New Brunswick) Minas Basin (Nova Scotia), and Deer Lake Basin (Newfoundland) are consistent with dextral shear.

For the above reasons, the hypothesis of 2000 km of sinistral motion is not considered very useful in explaining the regional geology of the Northern Appalachians. Recent paleomagnetic studies by Sequin (1982*b*) also cast doubt on the Kent and Opdyke (1978) model. The geologic evidence suggests that a much smaller amount of dextral slip occurred, mainly on faults parallel with pre-Acadian paleogeographic realms; this leads to the conclusion that head-on models of the Acadian collision are not at great risk of being discredited because of subsequent lateral motion.

MOLUCCA SEA COLLISION ZONE

The one modern example of a collision of two arcs over oppositely dipping subduction zones is in progress in the Molucca Sea (fig. 4), where at least 1000 km of oceanic crust has been subducted beneath the Helmahera and Sangihe Arcs during the Cenozoic (Hamilton 1978). Silver and Moore (1978) presented a model for the collision, based mainly on geophysical evidence, involving symmetric backthrusting over both accretionary prisms. This geometry seems only partly applicable in the case of the structurally asymmetric Acadian Orogen. Recent mapping in the Talaud Islands, where the Molucca Sea collision zone has emerged above sea level, suggests instead that the collision is asymmetric, with the Helmahera accretionary prism overriding its counterpart on the Sangihe side of the ocean (Moore et al. 1981). Seismic profiles show an undeformed flysch wedge in advance of the west vergent overthrust prism. Subsidence of the underthrust prism is presumably due to thrust loading (Silver and Moore 1978).

At present, the Sangihe Arc is emergent, and the collision zone itself is still almost completely below sea level. Hence, there is as yet no easterly source for clastics on the site of the arc. The most probable outcome of continued convergence would be the uplift of such a source area in the collision zone. Other developments which might result from continued convergence include subsidence of

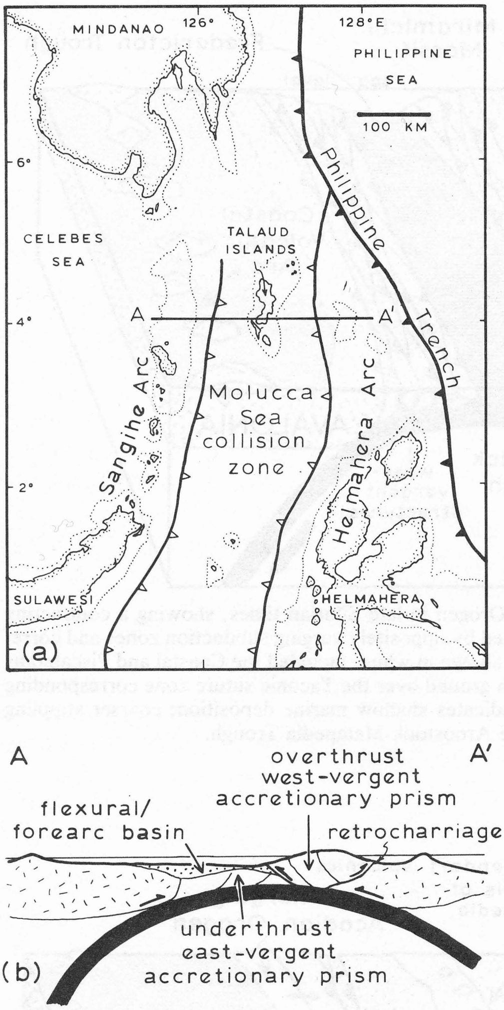


FIG. 4.—(A) Map and (B) cross section of the Molucca Sea collision zone, Indonesia, from Hamilton (1978) and Moore et al. (1981).

the arc beneath these clastics, followed by tectonic burial beneath the west vergent accretionary complex.

MODEL OF SILURO-DEVONIAN PALEOGEOGRAPHY AND PLATE GEOMETRY

The bilateral subduction model (McKerrow and Ziegler 1971) satisfactorily accounts for both the pre-Acadian paleogeography and for Acadian collisional tectonics. Figures 5 and 6 illustrate the major features of the model.

Figure 5 depicts the generalized paleogeography of the Northern Appalachian region during late Silurian. The Merrimack Trough is believed to have been a narrow, contracting ocean flanked by subduction zones where turbidites were scraped off the downgoing slabs and incorporated into oppositely-verging accretionary prisms. On the two continental margins, the Coastal and Piscataquis belts were chains of volcanic and nonvolcanic islands flanked by shallow water platforms (Boucot 1968; Roy 1980). Following McKerrow and Ziegler (1971), the Aroostook-Matapedia Trough is regarded as an embayment in the North American margin in which turbidite deposition was soon to be replaced by shallow marine and nonmarine volcanism. Behind the Piscataquis Volcanic Arc, the Connecticut Valley-Gaspe Trough is regarded as a zone of strike slip within which the Lac des Baies subbasin opened as a pull-apart.

Late Silurian conditions were probably not very different from those as far back as late Llandoverian, when the Merrimack-Fredericton ocean was wider, and the Taconic Orogen had greater relief. Paleogeographic maps by Boucot (1968), Lajoie et al. (1968), McKerrow and Ziegler (1971), and Roy (1980) illustrate the evolution of parts of the belt in greater detail.

Figure 6 illustrates the early Devonian paleogeography as the accretionary complexes began to collide. Analogous to the geometry proposed by Moore et al. (1981) in the Molucca Sea, the Avalonian accretionary prism is believed to have overridden (and thereby loaded) the western margin (Bradley 1982*b*). The cross-sectionary geometry depicted here resembles that proposed by Robinson and Hall (1979), except for the presence of three, rather than two plates; this eliminates the need for a delamination model (see figures by Robinson and Hall).

West-directed overthrusting created a migrating, asymmetric flexural basin of turbidite deposition. At the stage of development shown in figure 6, the turbidites (Seboomook, Littleton, etc.) had spread over the Piscataquis Arc and into the Connecticut Valley-Gaspe Trough. Sedimentary burial of the arc did not, however, coincide with an end to the supply from below of magmas. Hence, turbidites are interbedded with pillow lavas over the axis of the formerly emergent arc. These relations are shown in greater detail in figure 7, which also illustrates a mechanism for the

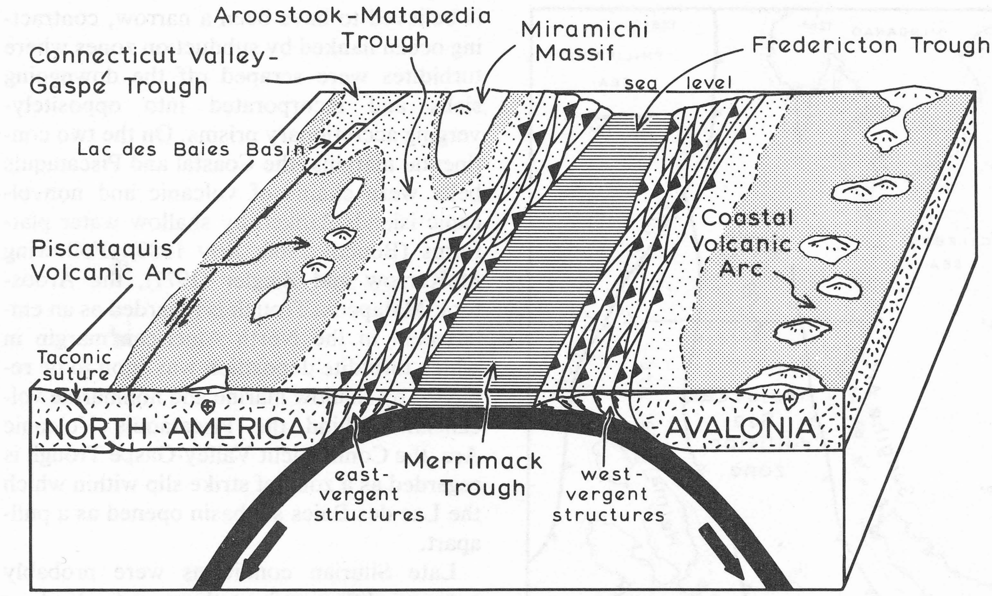


FIG. 5.—Proposed reconstruction of the Acadian Orogen in late Silurian times, showing a contracting Merrimack-Fredericton Ocean (horizontal lines) flanked by oppositely verging subduction zones and corresponding accretionary prisms. Emergent terranes are shown in white, included the Coastal and Piscataquis Volcanic Arcs, Miramichi Massif, and unlabelled high ground over the Taconic suture zone corresponding to "Appalachia" of Boucot (1968). Fine stippling indicates shallow marine deposition; coarser stippling shows areas of deeper water sedimentation, as in the Aroostook-Matapedia Trough.

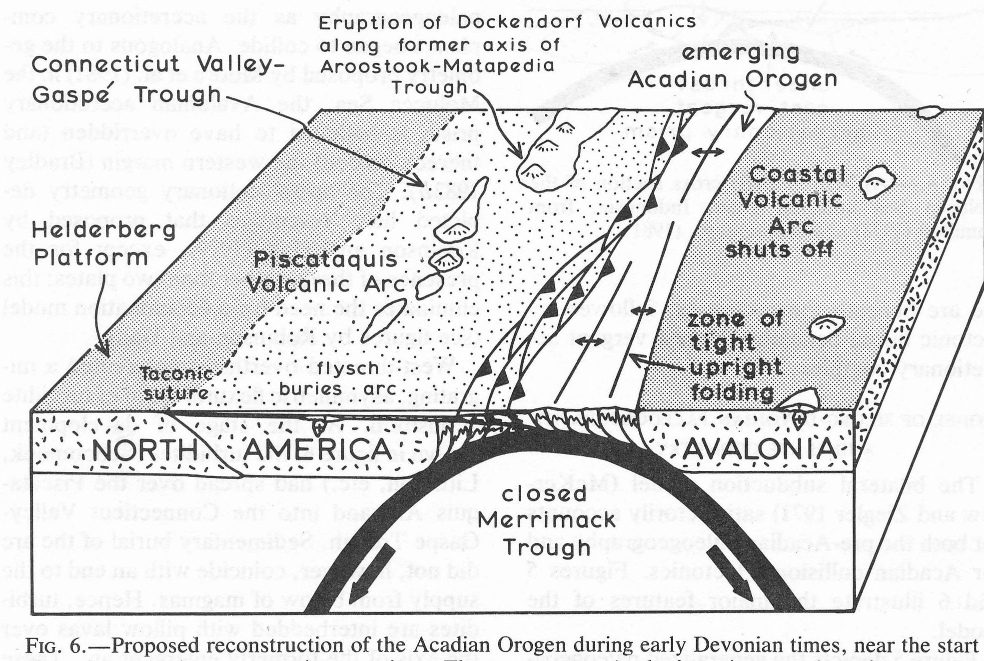


FIG. 6.—Proposed reconstruction of the Acadian Orogen during early Devonian times, near the start of collision between the two accretionary prisms. The west vergent Avalonian prism overthrust its counterpart on the North American side of the ocean, resulting in rapid burial of the Piscataquis Volcanic Arc and the Connecticut Valley-Gaspe Trough beneath a great wedge of easterly-derived flysch. Ornament as in figure 5.

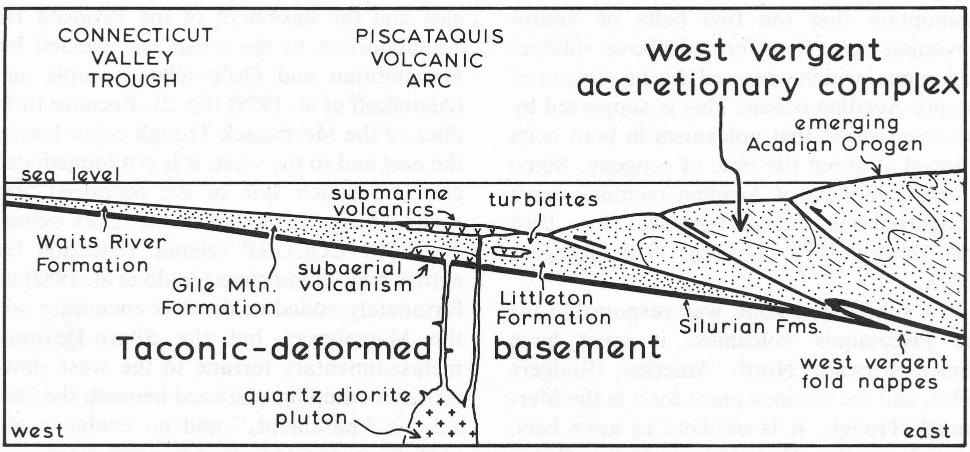


FIG. 7.—Illustration of the effects of downflexing of the North American margin beneath the weight of the advancing Avalonian accretionary complex. Heretofore subaerial and shallow marine conditions in the Piscataquis belt were replaced by deep water flysch sedimentation and sporadic submarine volcanism. Transport of the early west vergent fold nappes of Thompson et al. (1968) is here attributed to shear stress imposed by the overthrusting accretionary complex.

tectonic transport of the west-vergent nappes of Thompson et al. (1968). By early Devonian, volcanism in the Piscataquis belt had spread across strike, as lavas were erupted on Silurian turbidites in the former Aroostook-Matapedia Trough. The youngest volcanics of the Coastal belt were erupted during this time. Orogenesis was not yet evident on the craton and future molasse basin in New York, where limestones (Helderberg Group) followed by littoral sands (Oriskany Sandstone) were deposited.

Collision lasted into late Devonian, and was diachronous both along and across strike. In a classic paper, Donohoe and Pajari (1973) summarized the timing of orogeny, and demonstrated that Acadian deformation was progressively younger toward North America and to the south. Acadian deformation is dated as Siegenian at Chaleur Bay (Donohoe and Pajari 1973) (fig. 2, loc. 32), Emsian at Katahdin, Maine (Donohoe and Pajari 1973) (fig. 2, col. 21), and post-Emsian, presumably Eifelian, at Lac Memphremagog in southeastern Quebec (Boucot 1968) (fig. 2, loc. 11). Synsedimentary growth of anticlines in northern Pennsylvania during latest Devonian (Woodrow 1968) (fig. 2, loc. 35) indicates continued southward progress of deformation. This pattern within the Northern Appalachians is consistent with that recognized on a larger scale by Dewey and Kidd (1974) and Graham et al. (1975) for the Caledonian-Appalachian-Ouachita-Marathon system as a whole, in which collision ranged from Silurian in the north to Permian in the south.

Dextral strike slip on northeast-trending faults dominated the regional tactonics during the latest Devonian and Carboniferous (Bradley 1982*a*). Most of the motion took place on faults cutting the Avalonian side of the Acadian Orogen, but Carboniferous faults with small offsets also occur in the Fredericton Trough, Miramichi Massif, and Aroostook-Matapedia Trough. There is some evidence that this episode of strike slip began as early as mid-Devonian, while Acadian compressional deformation was still underway closer to the North American Craton. Ludman (1981) indicated that northeast-trending high angle faults were active in southeastern Maine during intrusion of medial Devonian plutons. This late- and post-orogenic strike slip is considered to be a manifestation of continental escape, with Avalonia moving southwards toward the ocean which had not yet closed in the Southern Appalachians, Ouachitas, and Marathons. Bobyarchick (1981) presented a similar interpretation of the presumably younger Eastern Piedmont fault system in the Southern Appalachians.

DISCUSSION

The early model of McKerrow and Ziegler (1971) is only one of many proposed for the Acadian Orogeny (fig. 1). It is based on the assumption that the two belts of Siluro-Devonian volcanism formed above subduction zones, which operated during closure of the pre-Acadian ocean. This is supported by the observation that volcanism in both belts stopped at about the time of orogeny. Some alternate models of Acadian tectonics have recognized one, but not both arcs (e.g., Bird and Dewey 1970; Osberg 1978; Rodgers 1981).

If a subduction zone was responsible for the Piscataquis volcanics, it must have dipped beneath North America (Rodgers 1981), and the obvious place for it is the Merrimack Trough. It is unlikely to have been located in the Connecticut Valley-Gaspe Trough, which, following the Taconic Orogeny, was underlain by continental crust. Some extension evidently did occur in that belt in Silurian, but subsidence was only localized, ruling out the presence of a post-Taconian ocean.

The case for ocean floor in the Merrimack Trough is stronger, but not without difficulties. One is that in Connecticut, the east-vergent accretionary prism of Rodgers (1981) is apparently surrounded on the west, south, and east by a belt of amphibolites that have been correlated on the basis of lithology and apparent continuity of outcrop with the Ammonoosuc Volcanics in New Hampshire. These rocks are believed to mark the Taconic arc terrane, and would not be expected on the east of the turbidites regarded by Rodgers (1981) as a post-Taconic accretionary prism. Such lithologic correlations are hazardous in any orogenic belt but are especially so in this part of southern New England, where already complex Acadian geologic relations were aggravated during the late Paleozoic Alleghanian Orogeny. This involved metamorphism to the sillimanite grade in the Narragansett Basin, Rhode Island (e.g., Rodgers 1970) (fig. 2, loc. 10), and large scale overthrusting on the south vergent Honey Hill and east vergent Lake Char Faults in eastern Connecticut (Rodgers 1981) (fig. 2, locs. 9 and 8).

Along strike in southern New Hampshire, the concept of a pre-Acadian ocean in the Merrimack Trough meets with some difficulty in accounting for the presence of the Massabesic Gneiss (Fitchburg Pluton of Billings 1956) (fig. 2). This continental basement, in common with Avalonian rocks to the east and the basement of the Bronson Hill Anticlinorium to the west, has yielded late Precambrian and Ordovician isotopic ages (Aleinikoff et al. 1979) (fig. 2). Because turbidites of the Merrimack Trough occur both to the east and to the west, it is not immediately clear on which side of the proposed Merrimack ocean these basement rocks belong. The 1981 COCORP seismic reflection line across New Hampshire (Ando et al. 1982) unfortunately ended at the first encounter with the Massabesic, but the Siluro-Devonian metasedimentary terrane to the west shows reflectors dipping eastward beneath the Massabesic "basement," and no evidence of a root zone for the west-vergent nappes of Thompson et al. (1968). This root zone must therefore be sought to the east, within the belt of ophiolite occurrences discussed earlier. By this reasoning, the Massabesic continental basement lies to the west of the site of the pre-Acadian ocean, as Osberg (1978) suggested.

If a subduction zone was responsible for the Coastal volcanics, it could have been located either (1) in the Merrimack-Fredericton Trough, or (2) in the present offshore area. The latter has been suggested by Ruitenberg et al. (1977) (fig. 1) and Poole (1976). If the Acadian Orogeny was the result of continental collision, a subduction zone southeast of the Coastal Volcanic Arc requires the arrival in Devonian of another continental fragment; this possibility is difficult to evaluate because there are no outcrops to examine. McKerrow and Zielger (1971) and Osberg (1978) advocated a southeast-dipping subduction zone located in the Merrimack-Fredericton Trough. This has the advantage of being testable, and is compatible with deep water conditions in Silurian in the trough.

As argued here, two subduction zones in the Merrimack-Fredericton Trough provide a framework for the regional Silurian paleogeography, as well as Devonian subsidence, flysch sedimentation, and west vergent deformation on the North American side of the trough. The same plate geometry has been proposed on independent grounds to rationalize the slightly earlier Caledonian collision along strike in the British Isles (Phillips et al. 1976). It is unclear whether or not this geometry can be carried southwards into the Central and Southern Appalachians, where later Paleozoic overthrusting was intense, or northward into Newfoundland. These possibilities might be profitably explored.

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