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Paleozoic orogens in New England, USA

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Abstract: Stratigraphy and isotope geochronology in the crystalline core of the Appalachians suggest revised interpretations of the extent, nature and timing of Paleozoic orogens in New England. Five major episodes of magmatism, deformation, and high-grade regional metamorphism are recognized: Taconian (455–442 Ma), Acadian (423–385 Ma), Neo-Acadian (366–350 Ma), Late Pennsylvanian (300–290 Ma) and Alleghanian (280–260 Ma). In the Taconian, the passive margin of Laurentia was subducted below a complex magmatic arc lasting from 480 to 442 Ma, founded in part on continental crust of a Medial New England terrane with possible affinities with Amazonia. Questions about Medial New England involve its coherence as a single plate, and the nature of its underlying crust. The Acadian began in Late Silurian as a collision between the amalgamated Laurentia-Medial New England and outer belts of Composite Avalon along a cryptic suture in coastal Maine, and progressed northwestward to the Connecticut Valley basin by mid-Devonian. Tonalitic-granitic magmatism and up to granulite-facies metamorphism culminated in Early Devonian, possibly tied to lithospheric detachment below the subducting northwestern plate and consequent asthenosphere upwelling. Newly discovered Neo-Acadian Late Devonian to Early Mississippian tonalitic-granitic magmatism, up to granulite-facies metamorphism, and severe deformation in central Massachusetts took place in a plate context poorly understood. Late Pennsylvanian effects include magmatism, metamorphism, and deformation near south New England gneiss domes and the Sebago batholith, and development of the right-lateral Norumbega fault system. Permian Alleghanian effects include penetrative deformation, granitic intrusions and up to sillimanite-grade metamorphism of Pennsylvanian beds in southeastern New England. These last two episodes relate to the arrival of Africa.

Keywords: Northern Appalachians, Taconian, Acadian, Alleghanian, stratigraphy, plate tectonics, plutonism, deformation, metamorphism, geochronology.

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Since the early days of geology in the 19th century, the Appalachian Mountains have served as a laboratory for work on the tectonics of mountain ranges and orogeny. This is explained in part by their early population by European settlers and early industrial development, relatively subdued topography and accessibility, and proximity to institutions of higher learning. They served as a breeding ground for ideas about orogeny (Hall 1859; Logan 1861; Dana 1873*a*), for the geosynclinal theory (Dana 1873*b*; Kay 1951), for understanding the role of ultramafic rocks (Hess 1946, 1955), and for the application of plate tectonics to mountain building (Wilson 1966; Kay 1969; Dewey 1969; Bird & Dewey 1970; Dewey & Bird 1970; Zen 1983, 1989). The Taconian, Acadian, and Alleghanian orogenies have become standard textbook fare, selected by Press & Siever (1982) as three of the 17 "Major Known Geological Events" to be displayed inside the front cover of their popular text. These orogenies have been factored into nearly all the recent models of global tectonics and plate collisions (Scotese 1984; McKerrow et al. 1991; Torsvik et al. 1992; van der Voo 1993; Dalziel 1995; MacNiocaill et al. 1997) yet in many cases attempts to divine a "global understanding" of these events have outstripped understanding of what has taken place on a local scale.

Significant progress is being made, notably in Newfoundland, the Maritime Provinces, and Quebec in Canada, where metamorphic intensity is low on average, and fossil evidence relatively abundant. It is also being made in the central and southern Appalachians, where the youngest events are well preserved in fossiliferous strata, but where the evidence for earlier events is obscured by intense metamorphism, poor outcrop and deep chemical weathering. The New England Appalachians, transitional between these northern and southern regions, have the advantage of proximity to the fossil records of both, but also experienced some of the most intense metamorphism and severe compressional deformation in the orogen, as well as extensional and strike-slip faulting. Near the latitude of Boston, the distance from weakly disturbed, little metamorphosed, fossiliferous Cambrian strata of the Avalon zone on the east, to the undisturbed fossiliferous Cambrian strata of Laurentia on the west is only 230 km, yet between these points there are areas where Silurian-Lower Devonian strata were metamorphosed to pyroxene-granulite facies!

Purpose

This paper is an effort by a diverse group of geologists with experiences that encompass a wide part of the region, to bring some broad aspects of New England geology into focus, based on stratigraphy, recent isotopic ages of igneous and metamorphic rocks, and time-scale refinements (Tucker & McKerrow 1995; Tucker et al. 1997 and in press *a*). Our attention is broad but not comprehensive. We hope this will give readers a clearer picture of the record of events as we presently understand them, a useful framework for future studies in the same region, and an outline for future global plate reconstructions.

Orogenies in New England

The word "orogeny" implies the formation of mountains by tectonic processes, commonly accompanied by erosion, transport

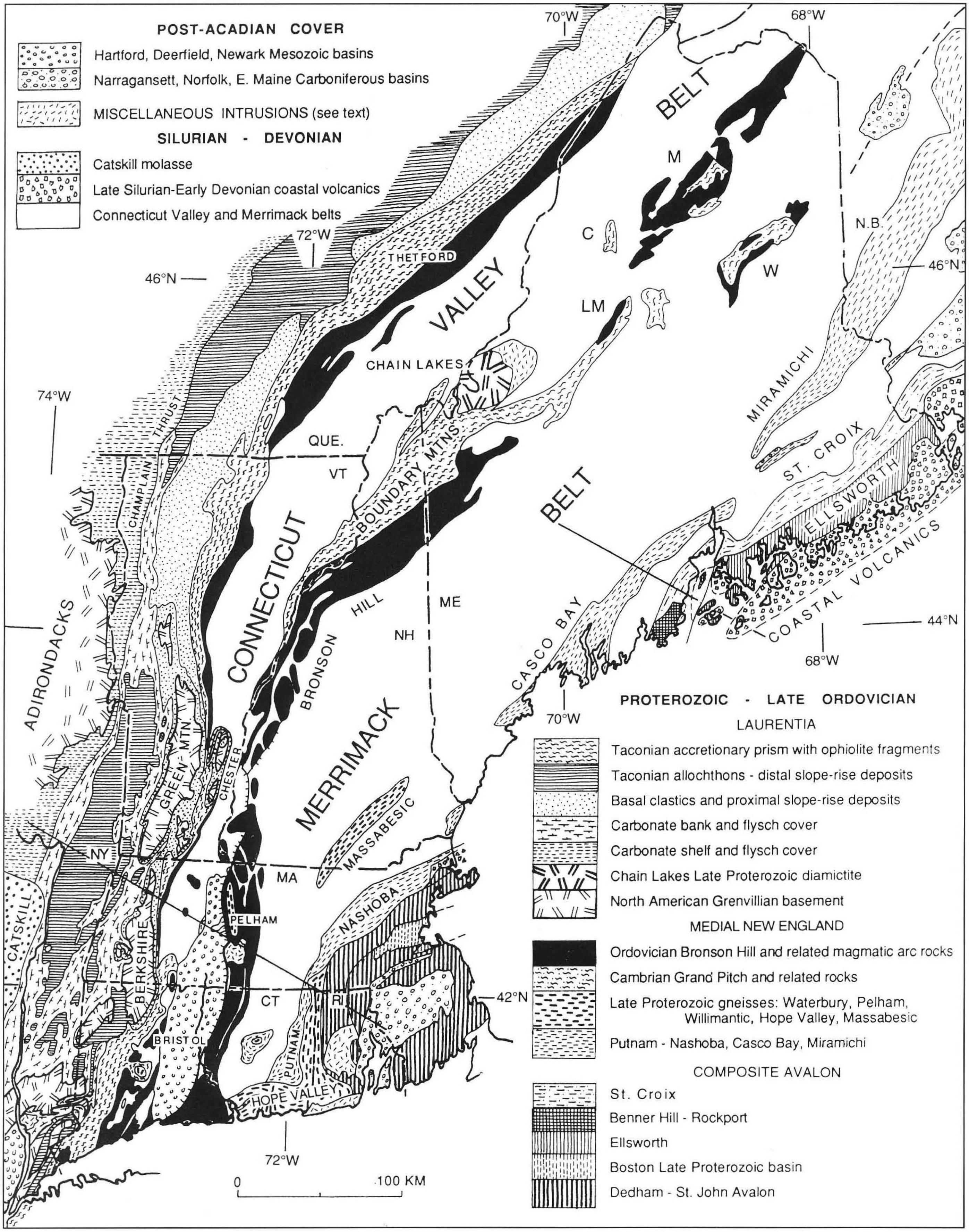
POST-ACADIAN COVER
Hartford, Deerfield, Newark Mesozoic basins
Narragansett, Norfolk, E. Maine Carboniferous basins
MISCELLANEOUS INTRUSIONS (see text)
SILURIAN - DEVONIAN
Catskill molasse
Late Silurian-Early Devonian coastal volcanics
Connecticut Valley and Merrimack belts
PROTEROZOIC - LATE ORDOVICIAN
LAURENTIA
Taconian accretionary prism with ophiolite fragments
Taconian allochthons - distal slope-rise deposits
Basal clastics and proximal slope-rise deposits
Carbonate bank and flysch cover
Carbonate shelf and flysch cover
Chain Lakes Late Proterozoic diamictite
North American Grenvillian basement
MEDIAL NEW ENGLAND
Ordovician Bronson Hill and related magmatic arc rocks
Cambrian Grand Pitch and related rocks
Late Proterozoic gneisses: Waterbury, Pelham, Willimantic, Hope Valley, Massabesic
Putnam - Nashoba, Casco Bay, Miramichi
COMPOSITE AVALON
St. Croix
Benner Hill - Rockport
Ellsworth
Boston Late Proterozoic basin
Dedham - St. John Avalon
70°W
68°W
72°W
74°W
46°N
44°N
42°N
BELT
M
C
W
LM
VALLEY
THETFORD
CHAIN LAKES
N.B.
MIRAMICHI
ST. CROIX
ELLSWORTH
COASTAL VOLCANICS
CASCO BAY
BELT
QUE.
VT
ME
NH
MA
CT
RI
NY
BOUNDARY MTNS
CONNECTICUT
BRONSON HILL
MERRIMACK
MASSABESIC
ADIRONDACKS
CHAMPLAIN THRUST
GREEN MTN
CHESTER
PELHAM
NASHOBA
BERKSHIRE
CATSKILL
BRISTOL
PUTNAM
HOPE VALLEY
0 100 KM

Fig. 1. Generalized tectonostratigraphic map for New England and adjacent regions. Explanation in lower right shows the grouping of Proterozoic to Late Ordovician rocks into three terranes, Laurentia, Medial New England, and Composite Avalon. Dashed line at the northeast corner of the map shows the location of the Brunswick subduction complex projected from the northern Miramichi Highlands. Explanation to upper left shows grouping of Silurian to Devonian strata, miscellaneous intrusions, and Carboniferous and Mesozoic strata. Most Silurian and younger intrusions are omitted. Pennsylvanian strata occur in the Narragansett and Norfolk basins, southeast New England, in a tiny basin in eastern Maine, and in four basins too small to show in central Massachusetts just west of the Nashoba belt. Mississippian-Pennsylvanian basins are also shown in New Brunswick. Abbreviations indicate the locations of Canadian Provinces and U.S. states: New Brunswick (N.B.), Quebec (QUE.), Maine (ME), New Hampshire (NH), Vermont (VT), New York (NY), Massachusetts (MA), Rhode Island (RI) and Connecticut (CT). The Cape Cod part of Massachusetts, consisting of sand and gravel, is not shown. Boston lies at the east end of the Boston Late Proterozoic basin. New York City is at the extreme southwest corner of the map at the mouth of Hudson River. Other locations shown by abbreviations as follows: Lobster Mountain volcanics (LM), Caucomgomoc inlier (C), Munsungun anticlinorium (M), and Weeksboro-Lunksoos Lake anticlinorium (W). Line of section in Fig. 3 is shown in coastal Maine; line of section in Fig. 8 is shown in southern New England.

and deposition of sediment in adjacent areas. In this paper, emphasizing the crystalline core of the New England Appalachians, we describe a limited though intriguing record of erosion and sedimentation, but lack the space and expertise necessary to track "orogenesis" in detail, as recorded in the sedimentary record outside the orogen. Instead we have concentrated much of our attention on crustal activity within the orogen as proxy for orogenesis; times of coupled plutonism, high-grade regional metamorphism, and ductile deformation as recorded by U–Pb geochronology of zircon, monazite and sphene.

Events indicated to dominate the New England Appalachians in earlier summaries were (1) Taconian (Middle to Late Ordovician); (2) Acadian (Latest Silurian to Middle Devonian); and (3) Alleghanian (Permian). In plate-tectonic terms these were commonly characterized, respectively, as (1) collision of the then south margin of Laurentia with an island arc (Chapple 1973, 1979; Stanley & Ratcliffe 1985); (2) continental collision between Laurentia and the Avalon fragment of Gondwana, and (3) continental collision of amalgamated Laurentia-Avalonia with the African fragment of Gondwana. Osberg (1978) defined a "medial zone" of the Appalachian Mountain belt, later modified to "medial New England terrane" (Osberg et al. 1989), which he considered as exotic to Laurentia until the Middle Ordovician. He showed Composite Avalon (his "Basement D") colliding with Medial New England (his "Basement C") in the Lower Devonian to produce the Acadian orogeny. Williams (1979) had suggested that the Taconian, at least in Newfoundland, was the main Laurentia-Avalon continental collision which closed the Iapetus Ocean in the Ordovician. His perspective was indicated by referring to the Silurian-Devonian basins of New England as "successor basins" and showing them on his famous tectonic-lithofacies map (Williams 1978) in yellow, a color reserved for Quaternary alluvium on U.S. Geological Survey quadrangle maps. Recently, workers based in New Brunswick (van Staal 1994; van Staal & de Roo 1995; van Staal et al. 1996, 1998*a*, 1998*b*) have indicated that the Miramichi terrane, equated with part of Medial New England of Osberg and this paper, and with the peri-Gondwanan Gander Zone of Newfoundland, was still at high paleomagnetic latitude in the Llanvirn and arrived in proximity to Laurentia only in the Late Silurian. Others, especially from work in southern New England, believed that Avalon did not arrive until the Late Paleozoic Alleghanian orogeny (Zartman & Naylor 1984; Wintsch & Sutter 1986; Mosher et al. 1993; see discussion in Wintsch et al. 1993).

In this paper we attempt to decipher the status of Medial New England and its potential roles, both in the Taconian orogeny on the northwest, and the Acadian orogeny on the southeast. From relationships in northern New England, we will argue that at least the St. Croix and Ellsworth belts of Composite Avalon collided with Medial New England in the Silurian-Devonian to produce the Acadian orogeny. However, the more traditional part of Avalon as represented by the rocks close to St. John, New Brunswick, and in southeastern New England lack evidence for Silurian-Devonian magmatism (except alkalic plutons), metamorphism and deformation, and may have been emplaced along strike-slip faults in the Late Paleozoic. With this possible exception, we suggest that the Late Paleozoic thermal and deformational effects in New England must have taken place entirely on the North American side of any suture with Africa. However, rather than a single post-Acadian orogeny, we here recognize three intense thermal and deformational episodes, Late Devonian to Early Mississippian (tentatively called Neo-Acadian), Late Pennsylvanian, and the Permian Alleghanian orogeny.

In carrying out our analysis we have attempted to account for the positions of the various rock units and terranes today. We recognize that many present juxtapositions, particularly of rocks of widely diverse character and metamorphic grade in eastern New England, occurred as a result of large scale dislocation by strike-slip or dip-slip faulting, mainly during the Late Paleozoic and Mesozoic. We believe that this evidence is important to kinematic models, but we downplay it here in favor of regional evidence for the formative stages of New England crust.

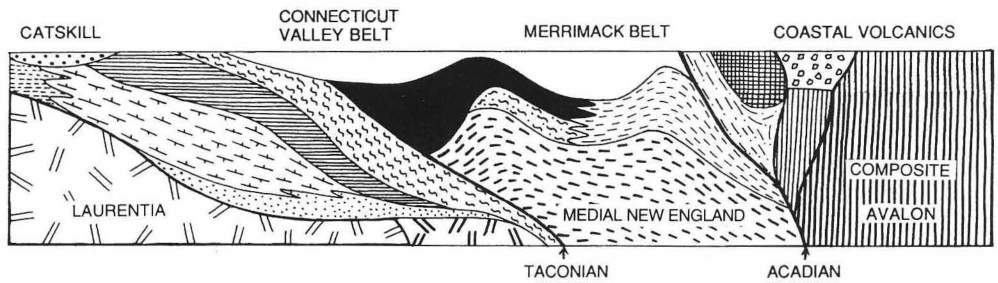

Fig. 2. Schematic east–west cross section across New England showing the main subdivisions of Proterozoic to Late Ordovician rocks into three terranes separated by two sutures, and also the main subdivisions of Silurian to Devonian cover which help to distinguish previously amalgamated Laurentia plus Medial New England from Composite Avalon.

Organization of the paper

We have chosen to organize this paper chronologically in terms of the five major series of events in the region: Taconian (460–440 Ma), Acadian (420–385 Ma), Neo-Acadian (370–354 Ma), Late Pennsylvanian (300–290 Ma) and Alleghanian (280–260 Ma). Figures 1 and 2 illustrate the broad features of New England bedrock geology, serve as a key to discussions throughout the paper, and provide an outline of the three major plates and two sutures believed to dominate the region. The three plates, Laurentia, Medial New England, and Composite Avalon are emphasized by their different Proterozoic-Late Ordovician rocks as outlined in the lower right part of Fig. 1 and illustrated in cartoon fashion in Fig. 2. After the proposed Late Ordovician amalgamation of Medial New England and Laurentia, there is a further distinction in the Silurian-Early Devonian cover on these amalgamated plates, and on Composite Avalon as outlined in the upper left of Fig. 1. This is emphasized by the variably thick sequences of marine clastic strata of the Merrimack and Connecticut Valley Belts on Medial New England-Laurentia, as contrasted with the Late Silurian-Early Devonian coastal volcanics on the western part of Composite Avalon.

In the far west of the map, the area labelled Catskill includes a thin Late Silurian-Early Devonian carbonate sequence resting unconformably on deformed Ordovician strata, and overlain by the Middle Devonian molasse that was shed westward from New England during the Acadian orogeny. With miscellaneous exceptions, the reader is cautioned that many post-Ordovician igneous intrusions are omitted from the map and is referred to a published summary map (Sinha 1988) to appreciate that, except for northern Maine and west of the Green Mountain axis, the region is pervaded by plutons, including those of the Triassic to Cretaceous White Mountain Magma Series. Late Triassic-Early Jurassic continental strata and basalts in the southwest part of the map were deposited during early phases of rifting that produced the modern Atlantic Ocean.

Taconian

The Taconian was the first orogenic event in New England to be understood in the context of plate tectonics because the Laurentian foreland edge of the Appalachians records some of its most important manifestations, well dated by fossils. The foreland record is only outlined here, in order to concentrate on presumed Taconian features of the hinterland.

Neoproterozoic rifting and Cambrian-Ordovician passive margin

The plate-tectonic record begins with the Neoproterozoic rifting of Laurentia from other continental masses, possibly Baltica and/or Amazonia, and formation of rift volcanics and sedimentary successions. These include the Tibbitt Hill Greenstones (Kumarapeli 1976; Kumarapeli et al. 1981, 1989; Doolan et al. 1982; Coish et al. 1985; Ratcliffe 1987) exposed in northern Vermont and southern Quebec, for which a U–Pb zircon age of 554 Ma has been obtained on an interbedded felsite (Kumarapeli et al. 1989). The rift setting is suggested by a large positive gravity anomaly, supposedly reflecting an ancient triple junction in a location just southeast of Montreal, in which the Ottawa-Bonnechere graben would correspond to the failed arm. Rifting was succeeded by the establishment of a passive margin sequence and a low-latitude carbonate bank on the Laurentian margin, which existed along the then south coast of Laurentia from earliest Cambrian through middle Ordovician (Rodgers 1968).

Ophiolite emplacement and its setting

The first record of compressional events was the emplacement of ophiolite onto sediments supposed to belong to the distal Laurentian continental margin in the late Cambrian to earliest Ordovician (St-Julien & Hubert 1975, 1979; Laird & Albee 1981*a*, 1981*b*). Ophiolites are exposed in two main belts, one along the Baie Verte-Brompton line (Williams & St-Julien 1982) from western New England through the Thetford area, Quebec, to Gaspé, and to Newfoundland, and a second belt, containing ophiolite of the Boil Mountain Complex in the Boundary Mountains anticlinorium in northwestern Maine (Boudette & Boone 1976; Boudette 1982; Kusky et al. 1997). The Boil Mountain Complex is emplaced above the Chain Lakes "massif" (Boudette et al. 1989), a unit now interpreted as a detrital assemblage of older high-grade Proterozoic gneiss fragments, probably deposited in the late Proterozoic proximal to the Laurentian margin (Dunning & Cousineau 1990; Trzcienski et al. 1992*a*) and intruded by the Ordovician 463 Ma Attean pluton (Fig. 1). Kusky et al. (1997), on the basis of the detrital zircons in Chain Lakes rocks, argue that they have Gondwanan affinities like the Gander zone margin of Avalon, but G.R. Dunning (pers. comm. 1998) argues that the signature is unmistakably Laurentian, with one group of zircons from 1170 to 1000 Ma that fits the range of nearby Grenvillian events. Opinion is divided as to whether the two ophiolite belts are widely separated parts of the same ophiolite thrust sheet (W.E. Trzcienski, pers. comm. 1990, 1997; Pinet & Tremblay 1995) or two separate belts (Osberg 1978; Boone & Boudette 1989; Kusky et al. 1997).

Young age plus geochemical characteristics led Shaw & Wasserburg (1984) to suggest that the Thetford ophiolite formed in a back-arc basin; Tremblay (1992) considered it to be fore-arc oceanic crust; Pinet & Tremblay (1995) suggested an intraoceanic setting; Hébert & Bédard (1998) give strong evidence for genesis in an arc setting. Plagiogranite in the Thetford ophiolite has been dated at 479 Ma (Dunning et al. 1986; Dunning & Pedersen 1988) and in Orford at 504 Ma (David & Marquis 1994), generally consistent with a wide geographic range of ophiolite localities in Newfoundland, Ireland, Scotland and Norway in the range 495–480 Ma (Pedersen & Furnes 1997). In the upper part of the Thetford ophiolite there is a transition in basalt volcanic chemistry from MORB-like to tholeiitic arc-like to boninitic (Laurent 1977; Laurent et al. 1979; Tremblay 1992; Hébert & Bédard 1998), suggesting ophiolite genesis in the setting of a rifted immature intra-oceanic arc, a process that may have led to subsequent hot emplacement of the ophiolite onto the continental margin (St-Julien & Hubert 1979; Stanley et al. 1984), as well as early high-P, low-T metamorphism (Laird & Albee 1981*a*, 1981*b*; Laird et al. 1984), as worked out in detail in the case of Oman (Coleman 1981; Ghent & Stout 1981; Lanphere 1981; Saddiqi et al. 1995). It is puzzling that thrust emplacement of ophiolite onto the supposed outer continental margin seems to have had no noticeable effect on deposition in the co-eval carbonate bank and shelf. The Thetford ophiolite is commonly overlain by the St. Daniel melange (St-Julien & Hubert 1979), a complex sedimentary melange dominated by fragments of the underlying continental margin sedimentary rocks as well as ophiolite fragments with evidence of the older metamorphism.

The St. Daniel melange is overlain by finer-grained clastic sedimentary rocks and in turn by the Ordovician Ascot-Weedon arc-volcanics. The Ordovician volcanics appear to be magmatically similar and broadly time-correlative with volcanics and contemporary intrusive rocks of the Bronson Hill anticlinorium in New Hampshire, Massachusetts and eastern Connecticut, as well as a broad region of volcanics extending discontinuously from the Boundary Mountains into northern Maine. However, Tremblay (1992) makes a strong case that the Ascot Volcanic Complex is older and separate from the Bronson Hill magmatic arc, and Pinet & Tremblay (1995) develop a tectonic model for Quebec and northern Maine, showing early arcs on oceanic crust and a younger arc on Medial New England continental crust which collided with the Laurentian margin between 450 and 440 Ma to produce the final phases of Taconian orogeny.

Tonalite intruding the Boil Mountain ophiolite has been dated at 477 Ma (Kusky et al. 1997), a suspiciously young age for the ophiolite because of its apparent pre-Ordovician stratigraphic position, and because a volcanic member of the overlying Jim Pond Formation has been assigned a tentative age of about 520 Ma (Moench et al. 1995) from U–Pb data on three of five zircon size fractions. The Boil Mountain ophiolite in northwestern Maine (Boone et al. 1989; Boone & Boudette 1989), is overlain by melange and other sedimentary rocks of the Hurricane Mountain Formation and in turn by fine-grained clastic sedimentary rocks of the Dead River Formation. Primitive sponges from the Hurricane Mountain Formation (Harwood 1973) indicate a probable Cambrian to possibly Early Ordovician age (R.M. Finks, Jr., pers. comm. to Boone et al. 1989). Metamorphosed gabbro intrusive into the Hurricane Mountain Formation yielded a ca. 485 Ma ^{40}Ar–^{39}Ar age on amphibole (Boone et al. 1989). In the Lobster Mountain anticlinorium (Fig. 1), the Hurricane Mountain Formation is overlain unconformably by the Lobster Mountain volcanics of Ashgill age (Neuman 1973). In a small syncline along the northwest side of the Weeksboro-Lunksoos Lake anticlinorium (Fig. 1) red and green slates of the Cambrian(?) Grand Pitch Formation are unconformably overlain by feldspathic sandstones, tuffs, and minor volcanics of the Shin Brook Formation, dated by fossils as Arenig (Neuman 1964, 1967). The presence of an early slaty cleavage below this unconformity and its absence above, marks the pre-Arenig Penobscottian orogeny. The unconformity in the Lobster Mountain area may also reflect the Penobscottian orogeny, even though the formations above and below it are not the same (Boone et al. 1989).

On the basis of field relationships in eastern Newfoundland and New Brunswick, van Staal et al. (1996) argue that the Penobscottian unconformity is a characteristic feature developed after earliest Arenig obduction of ophiolite onto the peri-Gondwanan Gander zone Avalon margin of Iapetus, and Kusky et al. (1997) adopt this setting for the Boil Mountain ophiolite and its overlying unconformity. We also suggest subtle but important distinctions between ophiolites and melanges of Thetford-St. Daniel *versus* Boil Mountain-Hurricane type, placing the pre-Arenig rocks of the Caucomgomoc and Munsungun areas in the former, and Weeksboro-Lunksoos Lake in the latter. If these interpretations are correct, then, as indicated by van Staal et al. (1996), ophiolite obduction on the Gander margin (here equated with part of Medial New England) was going on contemporaneously with ophiolite obduction on the Laurentian margin, and these two ophiolite belts, from once widely separated locations, are now separated by 40 km or less. A further implication is that the Bronson Hill magmatic arc rocks, discussed below, would appear to have been built on either oceanic or continental crust of Gondwanan affinity.

In Vermont, western Massachusetts and western Connecticut the stratigraphic-tectonic relationships between ophiolites and related sedimentary and volcanic rocks are greatly obscured by the more intense later deformation and metamorphism.

Taconian convergence on Laurentia and emplacement of thrust slices

On the carbonate bank, the first sign of an impending Taconian orogeny was uplift and erosion, events attributed to a migrating flexural forebulge (Rowley & Kidd 1981; Jacobi 1981). At this time, the platform was cut by normal faults with throws up to many hundreds of meters, believed to record flexural extension of the thrust-loaded North American margin (Bradley & Kidd 1991). The erosion interval was short but the unconformity locally profound so that Late Ordovician strata locally rest on Proterozoic basement (Thompson 1959, 1967; Zen & Hartshorn 1966; Hall 1968; Ratcliffe 1969). A diachronous drowning succession followed the unconformity (Bradley & Kusky 1986). Platform carbonates above the unconformity gave way to black shales, then graywacke turbidites of the Taconian foredeep.

The deposition of black shale and turbidites seems to have been followed very quickly by the emplacement of the Taconic allochthon, an enormous thrust sheet of continental slope-rise clastic sedimentary rocks of the same age range but thinner than the adjacent carbonate bank sequence. The allochthon covers very large areas above the bank carbonate rocks in southwestern Vermont, western Massachusetts, western Connecticut, and adjacent New York (Fig. 1). Evidence of the close proximity of the carbonate bank during deposition of the Taconic clastic facies is provided by beds of limestone conglomerate from Lower Cambrian through Middle Ordovician age, particularly abundant in the western part of the allochthon. As recognized by Zen (1961, 1967, 1972), the emplacement of the allochthon involved the thrusting of lithified shale into a basin of deposition of black shale and graywacke, and in many locations there is a conglomerate or breccia consisting of all kinds of rocks of the allochthon in a black shale matrix, a sedimentary melange. Graptolites in the matrix of melanges beneath the frontal Taconian thrusts record the arrival of the thrust package at a position near Albany during the *C. spiniferus* Zone of the late Caradocian (Bradley 1989), about 452±2 Ma on the time scale of Tucker & McKerrow (1995). The studies of Zen (1961, 1967, 1972) showed that the development of slaty cleavage in the rocks of the allochthon entirely postdated allochthon emplacement and could be as young as Devonian. However, students and co-workers of J.F. Dewey (Rowley et al. 1979; Rowley & Kidd 1981) described tectonic melanges in the Hudson Valley region which clearly deform slaty cleavage and indicated that thrusting postdated cleavage formation. Bosworth & Kidd (1985) provided a remarkable resolution of this problem, showing in a single outcrop the primary sole of the allochthon resting on Caradocian mudstone, a later slaty cleavage cutting across this contact, and a still later tectonic melange disrupting the slaty cleavage.

Relations between the Taconian foreland and hinterland were most extensively studied by Stanley & Ratcliffe (1985). In their model for Taconian thrusting, based on careful facies analysis of the strata, the Giddings Brook slice of the allochthon, which now rests the farthest forward of the thrust sheets, originated the greatest distance toward the hinterland. Successively higher thrusts cut through the Giddings Brook slice and carried rocks that originated progressively closer to the foreland, a sequence of thrusting quite opposite from standard models of thrust belts. In addition, they showed that later thrusts involved strata that had already been metamorphosed before they were emplaced, but could not have been metamorphosed until after passage of the Giddings Brook slice. Earlier Ar–Ar dating of metamorphic hornblende had suggested problematically old ages of around 460 Ma for these rocks (Sutter et al. 1985), but Hames et al. (1991) have more recently produced a more compatible age of 443±3 Ma in the same region. According to Stanley & Ratcliffe (1985) the root zone of the allochthons lies in the remains of a Taconian accretionary prism now exposed mainly along the east margin of the Proterozoic massifs of western New England and west of the remnants of the volcanic arc. Strongly deformed and metamorphosed ophiolite fragments are exposed within the latest Cambrian-earliest Ordovician part of this accretionary complex.

Taconian magmatic arc

Models of the Taconian collision in New England have commonly suggested that the impinging magmatic arc was founded on oceanic crust (Naylor 1969) and further that it existed east of the accretionary prism during an extended period of Cambrian-Ordovician time (Stanley & Ratcliffe 1985). Most tectonic models beginning with Chapple (1973, 1979) depict a subduction zone dipping away from Laurentia and beneath the postulated magmatic arc (Stanley & Ratcliffe 1985; van Staal 1994; also cited in van Staal et al. 1996; Kusky et al. 1997), although the original model of Bird & Dewey (1970) showed it west-dipping, and that was also suggested in paleomagnetic summary papers by MacNiocall et al. (1996, 1997). Subduction dipping northwest toward Laurentia has also been proposed on the basis of relationships in New Brunswick, but this was specifically tied to the 450–420 Ma life of the Brunswick subduction complex, not to the Taconian collision (van Staal 1987, 1994; van Staal & de Roo 1995; van Staal et al. 1998*b*).

The rocks of the magmatic arc include volcanic and sedimentary rocks, and intrusive rocks. The volcanics are partly subaerial, partly submarine. In some areas the volcanics are free of interbedded sediment, elsewhere they occur within extensive sections of feldspathic black shale. The intrusive rocks are commonly not easy to interpret or distinguish from the volcanics because of strong deformation. Ordovician magmatic rocks occur in two different settings in western and northern New England, and in a third setting in eastern New England.

Western and northern settings. – In western Connecticut, western Massachusetts, eastern Vermont, northern New Hampshire, southeastern Quebec and northwestern and northern Maine the volcanic and intrusive rocks rest physically above various rocks assigned either to the Taconian "accretionary prism", including rocks resting on previously obducted ophiolite, or to the Cambrian Grand Pitch Formation and associated formations in northern Maine (Figs. 1 and 2). The basal contact is known to be an unconformity in some locations and interpreted to be a thrust in others. The magmatic rocks rest above sections that include ophiolite and ophiolite fragments, melanges overlying the ophiolites, and usually a quartzose sedimentary unit.

In the Weeksboro-Lunksoos Lake anticlinorium in northern Maine, the Arenig Shin Brook Formation and unnamed Ordovician volcanics unconformably overlie the Grand Pitch Formation (Neuman 1962, 1964; Neuman & Rankin 1994), in the type area of the Penobscottian orogeny. While regional geochemical sampling has identified Middle(?) Ordovician arc and probable back-arc volcanics in northern Maine (Winchester & van Staal 1994), the tectonic setting of the Shin Brook Formation remains to be established. In northwestern Maine and northern New Hampshire the Ammonoosuc Volcanics and the Lobster Mountain volcanics unconformably overlie the Hurricane Mountain Formation, the Dead River Formation (Boone 1983; Boone & Boudette 1989), and the Albee Formation. Assuming that the unconformities in these places are related to the Penobscottian orogeny, the rocks below the unconformity should also be interpreted as near the Gander margin of Iapetus. However, particularly the quartz-rich Dead River and Albee Formations are strikingly similar to the Moretown Formation of the "Taconian accretionary prism" in eastern Vermont suggesting proximity to Laurentia in the Ordovician. In Quebec the Ascot-Weedon volcanics and related intrusions and Magog Group sedimentary rocks overlie the St. Daniel melange (Williams & St-Julien 1982). In northern Vermont, the Umbrella Hill Conglomerate and quartzose Moretown Formation lie unconformably above the ophiolite-bearing Ottauqueeche and Stowe Formations (Hall 1969) and are overlain by shales and volcanics. In southeastern Vermont the Barnard Gneiss overlies the Moretown Formation (Ratcliffe et al. 1997) and the contact here is interpreted as a major thrust fault, possibly even the trace of the subduction surface at the top of the accretionary prism (Ratcliffe et al. 1997).

The situation is unclear in Maine, where rocks shown in Fig. 1 as Taconian "accretionary prism", and which are lithically similar to the upper part of the accretionary prism in Vermont, show local stratigraphic differences, and their relationships to the Grand Pitch are uncertain. A potential explanation of this situation may lie in along-strike variations in the location and intensity of late Taconian convergence, as well as the eruption of volcanics on a variety of older substrates. In Quebec and Maine it appears that major Taconian convergence occurred along surfaces beneath the Thetford ophiolite and even beneath the Chain Lakes massif but had little involvement with the Penobscottian unconformity, whereas in southern New England the arc magmatic rocks appear to have been thrust above a section that may contain the unconformity.

Gneiss dome settings. – The second setting is in the gneiss domes of the Bronson Hill anticlinorium, as well as the Shelburne Falls, Goshen, and Granville domes of western Massachusetts and the Collinsville and Bristol (Fig. 1) domes of western Connecticut. Here the volcanics rest physically above extensive thicknesses of strongly deformed Ordovician intrusive rocks, and the underlying substrate is unknown with three exceptions. In the Bristol dome (Stanley & Hatch 1988) the intrusive gneisses physically overlie the Taine Mountain Formation, a quartzo-feldspathic sedimentary unit equivalent to the Moretown Formation. The base of the magmatic rocks is here interpreted as a Taconian thrust, similar to the interpretation given to the base of the magmatic rocks in Vermont (Ratcliffe et al. 1997). The other two exceptions are in the Pelham dome in central Massachusetts (Fig. 1) and the Stoney Creek dome on the Connecticut coast (nearly invisible in Fig. 1) where the intrusive rocks physically overlie late Proterozoic stratified rocks. The late Proterozoic rocks in the Stoney Creek dome may be continuous with late Proterozoic rocks of the Hope Valley terrane in southeastern

Connecticut, but the nature of their top contact is unknown. The contact relationships in the Pelham dome are discussed below.

The Ammonoosuc Volcanics exposed in the flanks of the gneiss domes of the Bronson Hill anticlinorium are well documented but range in thickness from only 30 to 1200 m (Schumacher 1988). They consist of a lower member of predominantly mafic volcanics, dominantly tholeiitic basalts and andesites with lesser low K dacites, and typified by cummingtonite, gedrite and gedrite-cordierite gneisses, many of which are basalts that underwent pre-metamorphic hydrothermal seawater alteration. The upper part of the lower member contains a widespread thin zone of calcareous rocks including volcanic conglomerate with a calcite marble matrix, possibly indicating reef environments on shores of islands. There is a local middle member 0.3 to 30 m thick consisting of garnet-amphibole quartzites believed to have been volcanic exhalative deposits, and an upper member dominated by metamorphosed rhyolites and dacites with subordinate amphibolites (Schumacher 1988).

The volcanics are overlain by a major unit of metamorphosed sulfidic black shale and feldspathic sandstone, the Partridge Formation, that is extensively interspersed with both mafic and felsic volcanics (Hollocher 1993). These Partridge volcanics show no significant differences from the Ammonoosuc Volcanics, except for a group of extremely Mg-rich mafic to ultramafic rocks in the Partridge that may be metamorphosed komatiites or picrites (Wolf 1978; Tracy et al. 1984). The volcanic geochemistry is strongly suggestive of a tholeiitic arc or back-arc basin origin (Schumacher 1988; Hollocher 1993), quite similar to data from northern Maine and New Brunswick (Winchester & van Staal 1994) where a wide back-arc basin has been inferred.

Two U–Pb zircon ages date these volcanics, both from the Bernardston area, Massachusetts, where the later metamorphism is only low staurolite zone. A quartz-phyric tuff in the upper part of the Ammonoosuc Volcanics gives 453±2 Ma (mid-Caradoc) and a 1–2 m thick quartz-phyric tuff in the lower part of the Partridge Formation yields 449^{+3}_{-2} Ma (base of Ashgill) (Tucker & Robinson 1990). The mafic lower member of the Ammonoosuc in southern New England has not been dated, but in the Chickwolnepy Complex in northern New Hampshire (Aleinikoff & Moench 1992; Fitz 1996) a tonalite, cutting both early volcanics and part of a syn-arc sheeted dike complex, has yielded a U–Pb zircon age of 467±3 Ma.

Physically beneath the Ammonoosuc Volcanics in the domes is a series of coarser-grained feldspathic gneisses and amphibolites. Many appear laminated, but the best estimate based on large exposures, is that they are predominantly metamorphosed and variably strained felsic intrusions with xenoliths of earlier gabbros and dikes of later mafic rocks, now amphibolites (Robinson et al. 1989). Geochemical characteristics, summarized by Hollocher & Bull (1996), Bull & Hollocher (1996), Hollocher et al. (in prep.), are similar to the plutonic roots of known calc-alkaline arcs. Gneisses in northern domes are mostly granite and might have formed near continental crust; gneisses in southern domes are granodiorite to tonalite, more likely derived by melting of a basaltic source resting on ocean crust. Nevertheless, Samson (1994) and Samson & Tremblay (1996) show that some southern gneisses as well as some volcanics of the Ascot Complex, Quebec, have negative ε_{Nd} values indicative of contamination by older continental crust.

Contact relations between overlying volcanics and underlying intrusive rocks are controversial. In central Massachusetts Robinson (1981) mapped three lenses of quartzite along the contact at the base of the Ammonoosuc with the underlying Monson Gneiss and thought the contact might be an unconformity. Others suggested that the gneisses are intrusive into the Ammonoosuc (Leo et al. 1984; Leo 1985, 1991), despite lack of clear cross-cutting relationships and of xenoliths of typical lower Ammonoosuc rock types. In selecting samples for U–Pb zircon dating, Tucker & Robinson (1990) made a special effort to seek out rocks in large outcrops that might span the largest range of ages, but the total range of ages was from 455 (Early Caradoc) to 442 Ma (base of Silurian). Absence of zircon inheritance in this study, indicative of crustal contamination, is not surprising because efforts were made to analyze only the latest euhedral growth on zircon, indicative of late igneous crystallization. The age results rule out an unconformity. Robinson (*in* Tucker & Robinson 1990) suggested that the contact between the volcanic and intrusive rocks could be a low-angle extensional detachment formed during late arc history or early Silurian post-Taconian relaxation, and recently has speculated on a west-dipping detachment with major crustal excision that brought shallow back-arc basin deposits into direct contact with the intrusive core of the main arc.

Eastern settings. – Ordovician magmatic rocks of eastern Medial New England are not separated in Fig. 1. They include the Oak Mountain Formation within Miramichi in New Brunswick; the Kossuth Formation on the SE edge of Miramichi in New Brunswick and Maine; the Cushing, Spring Point and Nehumkeag Pond Formations on the W side of the Casco Bay belt; probably the Marlboro Formation in the Nashoba belt and the Quinebaug Formation in the Putnam belt. In the Casco Bay belt these are dominated by metamorphosed volcanics (Hussey 1988) yielding ages in the range 471 to 460 Ma. These ages are similar to those of the "Shelburne Falls arc" of igneous rocks of western Massachusetts and eastern Vermont (Karabinos & Thompson 1997) in the range 488–458 Ma, to the rocks of the Bronson Hill belt in northern New Hampshire (Aleinikoff & Moench 1992; Fitz 1996), and to the Tetagouche Group in the Miramichi, New Brunswick (van Staal et al. 1998*b*). The door is open to an extensive volcanic arc on Medial New England during a time appropriate for an arc assembled before the Taconian collision, with the possibility of interarc splitting, as suggested along strike in New Brunswick (see below). Such a broad arc of present width 90 km in southern New England and 200 km in the north, has modern analogs in Java (200 km), Japan (300 km) and Sumatra (400 km). These rocks are distinctly older than the igneous rocks of the Bronson Hill belt in Massachusetts and southern New Hampshire in the range 455–442 Ma, that in part could represent an internal back-arc formed late in the subduction cycle.

Paleogeographic interpretations. – Based on the obtained ages of the volcanic and intrusive rocks in central Massachusetts and southwestern New Hampshire, Tucker & Robinson (1990) pointed out that these ages could not represent the pre-Caradocian volcanic arc in the history of closing of Iapetus as illustrated in the tectonic model of Stanley & Ratcliffe (1985), though they are completely compatible with the time of emplacement of the Giddings Brook slice of the Taconic allochthon and subsequent high grade metamorphism based on a metamorphic hornblende Ar–Ar age of 443±3 Ma (Hames et al. 1991).

Karabinos (Karabinos & Tucker 1992; Karabinos & Williamson 1994; Karabinos et al. 1996; Karabinos & Thompson 1997) suggested that the older western arc rocks exposed in the Barnard Gneiss and the western Massachusetts gneiss domes constitute a separate western "Shelburne Falls arc" which, with its igneous rocks in the range 488–458 Ma, does constitute a group of arc rocks that existed east of the Laurentian margin before the culminating features of the Taconian orogen. He indicates that the igneous rocks of the Bronson Hill arc in the range 455 to 443 Ma are too young to have participated in the Taconian collision and proposes the abrupt development of a new subduction system at about 455, such that the Bronson Hill magmatic rocks were formed over a west-dipping subduction zone. This model is not required by the known age range of Taconian deformation features, nor does it account for the 467±3 age of the Chickwolnepy Complex in northern New Hampshire or the broad distribution of Ordovician magmatic rocks through Medial New England east of the present exposures in the gneiss domes of the Bronson Hill anticlinorium. We suggest that the older western New England magmatic rocks were formed along the western edge of Medial New England and that the Bronson Hill magmatic rocks may be a more easterly exposure of the volcanic arc, or partly a back-arc assemblage located within the earlier Iapetus arc.

Important relationships that bear on these questions have been described and interpreted in northern New Brunswick (van Staal 1994; van Staal & de Roo 1995; van Staal et al. 1996, 1998*b*) and Newfoundland (Kusky & Kidd 1996). The Popelogan arc formed over a subduction zone dipping southeast beneath the northwest margin of Miramichi during the Arenig (475–473 Ma), interpreted as the Gander Margin of Composite Avalon. The Popelogan arc, equated paleogeographically with the Bronson Hill arc by van Staal et al. (1998*b*), although the rocks are older, rifted away from the Gander Margin to produce the Tetagouche back-arc basin, possibly as much as 1000 km wide, of ophiolite and mafic volcanics in the period 473–460 Ma. The Popelogan arc collided with the Laurentian margin at 455 Ma, while the Tetagouche Basin closed in the period 450–420 Ma along a northwest-dipping subduction zone, the Brunswick subduction complex, producing glaucophane and dated phengites and crossites in the range 453–416 Ma. Geochemistry of various Ordovician volcanics from northern Maine is compatible with this model (Winchester & van Staal 1994), though we have not yet identified an equivalent of the Tetagouche basin nor the Brunswick subduction complex, which appears to project somewhere into the Merrimack belt (Fig. 1). We also note the back-arc basin affinities of the volcanics in the Ammonoosuc and Partridge, which, like the Tetagouche basin, suggest that Medial New England may not have been a single coherent plate in the Ordovician.

Northwest subduction has also been inferred on paleomagnetic grounds (MacNiocall et al. 1996, 1997) to explain the low paleomagnetic latitudes (i.e. close to low latitude Laurentia) of some Middle to Late Ordovician arc rocks in Maine and Newfoundland. Assuming the validity of the paleomagnetic results, such volcanics, even if formed on the Medial New England (= Popelogan) plate, might have been sufficiently close to the Laurentian margin to record low paleomagnetic latitudes in the Middle to Late Ordovician. However, proximity to Laurentia is contradicted by paleomagnetic data from Llanvirn-age volcanics of the Tetagouche Group indicating a 52 degrees south latitude, which means that this part of Medial New England could not have been proximal to Laurentia until later.

The main part of the magmatic arc of Medial New England appears to have collided with Laurentia to produce the Taconian orogeny. To interpret it as based on either continental or oceanic crust involves extremely tenuous data. Such data include negative ε_{Nd} values, the broad distribution of rock types across Medial New England, and the location of Late Proterozoic continental crust in the Pelham and Stoney Creek domes. Relationships in the Pelham dome are important and the subject of recent research by two of us (Robinson et al. 1992). They are equivocal and tangled with the results of at least two post-Taconian deformations, but are presented briefly here.

The Pelham gneiss dome

Upper tectonic levels. – The Pelham dome is a simple broad north–south trending arch (Robinson et al. 1992). Beneath Silurian-Early Devonian cover, a thin layer of Ordovician Partridge Formation overlies a 1-km thick layer of Ordovician gneissic granitoid rocks of the Fourmile Gneiss, which has yielded a U–Pb zircon age of 454^{+3}_{-2} Ma. Locally Silurian Clough Quartzite rests unconformably above the Fourmile. East-directed recumbent folds involving the top contact of the Fourmile and Lower Devonian strata appear to be truncated on the map by the 380±5 Ma Belchertown intrusion (Ashwal et al. 1979), thus placing these folds as Early to Middle Devonian.

Late Proterozoic strata. – In the northern part of the dome, Late Proterozoic strata lie immediately below the Fourmile Gneiss along a sharp contact that is probably a thrust. At the top of the Proterozoic is the Poplar Mountain Gneiss, a metamorphosed feldspathic sedimentary rock about 30 m thick, overlying feldspathic Poplar Mountain Quartzite 10 m thick or less, which in turn overlies the Dry Hill Gneiss, a hastingsite-microcline gneiss of alkali rhyolite composition. Faceted igneous zircon from the Dry Hill Gneiss yields a concordant zircon age of 613±3 Ma (Tucker & Robinson 1990; Robinson et al. 1992). Beneath 180–350 m of Dry Hill Gneiss, Poplar Mountain Quartzite is repeated in inverted position, here about 60 m thick, physically underlain by 350 m more of Poplar Mountain Gneiss to the deepest exposed location in the dome. This repeated inverted section may be explained by an east-directed recumbent anticline within the Proterozoic section like the Devonian recumbent folds described above. Poplar Mountain Gneiss and Poplar Mountain Quartzite are shown to be Proterozoic like Dry Hill by the presence of actinolite quartzite and actinolite calc-silicate layers throughout all these units, by the presence of Dry Hill-like hastingsite gneiss layers in the Poplar Mountain, and by the presence of the Pelham Quartzite lens, up to 180 m thick, within the Dry Hill.

In addition to igneous ages of 613 Ma, single zircons from one sample of Dry Hill Gneiss show evidence of inheritance in three groups, 2850–2550 Ma, 2150–1850 Ma and 1510–1000 Ma (Tucker & Robinson 1991). Pelham Quartzite and other Proterozoic quartzites yield concordant to mildly discordant detrital zircons in roughly the same three major groups (Sutter et al. 1991; Robinson et al. 1992), with three grains in the range 2679 to 2616 Ma, and the youngest grain at 933 Ma. These zircon groups are consistent with derivation either from Laurentia or Amazonia.

Mount Mineral Formation. – In the southern part of the dome, Fourmile Gneiss is separated from Dry Hill Gneiss by a different metamorphosed sedimentary unit up to 200 m thick, originally mapped as Proterozoic Mount Mineral Formation. One sample of muscovite-garnet quartzite from near the top of this unit, yielded concordant detrital zircons as young as 459 and 439 Ma, indicating that it is probably the Lower Silurian Clough Quartzite, a prominent member of the regionally extensive post-Taconian Silurian-Devonian stratigraphy identified by Billings (1937). A feldspathic gneiss in the lower part, dominated by sulfidic mica schist, and amphibolite, has yielded a single U–Pb zircon age of 456 Ma (Robinson et al. 1992). The lower part of the Mount Mineral contains four huge boudins of coarsely recrystallized harzburgite enveloped in schist (Emerson 1898), rocks of depleted mantle composition hinting at a nearby suture. These observations indicate that the base of the Fourmile Gneiss is a Late Silurian or younger thrust fault bringing a slab of Ordovician intrusive rocks over Silurian and Ordovician stratified rocks that are in turn resting on Proterozoic stratified rocks along either a fault or an unconformity, the nature of which is crucial to regional interpretations.

Metamorphism. – Schists of the Mount Mineral Formation contain a relict sillimanite-orthoclase-garnet-biotite-rutile assemblage, much higher grade than any cover rocks above the Fourmile Gneiss (Roll 1987). These yield monazite ages of 367±3 Ma, similar to the Neo-Acadian zone to the east (see below) as well as a 350±2 Ma Mississippian igneous zircon age in a sillimanite-orthoclase pegmatite. These relict high-grade lenses locally contain an east–west trending, high-temperature, top-to-the-east shear fabric in which orthoclase underwent dynamic recrystallization. The dominant age of pegmatites and metamorphism in the Pelham dome and vicinity is Late Pennsylvanian, in the range 300–290 Ma (see below), associated with a north–south trending linear shear fabric with top-to-the-south indicators in which quartz, but not feldspar, behaved ductilely. Curiously, although the Proterozoic Dry Hill Gneiss shows abundant evidence of the Late Pennsylvanian metamorphism it appears to contain no clue of an Acadian or Neo-Acadian metamorphism.

Structural interpretations. – Similarity of the Late Proterozoic rocks to those of the Hope Valley terrane, southeastern New England is striking (Hodgkins 1985). Relationships in the Pelham dome have been interpreted as similar to those in the Willimantic dome of east-central Connecticut (Gromet 1989; Getty & Gromet 1992*a*, 1992*b*; Mosher et al. 1993), and these authors interpreted the top of the Proterozoic rocks in the Pelham dome as a huge Late Paleozoic thrust bringing Proterozoic rocks of the Hope Valley, with no evidence of Devonian metamorphism, beneath rocks which had been intensely metamorphosed. Robinson et al. (1992) gave circumstantial evidence against this timing, including the top-to-the-east, high-temperature shear fabrics in the Mount Mineral schists favoring Neo-Acadian underthrusting from the east. Although the Late Proterozoic rocks are now near the Ordovician magmatic rocks of the Bronson Hill arc as a result of thrusting, no trace of Ordovician intrusions has yet been identified in them. Cross-sections on the Massachusetts Bedrock Map (Zen et al. 1983) suggest that the Pelham dome Proterozoic could belong to the Laurentian margin, like the alkalic Late Proterozoic Yonkers Gneiss of the New York City area (Hall 1968), but if true, one might expect to find evidence of a Taconian metamorphism. It is thus unresolved as to whether the Proterozoic of the Pelham dome formed the substrate of the Bronson Hill arc or was even a part of Medial New England in the Ordovician.

Medial New England as exotic to Laurentia

Detrital zircons in Late Cambrian-Early Ordovician strata in the Miramichi, like the quartzites in the Pelham dome, give a range of ages consistent with derivation from a Gondwanan and, more specifically, an Amazon shield source (David & Machado 1992), and such a connection is proposed by van Staal et al. (1996). The Arenig Shin Brook Formation unconformably overlying the Grand Pitch Formation in the northwestern part of Medial New England in northern Maine (Neuman 1984) contains a Celtic benthic fauna supposedly characteristic of middle- to high-latitude island regions in Iapetus and distinct from the benthic Toquima-Table Head fauna for Laurentia in the same time period. Of all the paleomagnetic studies in the central mobile belt of the Canadian Appalachians (Liss et al. 1994; MacNiocall et al. 1997), only the results from the Llanvirn-age volcanic rocks of the Tetagouche Group in the northern part of the Miramichi Anticlinorium give evidence of deposition at a high paleomagnetic latitude. Based on the correlation of Miramichi with the basement of Medial New England in coastal Maine (Berry & Osberg 1989; Osberg et al. 1995; Tucker et al. in press *b*) we suggest this high latitude result supports the concept of this part of Medial New England as a terrane exotic to Laurentia and possibly consistent with assignment of Miramichi to the Gander margin of Composite Avalon (van Staal et al. 1996). Collectively, the above data suggest that much of Medial New England was built on Gondwanan continental crust. The cited paleomagnetic data would seem to preclude this part of Medial New England from having been in collision with Laurentia as early as Caradocian, and may support the view that Medial New England underwent significant back-arc splitting so that it should not be considered as a single coherent plate during the Ordovician. In this view, however, the western and northwestern splits from Medial New England, constituting the Popelogan, Bronson Hill, and possibly Shelburne Falls arcs could have been in a position for a Caradocian-Ashgill collision with Laurentia.

End of the Taconian Orogeny

An unconformity occurs at the base of Silurian strata in western New England (Pavlides et al. 1968). Near the Hudson Valley this is highly angular, cutting across traces of Taconian thrusts. Where Taconian deformation and metamorphism were most intense, Silurian strata were either not deposited or since eroded and no unconformity is known. In the Connecticut Valley region a widely exposed unconformity is overlain by thin Silurian quartzite and shallow-water marine calcareous rocks. Although locally angular, with Silurian strata even resting on Ordovician granitoid intrusions, evidence for intense Late Ordovician folding and faulting is limited. These relations suggest that much of this region lay on the upper plate of the Taconian collision zone, and that it was the site of shallow-water sedimentation or erosion in a tectonically inactive regime during most of the Silurian. Relationships are different in eastern New England.

Acadian

Medial New England suture with Composite Avalon in Maine

In this section we review the relationships between rocks of Medial New England and those of Composite Avalon. Berry & Osberg (1989) have defined tectonostratigraphic belts that underlie central and eastern Maine; Osberg et al. (1995) and Tucker et al. (in press *b*) have summarized the stratigraphy, structure and timing of deformation in part of this region. The Central Maine basin (an extensive part of the Merrimack belt of Fig. 1) and the Fredericton trough are located in Medial New England, and the outboard tectonostratigraphic belts belong to Composite Avalon.

Identification of a significant boundary between Laurentia-Medial New England and Composite Avalon is based primarily on differences in stratigraphy and fossil provinciality. A composite stratigraphic column from the Casco Bay and southern Miramichi belts of Medial New England is distinct from those of the St. Croix and Coastal Maine Volcanic belts. In the Central Maine basin and in the Miramichi anticline the oldest rocks consist of thick bedded quartzite and phyllite (Baskahegan Lake Formation), overlain by discontinuous Tremadocian graphitic phyllite, which is in turn overlain by mixed basalts and felsites (Oak Mountain, Kossuth, and Cushing Formations) having arc chemistry and dated at 479–473 Ma. The overlying Cape Elizabeth Formation in the Casco Bay belt (Fig. 1) consists of thin bedded quartzite and quartz-mica schist and less abundant thick bedded, micaceous quartz wacke intercalated with thin bedded quartz mica schist (Pankiwskyj 1996). Higher in the section is a thin unit of black sulphidic pelite, a thin mixed volcanic sequence (Spring Point Formation) dated at 470 Ma, and then a unit of mostly pelite, some of which carries sufficient graphite to color it gray (Passagassawakeag Formation), overlain by volcanic and volcaniclastic beds (Carrs Corner and Nehumkeag Pond Formations) dated at 460 Ma. This Cambrian-Ordovician sequence in the Casco Bay belt is overlain, probably conformably, by the wacke-shale sequence of the Central Maine basin to its west. This sequence is in thrust contact with rocks of the Fredericton trough to its southeast, which are similar to those of the Central Maine basin. While the thrust is shown in Fig. 3 as southeast-directed, it is shown northwest-directed in Fig. 4, and its geometry and vergence are still uncertain.

The stratigraphy of Medial New England has little in common with the stratigraphy of the St. Croix and Coastal Maine Volcanic belts of Composite Avalon. The St. Croix belt contains Precambrian(?) marbles, quartzites, and schists (Rockport sequence), somewhat similar to the Ashburn and Martinon Formations of southwestern New Brunswick. These are overlain by quartzite and quartz-pebble conglomerate (Battie Quartzite), followed by quartz-mica schist and thin to thicker beds of schistose quartz wacke (Megunticook Formation). Black, sulphidic schist of the Penobscot Formation is higher in the section, and near its base it contains a thin volcanic unit that has been dated at 501 Ma. The Benner Hill sequence partly overlies and partly interfingers with the Penobscot Formation. The Benner Hill consists of schistose quartzite, and thinly interbedded spessartite-bearing quartzite and quartz-mica schist. A thin metamorphosed and highly strained coquinite, which carries probable Caradoc brachiopods (Boucot et al. 1972), is found near the top of the micaceous quartzite. This section contains a paucity of volcanics and an exceptionally thick sequence of graphitic and sulphidic pelite in the Ordovician.

The oldest rocks in the Coastal Maine Volcanic belt are marbles, schists, and volcanics metamorphosed to amphibolite facies and intruded by pegmatites that are dated at 647±4 Ma (Stewart et al. 1998). These rocks are overlain unconformably by basal quartzite and a thick unit of siliceous phyllite (Islesboro). Two thin limestone units occur just above the basal quartzite, and lenses of polymictic conglomerate lie within the siliceous phyllite and above the lower limestones. The Coombs Limestone overlies the siliceous phyllite. It consists of bedded limestone, thinly bedded magnesian limestone intercalated with phyllite, and lenses of limestone-pebble conglomerate similar to the limestone at the base of the St. Croix belt and similar to the Ashburn Formation in southwestern New Brunswick. Although in fault contact, the Ellsworth Formation must lie stratigraphically above the Coombs. It consists of wavy, thin bedded quartzite and quartz-mica phyllite and thicker beds of quartz wacke interbedded with quartz-mica phyllite. Sparse, thin beds of limestone are a minor lithology, and thin layers of volcanic tuff and thicker volcanic flows and agglomerates are important parts of the formation. Tuffaceous units have been dated at 509 Ma (Stewart et al. 1995). The Castine Formation unconformably overlies the Ellsworth. It is made up entirely of mixed volcanics and volcaniclastic sedimentary rocks. A rhyolitic dome has an age of 503 Ma in coastal Maine and equivalent rocks in southwestern New Brunswick have an age of 493 Ma (Ruitenberg & McLeod 1993). Silurian to Pragian volcanic and volcaniclastic rocks, best preserved in eastern Maine (Gates 1977), unconformably overlie the Castine, and over large areas they cut down into the Ellsworth (Gates 1989), forming a hiatus of 60 Ma. Thus, this region had undergone significant erosion before the Silurian, and reflects a Silurian-Early Devonian environment that contrasts markedly with the co-eval marine turbidites of Medial New England.

The biogeography in Silurian and lowest Devonian time also indicates a separation between Medial New England-Laurentia and Composite Avalon, but for the Ordovician the paucity of fossils and their deformed character make such an analysis unconvincing (Boucot 1993). Silurian and lowest Devonian fossils found in Composite Avalon differ from those found in the same age range in Medial New England. Silurian European province brachiopods and ostracodes are found in Composite Avalon in southern New Brunswick and along coastal Maine, whereas Silurian North American brachiopods and ostracodes occur in Medial New England in northern New Brunswick, northern Maine, the Connecticut River valley, and areas farther west (Boucot 1993). In addition to the shelly fossils, Silurian fish scales belonging to *Thelodus parvidens* are found exclusively in Composite Avalon, in contrast to *Longanellia scotia*, a fish species found only in Medial New England and more westerly regions (Susan Turner, written comm. 1987 to A.A. Ruitenberg). Earliest Devonian shelly fossils from the Coastal Maine Volcanic belt are assigned to a European province as compared to the earliest Devonian shelly fauna of Medial New England, which belongs to a North American province. In the Middle Devonian the European and North American faunas are mixed, suggesting that the barrier to reproductive communication had been breached.

Although paleomagnetic data allow some variation in Paleozoic continental reconstructions, especially concerning longitudinal positions, Early Ordovician high southerly latitudes for Avalon clearly indicate a location close to northwest Africa and far from Laurentia at low latitudes (Van der Voo 1988). According to van der Pluijm et al. (1995), the Miramichi tract of Medial New England and Avalon moved to lower latitudes through the Ordovician, with Miramichi approaching Laurentia more rapidly than Avalonia. More paleomagnetic work is needed for rocks of the Coastal Volcanic belt in Maine and Composite Avalon of southern New Brunswick to see whether a separation from Miramichi can be detected through the Late Ordovician-Early Silurian.

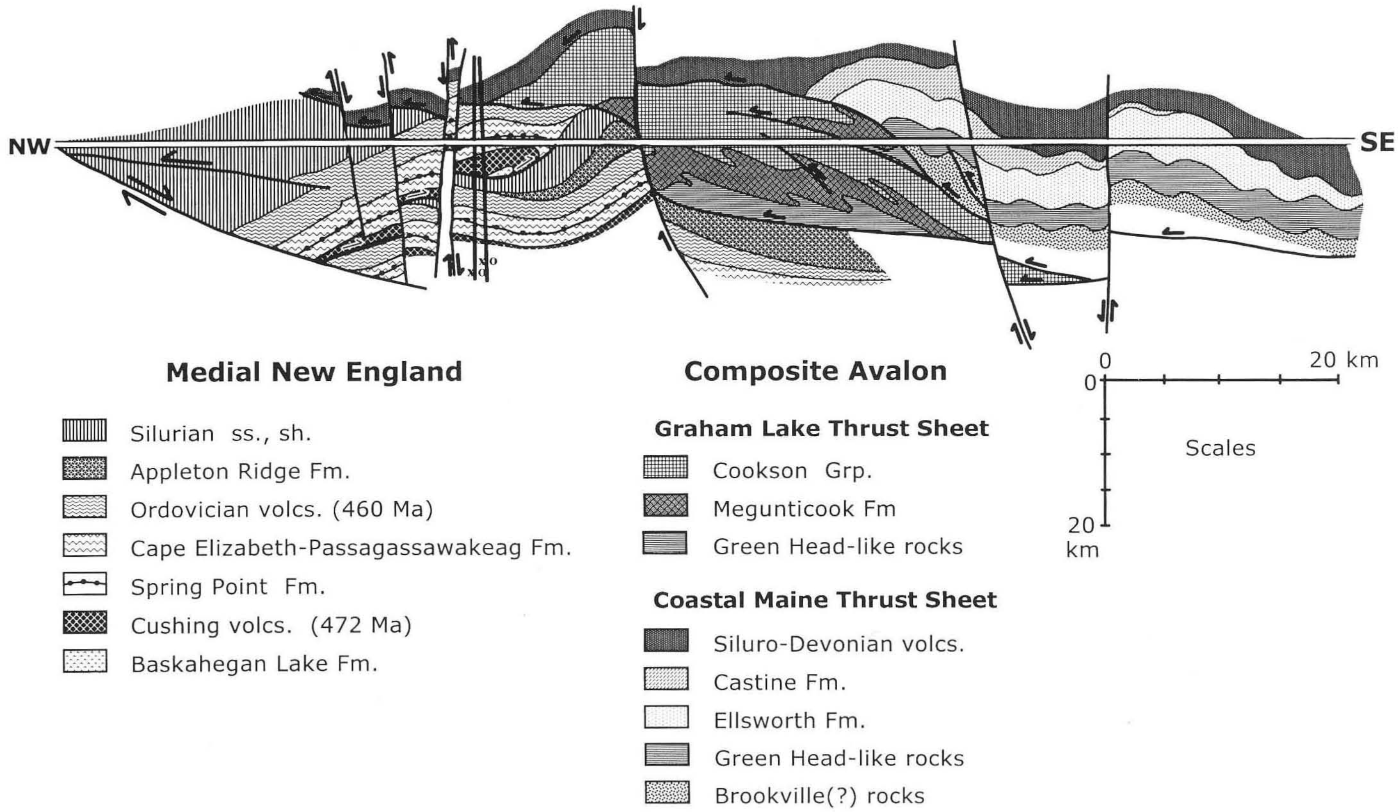

Fig. 3. Generalized structure section across the Medial New England-Composite Avalon boundary in central Maine. Ubiquitous upright folds have been omitted for clarity. The line of section is shown on Fig. 1.

The Central Maine basin consists of Ashgill(?) through Silurian, and possibly lowest Devonian rocks extending from a "hinge-line" in northwestern Maine eastward to the position of the Miramichi arch. Within this basin are local horst-like uplifts including the Miramichi, Weeksboro-Lunksoos Lake, and Haystack Mountain uplifts. Some of these uplifts were emergent during the lower Silurian, producing spectacular local debris flows in their flanks that interfinger with wackes farther out in the basin (Neuman 1967; Roy & Mencher 1976; Hopeck et al. 1989; Hopeck 1994). In deep parts of the basin thicker and more complete Silurian sections are present, and sedimentation may have been continuous from Caradoc into the Ludlow.

The Wenlock and Ludlow strata of the Central Maine basin are correlated with some confidence with the Rangeley sequence of northwestern Maine (Osberg et al. 1968; Moench & Boudette 1987; Osberg 1988; Moench et al. 1995). The central New Hampshire sequence (Hatch et al. 1983) and the Monadnock sequence of southwestern New Hampshire (P.J. Thompson 1985) also have been correlated with the Rangeley sequence. The Lower Silurian sections in the western part of the Central Maine basin represent clastic wedges deposited east of a "tectonic hinge" along the east margin of the Bronson Hill belt and contrast sharply with thin to absent Silurian strata on the Bronson Hill axis. The implication is that the Silurian rocks of the Bronson Hill axis formed a shelf facies which were bypassed by large amounts of debris carried by rivers from eroding lands to the west. Some of the conglomerates of the clastic wedge were carried far to the east where they interfinger with wackes and shales. The eastern part of the basin contains more limestone and shale than western parts of the basin (Ludman & Griffin 1974; Osberg 1988).

The Fredericton trough lies east of the Miramichi uplift and west of the rocks belonging to Composite Avalon. Poole et al. (1970) have estimated 3000 m of wacke and shale (Kingsclear, Flume Ridge) within the trough. The rocks resemble the calcareous wackes and shales of the Central Maine basin, but defining an internal stratigraphy in this sequence has proved difficult. A non-limy quartz-mica phyllite/schist interbedded with quartz wacke (Digdequash, Appleton Ridge) lies to the east of the Flume Ridge Formation. The Kingsclear Formation contains Wenlock-Ludlow graptolites. The Flume Ridge and the Digdequash Formations are barren but are cut by latest Silurian plutons, so they must be Silurian or older. The source of sediments in the Fredericton trough is dominantly from the east, though local sources along the east flank of the Miramichi uplift have been described (Poole et al. 1970). South of the present outcrop of the Miramichi anticline, wackes of the Fredericton trough with eastern provenance spread westward to interfinger with the Central Maine basin.

Rocks of Composite Avalon occur in thrust sheets (Fig. 3) that were transported westward onto rocks of the Fredericton trough and locally occur as small klippen on rocks of the Central Maine basin. Rocks of the St. Croix belt are found in the Graham Lake thrust sheet, and rocks of the Coastal Maine Volcanic belt define the Coastal Maine thrust sheet. The Graham Lake thrust sheet was emplaced in latest Silurian, and the Coastal Maine thrust sheet was emplaced in the Early Devonian. The stratigraphic section in the Graham Lake thrust sheet contains only sparse,

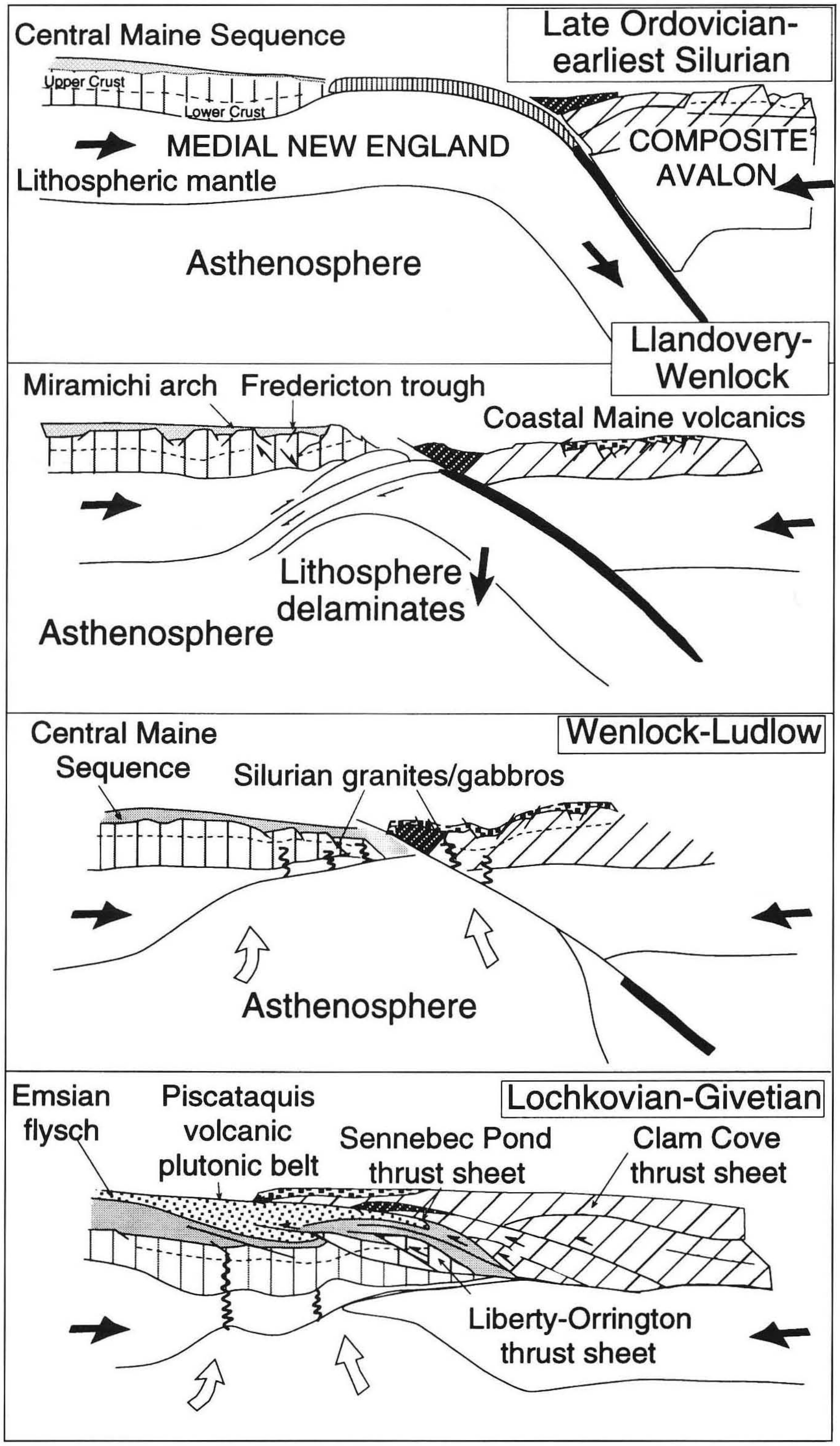

Fig. 4. Tectonic cartoon of the Acadian orogeny in central Maine as conceived by Tucker et al. (in press *b*). **Late Ordovician-earliest Silurian panel:** vertically decorated region is oceanic crust, solid black is eclogite, black with white diagonal lines is accretionary prism developed on Composite Avalon. **Llandovery-Wenlock panel:** shows initial impingement between Medial New England and Composite Avalon. Convergence of crustal plates and conversion of basalt to eclogite leads to delamination of lithosphere in the down-going plate and extensional faults in the Medial New England plate; continued arc volcanism in Composite Avalon. **Wenlock-Ludlow panel:** asthenosphere wells up under the contracting orogen, producing abnormally high heat flow under both Medial New England and composite Avalon, and late Silurian igneous activity and metamorphism. **Lochkovian-Givetian panel:** continued convergence results in west-directed thrust nappes, fold nappes, metamorphism, and a westward-migrating orogenic wedge.

thin volcanics, occurring at two horizons dated at 501 and about 458 Ma. The black, sulphidic phyllites (Penobscot) and thin bedded spessartite-bearing quartzite and quartz-mica schist (Benner Hill) are interpreted to have been deposited in a foredeep west of an advancing Andean-type arc (Fig. 4). Cambrian and Precambrian rocks of the Coastal Maine thrust sheet are thought to represent basement of the approaching continent, and the overlying Cambrian to earliest Devonian rocks represent several arc-related suites. Both the Cambro-Ordovician and the Siluro-Devonian volcanics have mixed chemical signatures relating to their tectonic environment, but particularly in the Siluro-Devonian, their within-plate chemical signature is similar to that of the rift basins in the present day Andean arc (Pinette & Osberg 1989). The arc volcanics show depletion of Nb and Ta (Hon & Thirlwall 1985), and trace element signatures indicate a continental arc environment (Hepburn et al. 1995).

The Graham Lake thrust sheet of Composite Avalon was emplaced probably in the Late Silurian. Its arrival indicates closure of the ocean separating Medial New England from Avalon, and at that time the volcanic arc in the Coastal Maine thrust sheet ceased to be active. Latest Silurian plutons in both the Graham Lake and Coastal Maine thrust sheets and adjoining Fredericton trough along with intrusion of shonkinite in earliest Devonian time suggest a heat source other than one directly related to subduction. We relate this heat to delamination of the crust (Nelson 1992) as the subducted slab dropped away and an asthenospheric plume rose and penetrated to the base of the crust (Fig. 4).

The structural (Fig. 3), plutonic, and metamorphic relationships suggest that the Acadian suture is cryptic. The Coastal Maine and Graham Lake thrust sheets would have to be pulled back to the east many tens of kilometers to expose the full width of the Fredericton trough and the suture.

Tracing a suture in southern New England

Southwest of coastal Maine and east of the Bronson Hill anticlinorium, other pre-Silurian stratified rocks assigned to Medial New England are exposed in the Rye anticline in coastal New Hampshire, the Massabesic Gneiss in southeastern New Hampshire and northern Massachusetts, parts of the Nashoba belt in eastern Massachusetts (Hepburn et al. 1995), thrust slices within the Merrimack belt in central Massachusetts (Berry 1989, 1992), the Putnam-Quinebaug belt, possibly the Hope Valley terrane, and parts of the Willimantic dome in eastern Connecticut.

The Rye anticline contains strongly deformed gneissic rocks similar to the westernmost parts of the Nashoba belt. The Massabesic Gneiss complex (Lyons et al. 1982) contains Precambrian migmatitic gneisses of inferred sedimentary protolith, intruded by plutonic rocks with an ion-microprobe (SHRIMP) age of 623±8 Ma (Aleinikoff et al. 1995), all of which are deformed into gneisses. Metamorphic zircon from amphibolite, and igneous zircon and monazite from a granitic dike give ages of 394±7 Ma and "about 390 Ma", respectively, indicating that Devonian metamorphism occurred (Aleinikoff et al. 1995). In northern Massachusetts the Massabesic contains a strong E–W shear fabric (Goldsmith 1991) that we now equate with the Neo-Acadian phase of deformation and metamorphism. U–Pb analyses of sphene and monazite indicate that these rocks were metamorphosed again in the Late Paleozoic, and were intruded by Permian granite. Although contact relations between the Massabesic and the surrounding Silurian strata are equivocal, the radiometric results indicate that the Massabesic had a similar magmatic and metamorphic history to the surroundings at least from Early Devonian onward.

Terrane assignment of rocks in the Merrimack Group (part of Merrimack belt of Fig. 1), southeast of the Massabesic Gneiss, has followed a tortuous course. Before isotopic dating had been widely applied, this group of schists and wackes was assigned to the Silurian based on lithic similarity and continuity with fossiliferous strata in central Maine, ca. 200 km along strike (Billings 1956; Hussey 1962; Osberg 1980). When the Massabesic Gneiss was discovered to be Precambrian and a major northeast-trending regional fault system was recognized to its west, the possibility of a Precambrian age for the Merrimack Group was raised (Lyons et al. 1982). Soon thereafter, a Rb–Sr whole-rock age of 473±37 Ma was reported for a cross-cutting pluton (Gaudette et al. 1984; Bothner et al. 1984), apparently precluding a Silurian sedimentary age and offering "confirmation of an exotic terrane". In Massachusetts, the older Silurian correlation was nonetheless maintained (Robinson & Goldsmith 1991). More recent precise U–Pb zircon dating (Bothner et al. 1993) has shown that this complex pluton crystallized at 406±3 Ma (early Emsian), similar in age to several other plutons that intrude the eastern margin of Medial New England. Finally, analyses of detrital zircons from the Merrimack Group show that some grains are as young as about 420 Ma (Aleinikoff et al. 1995), demonstrating that the rocks are indeed Silurian or Early Devonian as the early field geologists had thought, and eliminating the necessity for a separate terrane in southeastern New Hampshire.

The Nashoba belt has been the subject of extensive study and recent U–Pb dating by Hepburn et al. (1995). Those authors have suggested that this belt was part of Composite Avalon. The apparently oldest rock, the Fish Brook Gneiss, a probable metamorphosed felsic volcanic rock, is Late Cambrian at 499^{+6}_{-3} Ma, superseding earlier views that the belt contains Proterozoic rocks. Traditionally this is overlain by the Marlboro Formation, a unit dominated by mafic arc volcanics, and by the Nashoba Formation, a sequence of mainly volcanic-derived sedimentary rocks including some marbles, calc-silicate rocks and pelitic schists metamorphosed up to sillimanite-orthoclase grade. Earlier (Zen et al. 1983; Goldsmith 1991) the age of highest grade metamorphism had been considered as Ordovician based on the apparently cross-cutting Sharpners Pond Diorite at 430±5 Ma (Zartman & Naylor 1984). Monazite in the Fishbrook Gneiss at 425±3 (Wenlock) dates an early metamorphism which may be synchronous with the apparently synmetamorphic early phase of the peraluminous Andover Granite. A late phase of the Andover is dated at 412±2 (Pragian) based on igneous monazite, the Indian Head Hill Diorite at 402±5 using Rb–Sr whole-rock, and the Straw Hollow Diorite at 385±5 (Givetian) based on zircon.

Complexity in the metamorphism is indicated by an age of 395±2 Ma (late Emsian) for a migmatitic melt pod in the highest grade part of the Nashoba Formation. The youngest intrusion is the Indian Head Hill Granite dated by zircon at 349±4 Ma (Early Mississippian). This is the only intrusion showing zircons with substantial inheritance, in this case at about 600 Ma, suggesting derivation either from the Boston Avalon to the east or the nearby Hope Valley terrane. Characteristic Ar–Ar ages on hornblende in the Nashoba terrane are in the range 354–325 Ma, slightly younger than the peak Early Mississippian "Neo-Acadian" metamorphism in central Massachusetts (see below) and definitely older than the Alleghanian Permian hornblende cooling ages in the range 258–255 Ma in south-central Connecticut and southern Rhode Island. The range of rock types as well as the range of intrusive and metamorphic ages in the western part of the Nashoba belt are strongly suggestive of correlation with Medial New England in central Maine. On the other hand the Fish Brook Gneiss and other parts of the east edge of the Nashoba belt occupied by Silurian plutons or affected by Silurian metamorphism may belong to Composite Avalon, in which case the suture would be found within the Nashoba belt. In the granulite-facies region of south-central Massachusetts, Berry (1989, 1992) has mapped several thin thrust slices of pre-Silurian rocks in the Leadmine Pond Gneiss that he considers similar to parts of the Nashoba belt and to the Ordovician of the western part of the Casco Bay area in south-central Maine.

The east margin of the Nashoba belt is marked by the Bloody Bluff fault zone that appears to have a major strike-slip component. Where this crosses the northeast coast, the next unit to the east is the Newbury Volcanics (Shride 1976). This group of formations is overturned to the east, but is otherwise little deformed or metamorphosed. It contains Late Silurian and Early Devonian fossils, and in most respects is identified with the Silurian-Lower Devonian Coastal Volcanic Belt in eastern Maine and with Composite Avalon of the Ellsworth belt. Elsewhere along the Bloody Bluff fault, the Nashoba belt is situated adjacent to rocks of the Dedham-St. John Avalon belt with its weakly metamorphosed late Proterozoic volcanic and sedimentary rocks, late Proterozoic granitoid intrusions, Cambrian fossiliferous strata with Acado-Baltic fauna, and Ordovician through Devonian alkalic plutons. Recently Hepburn et al. (1998) have shown that much of the Dedham-St. John terrane northwest of Boston, previously mapped as Proterozoic, consists of Paleozoic alkali gabbros and differentiates yielding U–Pb zircon ages of 444±3, 427±2 and 378±3 Ma. These authors indicate a probable genetic relationship to the better known alkali granites in the same region, and also point out similarities with mafic and felsic intrusions in the Ellsworth belt of Maine.

The Dedham-St. John Avalon of Fig. 1, is intended to encompass the Avalon rocks near Boston, including the separately shown Boston basin, and the Avalon rocks near St. John, New Brunswick, which are now assigned to the Caledonia terrane. These rocks carry little deformation between Proterozoic and Late Carboniferous, and we are reluctant to rule out the possibility that they arrived in their present location long after the Acadian collisional activity so well shown by the western belts of Composite Avalon in coastal Maine. Parts of the Bloody Bluff and Hope Valley fault zones may be equated with the Clover Hill fault of New Brunswick, that separates the Dedham-St. John from the western part of Composite Avalon. The Clover Hill fault could be a major strike-slip fault about the same age as the Norumbega fault in Maine (see below). Note, however, that in New Brunswick all of the Composite Avalon terranes, the Fredericton trough, and the Miramichi terrane are unconformably overlain by broad Carboniferous sedimentary basins that locally include basal units as old as Late Devonian (Piskahegan, Horton Groups; Fyffe & Fricker 1987). The nature and distribution of deformation in these rocks suggests that post-Acadian deformation is localized, and much of it may be related to strike-slip faulting (Ruitenberg & McCutcheon 1982).

Most workers have long considered the high grade rocks of the Putnam-Quinebaug belt in eastern Connecticut to be essentially equivalent, both in rock types and in structural position to the Nashoba belt in Massachusetts. The Preston Gabbro at 424±5 Ma (Zartman & Naylor 1984) cross-cutting strongly foliated Putnam amphibolites, provides further evidence of Silurian or older deformation and metamorphism. At its east edge the Putnam-Quinebaug belt is in contact with the Proterozoic granitoid gneisses and quartzites of the Hope Valley terrane across the late Paleozoic Lake Char fault zone. The Hope Valley terrane rocks are very similar to the Late Proterozoic rocks exposed in the core of the Pelham dome. The same two units, in the same order, are also exposed across a low-angle fault in the core of the Willimantic dome. This fault contact, with shear fabrics that have been dated as Permian (Getty & Gromet 1992*a*, 1992*b*; Mosher at al. 1993), has been a major focus of interest. Above the fault the rocks contain isotopic evidence of high grade Devonian metamorphism that has been overprinted by Permian deformation and metamorphic recrystallization near the fault zone. The underlying Hope Valley gneisses contain evidence of the Late Proterozoic igneous events that formed them, and also of a Late Pennsylvanian ductile deformation and recrystallization, but appear to lack evidence of older Silurian-Devonian igneous activity and metamorphism. The contact is interpreted as a thrust fault on which Quinebaug-Putnam rocks, which had been subjected to intense Devonian regional metamorphism, were transported a very long distance over Late Proterozoic rocks which were not affected by Devonian metamorphism. In the same fault zone there are abundant tectonic indicators showing top-west shear sense and the zone has also been interpreted as a major Permian extensional fault (Getty & Gromet 1992*b*). Figures 1 and 2 were constructed assuming that the Late Proterozoic Hope Valley terrane and the Late Proterozoic core of the Pelham dome were part of Medial New England basement, but the basis for this is unconvincing in that evidence for Ordovician-Devonian igneous activity and Silurian-Devonian metamorphism are presently lacking.

O'Hara & Gromet (1985) identified the Hope Valley shear zone in western Rhode Island separating the western Hope Valley terrane from the eastern "Esmond-Dedham" terrane. The latter is co-extensive with the Dedham-St. John Avalon of this paper (Fig. 1), is dominated by Late Proterozoic calc-alkaline intrusions into the Blackstone Series of metamorphosed sedimentary rocks, and also contains Devonian alkalic to peralkaline granites and volcanics (note large miscellaneous granite in Fig. 1) which have undergone strong ductile deformation along the shear zone (Hermes & Zartman 1985). The disparate Proterozoic rocks along this boundary make it a possible candidate for the boundary between Medial New England and Avalon before the Acadian collision. The boundary itself, however, is now made up of mylonitic gneisses produced from rocks on both sides during Late Pennsylvanian subhorizontal shear best dated at 293 Ma by mineral isochrons (Getty & Gromet 1988; Gromet 1991).

Stratigraphic background for interpreting Acadian deformation

The Acadian of Acadia, relating to the convergence of Medial New England and Composite Avalon in central and eastern Maine, based on the new synthesis by Osberg et al. (1995) and Tucker et al. (in press *b*), has been outlined briefly above. The profound unconformity of Carboniferous red beds and coal seams resting on deformed and weakly metamorphosed strata was recognized in some of the earliest geological surveys of eastern Maine, southern New Brunswick, and Nova Scotia, a region known since the days of French settlement as "Acadia." That the early workers who described it (e.g. Jackson 1837) did not appreciate the regional significance of this unconformity is not surprising, because such basic geologic principles as faunal succession and isochemical metamorphism had not been established. But by the beginning of the 20th Century, the Devonian age and extent of this unconformity were known.

Modern paleontology has demonstrated a remarkably tight age bracket between Lower Devonian rocks below and Upper Devonian rocks above the Acadian unconformity (see Boucot 1993, for review). But we now realize that this unconformity dates only high level, relatively mild foreland deformation, and that related orogenic events in the hinterland and at deeper levels were occurring well before and long after the early Middle Devonian.

For most New England geologists, the widespread application of the term "Acadian" to events in the heart of the orogen began with Marland Billings' discovery of Early Devonian (Emsian) fossils in graphitic chlorite schist at Littleton, New Hampshire (Billings & Cleaves 1934) and his recognition that a stratified sequence of Ordovician, Silurian, and Devonian rocks could be traced from this fossil locality into regions with increasingly intense regional metamorphism up to sillimanite grade (Billings 1937). His field project beginning in 1931 (see Billings 1934) had been deliberately focussed here because of C.H. Hitchcock's 1870 discovery of Silurian fossils in the same area (Hitchcock 1871). This was then a bold new hypothesis, in that Billings himself, as late as January 1932, had acquiesced on the 1932 Bedrock Geologic Map of the United States in showing the high-grade rocks of New Hampshire as Precambrian, save for a small enclave around Hitchcock's fossil locality. This early work of

*An irony of this is that part of the argument for Devonian deformation and metamorphism came from a mistaken assignment of the unmetamorphosed White Mountain Magma Series (now known to be Mesozoic) to the Mississippian. The Mississippian assignment, in turn, came from a mistaken assignment of the unmetamorphosed pre-Pennsylvanian Quincy Granite to the Mississippian based on the fact that it had escaped Devonian regional metamorphism! The Quincy Granite, now known to be Ordovician, is an important element of the Boston Avalon zone here considered to have been on the upper plate during the Acadian collision. A further irony is that intense Mississippian and Pennsylvanian deformation and high-grade regional metamorphism can now be demonstrated in central New England. However, Billings' concept of a Devonian orogeny fit superbly with the timing of deposition of the Middle to Late Devonian Catskill Molasse in eastern New York State.

Billings brought on a wave of stratigraphic recognition and geologic mapping by his students and others that carried the idea of the Acadian orogeny* through all corners of New England (Robinson 1967*a*, 1992; Lyons 1996) and also brought sharp focus on the importance of stratigraphy of metamorphic rocks to understanding the evolution of mountain belts (Billings 1950).

One of the places this wave of mapping spread was into western, central and northern Maine, where, away from the most intense metamorphism, an increasing degree of fossil control was established (Boucot 1961; Neuman 1967; Osberg 1968; Moench & Boudette 1970; Albee & Boudette 1972; Boone 1973; Harwood 1973; Ludman & Griffin 1974; Ludman 1976; Pankiwskyj et al. 1976; Osberg 1988; Hall et al. 1976; Roy & Mencher 1976; Osberg et al. 1985; Pollock et al. 1988). As contrasted with the very thin Silurian section unconformably overlying Ordovician strata in the Littleton area and in the Boundary Mountains anticlinorium, this work was distinguished by recognition of a "tectonic hinge" (Moench & Boudette 1970) southeast of which the Silurian section thickens dramatically into major basin-filling sequences, with a sediment source presumably in the ruins of the Taconian orogen to the northwest.

An enigmatic aspect of this Silurian stratigraphy is whether it should be considered as a continental slope-rise sequence on a newly developed passive margin facing Iapetus, a newly developed convergent margin, or merely the western margin of an intracontinental extensional basin developed on Medial New England crust. An intracontinental basin interpretation would be consistent with the idea that Medial New England was part of an Ordovician Avalon continental collision with Laurentia. Paleomagnetic data (Van der Voo 1988) showing Avalon at high southern latitudes in the Ordovician appear to rule this out.

Acadian deformation in northern Maine

High in the Silurian section earlier work (Moench & Boudette 1970; Ludman & Griffin 1974; Ludman 1976) and more detailed sedimentological studies (Bradley & Hanson 1989; Hanson et al. 1993) suggest a reversal of source area to tectonic lands in the east, although earlier the Miramichi anticlinorium provided a local sediment source as indicated by an extensive though not ubiquitous pre-Ludlow unconformity (Hopeck et al. 1989; Hopeck 1994). Recent work (Bradley et al. 1996) on these fossiliferous Late Silurian and Lower Devonian strata and on local volcanic and intrusive rocks associated with them has made it possible to track the movement of an Acadian deformation front most of the way across Maine (Fig. 5A). The across-strike migration of the orogen and its flanking foredeep suggests that the Acadian orogeny was one in which a more southeasterly plate, which included Avalonia and rocks accreted to its leading edge, overrode Medial New England, along the Taconic-modified margin of North America.

The collisional paleogeography is particularly clear for the early Emsian (Fig. 5B), when the migrating orogenic front was midway across the state. Northwestern Maine was occupied by a foreland basin, where Acadian deformation had not yet happened (Bradley et al. 1996). Early Emsian strata include a widespread, thick succession of flysch (Seboomook Group in the Connecticut Valley-Gaspe basin), which was flanked on the southeast by a narrower belt of molasse (Tomhegan Formation). Sedimentological studies of a slightly older, Pragian, part of this same foreland-basin succession suggest deltaic and prodeltaic deposition of the molasse and flysch, respectively (Hall et al.

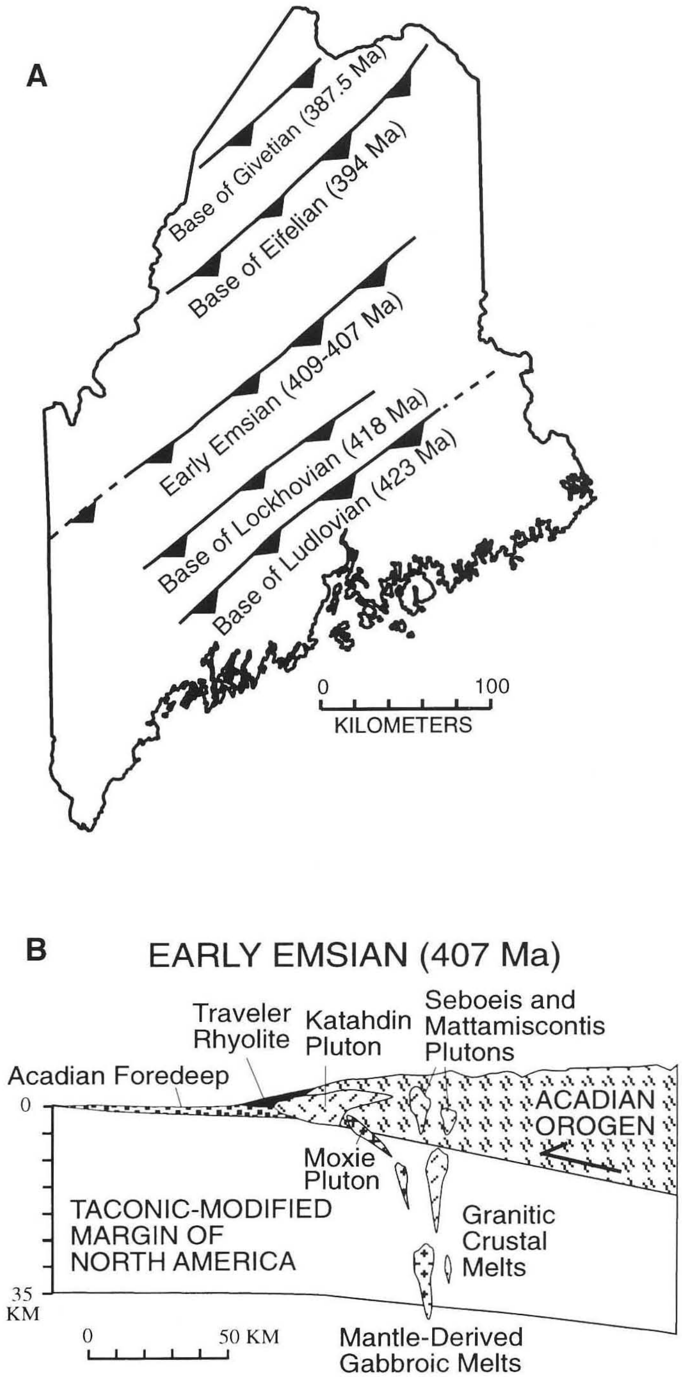

Fig. 5. Progress of Acadian deformation across Maine (after Bradley et al. 1996). **A.** Map showing the position through time of the Acadian deformation front. **B.** Schematic section through the Acadian deformation front near Mount Katahdin in early Emsian.

1976; Pollock et al. 1988). Paleocurrent studies reveal that sediment transport was broadly toward North America, away from newly risen orogenic sources (Hanson & Bradley 1989, 1994). The Traveler Rhyolite (406–407 Ma concordant zircon ages; Rankin & Tucker 1995) and the correlative Kineo Rhyolite were erupted in the proximal foredeep around the start of the Emsian. U–Pb and $^{40}Ar/^{39}Ar$ geochronology has revealed an extensive belt of early Emsian plutons (400–409 Ma) that meanwhile were being emplaced into the orogenic wedge (Fig. 5B). All of the following plutons cut regional Acadian folds: Sebec (409 Ma, zircon), Russell Mtn. (406 Ma, zircon), Mattamiscontis (407 Ma, zircon), Seboeis (404 Ma, zircon), Onawa (405 Ma, zircon), Shirley (407 Ma, zircon), Ebeemee (408 Ma, biotite), Hunt Ridge (402 Ma, cpx & hbl), Pleasant Lake (401 Ma, hbl & biotite), and Cochrane Lake (404, hbl). Midway between the southeastern limit of Emsian foreland-basin deposits and the plutons listed above are the Moxie (406 Ma, biotite) and Katahdin (407 Ma, zircon) plutons. Seemingly incompatible field relations around these plutons are perhaps best explained if plutonism occurred within a broad Acadian deformation front. In the Katahdin aureole near Harrington Lake, gently dipping Devonian strata were hornfelsed before ever acquiring the regional penetrative cleavage seen outside the aureoles. However, the Katahdin pluton truncates regional folds that involve its volcanic carapace, the Traveler Rhyolite (Rankin 1968)! Likewise, at the east end of the Moxie pluton, contact metamorphism predated regional cleavage (Hanson & Bradley 1989), but at the pluton's west end, contact metamorphism was syntectonic. Thus, in early Emsian, the Acadian front in Maine was a NE-trending zone that passed through the vicinity of Katahdin.

The simple paleogeography of a paired orogen and foredeep was complicated by an enigmatic magmatic pulse that affected a 75-km-wide zone (present distance) across the orogenic wedge, the deformation front, and the proximal foredeep. In the present model, the geochronologic evidence for northwest-migrating, northwest-vergent deformation across Maine seems to require a southeast-dipping subduction zone there. The magmatic activity of the Piscataquis belt, with its mantle-derived and mantle-activated crustal melts is now ascribed to lithosphere delamination as suggested in Fig. 4. In this model, the thickest Acadian sedimentation took place in the Acadian foredeep produced by progressive tectonic loading of the down-going Medial New England plate. The Traveler Rhyolite is unconformably overlain by post-tectonic, nonmarine conglomerate and sandstone of the Trout Valley Formation which contains terrestrial plants (Dorf & Rankin 1962), and which has yielded spores of latest Emsian to earliest Eifelian age (McGregor 1992). By this time, the Acadian deformation front had migrated to a new position closer to the craton. The age (Silurian or Devonian) and setting of the calcareous flysch that dominates the Connecticut Valley belt remains problematic (Robinson et al. 1988*a*; Hatch et al. 1988; Trzcienski et al. 1992*b*; Robinson 1994; J.B.Thompson et al. 1997).

Using the ages and distances traveled by the Acadian deformation front on Fig. 5A it is possible to calculate an average plate convergence rate of about 5 mm/yr. However, present distances are greatly reduced from older ones by later accordion-like folding, so the plate convergence rate was likely to have been in the range of 10 mm/yr, at the slow end of typical modern convergence rates during collision.

Two Acadian subduction zones or one?

The notion that prior to Acadian collision there existed a second subduction zone in the Merrimack belt, one that dipped to the northwest toward North America, has had many adherents (e.g., McKerrow & Ziegler 1971; Bradley 1983; van Staal 1987, 1994; Bradley & Hanson 1989; Ludman et al. 1993; Moench 1993; Eusden et al. 1996). The primary basis for this interpretation is episodic Ludlovian, Pridolian, Lockhovian, Pragian, and Emsian volcanism in northernmost New Hampshire, Maine, New Brunswick, and Quebec. Expanding on the more restrictive usage of Rankin (1968), Bradley (1983) assigned all of these volcanics to the Piscataquis magmatic belt. Figure 5A implies that *all* of the volcanic rocks are broadly syncollisional and were erupted in a foreland setting (Bradley et al. 1998). Most of the Ludlovian to Lochkovian volcanics in Maine (East Branch Group, West Branch Volcanics, and Fish River Lake, Spider Lake, Grand Lake Seboeis, and Allagash Lake Formations) were erupted in a far-foreland position. In addition, several volcanic units of Lochkovian and Emsian age are interbedded with or grade laterally into foreland-basin deposits, and hence formed in a proximal foreland position: the Hedgehog Volcanics, Edmunds Hill Andesite, Hartin Formation, Traveler Rhyolite, and Kineo Rhyolite.

Three alternative interpretations have been advanced for part or all of the Piscataquis magmatic belt. (1) On the basis of basalt discriminant plots, Hon et al. (1992) and Keppie & Dostal (1994) interpreted the Spider Lake and West Branch Volcanics as having formed in an intracontinental rift setting, related to so-called "transpressive rifting". In light of Fig. 5A, however, any purported extension would necessarily have taken place in a collisional foreland setting; extension in forelands is generally either caused by lithospheric flexure (Bradley & Kidd 1991), or by Baikal-style cracking of the lower plate (Sengör et al. 1978). (2) Bradley (1983), on the basis of first-order paleogeography, interpreted these units as arc volcanics. This model explains magmatism as the record of a collisional orogenic belt and its foreland basin advancing over a magmatic arc. Similarly, taking into account the extensional geochemical signature, Moench (1993) suggested that his Silurian Frontenac rift was a back-arc rift relating to a northwest-dipping subduction zone. (3) Tucker et al. (in press *b*) have suggested that the Emsian-age foreland-basin rhyolites and the Emsian plutons just to the south were a consequence of lower-lithospheric delamination of the downgoing (North American) plate (Fig. 4).

A second line of evidence bearing on the postulated northwest-dipping Silurian subduction zone involves chaotically deformed Silurian turbidites. In the Mount Washington area of New Hampshire, Eusden et al. (1996) identified a complex melange in the unfossiliferous but probably Lower Silurian Rangeley Formation of the thick Silurian sequence southeast of the "tectonic hinge". They interpreted this as a subduction melange which they related to a northwest-dipping early Silurian subduction zone beneath the Bronson Hill magmatic arc. Other chaotically deformed Silurian strata that might turn out to be tectonic melanges, at least in part, have been identified near Bangor by Griffin & Linsley-Griffin (1974) and near Millinocket by Roy et al. (1983). In each of these cases, it is unclear whether they are chaotic slump accumulations (which only reveal the presence of submarine slopes steep enough to fail), or tectonic melanges. Interpretations are equivocal because early fabrics are overprinted by a strong regional foliation associated with the main phase of Acadian shortening. An absence of melanges has often been cited as evidence against a northwest-dipping subduction zone, so careful structural studies would be worthwhile.

The two-subduction-zone model has been difficult to test because of a dearth of modern collisions with this plate geometry – the only two are the Molucca Sea and eastern Papua New Guinea-Solomon Sea – and a lack of a clear picture of what might be expected in a now-exhumed ancient example, especially a sediment-choked variant that would be appropriate for the Acadian. The coauthors of the present paper are themselves divided on the matter of Acadian plate geometry, which remains a ripe area for investigation.

Acadian deformation in western New England

Evidence of major, probably Early Devonian recumbent folds is first encountered near Waterville, Maine, where there are extensive regions of downward-facing Silurian strata deformed by later isoclinal upright folds (Osberg 1988). A granite dike, post-dating the earliest folds as well as the upright folds, is dated at 399±1 Ma (Emsian; Tucker et al. in press *b*). This age is the minimum age for formation of these folds. The maximum age is given by the age of the youngest rocks (Lochkovian?) in the sequence folded by these particular folds.

In the northern Bronson Hill-Boundary Mountain anticlinorium, Moench (Moench & Hafner-Douglas 1987; Moench & Aleinikoff 1991; Moench 1993, 1996) has proposed an enormous allochthon (Piermont allochthon) transported northwest for more than 50 km, consisting dominantly of Silurian rocks, including rare volcanics (Aleinikoff & Moench 1985), variously emplaced on Ordovician, Silurian and Devonian strata and supposed to have moved in the Early Devonian. This model, in which rocks previously mapped as Ordovician are included in the Silurian, has been challenged by Billings (1992), and in part by Rankin (1996, 1998), but remains as a viable model for at least some areas.

In the Connecticut Valley region of New Hampshire-Vermont, four giant west-directed fold nappes with tens of kilometers of overfolding have been recognized (Thompson 1954, 1956; Trask 1964; Trask & Thompson 1967; Thompson et al. 1968; Rumble 1971; Robinson et al. 1979, 1991; Thompson & Rosenfeld 1979; Robinson 1979; Thompson 1988; Allen 1997). They are intimately involved with enormous sheet-like intrusions of granitoid rocks (Clark & Lyons 1986), like peraluminous parts of the Piscataquis belt in Maine, yielding ages slightly greater than 400 Ma and producing major metamorphic overhangs of high grade rocks structurally above low-grade rocks of the Connecticut Valley synclinorium (Thompson et al. 1968; Spear & Chamberlain 1986; Spear et al. 1990; Kohn et al. 1992; Spear 1992). Much interest and effort has been focussed on the tectonothermal evolution of this region. Did the nappes actually carry hot rocks over cool, or were already metamorphosed layers stacked in nappes with highest grade rocks at the top? These nappes have been traced southward at least into west-central Massachusetts (Thompson et al. 1968; Elbert 1988; Robinson et al. 1988*b*, 1991; Robinson & Elbert 1992).

In the Mount Monadnock area of southwestern New Hampshire, P.J. Thompson (1985, 1988*a*, 1988*b*) recognized two major thrust nappes on the basis of stratigraphic relationships, the truncation of pre-existing west-directed recumbent folds, and the thrusting of higher grade rocks over lower grade rocks. The concept of thrust nappes truncating fold nappes has influenced reinterpretation of an extensive area in the Bronson Hill anticlinorium and adjacent areas in Massachusetts and southwestern New Hampshire (Elbert 1988; Robinson et al. 1988*b*, 1991; Chamberlain et al. 1988; Robinson & Elbert 1992), but has not yet been fully extended into west-central New Hampshire. A feature of these thrust nappes is that they carry thick, highly metamorphosed Silurian strata from east of the "tectonic hinge" at least 30 km westward over the much thinner "Bronson Hill sequence" to a position where some of them are now exposed as erosional inliers beneath the Deerfield and Hartford Mesozoic basins.

Work in central New Hampshire (Eusden et al. 1987; Eusden 1988; Lyons 1988) and in the Presidential Range (Eusden et al. 1996; Allen 1996) has also demonstrated both early recumbent folding, northwest- and southeast-directed, and synmetamorphic thrusting. The earlier difficulty of integrating these deformation patterns with the Monadnock area and central Massachusetts is now better understood by the discovery that much of the most intense deformation and highest grade metamorphism in central Massachusetts is Mississippian and locally even Late Pennsylvanian (see below). Most workers agree that the recumbent folding and thrusting were followed by a phase of gneiss dome formation, but the exact timing of this event or events is currently uncertain. In central Massachusetts, U–Pb ages on monazite, sphene, and metamorphic and pegmatite zircon indicate that dome formation was partly Neo-Acadian, partly Late Pennsylvanian (Tucker & Robinson 1993, 1995; Robinson & Tucker 1991, 1996). Comparable studies have not been completed on gneiss domes in western New Hampshire.

Geology typical of western New Hampshire, central Massachusetts and eastern Connecticut is separated from that typical of eastern Vermont, western Massachusetts and western Connecticut by the Connecticut Valley metamorphic low, commonly at chlorite zone (Fig. 6). In the western zone Acadian deformation seems to consist of an early phase of recumbent folding (Thompson et al. 1993*b*) followed by the formation of gneiss domes, some involving Proterozoic Laurentian basement, with no firm evidence for the Neo-Acadian and Late Pennsylvanian phases (Ratcliffe et al. 1992). Unlike western New Hampshire, the pattern of isograds seems to wrap around the gneiss domes (Thompson at al. 1986), suggesting heating from below rather than emplacement of high-grade rocks above lower-grade rocks. The status of western Connecticut is changing (Sevigny & Hanson 1993, 1995) but we have placed it beyond the scope of this paper.

Patterns of Acadian metamorphism

Tectonic and metamorphic studies in the central high-grade regions are facilitated where there is a well developed Silurian - Lower Devonian stratigraphic sequence and an abundance of pelitic bulk compositions, but greatly hindered in those large areas where plutons and ubiquitous pegmatites obscure stratigraphic and structural relationships. The mapping is less difficult in Vermont (Rumble et al. 1993) and western Maine (Moench & Zartman 1976; Guidotti 1989; Guidotti & Holdaway 1993), but here the pattern of regional isograds is punctuated by contact effects around plutons and the full history of metamorphism and plutonism has yet to be worked out precisely. The pattern of supposed Acadian metamorphic isograds is shown in Fig. 6. The last seven years of U–Pb geochronology in central Massachusetts have demonstrated conclusively that this map melds unrelated metamorphic features of several ages. We now know that the central Massachusetts granulite-facies metamorphic high is a Latest Devonian-Early Missippian Neo-Acadian feature, and the kyanite zone in the western part of the Bronson Hill anticlinorium as well as the metamorphic zone around the Sebago pluton in Maine are Late Pennsylvanian features. Even Fig. 6 hints at the different character of the highest grade isograds in central New Hampshire and central Massachusetts. In New Hampshire the patterns seem related in a complex way to the distribution of plutons or to thermal conduits variously ascribed to the passage of isotopically distinct metamorphic fluids (Chamberlain & Rumble 1988, 1989) or to hot intrusions that passed through without leaving a trace (Brady 1988). Zircon in one of these hot spots has been dated at 400 Ma (Zeitler et al. 1990). In central Massachusetts, by comparison, the Neo-Acadian pattern appears to be much smoother and clearly overprinted on country rocks and plutons alike.

The latest information from the Nashoba and Putnam belts west of Boston (Hepburn et al. 1995) indicates there was late Silurian high-grade metamorphism (about 425 Ma) in the eastern parts, but that the sillimanite-orthoclase and sillimanite-orthoclase-garnet-cordierite zones were probably early Devonian (ca. 395 Ma). The eastern limit of the high grade region in mid-coast Maine is likewise complex. The closely-spaced garnet through sillimanite-orthoclase zones in rocks of Composite Avalon reflect a probable Silurian event, partially dated by Late Silurian to Early Devonian (419–414 Ma) Ar–Ar hornblende cooling ages (West et al. 1995) and Late Silurian (420±2 Ma, zircon) post-tectonic plutons (Tucker et al. in press *b*). These rocks are faulted against Medial New England rocks metamorphosed in the Early Devonian that, curiously, attained similar metamorphic grades (Fig. 6). The patch of sillimanite-orthoclase zone to the northeast is confined to the Passagassawakeag Formation in thrust contact with rocks to the southeast. The metamorphism of this region is not well characterized. U–Pb monazite analyses from migmatites have given ages consistent with Devonian regional metamorphism that affected central and western Maine, but the discovery of Silurian plutons (Lake St. George, 422±2 Ma; Blinn Hill, 423±2 Ma, zircons) intruding the Cape Elizabeth Formation suggests that Silurian metamorphic relics might also be present (Tucker et al. in press *b*).

Neo-Acadian

Discovery of Neo-Acadian metamorphism

For many years it was believed that most of the pre-Mesozoic plutonism and regional metamorphism in central New England took place during or soon after the early Devonian deformation, at a time closely preceding deposition of the post-Acadian molasse of the Catskill delta in New York State and in basins and outliers in eastern Maine and New Brunswick. This view was not entirely supported by radiometric ages on plutons but was confirmed by a series of ages around 390–400 Ma on metamorphic monazite in high grade mica schists within or near the large sillimanite-grade metamorphic high of central New Hampshire which locally reaches conditions for the formation of sillimanite-orthoclase-garnet-cordierite assemblages (Eusden & Barreiro 1988). It was naturally assumed that the nearby granulite-facies metamorphic high of central Massachusetts, also with sillimanite-orthoclase-garnet-cordierite assemblages, would be the same age, although there are substantial differences in metamorphic character between the two zones. In particular, an intense post-peak shearing is characteristic of the central Massachusetts high (Robinson et al. 1986, 1989; Schumacher et al. 1990).

This assumption was recently disproven by U–Pb ages of 363±1 and 367±2 Ma from metamorphic monazite from schists in the core of the central Massachusetts high by Barreiro (Thomson et al. 1992), and by numerous U–Pb ages on monazite, sphene, and metamorphic zircon from a large region in central Massachusetts east of the Mesozoic border fault in the range 370–350 Ma (Robinson & Tucker 1991, 1996; Robinson et al. 1992; Tucker & Robinson 1993, 1995). The older ages of 400–390 Ma were found, however, in the sillimanite-grade rocks of the Amherst block to the west of the border fault (Fig. 7). These are interpreted as part of high-level thrust nappes transported over the site of the present gneiss domes and then dropped down approximately 5 km along the Mesozoic fault. These rocks were apparently at too high a structural level to feel the effects of the younger metamorphisms. The northern boundary of the zone of 360 Ma metamorphic monazite ages in western New Hampshire is not well known and is the subject of ongoing research by Tucker and Robinson. Falling within the time gap between the older Acadian and Neo-Acadian metamorphisms was the peculiar 380±5 Ma Belchertown Quartz Monzodiorite intrusion (Ashwal et al. 1979), with its relict contact aureole, and geochemically and temporally similar dikes and sills at widely distributed locations (Fig. 7).

Neo-Acadian plutons and their involvement in ductile deformation

Even more surprising has been the discovery that the strongly foliated plutons in the high grade zone are widely different in age. As expected, the Ashuelot pluton of Kinsman granite in southwestern New Hampshire gave a U–Pb zircon age of 403±3 Ma (Emsian) consistent with other members of the Piscataquis magmatic belt, and the chemically similar Coys Hill Granite of northern Massachusetts gave an age of 396±2 Ma (late Emsian) on igneous zircon. The involvement of the Kinsman Granite and the related Bethlehem Gneiss in the location of westward overturned metamorphic isograds associated with Acadian recumbent folding in southwest New Hampshire has long been known (Thompson et al. 1968; Allen 1997). Furthermore, the Spaulding Tonalite in the Spaulding type area in the Monadnock Quadrangle, New Hampshire (P.J. Thompson 1985) gave a U–Pb zircon age of 408±2 Ma (early Emsian). The first big surprises came in the ages of Hardwick hornblende tonalite and enclosed microcline porphyritic gneiss at 360±1 and 361±2 Ma (Tournasian), respectively (Robinson & Tucker 1992; Tucker & Robinson 1995). The Hardwick tonalite is a strongly foliated sheet-like mass petrologically similar to the Spaulding tonalite (Shearer 1983; Shearer & Robinson 1988) that is more or less directly along strike from the Spaulding and had been considered a related intrusion. Based on the highly foliated and attenuated character of the Hardwick intrusions, and the relict andalusite pseudomorphed by sillimanite in their contact zones and xenoliths (Shearer & Robinson 1980) they had been interpreted as having been intruded just before or during the early Acadian "nappe" stage. According to the new Devonian time scale these are not even Devonian intrusions!

A similar surprise was created by the new U–Pb zircon age of the Wachusett Tonalite at Calamint Hill of 359±1 Ma (Tournasian), based on 6 zircon fractions, three of which are concordant (R.D. Tucker, unpubl. data 1997). The Wachusett Tonalite forms an enormous thin, strongly foliated and lineated sheet, permeated by deformed pegmatites and enclosed by mica schists structurally beneath the main granitic intrusions of the Fitchburg Complex that lie in the core of a broad structural syncline (Zen et al. 1983). Structural interpretations beneath the complex suggest that it is riding on the back of a major east-directed fold nappe. Tucker (1978) and Peterson (1984) mapped a series of E–W trending isoclinal folds in the Wachusett Tonalite, and also a strong E–W trending mineral lineation then considered to belong to the "backfold stage" that can be observed westward across central Massachusetts virtually into the Bronson Hill anticlinorium (Fig. 8). This lineation is related to a top-to-the-east shear fabric that appears to overprint or be impressed on peak granulite-facies metamorphic minerals. In the Monson area, in the Conant Brook shear zone (Peterson et al. 1990; Peterson 1992*a*, 1992*b*; Peterson & Robinson 1993), this lineation is overprinted

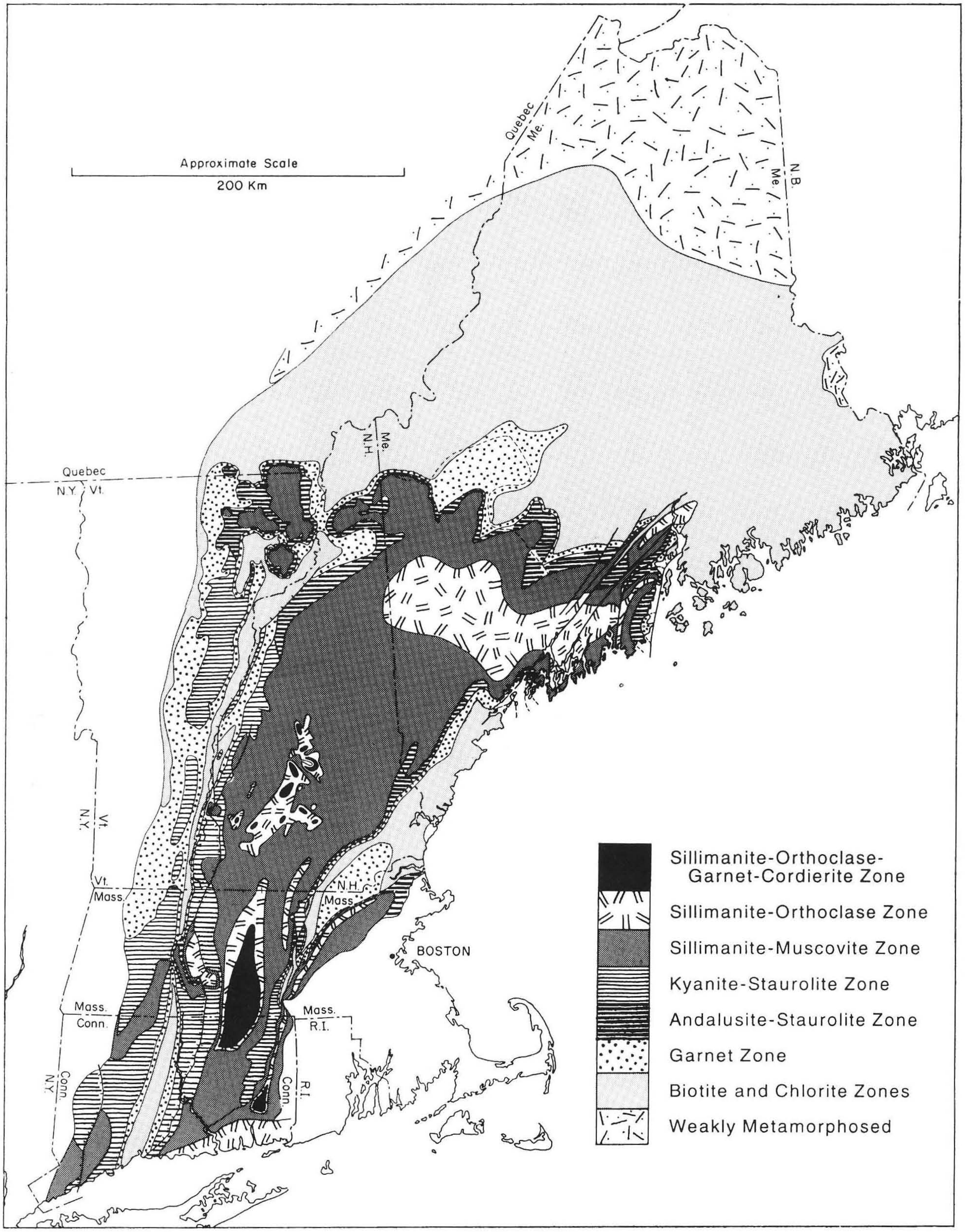

Fig. 6. Generalized map of New England showing the intensity of "Acadian" metamorphism as compiled in 1989 with minor additions.

by a second high-temperature linear fabric that is subhorizontal and dextral. The latter fits in a group originally assigned to the "Acadian dome stage" but now known to be Neo-Acadian. Adding an abrupt termination to this episode of intense early Mississippian high-temperature ductile deformation, the ductilely deformed rocks at the north edge of Massachusetts are cut by unde-

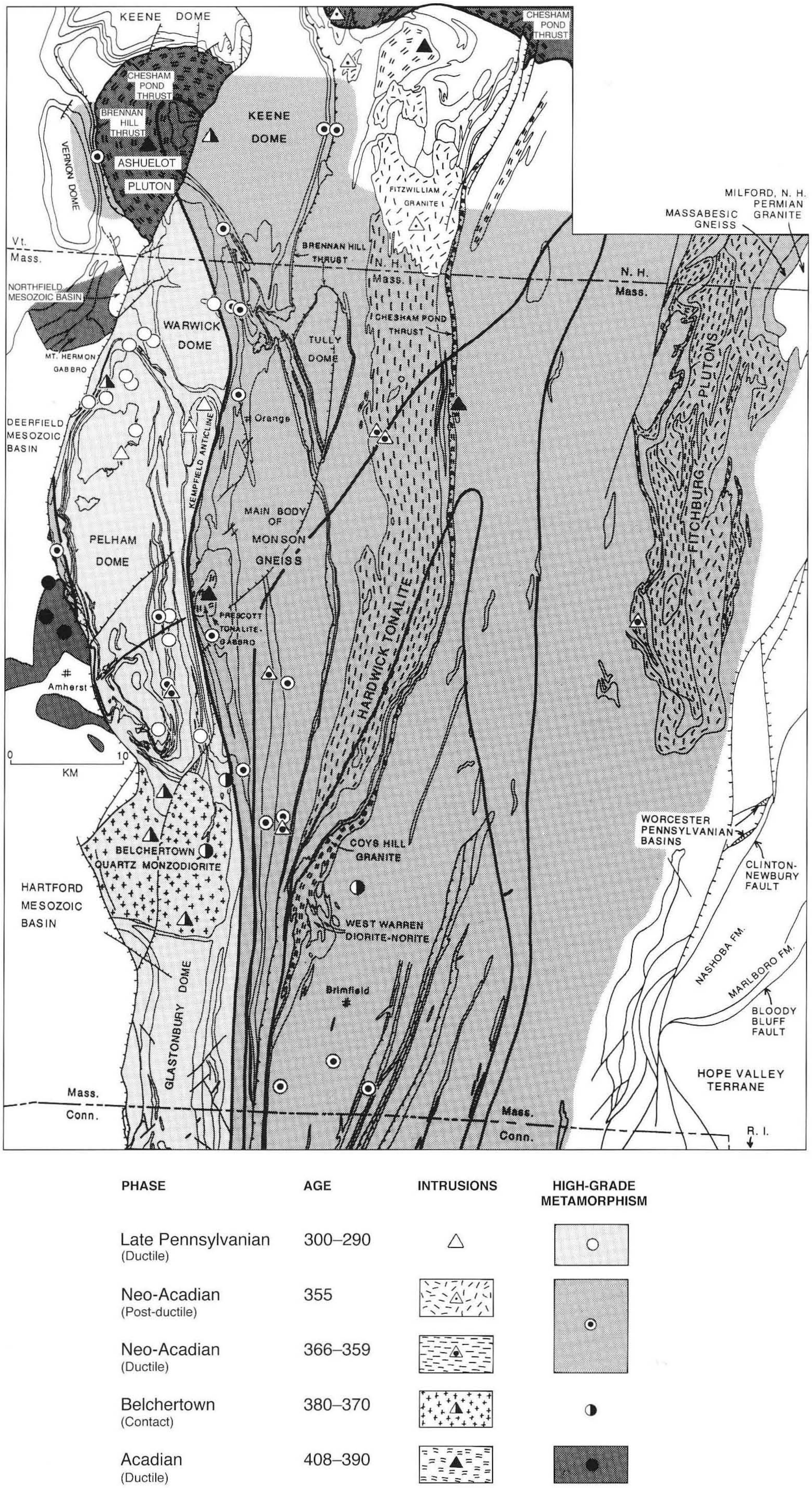

Fig. 7. Detailed map showing ages of overlapping igneous intrusive and metamorphic effects in central Massachusetts and southwestern New Hampshire. Small symbols indicate locations of individual igneous or metamorphic age determinations, mostly U–Pb on zircon, monazite, and sphene by Tucker. Effects include: (1) Acadian intrusions and locally preserved Acadian metamorphism west of the Mesozoic Connecticut Valley normal fault and also north of the Chesham Pond thrust; (2) the Belchertown Quartz Monzodiorite intrusion and contact metamorphic effects. This episode includes petrologically similar small intrusions in the Pelham and Keene domes; (3) Neo-Acadian ductilely deformed intrusions and high-grade regional metamorphism that dominates central Massachusetts. The eastern limit of this zone has not been adequately delineated. The zone includes isolated patches of Neo-Acadian metamorphism on the west limb of the Pelham dome and west of the Ashuelot pluton, and also relict patches of high-grade neo-Acadian metamorphism of the Mt. Mineral Formation within the large area of Late Pennsylvanian overprint in the Pelham dome. Late neo-Acadian little deformed granites are shown separately; (4) an area of Late Pennsylvanian pegmatite intrusions, kyanite-grade metamorphism and ductile deformation centered on the Pelham dome. Heavy dark loop encloses the Neo-Acadian sillimanite–orthoclase–garnet–cordierite zone, and is surrounded by the sillimanite–orthoclase–muscovite isograd. The same isograd, probably of Acadian age, occurs near the base of the Ashuelot pluton and near the Chesham Pond thrust.

formed muscovite-biotite granites of the Fitzwilliam type consistently dated by U–Pb monazite at 354±1 Ma (Robinson & Tucker 1996).

Evidence for overlap of Acadian and Neo-Acadian features

A large outcrop in the Quabbin Reservoir has served as a "Rosetta Stone" for understanding the deformation sequence in central Massachusetts (see Figures in Robinson 1967*b*; Robinson et al. 1989; Tucker & Robinson 1990). A coarse pink pegmatite dike cross-cutting two phases of folds, and deformed by later mylonite and a third phase of folds, yields a U–Pb zircon age of 366±1 Ma (Tucker & Robinson 1995) corresponding to latest Devonian (Famennian, Tucker et al. 1997 and in press *a*), and probably to the beginning of the Neo-Acadian pulse. The mylonites correspond to the post-360 Ma shear fabric with east–west lineation described in the Wachusett Tonalite and Conant Brook shear zone, and the third folds with subhorizontal fold axes and lineation correspond to the "dome stage", now considered Neo-Acadian. Pegmatitic migmatite layers in an adjacent outcrop of sillimanite-orthoclase schist behaved as "competent" layers during the second folding (Tracy 1975; Tracy & Robinson 1980, 1983), indicating that the partial melting that produced the layers was much older than 366 Ma, possibly the true Acadian, and that the rocks may even have cooled significantly between these two episodes. These early migmatites are an obvious target for U–Pb zircon geochronology.

The stratigraphy in the Brimfield-Sturbridge area consists of pre-Silurian basement of Medial New England, the Leadmine Pond Gneiss, and Silurian cover of a Rangeley or Central Maine sequence (Berry 1989, 1992; Berry & Robinson 1989). There are rare early recumbent folds, but the dominant structural features are thrust slabs consisting of Leadmine Pond Gneiss stratigraphically overlain by Rangeley sequence strata. The thrusts are believed to have been originally west-directed like the Acadian thrust nappes of the Connecticut Valley region, but the contacts now dip steeply to shallowly northwest as a result of later eastward overturning of the entire stack (Fig. 8). The thrust nappes are truncated by mafic tonalites, themselves highly deformed and overprinted by granulite-facies metamorphic minerals and fabrics. Early attempts to date one of the tonalites by bulk zircon analysis in 1979 produced discordant results (R.E. Zartman, written comm. 1988) so their age is not well known (Berry 1992). Analogy would suggest they were intruded around 360 Ma, consistent with the other early Mississippian tonalites involved in the intense Neo-Acadian deformation and metamorphism.

Pattern of Neo-Acadian metamorphism

The pattern of apparently Acadian metamorphic isograds so clearly related to tectonic level in the pile of fold and thrust nappes in the Connecticut Valley region (Thompson et al. 1968; Robinson et al. 1991) does not at all fit the pattern of high grade Neo-Acadian isograds in central Massachusetts (Robinson et al. 1986, 1989). These have a blob-like form, cutting across all stratigraphic and most structural features without deviation, except at the east margin of the Fitchburg Complex where eastward overturning of isograds is suspected.

Tectonic setting

What was the tectonic setting of this intense plutonism, very high-grade metamorphism and intense ductile deformation? Because it happened 40 to 50 million years later, it cannot be directly related to the Late Silurian-Early Devonian wave of deformation and postulated lithospheric delamination described above for northern New England. The style of plutonism and apparently high heat flow might again be explained by lithospheric delamination, but it seems unlikely that subduction of Medial New England beneath Avalon was still active, so some other cause for delamination must be sought. The intense ductile deformation shown throughout the central Massachusetts metamorphic high indicates that major tangential forces were active there, but the plate mechanism that brought this about has still to be identified.

Late Pennsylvanian

Ductile deformation and metamorphism in west-central Massachusetts

Robinson (1963) described a complex swirling pattern of lineation near the Warwick dome in central Massachusetts. Areas to the east have a strong mineral lineation plunging gently south, whereas areas 5–8 km to the west have a strong lineation plunging gently north. As one travels from the east to the west, the lineation becomes steeper toward the southeast until it plunges down the dip of the east-dipping foliation and further west the plunge is to the northeast and becomes progressively flatter until it plunges gently north. There was much speculation on the origin of this pattern and it was generally thought to be a complex function of Acadian dome dynamics (Robinson 1979). West of the swirl, Ashenden (1973), Onasch (1973), Laird (1974), and Robinson (1979) identified a series of late asymmetric folds in the center of the Pelham gneiss dome. These are essentially sheath folds that deform the mineral lineation about great circles, but the north-south trending lineation in this dome can also be shown to be within an 18 degree fold separation angle in the direction of transport that formed the folds. Furthermore, the asymmetry of the sheath folds indicates that the higher layers of the dome were moving south with respect to the lower layers. Reed & Williams (1989) and Reed (1993) showed that the same shear sense could be determined from the asymmetry of delta tails around deformed microcline porphyroclasts and also that the conditions of shearing were such that quartz easily underwent dynamic recrystallization but microcline did not.

In a broad survey of hornblende Ar–Ar ages, Spear & Harrison (1989) determined an age of 287±1 Ma from Dry Hill Gneiss in the center of the dome. From the same outcrop, Tucker (Tucker et al. 1988, 1989; Tucker & Robinson 1990) determined an age on sphene of 292±5 Ma, which initially was considered a late cooling age. About the same time and again at the same outcrop Gromet (Gromet & Robinson 1990) determined Rb–Sr, Sm–Nd and U–Pb mineral isochrons on sphene, garnet, hornblende, biotite and whole-rock and suggested that these minerals equilibrated at the same time as the formation of the strong foliation and north–south lineation. Earlier work by Hodgkins (1985) had indicated that the tiny garnets in this rock, which control the Sm-Nd mineral isochron, show chemical zoning indicative of prograde growth, thus garnet growth was Pennsylvanian.

A broader program of U–Pb dating by Tucker of metamorphic monazite and sphene, as well as igneous zircon in a group of pegmatites that range from massive to extremely foliated, and a program of selected Rb–Sr, Sm–Nd and U–Pb dating of mineral isochrons by Gromet soon showed the extent (Fig. 7) of a new province of Late Pennsylvanian pegmatite intrusions, ductile deformation, and metamorphic recrystallization (Robinson et al. 1992). This extends eastward about 8 km from the Pelham dome crest nearly to the east margin of the Warwick dome, at the approximate location of the lineation swirl. Further study of asymmetric shear fabrics in the Warwick dome (DelloRusso & Robinson 1989; Peterson et al. 1990, 1993) and in the Northfield syncline (Reed 1993) between the Pelham and Warwick domes, showed a top-to-the-north movement of cover relative to basement in western part of the Warwick dome, and consistent dextral shear across the entire isoclinal Northfield syncline. On the basis of these studies Peterson et al. (1993) showed that the "great swirl" could be well explained by the progressive imposition of an intense Late Pennsylvanian ductile strain field on rocks that had previously been strongly deformed in the Acadian. More recently at Leverett on the extreme western exposed edge of the Pelham dome (Fig. 7), sillimanite-mica schist interbedded in Silurian Clough Quartzite has proved to contain Neo-Acadian monazite dated at 359±1 Ma (Tournasian), and here also there is evidence in the form of a swirl of a pre-existing Acadian linear fabric and folds being reoriented in passing eastward into a Late Pennsylvanian strain field (Oxboel et al. 1997). Since the outlining of this zone of Late Pennsylvanian deformation and metamorphism, similar Ar–Ar ages on hornblende as well as U–Pb ages on sphene and monazite have been determined from an extensive region along the Bronson Hill anticlinorium in southern Massachusetts and adjacent Connecticut (Wintsch et al. 1993; Coleman et al. 1997). The limit of this zone to the north is not known although it may be truncated by the Mesozoic border fault where it cuts the northern corner of the Warwick dome.

Late Pennsylvanian in New Hampshire and Maine

In southern New Hampshire, Late Paleozoic metamorphism has been detected only southeast of the Campbell Hill fault, in the Massabesic Gneiss Complex and in the Merrimack Group. The few U–Pb analyses available from metamorphic sphene and monazite have been interpreted to show that a metamorphic event occurred from ca. 285 to 275 Ma (Aleinikoff et al. 1995) and from ca. 282 to 261 Ma (Eusden & Barreiro 1988). Permian Ar–Ar hornblende release spectra also show that a Late Paleozoic thermal event reached amphibolite grade (West 1993). It appears that these rocks may have experienced a Late Pennsylvanian event, although more precise data are needed to see whether such an event can be distinguished from somewhat younger Permian effects.

Another zone of young metamorphism has been detected around the Sebago Batholith in southern Maine, the largest plutonic complex in New England, which appears to have a flat, sheet-like nature. As with most undated New England plutons, the Sebago was presumed to be Devonian. But in 1984, Rb–Sr whole-rock (Hayward & Gaudette 1984) and U–Pb zircon analyses (Aleinikoff 1984) demonstrated a Late Paleozoic age. The original analysis of bulk zircon separates (2–18 mg) yielded discordant results from which an upper intercept age of 325±3 Ma was inferred. A recent re-investigation by Aleinikoff has produced a concordant U–Pb zircon age of 296±3 Ma (Foord et al. 1995), consistent with his earlier monazite ages and overlapping with a new monazite age of 293±2 Ma (Tomascak et al. 1996), which indicate crystallization in the Late Pennsylvanian. Regional metamorphic effects which had been described previously in the adjacent rocks (Evans & Guidotti 1966; Guidotti et al. 1973), were shown on the basis of argon cooling ages and other geologic relationships to be an overprint related to the Sebago, whereas metamorphism farther north was Acadian (Lux & Guidotti 1985).

A program of ^{40}Ar–^{39}Ar dating in south-central Maine by West et al. (1988), has shown that hornblende gives plateau ages of 368 to 372 Ma in the northeast, decreasing in age across 40 km toward the southwest to 323 Ma. They interpreted this pattern to reflect slow cooling in response to differential unroofing following Acadian metamorphism, in which more deeply buried rocks to the south cooled later. Within 40 km of the Sebago pluton on the ground, structurally above this sheet-like mass, the hornblende ages become abruptly and uniformly young. Along a 60-km transect, six analyses gave ages between 283 and 287 Ma; the other two, near Topsham, are younger at 266 and 270 Ma (West et al. 1993). West et al. (1993) noted the obvious geographic relationship of this thermal event to the Sebago Batholith. Since the Sebago was then believed to be 325 Ma old, and thermal modeling by De Yoreo et al. (1989*a*) indicated that the thermal effect of the Sebago would have decayed within 10 Ma, West et al. (1993) were forced to appeal to a regional, post-Sebago thermal event. The new age for the Sebago now reconciles the metamorphic and plutonic episodes to within the time window allowed by thermal models, and suggests that the Sebago intrusion was accompanied by a widespread thermal disturbance that affected much of southern Maine in the Late Pennsylvanian. This event in southern Maine does not appear to be related to regional deformation, although local structural effects within a few km of the pluton have been ascribed to the intrusion process (Hussey et al. 1986; Thomson & Guidotti 1989).

In coastal Maine, northeast-trending high-angle faults assigned to the Norumbega fault zone (Stewart & Wones 1974) cut through the eastern part of Medial New England, offsetting plutons and Devonian isograds by up to a few tens of kilometers. These faults are characterized by intensely deformed, mylonitic rocks with vertical foliation and sub-horizontal lineation showing dextral shear sense (West & Hubbard 1997). The mylonite zones are several hundred meters wide in the deeper exposed levels and apparently narrow to thinner, brittle fault zones along strike in eastern Maine. ^{40}Ar–^{39}Ar analyses on five grain-size fractions of muscovite from a single mylonitic sample gave systematically disturbed release spectra that allowed West & Lux (1993) to fix the age of deformation at approximately 290 Ma. Although this technique yields only a maximum age, it suggests that parts of this regionally extensive dextral fault system were active in the Late Pennsylvanian.

Late Pennsylvanian in southeastern New England

The Hope Valley ductile shear zone in western Rhode Island, although a boundary between two terranes of Late Proterozoic rocks (O'Hara & Gromet 1985; Mosher et al. 1993) is a zone of deformation that has been dated at 293 Ma by mineral isochrons (Gromet 1991). A similar age of deformation has been recorded in the Proterozoic basement of the Willimantic dome (Gromet 1989; Getty & Gromet 1992*a*, 1992*b*; Mosher et al. 1993).

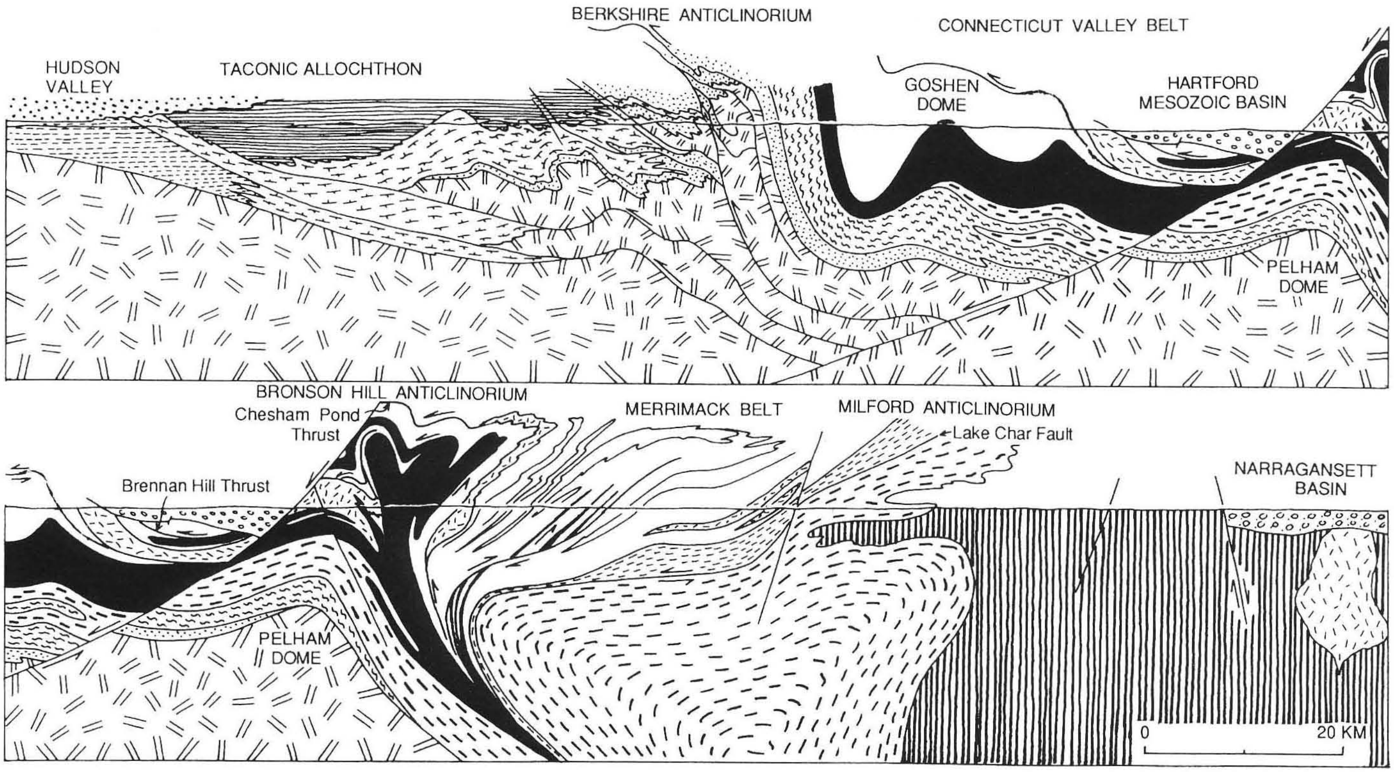

Fig. 8. Generalized structure section across southern New England along a line shown on Fig. 1. Key to patterns the same as in Fig. 1. Modified from Thompson et al. (1993*a*).

Tectonic setting

What do we know about the regional setting of these peculiar zones of local granitoid intrusions, kyanite-grade regional metamorphism and distinctive ductile deformation? Not very much, nor have we learned much about plate interactions based on the detailed study of shear sense within the zone in Massachusetts. In Maine, where the Late Pennsylvanian effects are mainly thermal with apparently little accompanying deformation, thermal models (De Yoreo et al. 1989*a*, 1989*b*) can account for the advection of magmas in the Pennsylvanian as a consequence of conductive heating of the lower crust following Acadian crustal thickening. But with a growing body of data indicating that other areas of New England were geologically active at the same time, it is tempting to think of these as being early effects of the collision with Africa as discussed by Mosher et al. (1993) and Cogswell & Mosher (1994). As they point out, these deformations were in progress in the Late Pennsylvanian at about the same time as sedimentation in the nearby Pennsylvanian continental sedimentary basins in Rhode Island and southeastern and central Massachusetts. For this reason they are clearly older than the classic Alleghanian orogeny of the central Appalachians which strongly folded Pennsylvanian and even Permian strata to produce the Valley and Ridge province of Pennsylvania and states to the southwest.

Alleghanian

None of the present authors has expertise on the Late Paleozoic tectonic history of southeasternmost New England. Excellent summaries are provided by Mosher et al. (1993) and Cogswell & Mosher (1994), and a complex model is presented by Wintsch et al. (1993), based on a wide range of Ar–Ar ages. Cogswell & Mosher (1994) believe that their study "offers conclusive evidence that the early deformation within the Narragansett basin resulted from collision-driven convergence" believed to have occurred as a result of the collision of Africa. They point out the importance of studies confined to Pennsylvanian stratified rocks in the Narragansett and adjacent basins where there can be no confusion with structural features formed earlier.

Plant fossils indicate the time of deposition of the Pennsylvanian continental sedimentary strata was between Westphalian A or B and Stephanian B or C, or 310–290 Ma (Mosher et al. 1993), the same time as the Late Pennsylvanian ductile deformation described above. Cogswell & Mosher's (1994) D1 in the southwestern part of the basin represents west-directed tectonic transport shown by large-scale recumbent nappe-like folds that formed synchronous with upper amphibolite-facies regional metamorphism to the kyanite-staurolite and even the sillimanite zone. Their D2, mainly expressed in the less metamorphosed eastern part of the basin, has an eastward sense of overturning suggestive of backfolding. The D1 deformational fabric is cut by the 273 Ma Narragansett Pier granite which was intruded during sinstral transcurrent motion within the basin. The Narragansett Pier is also a stitching pluton intruding across the Hope Valley shear zone separating the Esmond-Dedham and Hope Valley terranes. Interestingly, dikes of Westerly Granite related to the Narragansett Pier contain the oldest objects yet dated in New England, zircons with inheritance going back to about 3 Ga (Zartman & Hermes 1987). Mosher et al. (1993) speculate that these might somehow derive from impinging African basement.

Pressure estimates suggest about 6 km of unroofing took place between the peak of regional metamorphism and the intrusion of the granite, and these estimates might be consistent with evidence for extensional faulting in eastern Connecticut (Goldstein 1989) during the period 285–272 Ma (Getty & Gromet 1992*a*, 1992*b*).

After the Narragansett Pier intrusion, the basin was affected by late-stage dextral shearing with a minimum age of 250–240 Ma, based on biotite Ar–Ar plateau ages, that might relate to counterclockwise motion of Africa before extension in the Late Triassic. The array of hornblende Ar–Ar ages presented by Wintsch et al. (1993) suggests that peak Alleghanian metamorphism probably extended from the area of the Narragansett Basin westward along the Connecticut coast at least as far as the Hartford Mesozoic basin.

In central Massachusetts (Grew 1976) exposures of Pennsylvanian strata are much smaller and radiometric dating is not abundant, but the structure is similarly complex. For example, at Pin Hill in the small town of Harvard a strong early pebble and cobble stretching lineation in conglomerate is folded by later westward overturned folds associated with a well developed axial-plane cleavage in phyllites (Thompson & Robinson 1976). Nearby outcrops of pre-Pennsylvanian rocks show extensive retrograde effects, including white-mica pseudomorphs of andalusite and white-mica chlorite pseudomorphs of staurolite (Goldstein 1992), and such effects are also seen at widely scattered locations away from Pennsylvanian basins. For example, rocks with staurolite pseudomorphs and a distinctive deformation fabric (Robinson 1963; Hollocher 1981, 1987) are abundant in the New Salem retrograde zone in the Bronson Hill anticlinorium where they overprint both Neo-Acadian and Late Pennsylvanian fabrics near the "great swirl". Although this zone has not been radiometrically dated, it must be post-Pennsylvanian and pre-Triassic.

The Permian thermal effects are not restricted to southern New England, however. In southern New Hampshire the fine-grained Milford Granite, cutting the Late Proterozoic Massabesic Gneiss Complex and also its Silurian cover, and with local contact metamorphic effects, has yielded U–Pb zircon and monazite ages of 272±2 Ma (Aleinikoff et al. 1979, 1995). East of the Sebago Batholith, near Topsham Maine, granite and pegmatites crystallized at 278±2 and 268–275 Ma, respectively (Tomascak et al. 1996), and hornblende gives Ar–Ar ages of 266 and 270 Ma (West et al. 1993).

Summary

Analysis of the tectonostratigraphy, plutonism, regional metamorphism and geochronology of the New England Appalachians provides some new guidelines for the application of plate tectonics to the region as well as constraints on global reconstructions.

A key element in our guidelines is the increasing body of evidence clarifying the role of Medial New England. Features of Medial New England, including suites of detrital zircons in Late Proterozoic and Early Paleozoic sedimentary rocks, and rare Cambrian and abundant Ordovician volcanics, are consistent with, but do not prove, that Medial New England was part of an arc founded on continental crust of Amazonian affinities. Basement age alone is not a sufficient basis for identifying tectonic plates. Of equal importance to plate reconstructions is to understand the characteristics, origin and age of the apparent oceanic belts that closed between Medial New England and Laurentia to produce the Late Ordovician Taconian orogeny, and between Medial New England and Composite Avalon to produce the Late Silurian-Early Devonian Acadian orogeny. In addition, evidence from New Brunswick strongly suggests that Medial New England was split by a major back-arc basin in late Early Ordovician and the northwestern fragment moved rapidly toward collision with Laurentia.

The Taconian orogeny in western New England resulted in the Late Ordovician when the eastern margin of Laurentia was subducted beneath the volcanic arc founded on this western part of Medial New England. Also in the Late Ordovician, the back-arc basin present in New Brunswick began to close in a northwest-dipping subduction complex that continued into middle or late Silurian.

In the early Silurian, following the Taconian collision, the ruins of the Taconian orogen in the west were eroded, while the eastern part of Medial New England was buried by thick marine clastic sediments, possibly in an extensional regime.

At its east margin, Medial New England, although fundamentally a terrane of Gondwanan (Amazonian) affinity, is distinguished from Composite Avalon by very distinctive biogeographic faunas from Cambrian to Lower Devonian. In addition, these two belts show distinctive Proterozoic, Cambrian and Ordovician sequences, and also have completely different Silurian and Devonian cover. In Medial New England, the thick Silurian marine basin fill was supplied from western sources until late in the Silurian when sediments began to be shed westward from the early phases of Acadian collision. This eastern source was accentuated in the Lower Devonian with extensive marine deltaic complexes forming in front of the moving Acadian deformation front. Silurian and Devonian cover on Composite Avalon consists mainly of bimodal volcanics, the so-called coastal volcanic belt, possibly of arc affinities, which is little metamorphosed and commonly quite fossiliferous. These rocks escaped intense metamorphism twice, once in the Silurian due to their high structural level in the overriding plate, and again in the Devonian due to their position southeast of the metamorphic high. However, Silurian metamorphic and plutonic rocks are found in both terranes near their boundary, due to magmatic activity associated with their collisional suturing beginning in the Late Silurian which marks the beginning of the Acadian orogeny.

Across the state of Maine, where the time of deformation can be bracketed in many places between fossil ages of deformed strata and isotopic ages of cross-cutting plutons, the northwestward progress of the onset of Acadian deformation can be traced in some detail, beginning at the base of the Ludlovian at 423 Ma, passing Mount Katahdin at the base of the Emsian at 409 Ma and reaching the western edge of the Connecticut-Valley Gaspé basin at 385 Ma. The volcanic and intrusive rocks of the Piscataquis Belt which were erupted in the Emsian extend into more intensely deformed and metamorphosed regions to the southwest, where they appear to have been more or less contemporaneous with a series of major west-directed fold and thrust nappes, and only a few million years earlier than the imprint of peak regional metamorphism up to sillimanite-orthoclase-garnet-cordierite grade, at 400 to 390 Ma. The Piscataquis belt as well as other igneous activity and high temperature metamorphism in Medial New England is proposed to have resulted from delamination of mantle lithosphere from the descending plate of the subduction zone and movement of asthenosphere close to the base of the continental crust in northern New England. An alternative view of the Piscataquis belt is that it records the existence of a second, northwest-dipping subduction zone in a Molucca Sea type setting.

A surprising result of new U–Pb geochronology in central Massachusetts is to show that the sillimanite-muscovite-staurolite up to granulite-facies metamorphism and intense ductile deformation, as well as the intrusion of syntectonic tonalites and granites, in that region is not a simple southward continuation of the Acadian in New Hampshire. It occurred around 366 to 355 Ma in the latest Devonian and Early Mississippian, 30–50 m.y. following the traditional Acadian, and was terminated by a series of granite plutons at 354 Ma. The early part of the ductile deformation was characterized by top-to-the-east shearing with eastward overturning of previously west-directed Acadian structural features. This was immediately followed by pervasive subhorizontal longitudinal dextral shear along at least the gneiss domes of the Bronson Hill anticlinorium in Massachusetts. The plate setting of this separate series of "Neo-Acadian" events, remains uncertain, but its abrupt, intense, localized character also may favor an event involving lithosphere delamination in southern New England.

Several locations in New England contain evidence for Late Pennsylvanian intrusions, kyanite- to sillimanite-grade regional metamorphism, and ductile deformation overprinting older features, again in areas previously considered to be Acadian. These may be related to early impingement of Africa on the previously amalgamated Laurentia - Medial New England - Composite Avalon, and occurred during the time of Late Pennsylvanian sedimentation in southeastern New England. Finally, in the Permian, Late Pennsylvanian continental clastic sedimentary rocks in southeastern New England were strongly deformed, regionally metamorphosed up to sillimanite grade, and cut by intrusions, in events related to the Alleghanian continental collision with Africa. This collision caused the folding and thrusting of the Valley and Ridge Province in the central and southern Appalachians.

Above all else, these results demonstrate the power of precise isotopic dating when applied to rocks in a tightly calibrated part of the time scale that have been intensively studied for their stratigraphy, structure, and petrology. They point to the continued need for such work to provide the hard data upon which tectonic models can be successfully constructed.

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