19.7 The Northern Appalachians—Dwight C. Bradley[1]

19.7.1 INTRODUCTION

The Appalachian Orogen of eastern North America extends more than 3000 km from Alabama to Newfoundland (Figure 19.7.1). The idea that the Appalachians represent the site of a long-vanished ocean basin was put forward in the classic paper by J. T. Wilson in the mid-1960s. The destruction of this ocean is recorded in three main phases of orogeny, known as the Taconic (Ordovician), Acadian (Silurian and Devonian), and Alleghanian (Carboniferous and Permian) orogenies. Many 'hard-rock' aspects of Appalachian geology (structure, metamorphism, plutonism, and geochronology) have been studied in great detail, and these disciplines have played a key role in formulating plate-tectonic interpretations. This essay, however, focuses on the fundamental contribution of stratigraphy in unravelling the tectonic history. To illustrate this approach I will focus on the rocks of New England and adjacent New York. In particular, I will show how information about the timing, location, and plate geometry of orogenic events can be gleaned from foreland basin sequences.

[1]U.S. Geological Survey, Anchorage, Alaska.

19.7.2 MAIN GEOLOGIC FEATURES

Along strike, the Appalachians are traditionally divided into the southern, central, and northern Appalachians (Figure 19.7.1). A simple four-fold scheme is often used for dividing the orogen across strike into subparallel zones (Figure 19.7.1): (1) Early Paleozoic North America and its deformed continental margin; (2) a complex belt containing various remnants of the Paleozoic Iapetus Ocean (deep-water sedimentary sequences, ophiolites, and arcs; sometimes called the *Central Mobile Belt*); (3) a Late Precambrian to Early Paleozoic microcontinent called *Avalonia;* and (4) a sliver of Early Paleozoic rocks formed along the African continental margin, called *Meguma.* Additional subdivisions of North America and the Central Mobile Belt in New England will be introduced below (see also Figure 19.7.2).

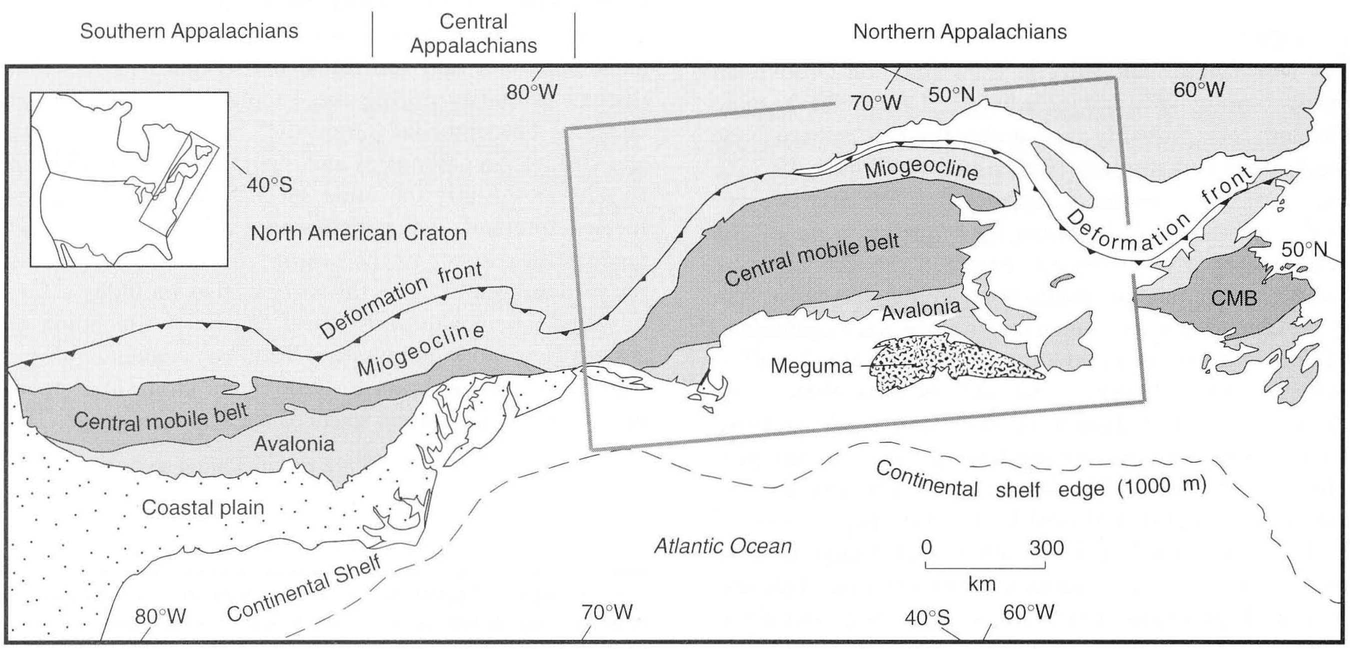

Figure 19.7.1 Map of the Appalachian Orogen showing four major lithotectonic zones and subdivision into northern, central, and southern Appalachians.

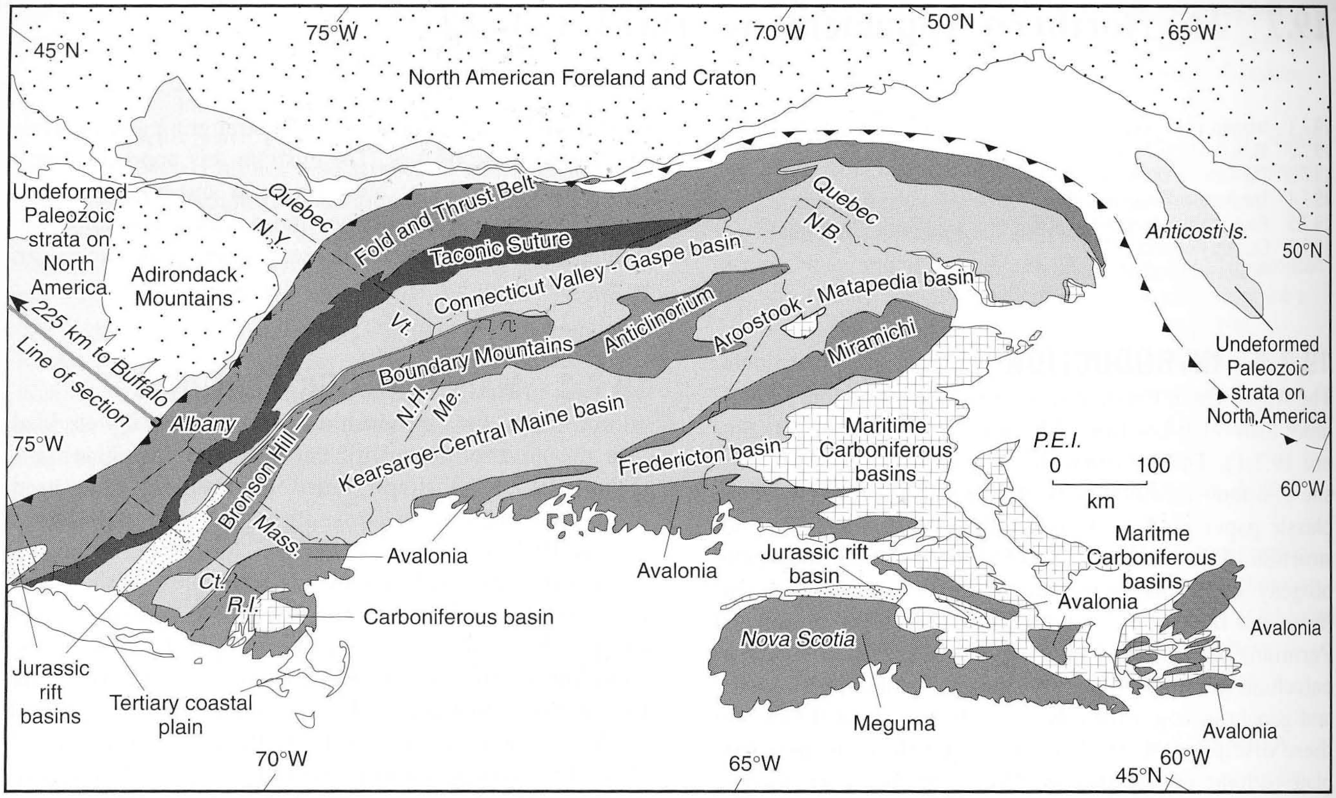

Figure 19.7.2 Map of the northern Appalachians showing major tectonic belts.

19.7.3 THE TACONIC OROGENY

Geology

The North American Margin. Cambrian and Ordovician events leading up to and including the Ordovician Taconic Orogeny are probably best understood in eastern New York state and western New England (Figure 19.7.2). This part of the northern Appalachian foreland is especially informative because Neogene doming of the Adirondack Mountains has exposed the Precambrian (~1.1 Ga) continental basement as well as the entire flat-lying Cambrian to Devonian cover sequence. Cambrian to Middle Ordovician shallow-marine quartzites and platformal carbonates of the foreland (in New York, these go by the names of Potsdam Sandstone and Beekmantown Group) form an eastward-thickening wedge or miogeocline. In Middle Ordovician time, the platform experienced gentle uplift, followed by rapid deepening, normal faulting, and inundation beneath a thick wedge of east-derived shale and graywacke turbidites (Utica Shale and Schenectady Formation in New York; together these compose what is informally known as the Taconic Flysch) (Figure 19.7.3). The flysch thickens and coarsens markedly toward the orogenic front in the east. The graywacke contains low-grade metamorphic and volcanic detrital grains that must have come from an easterly source—thought to be the Taconic Orogen—that had formed on the site of the former miogeocline. The flysch basin is known as the Taconic foredeep.[2]

The western, frontal portion of the northern Appalachians is a fold-and-thrust belt (Figure 19.7.2) that formed primarily during the Taconic Orogeny. Thrust slices of Precambrian (Grenville) basement, Cambrian and Ordovician carbonates and quartzites, and Ordovician flysch—essentially the same succession as in the undeformed foreland—were displaced a relatively short distance with respect to the craton, and are described as parautochthonous. The thrust belt also includes a far-travelled, composite thrust sheet (Taconic Allochthon of eastern New York and western Vermont) containing deep-water Late Precambrian to Ordovician strata that structurally overlie platformal rocks of the same age range. The

[2]A foredeep (or foreland basin) is a sediment-filled depression that forms next to an orogenic belt, due to flexure of the foreland lithosphere beneath the orogenic load. During collision, a foredeep will migrate toward the craton, keeping ahead of the advancing orogenic load. In the process, older parts of the foredeep commonly get deformed as they are overridden by thrusts, and may become part of the thrust load itself. Typically, the older sedimentary fill of a foredeep consists of syntectonic, deep-marine turbidites (flysch), whereas the younger fill consists of shallow-marine or fluvial sandstone and conglomerate (molasse).

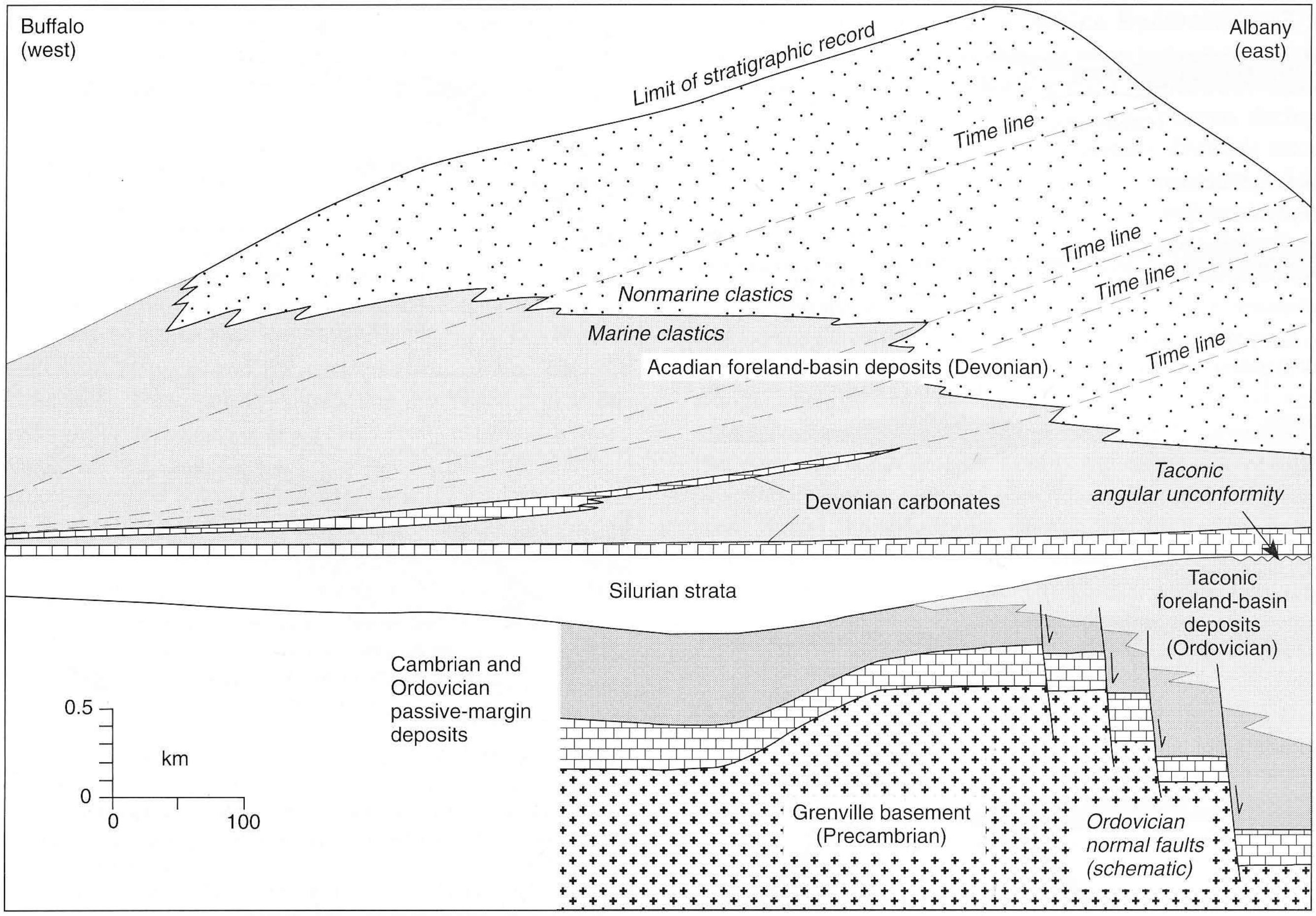

Figure 19.7.3 Cross section through Taconic and Acadian forelands of New York, showing two clastic wedges and two carbonate successions. Datum is the base of the Lower Devonian Helderberg Group.

Taconic Allochthon originally must have lain many tens of kilometers to the east because the Cambrian and Ordovician platformal sequence can be found on the east side of the Green Mountains, leaving no room for the allochthon except still farther east.

The Central Mobile Belt. Just east of the fold-and-thrust belt is a discontinuous zone of ophiolites that occur as fault slices ranging from outcrop-size to several kilometers thick. They are enclosed within complexly deformed and metamorphosed black shales and turbidites of deep-water origin (Rowe Schist). This belt is interpreted as the Taconic suture zone (Figure 19.7.2), demarking the boundary between rocks of North American origin to the west, and rocks of an island-arc complex to the east.

East of the suture lies the Connecticut Valley Basin (Figure 19.7.2). Deposition in it was essentially continuous from Ordovician to Devonian—without a break corresponding to Taconic deformation. Its position suggests that at the time of the Taconic Orogeny, it was a forearc basin. Ordovician volcanic and plutonic rocks (e.g., Ammonoosuc Volcanics and Highlandcroft Plutonic Suite in New Hampshire) along the Bronson Hill-Boundary Mountains Anticlinorium (Figure 19.7.2) are generally interpreted as marking the axis of a Taconic magmatic arc. In Maine, Ordovician volcanics of the Bronson Hill-Boundary Mountains anticlinorial belt unconformably overlie two distinct terranes—an inboard one consisting of Precambrian gneiss (Chain Lakes Massif), and an outboard one consisting of a Cambrian ophiolite and volcanic sequence (Boil Mountain Complex and Jim Pond Formation), Cambrian melange (Hurricane Mountain Formation), and Cambrian and Early Ordovician flysch (Dead River Formation).

Plate Tectonics of the Taconic Orogeny

Plate-tectonic interpretations of events leading up to and including the Taconic Orogeny are fairly straightforward (Figure 19.7.4a–d). The Cambrian and Ordovician miogeocline is interpreted as a passive-margin platform that faced an ocean to the east (Iapetus); and the deep-water strata of the Taconic Allochthons are interpreted as rift, slope-rise, and early foredeep deposits. By Early Ordovician, the thermally subsiding passive margin was attached to some unknown width of oceanic crust. The Taconic Orogeny is interpreted as the result of closure of this tract of ocean crust at a relatively short-lived, east-dipping subduction zone, marked in New England by the ophiolite belt. This plate geometry led, inevitably, to collision between the passive margin and magmatic arc. The Taconic

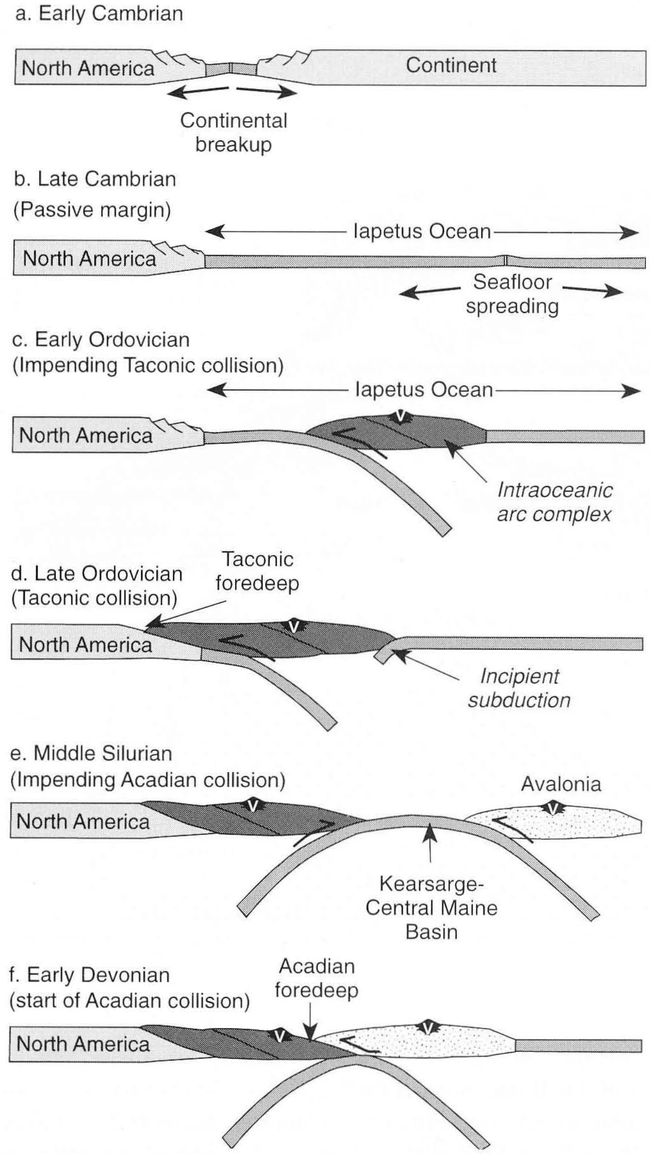

Figure 19.7.4 Schematic diagram showing postulated Early and Middle Paleozoic tectonic evolution of the northern Appalachians. (a) Late Precambrian rifting. (b) Cambrian passive margin. (c) Early Ordovician impending collision with an island arc. (d) Middle and Late Ordovician arc-continent collision (Taconic Orogeny). (e) Silurian subduction leading to impending Acadian collision. (f) Early Devonian, during start of Acadian collision.

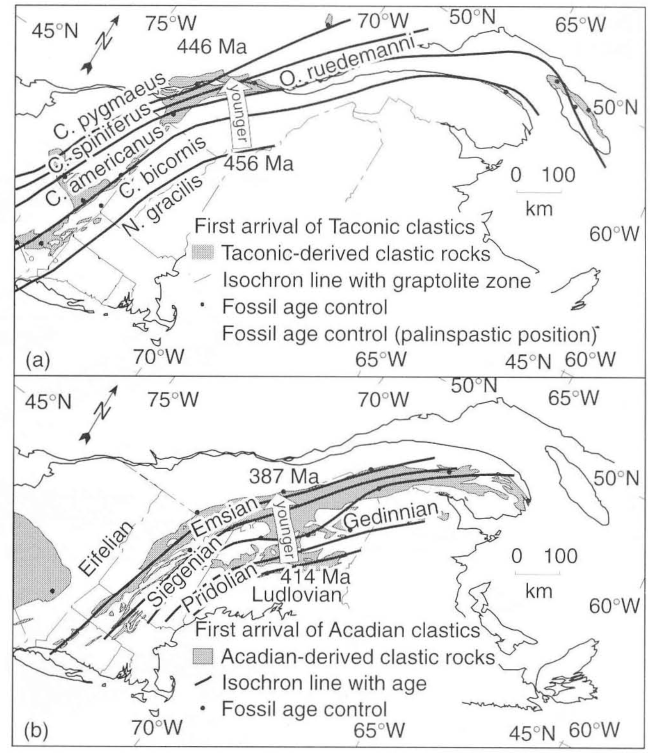

Figure 19.7.5 Maps of (a) the Taconic and (b) Acadian foredeeps showing age of inception of foredeep sedimentation with contour (isochron) lines. For the Taconic foredeep, the contour gradient is based entirely on autochthonous rocks, and therefore approximates the plate convergence rate (10–20 km/m.y.). In the case of the Acadian foredeep, the contours are based on deformed rocks that have been telescoped and displaced relatively toward the North American craton, and therefore yield only a minimum syncollisional plate convergence rate (about 5 mm/y).

is commonly described as an "arc-passive margin collision," but in fact, the forearc that overrode and downflexed the passive margin was located perhaps 200 km west of the magmatic arc, which itself felt little if any Taconic deformation. The end result of the Taconic Orogeny was accretion of an arc onto the North American continental margin. The new margin was located somewhere farther east, probably just east of the Bronson Hill-Boundary Mountains Anticlinorium.

Much work on the Taconic Orogeny has focused on the relationships between flysch sedimentation and tectonics. Flysch along the frontal thrust zone preserves three lines of evidence that the Taconic Orogeny was an Ordovician event: (1) Silurian and Devonian strata overlie deformed Ordovician rocks with pronounced angular unconformity (the Taconic unconformity; Figure 19.7.3); (2) Ordovician graywacke contains detrital grains of already metamorphosed Taconic slate; and (3) beneath and immediately west of the Taconic Allochthon is an olistostromal melange with a matrix of chaotically deformed turbidites and black shales, and blocks derived from both the Taconic Allochthon and the miogeocline, which presumably were shed in front of the advancing thrust sheets. Graptolites within the matrix shales date the emplacement of the Taconic Allochthon to within a few million years (*C. spiniferus* graptolite zone; 450–446 Ma according to the DNAG time scale). Another important aspect of the Taconic Flysch is that its age systematically varies across strike, being older in the thrust belt and younger in the foreland. The area of flysch deposition (foredeep axis) presumably migrated toward North America because the thrust load also moved, and thus the rate of migration is approximately the plate convergence rate, which has been found to be 10–20 km/m.y. (Figure 19.7.5a). This is comparable to some of the slower rates of convergence in the present plate mosaic. By combining this information with the known duration of Ordovician arc magmatism (about 45 m.y. in Maine), the width of the ocean that closed during the Taconic Orogeny has been estimated at 500 to 900 km.

This is considerably less than the full width of Iapetus, which has been estimated at 4000 km on the basis of paleomagnetic and faunal data.

19.7.4 THE ACADIAN OROGENY

Geology of the Acadian Orogeny

The North American Margin. By the Early Devonian, a slowly subsiding carbonate platform (Helderberg Group of New York) had been reestablished across the earlier Taconic foredeep and the eroded front of the Taconic Mountains. This platform shows that the Taconic foredeep had rebounded to near sea level, from estimated water depths of 1–3 km. In Middle Devonian, the rate of subsidence increased dramatically, as a second east-derived clastic wedge (the Catskill delta of New York) prograded across the foreland (Figure 19.7.3). West-directed paleocurrents indicate that the source of the Catskill clastics was a new mountain belt to the east—the Acadian Orogen. Conglomerate clasts in the eastern Catskills (a few kilometers west of the thrust front) include Catskill-like sandstones that must have been deposited in a more easterly foredeep basin, one that was uplifted and eroded away during the Devonian.

The Central Mobile Belt. Within the mountain belt, stratigraphic studies reveal the presence of two Silurian magmatic arcs (one on the Bronson Hill-Boundary Mountains Anticlinorium, one on Avalonia) and two deep-water basins (Connecticut Valley and Kearsarge-Central Maine Basins). During the Devonian, each of these belts except Avalonia was inundated by outboard-derived flysch deposited in a foredeep that eventually migrated to its final position in the Catskills.

Stratigraphic relations along the Bronson Hill-Boundary Mountains Anticlinorium and Kearsarge-Central Maine Basin are an important key to unravelling the tectonic history of the Acadian Orogeny in New England. Along the anticlinorial belt, Silurian sedimentary rocks are mainly quartzites and impure limestones (e.g., Clough Quartzite and Fitch Formation in New Hampshire; Ripogenus Formation in Maine) that contain shallow-water fossils such as stromatoporoids, corals, and brachiopods. These units record an interval of shallow-marine deposition at slow to moderate subsidence rates along the Taconic-modified margin of North America, in sharp contrast with what came next. Another key feature of the anticlinorial belt is the presence of volcanic rocks representing all four stages of the Silurian and the first three of the Devonian. These volcanic rocks compose the Piscataquis magmatic belt, an arc that was built on the older, Ordovician arc. Deeper-water flysch sedimentation commenced in Devonian time (Littleton Formation in New Hampshire, Seboomook Group in Maine), followed, at least in Maine, by progradation of a deltaic complex (Matagamon Sandstone). The Devonian clastics are partly younger than, partly coeval with, and partly older than, magmatism along the Piscataquis Belt.

The Kearsarge-Central Maine Basin—the main source of controversy regarding Acadian tectonics in New England—is underlain deep-marine strata that were folded, metamorphosed, and intruded by plutons during the Devonian. The stratigraphy is broadly divisible into: (1) a lower sequence derived from the Taconic-modified margin of North America that lay to the northwest (e.g., Silurian Rangeley, Perry Mountain, and Smalls Falls Formations in Maine), and (2) an upper sequence derived from outboard sources (Upper Silurian Madrid Formation and Lower Devonian Carrabassett Formation in Maine).

Avalonia. The next major belt to the southeast is a complex belt of rocks that have been collectively assigned to the Avalon zone or "Avalonia." Recent findings reveal that Avalonia is not a distinct entity but rather a composite of several terranes, some of which have Precambrian basement. From the standpoint of Acadian tectonics, three points are salient. (1) In Maine, a thick succession of Silurian through Lower Devonian volcanics, and related plutonic rocks, compose a long-lived magmatic arc that shut off during the Early Devonian, at virtually the same time as Acadian deformation was happening in the Kearsarge-Central Maine Basin. (2) There is no evidence of a Devonian clastic wedge in the Avalon zone. (3) Acadian deformation and metamorphism in Avalonia were mild, in stark contrast with the intense Acadian tectonism experienced by the Kearsarge-Central Maine Basin.

Plate Tectonics of the Acadian Orogeny

The Acadian Orogeny is much more controversial than the Taconic Orogeny. A generally (but still not universally) accepted starting point is the interpretation that the Taconic Orogeny resulted in the accretion of an arc to the edge of North America. The main problem is whether or not the Kearsarge-Central Maine Basin is the site of a second ocean that also closed by subduction, leading to an Acadian collision. The mode of closure of the Kearsarge-Central Maine Basin is also controversial; options include subduction beneath its northwestern margin, subduction beneath its southeastern margin, subduction beneath both margins, or deformation of the basin fill without true subduction of the basement.

The distribution and age of Acadian foredeep deposits provide several clues to Acadian plate tectonics. An influx of Devonian clastics, derived from outboard sources, has been recognized in the Kearsarge-Central Maine Basin, Piscataquis magmatic belt, Connecticut Valley-Gaspe Basin, locally within the parautochthonous thrust belt, and in the undeformed foreland (Catskill delta). These clastics were deposited in a migrating foredeep basin that advanced in concert with an advancing Acadian orogenic load. The load must have originally been outboard of the oldest part of the clastic wedge, that is, in about the present location of Avalonia. The clastics occur on both sides of the Piscataquis magmatic axis, as well as along its axis, but were not derived from the arc. This extremely unusual stratigraphic pattern implies that the foredeep was superimposed on an active arc, and that subsidence was the result of flexure of the arc beneath a thrust load that lay farther outboard (southeast). The obvious candidate, once again, is Avalonia. The pattern of foredeep sedimentation and the presence of two magmatic arcs is therefore best explained by a plate geometry like that shown in Figure 19.7.4e and f.

The Devonian clastics were clearly diachronous, both across strike, younger toward the craton, and along strike, younger toward the south. By analogy with the Taconic foredeep, the rate of migration should approximate the plate convergence rate during Acadian collision (Figure 19.7.5b). This rate, unfortunately, is not so readily determined, because Acadian shortening has partly closed the gaps between what originally were widely spaced sections. Nonetheless, we can say with reasonable confidence that the plate convergence rate in northern New England during Acadian collision must have been at least 5 km/m.y., and likely was much faster.

19.7.5 POST-ACADIAN TECTONICS

The stratigraphic record in the northern Appalachian foreland ends with the Catskill clastics, but in the central and southern Appalachians, there is yet a third east-derived clastic wedge, of Carboniferous age. These clastics were derived from, and deformed during the Alleghanian Orogeny, which resulted from the final collision between Africa and North America. In the northern Appalachians, the Carboniferous was for a time dominated, instead, by strike-slip tectonics. Most of the faults strike northeast-southwest or east-west. Avalonia and Meguma are juxtaposed across such a fault system in Nova Scotia. Episodic motion along numerous anastomosing fault strands caused subsidence of transtensional basins, and uplift of areas of transpressional deformation. The overall setting of this strike-slip regime is unresolved, but probably relates to oblique convergence between Africa and North America, prior to the final Alleghanian collision that completed the assembly of Pangaea around the end of the Carboniferous. Mesozoic breakup of Pangaea produced a series of rift basins, three of which are shown in Figure 19.7.2. When Africa drifted away, a piece was left behind—the Meguma terrane.

19.7.6 CLOSING REMARKS

Ordovician and Devonian flysch sequences in the northern Appalachians have long been snubbed as monotonous, but they're quite interesting when you get to know them. As discussed here, they contain important clues to quantifying ancient plate motions. Ultimately, however, this sort of analysis rests on those no longer glamorous geologic specialties that are threatened with extinction: regional mapping, stratigraphy, and paleontology.

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Earth STRUCTURE

AN INTRODUCTION TO STRUCTURAL GEOLOGY AND TECTONICS

Ben A. van der Pluijm
University of Michigan

Stephen Marshak
University of Illinois at Urbana-Champaign

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