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AN INTRODUCTION TO STRUCTURAL GEOLOGY AND TECTONICS

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22.4 THE APPALACHIAN OROGEN—An essay by James P. Hibbard[1]

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22.4.1 Introduction

The **Appalachian Orogen** (Figure 22.4.1) is a northeast-trending belt of Late Precambrian to Paleozoic rocks in eastern North America that were deformed during the Paleozoic. Its strike length is more than 3000 km, extending from Alabama to Newfoundland, and it forms a segment of a much larger Paleozoic orogenic system that encompasses the Caledonide Orogen of the British Isles, Greenland, and Scandinavia to the northeast, and the Ouachita Orogen to the southwest. The northwest limit of the Appalachians is the deformation front between rocks of the orogen and older orogens and platform rocks of North America. On its southern and southeastern flanks, the orogen is onlapped by Cenozoic sedimentary rocks of the Atlantic Coastal Plain.

The orogen is important from a historical standpoint, as many significant tectonic ideas are rooted in Appalachian bedrock. The concept of geosynclines, which dominated thought on mountain building for more than a century preceding the advent of plate tectonics, was conceived in the Appalachians. Appropriately, the geosynclinal theory was supplanted on its native Appalachian turf by plate tectonics in the 1960s and 1970s. Initial questioning of whether the Atlantic closed and then reopened was followed by the first detailed application of plate tectonic theory to an ancient orogen. In addition, the idea of "thin-skinned tectonics," meaning the deformation of cover strata above a master décollement that is independent of underlying basement, was first developed in the classic Valley and Ridge fold-and-thrust province of the southern Appalachians. Closely related to the thin-skinned concept was the realization that there is a mid-crustal detachment within the orogen that places a large portion of the deformed southern Appalachians onto the relatively undeformed North American platform. This realization lead to the general acceptance that substantial portions of orogenic belts form relatively thin, highly allochthonous sheets (or tectonic flakes) emplaced onto cratons.

Having established the prominent role of the Appalachians at the forefront of tectonic research, we turn, in the remainder of this essay, to a sketch of current thought on the orogen. Following an overview of the mountain belt, there is a brief description of the first-order crustal components, an explanation of how and when they were assembled, and finally a highlighting of potential directions for future thought and development of Appalachian tectonics.

22.4.2 Overview

The structural grain of the Appalachians is remarkably consistent, defining a series of broad, harmonically curved promontories and reentrants (Figure 22.4.1); their grace and regularity lead the renowned North American tectonicist, P. B. King, to proclaim the Appalachian Orogen as the most elegant mountain chain on earth. As we will see, this structural architecture reflects a fundamental feature of the orogen that was important in its evolution. For our purposes, the New York promontory will serve as the divide between segments referred to as the northern and southern Appalachians.

In contrast to structural divisions, lithotectonic divisions of an orogen distinguish rock associations that were either formed or deposited in a common tectonic setting during a finite time-span. These divisions are scale dependent, that is, contingent on the scale of the tectonic process considered. In this essay, the hierarchy of lithotectonic divisions consists of the realm at orogen scale and the zone at the scale of two or less reen-

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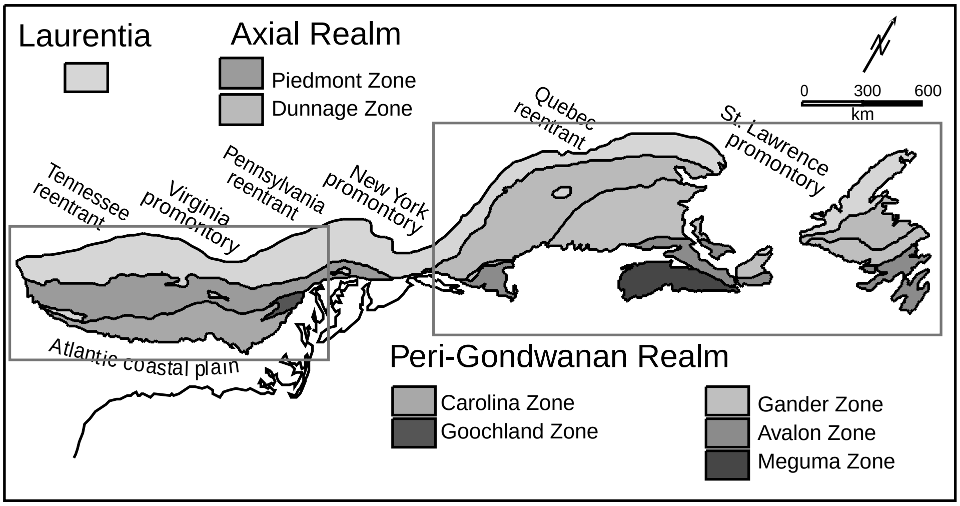

FIGURE 22.4.1 Realms and zones of the Appalachian Orogen, defined on the basis of Middle Ordovician and older geologic history. The boxes outline areas shown in Figures 22.4.4 and 22.4.5.

trants. At yet smaller scale, terranes are recognized as regional subdivisions of a zone; however, in this essay we will mainly be concerned with realms and zones.

The Appalachians are composed of three realms, the Laurentian realm,[2] the Axial realm, and the peri-Gondwanan realm (Figure 22.4.1), all of which acquired their defining geologic character before the Middle Ordovician. The Laurentian realm encompasses essentially all of the rocks deposited either on, or adjacent to, ancient North America and forms the western flank of the orogen; however, windows of Laurentian rocks occur locally among the more easterly accreted terranes (Figure 22.4.1). In contrast, peri-Gondwanan realm rocks are interpreted to have formed proximal to Gondwana[3] and thus are considered to be exotic with respect to Laurentian elements; they are distributed along the eastern flank of the Appalachians. The Axial realm is a collection of zones and terranes of mainly oceanic and volcanic arc affinity that has been caught between the Laurentian and peri-Gondwanan realms during Appalachian orogenesis. Unlike the uniformity of the Laurentian realm, both the peri-Gondwana and the Axial realms change character along strike of the orogen.

The orogen was assembled during the approximately 300 m.y. time-span between the existence of two supercontinents, the Middle Proterozoic Rodinia and the Late Paleozoic Pangea. The Appalachians formed as a result of the progressive accretion of Axial and peri-Gondwanan elements to the Laurentian realm. Classically, it has been accepted that three major events, the Taconic, Acadian, and Alleghanian Orogenies record the accretion of these elements. However, as more data are acquired, we are finding that accretionary events along the Laurentian margin were continuous for protracted periods of time and were less punctuated than is implied by the simple mantra of "Taconic, Acadian, and Alleghanian."

22.4.3 Tectonic Components

THE LAURENTIAN REALM The template for Appalachian accretionary events, the eastern Laurentian continental margin, was initiated by Late Precambrian rifting along the axis of the ~1-Ga Grenville Orogen within Rodinia; thus Grenville rocks form basement to the continental margin. The west flank of the Amazonian craton likely formed the conjugate margin to eastern Laurentia during this extensional event. The main pulse of rifting affected the entire length of the Appalachians at roughly 600–550 Ma. Sedimentation was synchronous with rifting, leading to thick deposits confined to elongate basins and characterized by abrupt changes in the thickness of strata, with most of the sediment supplied from the Laurentian craton. Bimodal magmatism accompanied rifting; however, there are two pulses of rift magmatism, an early pulse (~750–700 Ma) (Figure 22.4.2) confined to the southern Appalachians, and a later, main pulse (~600–550 Ma) along the length of the orogen. The

[2]Laurentia refers to early Paleozoic North America, including portions of Greenland, Scotland, and Ireland that rifted away in the Mesozoic.

[3]Gondwana is the ancient continent approximately equivalent to an amalgamation of modern southern hemisphere cratons.

early pulse appears to be coeval with the early breakup of Rodinia along the Pacific margin of Laurentia and may well be a far-field effect of this event.

Rifting led to continental breakup, the onset of seafloor spreading, thermal subsidence of the newly formed passive margin, and deposition of a drift sequence atop the rift deposits (Figure 22.4.2 and 22.4.3). The drift sequence consists of basal clastic rocks overlain by a shallow marine carbonate sequence up to 10 km thick. In contrast to the heterogeneity of the rift deposits, the drift sequence displays an orderly stratigraphy with little thickness variation and remarkable lateral continuity. Paleomagnetic studies indicate that the margin was at near equatorial latitudes during establishment of the passive margin. The seaward edge of this extensive carbonate shelf is marked by a facies change into deep water shaley rocks that locally contain carbonate blocks and boulders that spalled off the precarious edge of the shelf. The Paleozoic ocean that formed outboard of eastern Laurentia, preceding the modern Atlantic, is called Iapetus, after the mythical Greek father of Atlantis.

The geometry of the continental margin was controlled by the zigzag pattern formed by spreading and transform segments of the rift system. This shape influenced the distribution of rift and drift sequences; former ridge-transform junctions along the margin tended to form steep-sided terminations for rift basins, whereas the distribution of the drift sequence facies change from shelf to slope-and-rise was controlled by the jagged shape of the margin. Where the trace of the drift sequence facies change is preserved, it presently follows the curves of the structural promontories and reentrants in the orogen. This relationship indicates that the promontories and reentrants are inherited from the original shape of the margin at breakup.

The Axial Realm

Elements of the Axial realm record the evolution of Iapetus and its component volcanic arcs, backarc basins, and accretionary complexes. There appears to be a major change in the realm at the New York promontory; in the northern Appalachians, the Dunnage Zone records a complex history of multiple volcanic arcs and backarc basins, whereas in the southern Appalachians, the Piedmont Zone appears to record a simpler history of a single composite arc system.

The Dunnage zone is in tectonic contact with Laurentian rocks along the Baie Verte–Brompton line (Figure 22.4.4), which is a steep, relatively narrow fault system that has experienced multiple episodes of movement; in many places it is marked by narrow, elongate ultramafic bodies. The zone is best exposed along the north coast of Newfoundland, where its entire width is at low metamorphic grade; here, the zone records the evolution of at least two distinct oceanic tracts. Contrasts in stratigraphy, fossil faunas, and paleomagnetic and isotopic data indicate that the western tract of the zone was associated with the Laurentian side of Iapetus, whereas the eastern tract developed on the Gondwanan side of the ocean realm. They are tectonically juxtaposed along the Red Indian Line. Both tracts record an early arc phase that starts in the Early to Middle Cambrian and a younger arc phase that ranges into the Late Ordovician (Figure 22.4.3b).

Elements of the Newfoundland Dunnage zone can be correlated with units in New Brunswick, Quebec, and northern Maine; however, most Dunnage zone elements from central Maine to New York are multiply deformed and have been subjected to high-grade metamorphism, thus obscuring original relationships between units. Consequently, the early evolution of the zone is not as well understood in New England, although there are strong hints that it conforms to that of the Canadian Dunnage zone.

The Piedmont zone is tectonically severed from Laurentian rocks to the west along a series of faults, most of which have multiple movement histories. Much of the zone has been subjected to intense, polyphase deformation and medium- to high-grade metamorphism and thus unraveling the depositional-magmatic history is somewhat tenuous. The zone is split into two components by the Brevard zone, a polygenetic ductile shear zone, and other faults northward along strike of the Brevard zone (Figure 22.4.5).

The western portion of the zone is dominated by metamorphosed clastic rocks and associated mélanges disposed in imbricate thrust stacks. In northern Virginia, the thrust stacks were assembled by the Early Ordovician, but locally, in southwest Virginia, radiometric ages suggest that the clastic rocks have been subjected to Early Cambrian shortening and medium-grade metamorphism (Figure 22.4.2). In North Carolina, metamorphosed clastic rocks at the western edge of the zone contain pods of eclogite. Across the Brevard zone, the eastern portion of the zone contains substantially more metamagmatic rocks than the western area. Magmatism appears to have been active from the Early Ordovician to the Early Silurian, with a Late Ordovician lull during which black slates were deposited in central Virginia (Figure 22.4.2). Where studied, the magmatic rocks are geochemically consistent with a suprasubduction zone, volcanic arc setting.

Despite the strong tectonothermal overprint, all of the characteristics just outlined are consistent with the

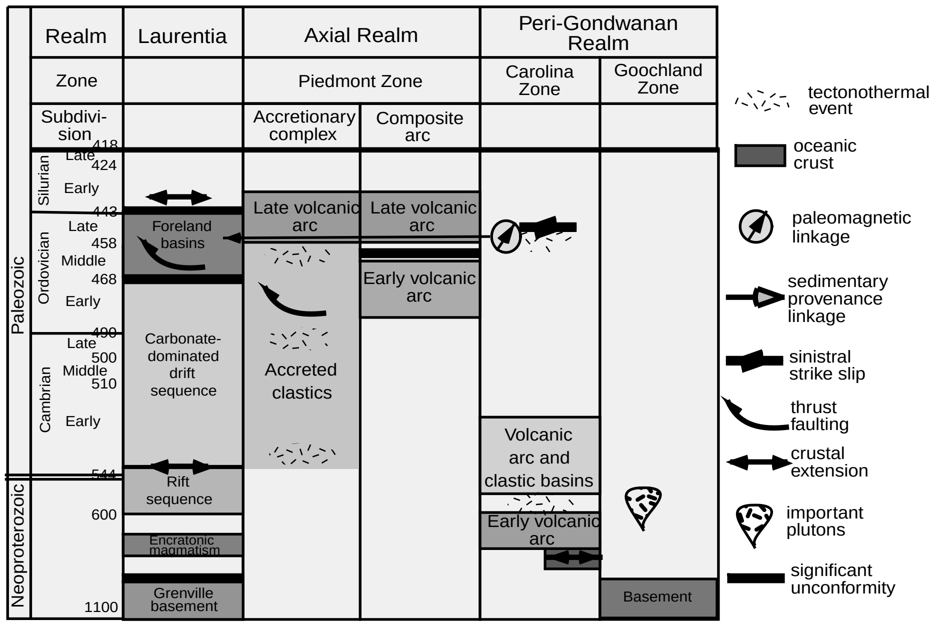

FIGURE 22.4.2 Major elements and events of the southern Appalachians from the Precambrian to the Silurian.

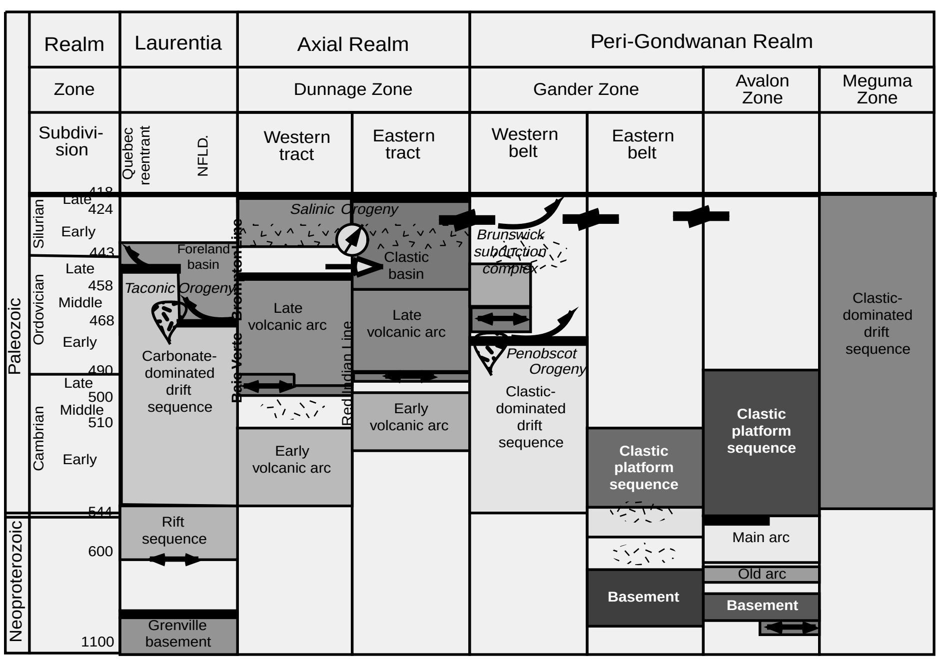

FIGURE 22.4.3 Major elements and events of the northern Appalachians from the Precambrian to the Silurian. See Figure 22.4.2 for explanation of symbols.

interpretation that the Piedmont zone encompasses a long-lived, west-facing accretionary complex in front of a more easterly suprasubduction-zone magmatic arc. If the interpretation of an Early Cambrian tectonothermal event is valid, it suggests that the Piedmont Zone formed in an ocean older than Iapetus, which was just in its rift-to-drift stage at this time.

The Peri-Gondwanan Realm

A collection of diverse crustal remnants of Proterozoic to Early Paleozoic rocks that lay across the Iapetus Ocean from the eastern Laurentian margin is grouped here as peri-Gondwanan elements. In the northern Appalachians, the realm is represented by the Gander, Avalon, and Meguma zones, whereas the Carolina and Goochland zones occupy the east flank of the exposed southern Appalachians (Figures 22.4.1, 22.4.4, and 22.4.5). The nature of the Goochland zone is controversial and it is tentatively grouped here with the peri-Gondwanan Zones.

The Gander zone is in both fault and stratigraphic contact with the Dunnage zone. For example, in central Newfoundland, the contact is marked by a thrust fault that emplaces Dunnage ophiolite on top of the Gander zone, whereas in northern Maine and New

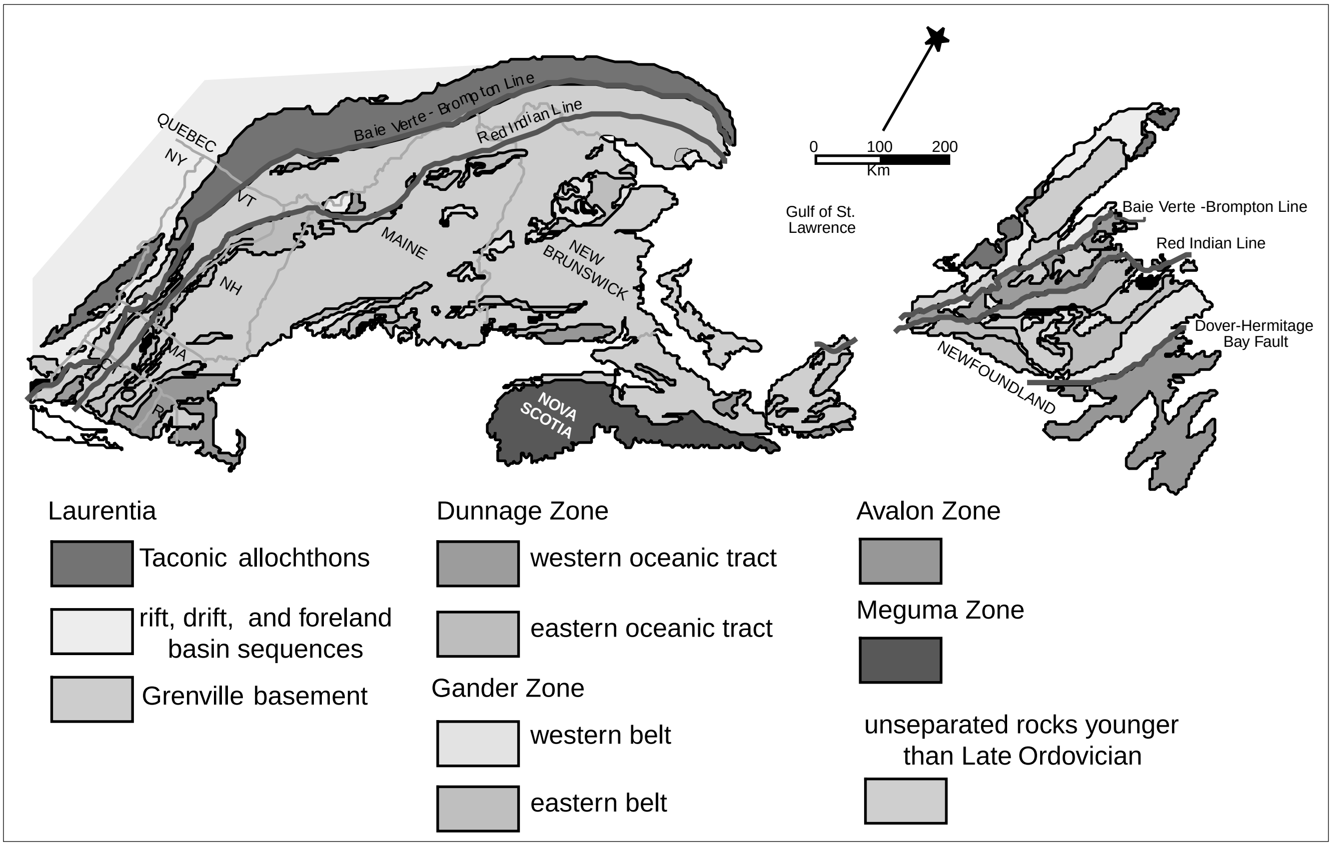

FIGURE 22.4.4 Distribution of Middle Ordovician and older elements in the northern Appalachians.

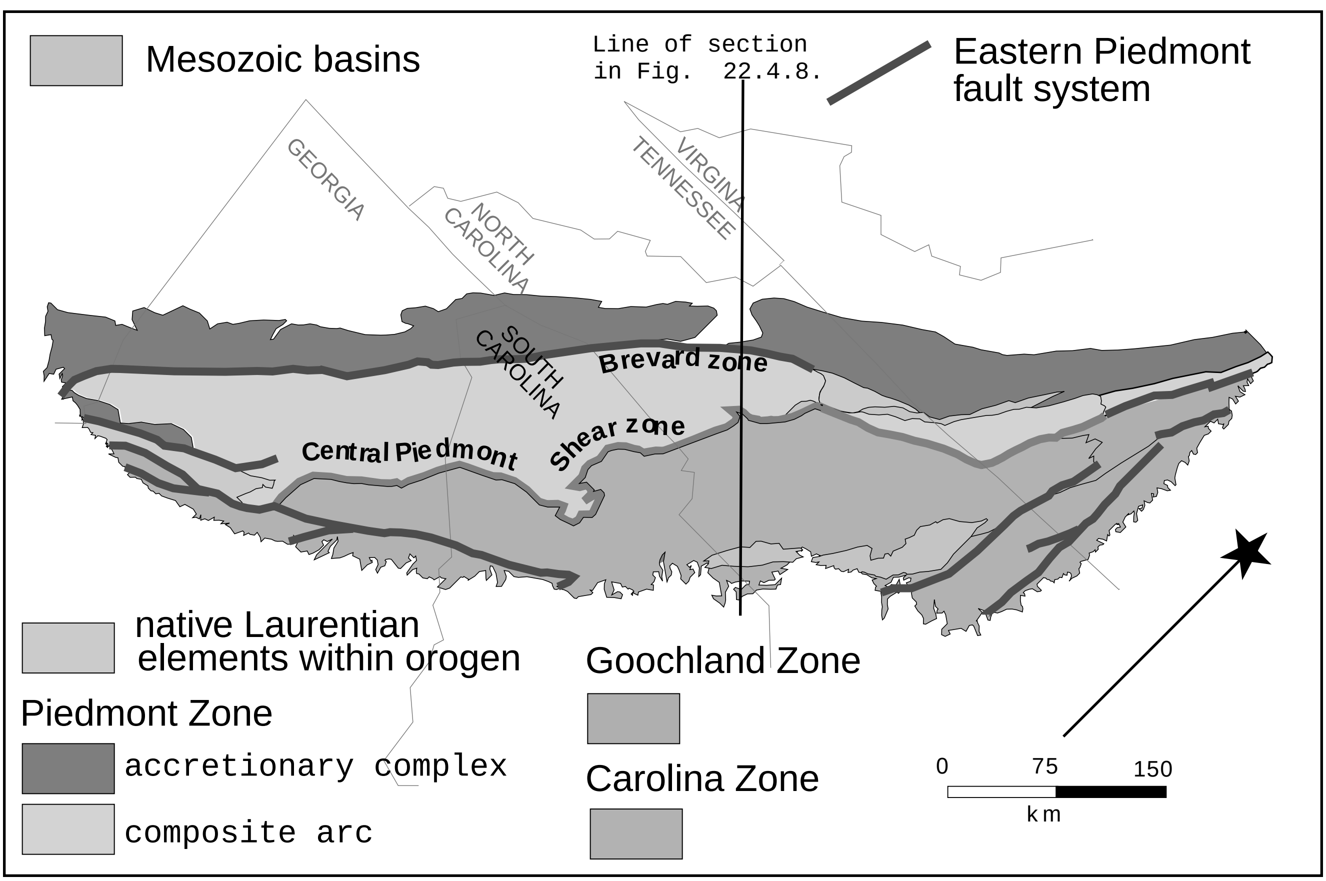

FIGURE 22.4.5 Distribution of Middle Ordovician and older elements in the southern Appalachians. Line of section is for Figure 22.4.8.

Brunswick, Dunnage volcanic rocks unconformably overlie the Gander zone (Figure 22.4.4). Elements grouped here as the Gander zone define two distinct belts on either side of the zone (Figures 22.4.3, and 22.4.4). The eastern belt (called the Avalon zone by some workers) is composed of older crystalline basement that is faulted against a younger magmatic sequence. Basement rocks consist of marble, quartzite, greenstone, and pelite that appear to have protolith ages greater than 800 Ma and that have been involved in metamorphic events prior to 600 Ma. The younger magmatic sequence includes mafic and felsic volcanic and plutonic rocks with an approximate age range of 600–545 Ma. The western belt is characterized by Cambrian-Early Ordovician continentally derived quartz arenite and pelite with minor mafic magmatic rocks that, collectively, have been interpreted as representing a passive margin sequence. The eastern belt may form the basement on which the western belt passive margin was deposited, but the contact between the two is unknown.

The Avalon zone is in fault contact with the Gander zone; in Newfoundland the contact is represented by the Dover-Hermitage Bay Fault (Figure 22.4.4), which is vertical; it is documented on seismic reflection profiles as reaching the base of the crust. The zone is dominated by Neoproterozoic magmatic rocks that exhibit diverse compositions and have mainly suprasubduction zone signatures. Geochemical studies indicate that the volcanic pile likely formed on thin continental crust, although this basement does not appear to be exposed. Magmatism extended over the broad time period of 685–540 Ma (Figure 22.4.3), with a preponderance of activity in the range of 630–580 Ma. Locally, deformation was synchronous with deposition and appears to have been dominated by extension.

The magmatic rocks are overlain by a Lower Paleozoic transgressive, shallow marine platform sequence (Figure 22.4.3); the lack of substantial carbonate in this sequence as well as paleomagnetic data attests to the platform's being deposited at high paleolatitudes. Fossil faunas in the platform sequence are of "Avalonian" affinity, distinct from those of the Laurentian and Axial realms.

The Meguma zone underlies most of southern Nova Scotia and forms the southeastern most exposed crustal block in the orogen (Figures 22.4.1 and 22.4.4). It is faulted against Carboniferous cover rocks to the north, which in turn are unconformable upon the Avalon zone. The zone is dominated by Early Paleozoic turbidites that have been interpreted as being deposited in an abyssal fan setting along a passive continental margin. On the basis of sedimentology, stratigraphy, paleontology, petrology, and geophysics, the zone has been correlated with rocks in Morocco.

The Carolina zone is in tectonic contact with the Piedmont zone along the central Piedmont shear zone, a Late Paleozoic thrust fault (Figure 22.4.5). The zone is an amalgamation of Neoproterozoic to Early Paleozoic volcanic arcs and associated sedimentary rocks that have an approximate age range of 675–530 Ma (Figure 22.4.2). It appears that one or more deformational events coincided with magmatism, although the nature of these events is poorly known. The Carolina zone resembles the Avalon zone, but appears to be distinct from its northern Appalachian counterpart. Neoproterozoic magmatism in the Carolina Terrane peaked at 630–610 Ma and again at ~550 Ma, whereas in Avalon, peak magmatism is in the period 630–580 Ma. Although the Carolina zone contains an Early Paleozoic clastic sequence, it does not appear to represent a transgressive platformal sequence as found in Avalon. Also, Carolina fossil faunas have a peri-Gondwanan affinity, but are not "Avalonian."

The Goochland zone is in tectonic contact with the Piedmont zone and is likely faulted against the Carolina zone (Figure 22.4.5). The zone comprises orthogneiss and paragneiss that have been intruded by anorthosite dated at ~1 Ga. In addition, this package is intruded by alkalic granite dated at ~630 Ma. The zone may represent a structural window into Laurentian basement, with the younger granite representing rift magmatism; however, the 630-Ma age of this granitoid does not coincide with known rift magmatism on the Laurentian margin. Alternatively, the zone represents peri-Gondwanan basement with the granitoid equivalent with Neoproterozoic plutons in the Carolina zone.

22.4.4 Assembly

EARLY PALEOZOIC DESTRUCTION OF IAPETAN PASSIVE MARGINS The eastern Laurentian passive margin came to an abrupt demise in the Early to Middle Ordovician. This event, termed the Taconic Orogeny, is marked by a regional unconformity on the continental shelf, a change in sedimentation along the margin, the development of a submarine thrust belt, and accompanying metamorphism; it is best preserved in the northern Appalachians (Figure 22.4.3).

Carbonate sedimentation along the Laurentian shelf, slope, and rise was choked off in the Early to Middle Ordovician, and a Middle Ordovician erosional to slightly angular unconformity was developed along the length of the carbonate shelf (Figure 22.4.3). The new sedimentary regime was marked by deep water, foreland deposition of easterly derived clastic sediments. The continental shelf and clastic foreland basin were overridden by thrust sheets containing Laurentian slope and rise- and rift-related sediments; the highest thrust sheets in Newfoundland and Quebec are composed of ophiolite. Where they are emplaced upon the passive margin, there is a striking contrast between autochthonous rocks of the shelf and allochthonous, deeper water, rocks of the thrust sheets; the conspicuous thrust sheets are termed the "Taconic allochthons." Perhaps one of the most inspirational geologic sights in the Appalachians is the view of the barren, flat-topped ophiolite sheet in eastern Newfoundland (now a UNESCO World Heritage Site).

Taconic events are interpreted as reflecting the introduction of the Laurentian margin into a subduction zone beneath the eastern tract of the Dunnage zone (Figure 22.4.6a). The unconformity represents the flexural bulge due to loading of the continental margin by an overriding accretionary complex, the clastic sedimentation represents foreland basin, or trench, sedimentation on top of the downgoing continental margin, and the thrust sheets represent an accretionary wedge. However, this tectonic system must have been more complex than the simple subduction of Laurentia beneath the Dunnage zone, for some of the obducted ophiolites were just forming while obduction was in progress elsewhere along the margin. Additionally, Early Ordovician plagiogranites intrude obducted ophiolites; in contrast to the obduction process, these plutons and other geologic evidence require a rapid change in subduction polarity involving west-directed subduction beneath the margin and volcanic arc (Figure 22.4.6b).

The Taconic Orogeny in the southern Appalachians appears to represent the attempted subduction of the Laurentian margin beneath the Piedmont zone accretionary prism and arc. However, the foreland clastic wedge in the southern Appalachians is overlain by that of the northern Appalachians, indicating that the Taconic event was slightly older in the south. Also, the hallmark Taconic thrusting and metamorphism have been severely overprinted and obscured by younger tectonothermal events.

Nearly synchronous with the Taconic Orogeny along the Laurentian margin, the Gander passive margin of Iapetus was also tectonically terminated. This event, the Penobscot Orogeny, is recognized by an unconformity of Early Ordovician volcaniclastic rocks affiliated with the Dunnage Zone atop Cambrian-Early Ordovician Gander quartzose clastic rocks. This unconformity persists along strike from northern Maine to Newfoundland. In Newfoundland, the Penobscot Orogeny also involved the eastward obduction of Dunnage zone ophiolite onto the Gander passive margin (Figure 22.4.6b). The timing of Penobscot obduction is tightly constrained by Early Ordovician fossils in the overthrust oceanic rocks and by an Early Ordovician granitoid that intrudes and "stitches" both Gander and Dunnage zone rocks. Thus, Iapetus commenced closure from both margins in the Early Ordovician.

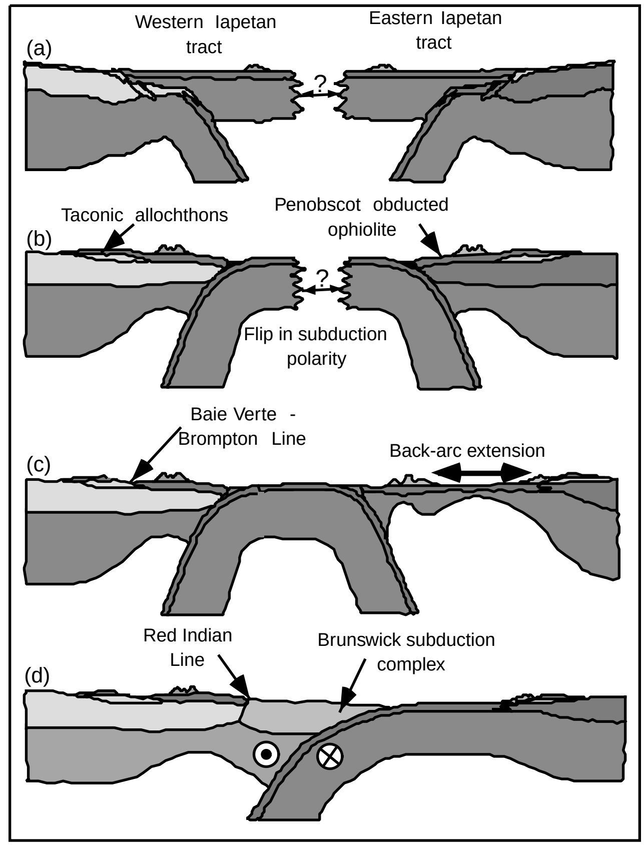

FIGURE 22.4.6 Cartoon depicting possible tectonic evolution of the northern Appalachians: (a, b) Early to Middle Ordovician; (c, d) Middle to Late Ordovician.

MID-PALEOZOIC CLOSURE OF IAPETUS Late Ordovician to Late Devonian events that contributed towards the closure of Iapetus and construction of the Appalachians are best recorded in the northern Appalachians, where Silurian and younger strata blanket the orogen. In the southern Appalachians, Middle Paleozoic strata are largely confined to covering the Laurentian realm. However, the earliest interaction of Laurentia with the peri-Gondwanan realm is apparently recorded in the southern Appalachians, where circumstantial evidence from across the orogen indicates that the Carolina zone commenced docking in the Middle to Late Ordovician, immediately on the "coattail" of the Taconic accretion of the Piedmont zone (Figure 22.4.2).

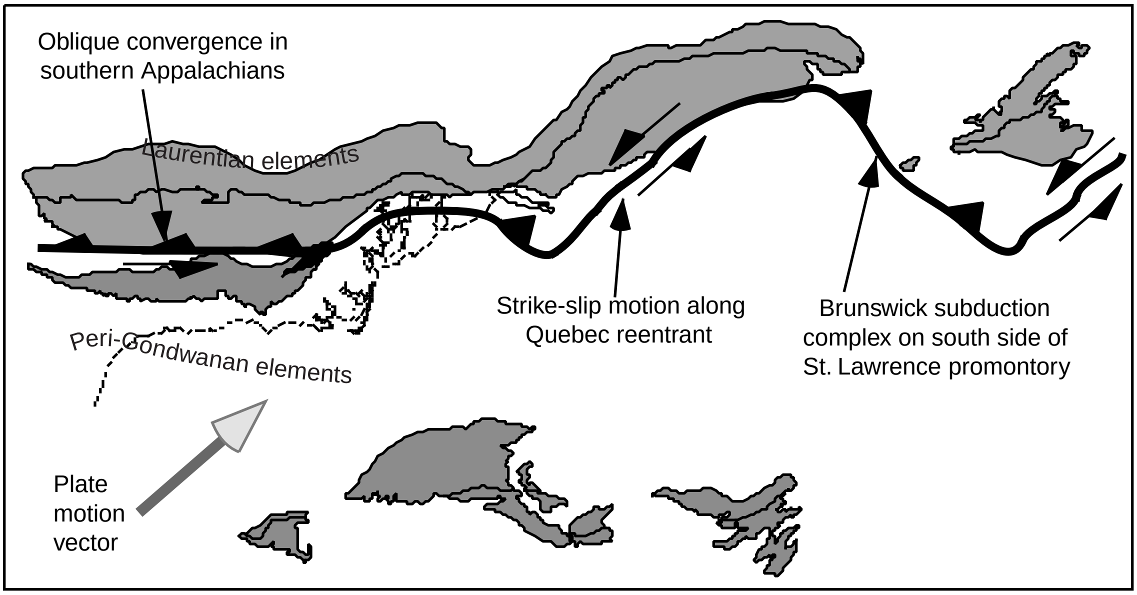

FIGURE 22.4.7 Cartoon of possible tectonic setting during the Late Ordovician to Silurian Salinic Orogeny. The interaction between Laurentia and peri-Gondwana elements involved a strong component of sinistral shear, which may have produced oblique subduction in the southern Appalachians, and sinistral shear and convergence along reentrants and promontories, respectively, of the northern Appalachians. Bold arrow shows approximate plate motion vector for peri-Gondwana elements relative to Laurentia.

In native Laurentian rocks of the southern Appalachians, an unconformity at the Ordovician-Silurian boundary has been attributed to tectonic loading of the post-Taconic margin (Figure 22.4.2). Furthermore, the post-Taconic margin of Laurentia, the Piedmont zone, was intruded by a pulse of Late Ordovician granodioritic to tonalitic plutons that likely reflects subduction beneath the Laurentian margin (Figure 22.4.2). Finally, in the Carolina zone, Late Ordovician upright folding, greenschist facies metamorphism, and uplift probably mark the initiation of the collision of Carolina with Laurentia, as paleomagnetic data indicate that it was at Laurentian paleolatitudes by this time (Figure 22.4.2). Folds in the Carolina zone define an *en echelon* array that is consistent with a component of sinistral shear during collision.

In the northern Appalachians, closure of Iapetus continued after the Late Ordovician flip in subduction polarity (Figure 22.4.6b), but it was counteracted by the generation of a backarc basin on the peri-Gondwanan side (Figure 22.4.6c). However, the western and eastern oceanic tracts of the Dunnage zone, which had distinct Early Paleozoic faunas, shared a mixed Late Ordovician fauna, indicating that they were proximal to one another. Additionally, similar Silurian paleomagnetic data from each tract as well as an Early Silurian stitching pluton along the trace of the Red Indian Line further support a Late Ordovician juxtapositioning of the two tracts (Figures 22.4.3 and 22.4.6c).

Evidence for the convergent closure of the Middle to Late Ordovician peri-Gondwanan backarc basin is preserved only along the east-west trending portions of the orogen in the vicinity of the St. Lawrence promontory; there, the Brunswick subduction complex, a southeast vergent stack of thrust sheets that includes Late Ordovician to Silurian blueschist and ophiolitic mélange, records this closure. Elsewhere, along more northeast-trending segments of the northern Appalachians, Silurian sinistral shear is recorded, from the Avalon zone across to the Laurentian margin (Figure 22.4.7). Thus, it appears that by the end of the Silurian, most components along the length of the orogen had been assembled along the Laurentian margin through the closure of Iapetus with a strong component of sinistral shear displacement (Figure 22.4.7); this kinematic regime, with regional shortening oriented approximately north-south, has been termed the Salinic Orogeny in the northern Appalachians.

At the end of the Silurian, the Laurentian margin underwent an abrupt change in kinematic character. Following a Late Silurian unconformity found in many places in the northern Appalachians, regional shortening reoriented to a position more at right angles to the trend of the orogen, with a component of dextral strike slip; this new kinematic regime is responsible for the

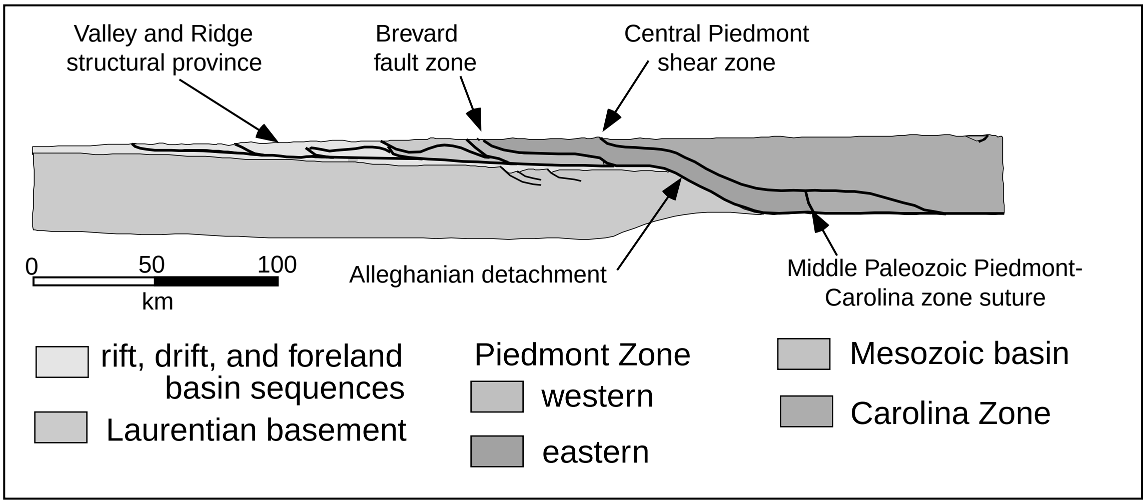

FIGURE 22.4.8 Cross section of the southern Appalachians showing major features of the Alleghanian thrust system. Line of section shown in Figure 22.4.6; no vertical exaggeration.

Acadian Orogeny. The change in kinematics is heralded by an Early Devonian westward transgressive clastic wedge in northern New England. However, the most intense manifestation of the Acadian event is recorded on the New York promontory, in southern New England, where Middle Paleozoic and older rocks were deformed into regional-scale recumbent fold nappes at high metamorphic grade. Subsequent rapid uplift resulted in the removal of up to 20 km of crust in the southern New England area and the deposition of the thick Devonian Catskill clastic wedge to the west. The plate-scale process responsible for the Acadian Orogeny may have been the docking of the Meguma zone to the orogen, for the Acadian is the first deformation shared by the Meguma rocks and the remainder of the orogen. Regardless, it is noteworthy that at the scale of the northern orogen, intense Acadian tectonism and uplift appear to be limited to the region of the New York promontory.

Late Paleozoic Formation of Pangea

The final phases of Appalachian orogenesis took place from the Mississippian to the Permian; events within this time frame are ascribed to the Alleghanian Orogeny. The orogeny is penetratively developed in the southern Appalachians as well as in southern New England; in both areas Alleghanian events strongly overprint earlier deformation and metamorphism; in contrast, it is more limited in development in most of the northern Appalachians.

In the southern Appalachians, the Valley and Ridge Province along the western flank of the orogen records the Late Paleozoic westward-directed thrusting of Cambrian to Permian strata onto the Laurentian platform. This thrust belt was studied in detail for more than a century before it was discovered that it represented merely the toe of what is now recognized as an orogen-scale thrust wedge (Figure 22.4.8). The full magnitude of this thrust wedge was only realized in a seismic reflection profile study across the southern orogen. It revealed that the Laurentian platform sequence extends in the subsurface to at least as far east as the central Piedmont shear zone. The crystalline thrust sheet encompasses the Piedmont zone and is separated from the underlying Laurentian platform by a major detachment fault; this geometry resolves into at least 175 km of shortening along the Alleghanian detachment.

The oldest documented west-directed thrusting is within the crystalline sheet along the central Piedmont shear zone in northern North Carolina; here Middle Mississippian granitoids are syntectonic with respect to ductile thrusting. This early thrusting is roughly coeval with the initiation of Carboniferous clastic wedges shed out over the Laurentian platform. Although thrusting continued into the Permian in the Valley and Ridge, there was a major change in kinematics in the Early Pennsylvanian in the eastern Piedmont and Carolina zones. There, thrusting was replaced by dextral strike-slip motion along a network of large faults, termed the eastern Piedmont fault system. This kinematic change appears to be reflected in the clastic wedges by a Morrowan (Early Pennsylvanian) unconformity. Partitioning of deformation between shortening in the Valley and Ridge and strike-slip motion in the eastern portion of the orogen is likely related to dextral transpression between Laurentia and Gondwana. In the eastern portion of the orogen, both thrusting and younger strike-slip motion were accompanied by medium-grade metamorphism and plutonism that are spatially related to the major Alleghanian fault zones.

In most of the northern Appalachians, Alleghanian deformation is manifested mainly by dextral strike-slip faults. Sedimentation was generally localized in narrow elongate basins associated with these faults, and multiple unconformities in the basins attest to synkinematic deposition. The Alleghanian Orogeny is attributed to the oblique collision of Laurentia with Gondwana, associated with the assembly of Pangea, the Late Paleozoic supercontinent. Clearly, in the northern Appalachians the event was more of a "grazing" of Laurentia by Gondwana, whereas in the southern Appalachians, the two crustal blocks collided more head-on, although the partitioning of strain in the southern Appalachians attests to the transpressive nature of the collision there.

Just as the Grenville Orogen served as one of the seams along which Rodinia broke up, the Appalachian Orogen formed the locus of Mesozoic rifting that led to the breakup of Pangea and the formation of the modern Atlantic. Elongate basins containing rift facies clastic sedimentary rocks and mafic magmatic rocks are preserved along the length of the orogen, much as in their ancestor Iapetan rift basins.

22.4.5 Closing Remarks

The orogen has provided fodder for many tectonic concepts and continues to lure us with the many stones still unturned in its mountains, hollows, and coves. Some of the first-order observations and questions that arose as I composed this essay are:

- Does the New York promontory mark the end of a major transform in the Iapetus Ocean—perhaps one that split the ocean into two major domains, as reflected in the difference in accretionary history between the northern and southern Appalachians?
- The Taconic Orogeny, one of the oldest events in the orogen, is well preserved in the north but strongly overprinted by the Alleghanian Orogeny in south. These relations suggest that during the Middle and Late Paleozoic, accretion in the northern Appalachians mainly involved a strong strike-slip component and that areas of intense Salinian and Acadian deformation and metamorphism were localized collisions (at the scale of the orogen) where strike-slip motion was impeded by promontories.
- The traditional "mantra" of "Taconic, Acadian, Alleghanian" is giving way to the realization that tectonic activity was ongoing along the Laurentian margin and that it is somewhat naive to view the development of the orogen exclusively in the time frames of three named events.
- The nature of Late Mesozoic and Cenozoic erosional and epeirogenic events that are responsible for the modern form of the mountain range are not well known and await the attention of future researchers.

ADDITIONAL READING

Colman-Sadd, S. P., Dunning, G. R., and Dec, T., 1992. Dunnage-Gander relationships and Ordovician orogeny in central Newfoundland: a sediment provenance and U-Pb age study. *American Journal of Science*, 292, 317–355.

Hatcher, R. D., Jr., Thomas, W., Geiser, P., Snoke, A., Mosher, S., and Wiltschko, D., 1989. Alleghanian orogen. In Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., eds., *The Appalachian-Ouachita orogen in the United States, The geology of North America, v. F-2.* Boulder, CO: Geological Society of America, 233–318.

Hibbard, J. P., 1994. Kinematics of Acadian deformation in the northern and Newfoundland Appalachians. *Journal of Geology,* 102, 215–228.

MacNiocaill, C., van der Pluijm, B. A., Van der Voo, R., 1997. Ordovician paleogeography and the evolution of the Iapetus Ocean. *Geology,* 25, 159–162.

Murphy, J. B., Keppie, D., Dostal, J., and Nance, R. D., 1999. Neoproterozoic—early Paleozoic evolution of Avalonia. In Ramos, V., and Keppie, D., eds., *Laurentia-Gondwanan connections before Pangea, Geological Society of America Special Paper 336*, 253–266.

Rankin, D. W., 1994. Continental margin of the eastern United States: past and present. In Speed, R. C., ed., *Phanerozoic evolution of North American continent-ocean transitions, DNAG continent-ocean transect volume.* Boulder, CO: Geological Society of America, 129–218.

Rodgers, J., 1968. The eastern edge of the North American continent during the Cambrian and Early Ordovician. In Zen, E., White, W., Hadley, J., and Thompson, J., eds., *Studies of Appalachian geology, northern and maritime.* New York: Wiley & Sons.

Thomas, W. A., 1977. Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin. *American Journal of Science*, 277, 1233–1278.

van Staal, C. R., Dewey, J. F., MacNiocaill, C., and McKerrow, W. S., 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. In Blundell, D. J., and Scott, A. C., eds. *Lyell: the past is the key to the present*, *Geological Society of London, Special Publication 143*, 199–242.

Williams, H., 1995. Taconic allochthons. In Williams, H., ed., *Geology of the Appalachian-Caledonian Orogen in Canada and Greenland*, *Geological Survey of Canada*, *Geology of Canada*, no. 6, 99–114.