

A GEOLOGIC HISTORY OF THE NORTH-CENTRAL APPALACHIANS, PART 2: THE APPALACHIAN BASIN FROM THE SILURIAN THROUGH THE CARBONIFEROUS

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ABSTRACT. The north-central Appalachians occupy a critical position within the 3000+ km-long Appalachian orogen, lying southwest of the boundary between the central and northern Appalachians (CNAB). The one-billion-year-long history of tectonic activity in the north-central Appalachians includes the assembly and breakup of a late Proterozoic supercontinent, the creation and evolution of the Appalachian orogen during the Paleozoic, and the Mesozoic transformation of the active orogen into a passive margin during Pangea's disassembly. An important part of the Middle and Late Paleozoic history is the formation and growth of the Appalachian basin, an enormous, elongate continental basin lying cratonward of the active Appalachian internides along Laurentia's eastern margin.

The Appalachian basin developed out of the Taconic orogeny, the second of the four orogenies that formed and modified the character of the Appalachian orogen. Prior to the Taconic orogeny, the eastern margin of Laurentia consisted of a broad carbonate shelf facing the Theic Ocean. The Taconic orogeny obducted various Theic components, including microcontinents, magmatic arcs, and accretionary prisms, onto the carbonate shelf. The resulting Taconic highlands formed a topographic barrier between Theia and the craton's interior. Because tectonic activity in the internides continued more or less throughout the remainder of the Paleozoic, the Appalachian basin never had a direct connection with Theia.

The coarse-grained molasse from the newly uplifted Taconic highland spread westward over most of the basin during the Early Silurian. Carbonate deposition gradually encroached eastward over the basin as the siliciclastic input from the southeast waned. A resurgence in the earliest Late Silurian, perhaps related to orogenesis in Newfoundland and the Maritimes, expanded the clastic wedge somewhat. Before long, however, carbonate deposition once again dominated most of the north-central basin for the remainder of the Silurian and into the Early Devonian.

The Early-to-Middle Devonian Acadian orogeny began introducing siliciclastic material into the eastern part of the Appalachian basin, thereby ending the largely paralic environment that persisted from the Late Silurian. A number of deltas formed around local sediment-input centers during the Middle Devonian. Continued uplift and/or orogenesis must have continued into the Late Devonian because a vast amount of terrigenous sediment was introduced into the Appalachian basin to form the vast Upper Devonian Catskill delta. Although the principal tectonic activity appears to have centered in New England, the large volume of sediment input suggests that orogenesis may have extended southward to the north-central Appalachians. However,

direct evidence of actual Acadian deformation and metamorphism is lacking at this latitude.

The north-central Appalachian basin underwent a significant change during the Carboniferous. Prior to this time, the shoreline shifted laterally through transgressions and regressions largely as a function of sediment input and regional subsidence. In the Carboniferous, vertical movements in the basin became more important. During the Early Carboniferous, much of the Mauch Chunk delta was eroded in the central and western parts of the basin. At the end of the Early Carboniferous, an unconformity truncated progressively older rocks to the north toward New York. New sediment transport patterns and depositional environments within the basin during the Late Carboniferous probably reflect significant topographic and tectonic changes, not only in the hinterland, but in the basin itself, perhaps in conjunction with climatic changes. Extensive interfluvial swamps on a lower delta plain accumulated thick organic deposits which would become coal. This delta plain graded southwestward into tidal and marine environments.

The Alleghany orogeny in the Early Permian interrupted deposition in much of the north-central Appalachian basin and profoundly altered its structure.

INTRODUCTION

The early history of rocks within the Appalachian orogen (largely the "basement") began with the late Mesoproterozoic assembly of several continental masses into the Neoproterozoic supercontinent, Rodinia, during the Grenville orogeny. This assembly brought to a close the Grenville Wilson cycle.

The Theic Wilson cycle began with the final rifting of Rodinia at the end of the Neoproterozoic, which opened the Theic Ocean between Laurentia and West Gondwana (South America). The initial siliciclastic deposits on Laurentian eastern margin (in the area of the future north-central Appalachians) graded offshore into continental slope deposits and sediments of the Theic Ocean (soon to become the Octoraro Sea). Shortly thereafter, in the Early Cambrian, carbonate deposition developed on the continental margin. Throughout the Middle and Upper Cambrian, this shelf spread progressively westward, covering at least the eastern third of the craton by the beginning of the Ordovician.

The Appalachian orogen began, in a sense, in the Theic Ocean, some distance from the Laurentian east margin. At some time in the Cambrian, one or two microcontinents exotic to Laurentia (but containing rocks of Grenville age) moved through Theia to a position offshore of where the north-central Appalachians would develop. This positioning transformed the westernmost part of Theia into the Octoraro Sea, separating it from the main ocean. Late in the Cambrian, an east-dipping subduction zone developed within Theia, above which one or more magmatic arcs formed. Continued convergence in this part of Theia assembled various Theic components into amalgamates of oceanic crust, microcontinental rocks, oceanic sediments, magmatic arcs, and

accretionary prism sediments. This tectonism constituted the Potomac orogeny.

The amalgamates were then carried westward by continued subduction until they encountered Laurentia. These Theic components were thereupon docked against Laurentia's margin and partially obducted onto the submerging carbonate shelf. The resulting complex interplay of Theic amalgamates, Octoraro sediments, and Laurentian-margin rocks constituted the Taconic orogeny. This orogeny transformed the broad Early Paleozoic carbonate shelf into two major features: to the southeast, internide highlands along the continental margin that separated Theia from the craton interior; and, on the craton-side to the northwest of the highlands, a major, elongate continental basin, the Appalachian basin, that paralleled the highlands and persisted as a major depocenter throughout the Middle and Late Paleozoic. What transpired on the other, ocean-side of the Taconic highlands is not known, because remnants of whatever terranes or continental margin deposits that were there are not presently exposed in the north-central Appalachians.

The Taconic orogeny extended along the Appalachian orogen from Alabama to Newfoundland, a consequence of diachronous continent-arc collisions. In the north-central Appalachians, erosion of the highlands produced by the Taconic orogeny carried sediment northwest over the drowned carbonate shelf which by now had become the Appalachian basin. The gradual reduction in the coarseness and amount of sediment during the Silurian implies relatively quiescent tectonics, suggesting that convergence in this immediate part of Theia had largely, if only temporarily, ceased, even as it may have continued elsewhere. And so the story continues.

The early history of the north-central Appalachians summed above was discussed in some detail in Faill (1997a). This paper treats the history of the Appalachian basin from the Early Silurian to the end of the Carboniferous. Subsequent papers will cover the Alleghany orogeny (Faill, 1997b) and the post-Alleghany Mesozoic and Cenozoic events (Faill, 1997c).

APPALACHIAN BASIN (EARLY PHASE)

The Appalachian basin developed above the Laurentian carbonate shelf deposits as a flexural-load consequence of the Taconic orogeny, which produced a crustal downwarp cratonward of the new highlands (Jacobi, 1981; Quinlan and Beaumont, 1984; Etensohn, 1994). Additional descent of the basin floor continued nearly uninterrupted throughout the remainder of the Paleozoic, augmented by the Acadian and Alleghany orogenies and other tectonism in the orogen.

Areal extent of the Appalachian basin.—The initial Appalachian basin was bordered on the southeast by the Taconides and reached westward into the Midcontinent to the crest of the Algonquin axis, the Findlay arch, and the Cincinnati arch, a series of broad, Paleozoic structures which roughly parallel the Appalachian orogen (fig. 1) and across which the Appalachian basin stratigraphy merges with that of the Michigan and Illinois basins (Colton, 1970; Milici and de Witt, 1988). Its present exposed southwestern limit is the Cretaceous overlap of the Mississippi embayment in Alabama. Colton (1970)

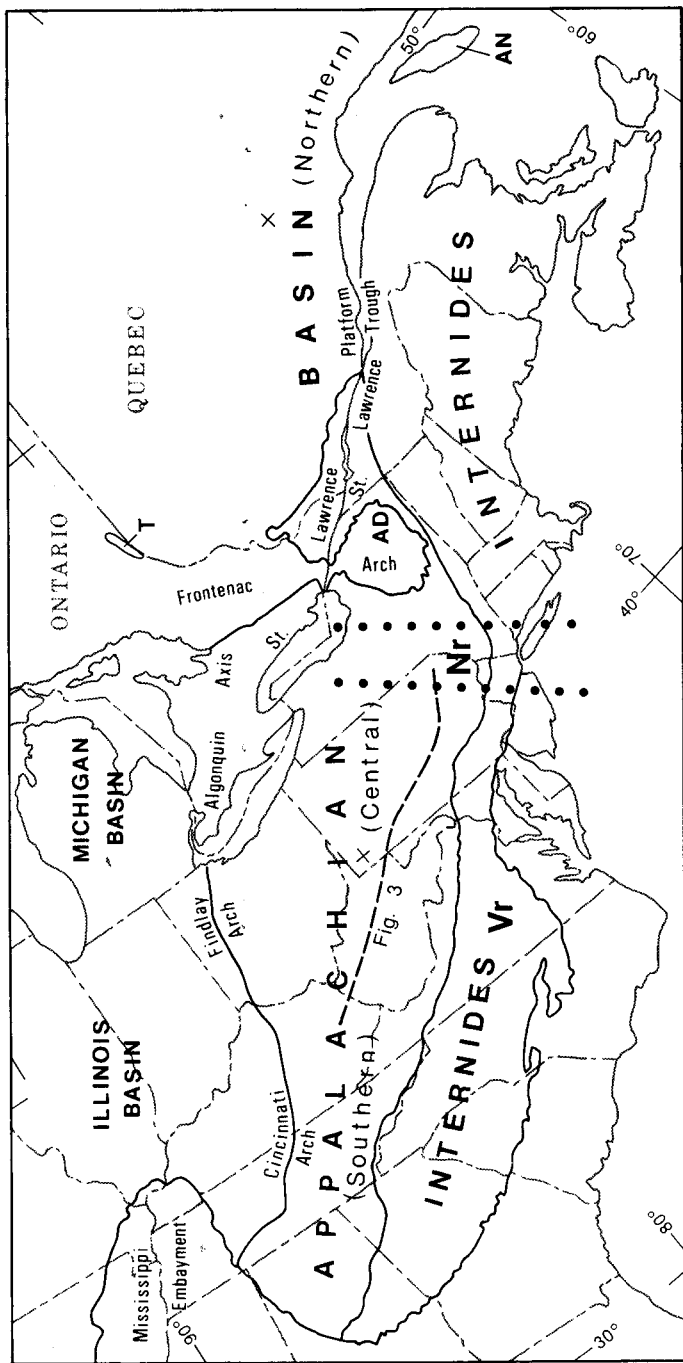


Fig. 1. Map of the Appalachian basin within the Appalachian orogen, showing the locations of the different parts of the basin and various structural features. AD—Adirondacks; AN—Anticosti Island; Q—Quebec City; T—Lake Timiskaming outlier. Nr—New York recess (“promontory”), Vr—Virginia recess (“promontory”). Solid line across the central Appalachian basin is trace of figure 3.

included in the Appalachian basin the St. Lawrence platform south of the presently exposed Grenville craton in southeastern Ontario and southern Quebec. How much farther the basin extended northeastwardly along the northwest side of the Taconic orogen during the Middle and Late Paleozoic is moot.

Structurally, the top of Grenville basement presently rises northward across New York from a depth of approximately 10 km in central Pennsylvania to the surface at the southern edge of the Adirondacks and the Frontenac arch. However, as will be discussed below, these structures were not present during the Silurian and perhaps not even by the Carboniferous, which precludes their being a factor in the basin geometry. Indeed, the pre-basin carbonate shelf, the St. Lawrence platform, reached at least to Labrador (Read, 1989; Sanford, 1993), and during the Caradocian, it covered a considerable area of the Grenville terrane to the north and west, as indicated by the Lake Timiskaming outlier in eastern Ontario (fig. 1; Russell, 1984). The Appalachian basin may have reached that far as well.

For example, the eastern part of the St. Lawrence platform evolved into the St. Lawrence trough in response to the onset of the Taconic orogeny. The similarity of the Upper Ordovician flysch deposits of the Quebec basin to those farther south suggests that they were continuous with the Martinsburg flysch that extended from Virginia to south-central New York. Indeed, the north-northeast axial paleocurrent indicators in the Martinsburg Formation in the north-central Appalachians and the southwest axial paleocurrent indicators in the Quebec basin indicate that a bathymetric low existed at that time in northern and central New York (Lehman and others, 1995) in the vicinity of the present Adirondacks. This suggests that the Adirondack massif was still not emergent at that time and that the evolving Appalachian basin continued uninterrupted at least to the Quebec basin, if not farther to the northeast. I suggest, therefore, that the Appalachian basin is not simply a central/southern Appalachian feature. Rather, during most of the Middle Paleozoic, it extended as a single continuous elongate basin from Alabama (where it passes westward into the Black Warrior basin (see Thomas, 1988)) northeastward across the New York recess ("promontory") to Quebec and perhaps continued as far as Anticosti Island and even Labrador. If so, then the Appalachian basin can be subdivided into southern, central, and northern portions, corresponding with the tectonic subdivision of the Appalachians, with boundaries at the Virginia and New York recesses (fig. 1). Additional evidence that the Appalachian basin persisted over the Adirondack area and beyond to the northeast at least throughout the Middle Paleozoic will be presented at appropriate places below.

The basin in the north-central Appalachians apparently became the deepest part of the Appalachian basin. Deposition here was nearly continuous from the Ashgill to the Early Permian and possibly for some time beyond then. Continued crustal descent over this ~150 my interval provided for the accumulation of thousands of meters of sediment in its deepest part (fig. 2). The nature of the deposits was largely dependent on subsidence rates and on tectonic events in source areas outside the basin. Controlled by these

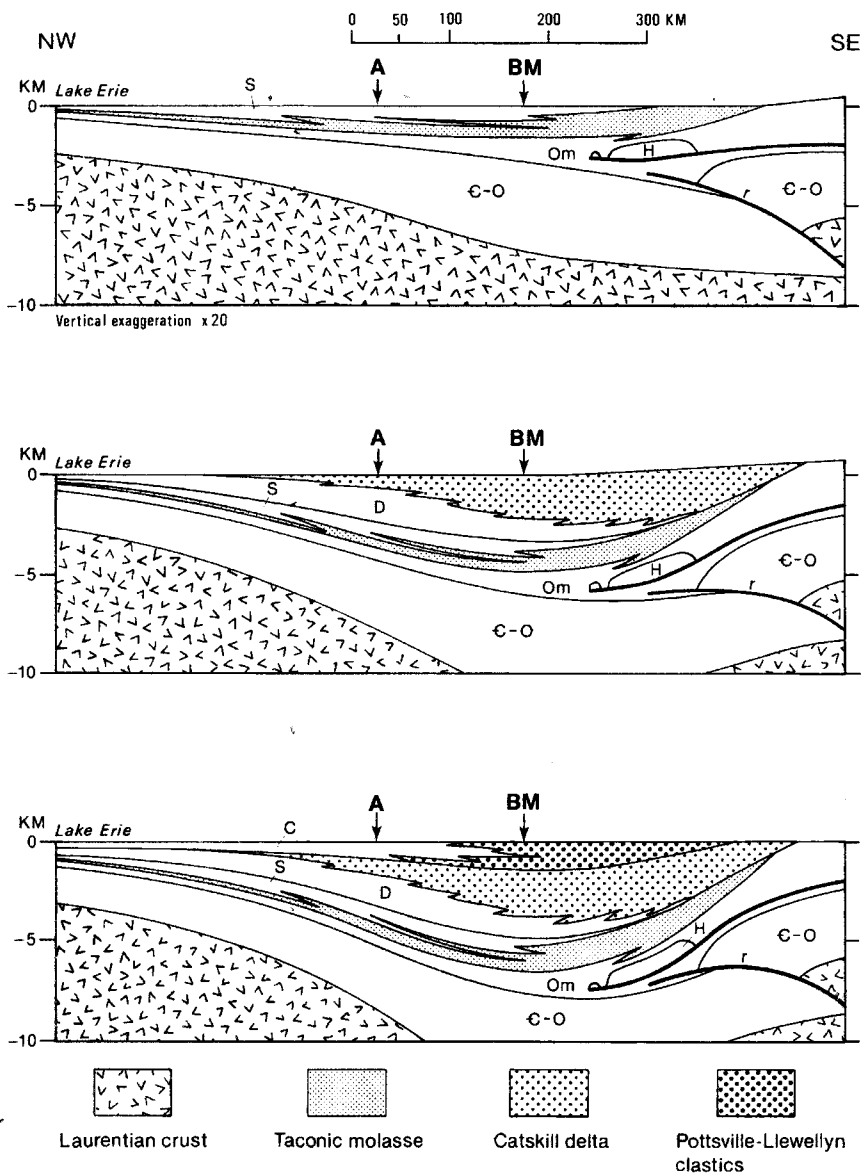


Fig. 2. Schematic cross sections of the Appalachian basin, underlying shelf deposits, and northwesternmost Taconides: (A) at the end of the Silurian; (B) at the end of the Devonian; (C) in the Late Carboniferous. A—present location of Allegheny structural front; BM—present location of the Blue Mountain structural front; C—Carboniferous rocks; C-O—Cambrian and Ordovician carbonates and siliciclastics; D—Devonian rocks; H—Hamburg klippe; Om—Ordovician Martinsburg rocks; r—Reading megathrust faults; S—Silurian rocks.

parameters, lateral shifts of depositional environments produced complex facies relations throughout the basin's history.

Taconic clastic wedge and succeeding carbonates.—The Taconic mountain system to the east and southeast was the source of most of the sediment that accumulated in the north-central Appalachian basin during the Late Ordovician and Early Silurian. This molasse of conglomerate, sandstone, siltstone, and shale spread northwestward across the basin as a large, low-lying alluvial plain (forming in succession the Bald Eagle, Juniata, and Tuscarora (Shawangunk) Formations). Detrital zircons in clasts from the lowest part of the Shawangunk Formation (immediately above the Taconic unconformity) yield U-Pb ages primarily from 1200 to 950 Ma (Gray and Zeitler, 1997). This suggests that rocks containing Grenville-age zircons were being eroded in the Taconic highlands and that bodies containing younger zircons (such as the Wilmington Complex) were not significant contributors of sediment to the Appalachian basin at this time.

An unconformity developed on the Queenston shale in the western and southern parts of the basin during the Late Ordovician and Early Silurian. In contrast to the probable compression-induced Taconic unconformity in southern New York to eastern Pennsylvania (Epstein and Lytle, 1987), a "Tuscarora" unconformity to the southwest in Virginia and eastern Tennessee may have developed in response to the cessation of compressional tectonism at the end of the Taconic orogeny (Dorsch and Driese, 1995). Several subregional unconformities developed in the western part of the basin during the Silurian (Ettensohn, 1994). However, sedimentation seems to have continued largely unabated and uninterrupted over much of the eastern part of the north-central Appalachian basin.

The Early Silurian Tuscarora Formation represents an eastward transgression across the basin, in which the coarsest sediments remained in fluvial and shore-zone environments to the east, while the finer fractions were carried to the paralic and marine environments in the west (Cotter, 1983). A continent-wide transgression late in the Llandovery brought marine shale and carbonate sedimentation eastward over much of the basin (Cotter, 1983; Cotter and Link, 1993), even as medium- to coarse-grained siliciclastics continued to be deposited along the southeast margin of the basin, adjacent to the source area (Epstein and Epstein, 1972).

Tectonic resurgence in southwestern Newfoundland during the Late Silurian (Dunning and others, 1990) and farther to the southwest in the Maritimes and Maine (Hibbard, 1994) is reflected by a widespread unconformity in New England, the Salina Disturbance of Boucot (1962). The highlands resulting from this orogeny apparently shed terrigenous sediment to the eastern margin of the St. Lawrence platform (Sanford, 1993). Some of this sediment may also have traveled farther south along the eastern Appalachian basin to feed the Upper Silurian clastic wedge of the upper Shawangunk Formation and its lateral facies, the Bloomsburg delta (Epstein, 1993), from northern New Jersey and eastern New York southward through Pennsylvania. Thereafter, the volume and coarseness of the siliciclastic debris eroded from the Taconic mountains to the southeast progressively decreased. Whereas

tectonic events outside the basin dominated sedimentation in the basin primarily through sediment supply and subsidence, the widespread higher-order cyclicity within these rocks suggests a strong component of eustatic effects, possibly related to Milankovitch periodicity (Goodman and Brett, 1995).

A series of transgressions and regressions across the northwestward deepening basin through the remainder of the Late Silurian repeatedly shifted the shore zone and shallow marine facies (Cotter, 1988). Northwest of the proximal delta lay a lagoonal-tidal flat-sebkha environment in which cyclic calcareous and dolomitic siltstones and mudstones (Wills Creek Formation) and laminated limestones (Tonoloway Formation) accumulated (Cotter and Inners, 1986). Farther to the north and west, along the New York-Pennsylvania border, restricted circulation (because of low paleoslopes?) in an apparently closed basin led to the precipitation of the evaporitic Salina Formation (Rickard, 1969; Smosna and Patchen, 1978) from northern West Virginia across western Pennsylvania to western New York. Carbonate deposition continued in the eastern part of the basin from the latest Silurian into the Devonian, indicating the absence of any significant tectonic activity to the east during this time (Epstein and others, 1967).

It is uncertain whether the central Appalachian basin continued uninterrupted over the Adirondack area into the northern Appalachian basin during the Silurian. The present absence of Silurian strata from Albany (Rickard, 1975) northward to Montreal (Boucot and others, 1986) implies that either this part of the basin was emergent through most of the Silurian or that sediments were deposited there and eroded later, after the Early Devonian. The youngest intact sedimentary rocks presently in the Quebec basin are Ashgillian, but the presence of outliers of Upper Ordovician to Upper Silurian rocks on the craton, including Wenlockian reefal beds in the Timiskaming outlier to the west, indicate that the St. Lawrence Platform was connected to the Michigan basin and Hudson Platform during this interval (Sanford, 1993). Such widespread deposition in the northern basin suggests that deposition was occurring in the Adirondack area as well.

The absence of even younger rocks in preserved outliers does not preclude their having been deposited on the craton. Indeed, the presence of Middle Devonian limestone and sandstone fragments in the St. Helens diatreme breccia near Montreal (Boucot and Johnson, 1967; Boucot and others, 1986) indicates that deposition continued in this part of the Appalachian basin (St. Lawrence platform) at least into the Middle Devonian. However, an eastward regression from the craton apparently occurred during the late Silurian, and deposition on the presently-exposed Precambrian craton may have largely ceased by the Early Devonian.

The apparent absence of a thick, widespread Taconic molasse in the northern Appalachian basin is remarkable, considering the present proximity of the Taconic highland remnants (Green Mountain and associated massifs). The contrast between the largely carbonate-filled northern Appalachian basin to the west and southwest and the huge volume of Silurian and Lower Devonian siliciclastic sediment transported eastward into the Connecti-

cut Valley-Gaspé synclinorium (Eusden and Lyons, 1993; Ludman, Hopeck, and Brock, 1993) suggests that the Taconic highlands in New England may have been much farther to the east during the Silurian and were transported westward to their present position during the Acadian orogeny (Zen, 1991). If so, the molassic eastern part of the central Appalachian basin seems to have no present counterpart in the northern Appalachian basin. This molassic part may have been deposited east of the present outcrop along the Hudson Valley-Lake Champlain-St. Lawrence belt in a no-longer-preserved eastern part of the northern Appalachian basin. Conceivably, Acadian thrusting may have pushed this eastern part of the basin westward over the present outcrop belt in front of the Green Mountain massifs, and it has since been eroded.

THE ACADIAN OROGENY AND THE APPALACHIAN BASIN (MIDDLE PHASE)

The sedimentary quiescence of the north-central Appalachian basin ceased at the end of the Early Devonian Emsian with the initiation of the Acadian orogeny in the southern part of the northern Appalachians (Bradley, 1983; Osberg and others, 1989; Rast and Skehan, 1993). The accretion of several amalgamated terranes there was the driving force behind this orogeny (Rankin, 1994); how far south along the orogen the Acadian orogenesis reached is not known—Acadian structures apparently extend under Long Island but are truncated a short distance farther south (Phinney and Roy-Chowdhury, 1989). The major consequence of the Acadian orogeny in the presently-exposed north-central Appalachians is the voluminous influx of sediment into the Appalachian basin during the Middle and Late Devonian (Barrell, 1913, 1914; see also Ettensohn, 1985; Fail, 1985; and Sevon, 1985).

The Acadian orogeny in New England may be the final event of a diachronous tectonism that began with the closing of Iapetus ocean (*sensu stricto*) between Baltica (Scandinavia) and Laurentia (Greenland) during the Silurian to form the combined continent, Laurussia. Southward closing of the Iapetus ocean (*sensu lato*) progressed into the Early and Middle Devonian with the Laurentian docking of the Central Mobile belt of Newfoundland and various terranes in the Canadian Maritime provinces and northern New England (Robinson and others, 1988; Rodgers, 1988).

In the southern Appalachians, the clearest evidence for Acadian tectonism is in the Talladega block in Alabama and western Georgia (Tull and others, 1988). Late Mississippian and Pennsylvanian post-metamorphic cooling dates from the Inner Piedmont of South Carolina (Dallmeyer, 1988) admit but do not require a Late Devonian high-grade metamorphism of an Acadian orogenesis; the dates may reflect cooling from Taconic metamorphism there. More important, the paucity of Devonian flysch and molasse sequences in the southern Appalachian basin to the west points to an absence of orogenic-driven highlands. Also, the absence of terranes between the Taconic(?)-accreted Carolina terrane and the more outboard Alleghany-accreted terranes (for example, the Raleigh and Kiokee belts and the Goochland terrane (Rankin, 1994) suggest there may have been no Devonian dockings to drive an Acadian-age orogeny in the southern Appalachians.

In New England, the main Acadian deformation lasted only from the Early to early Middle Devonian, but its effects to the southwest in New York and Pennsylvania began only in the latest Early Devonian and continued through at least the end of the Devonian. The metamorphism and plutonism associated with the Acadian in New England has no counterpart in the Piedmont of the north-central Appalachians, nor for that matter farther south, except possibly the Falls Run Granite Gneiss (Rankin, 1994). Indeed, the few available radiometric dates in the north-central Appalachians (Lapham and Bassett, 1964; Lapham and Root, 1971) suggest that the Piedmont was undergoing a prolonged period of gradual cooling during the Devonian and Early Carboniferous. Acadian deformation could possibly have affected the rocks southeast of Pennsylvania, under the Coastal Plain cover in New Jersey, Delaware, and eastern Maryland. However, this area is presently occupied by the Alleghany-emplaced Chesapeake terrane (Lefort and Max, 1991) or by terranes accreted during the Taconic orogeny (Hansen and Edwards, 1986; Volkert, Drake, and Sugarman, 1996). The presence of any pre-existing Acadian-deformed rocks displaced by the Chesapeake terrane has not been reported. In the exposed Piedmont, latest Devonian–Early Carboniferous K-Ar dates (Lapham and Bassett, 1964) suggest that the rise of Mine Ridge and the Tucquan antiform (Wise, 1970) could possibly have been a late “Acadian” event, although the subvertical foliation associated with this antiform is more congruent with the Alleghany structures in the Piedmont (see discussion in Faill, 1997b). All this notwithstanding, the Acadian orogeny had, indirectly, a profound effect on the exposed north-central Appalachians through the production of sediment that accumulated in a thick, widespread clastic wedge within the rapidly subsiding central Appalachian basin during the Middle and Late Devonian.

Acadian flysch.—Several events and perturbations at the end of the Early Devonian suggested impending changes to the north-central Appalachian basin. Three thin ash falls (Bald Hill Bentonite beds) in the middle of the Gedinnian Stage signaled some distant volcanic activity (Smith and Way, 1988) and the end of some 35 my of mostly carbonate deposition in the Appalachian basin. By the end of the Siegenian, a distinct increase in the amount of silica had been introduced to the basin, represented by the Ridgeley (“Oriskany”) quartzite and the Shriver chert. A widespread but irregular disconformity of eustatic origin (the Wallbridge unconformity) developed on top of the Ridgeley and eroded older rocks to varying degrees, particularly in the southwestern and northwestern parts of the basin where all the Lower Devonian rocks were removed (Hamilton-Smith, 1993; Ettensohn, 1994). The influx of fine-grained siliciclastic detritus (Needmore and Esopus shales and siltstones) into the eastern and northern parts of the basin (and sands along the present eastern margin) in the early Emsian Stage (Rickard, 1973, 1989) represented the earliest stratigraphic effect of the Acadian orogeny on the central Appalachian basin.

The Needmore shale graded westward into the Huntersville chert and Onondaga limestone. With diminution of siliciclastic input, the latter progressively spread eastward across the basin by the late Emsian. The Tioga Ash

falls blanketed the basin (Way, Smith, and Roden, 1986) from a southeast source (Dennison and Textoris, 1987) in the early Eifelian (390.0 \pm 0.5 Ma for Tioga B) (Roden, Parrish, and Miller, 1990). At about this time, carbonate deposition was progressively supplanted from the northwest to the southeast by siliciclastic deposition; that is, contrary to common expectation, the carbonate-to-black-shale contact becomes younger southeastward across the Valley and Ridge in Pennsylvania (Way, Smith, and Roden, 1986). The earliest siliciclastics above the Onondaga were the black shales of the Marcellus Formation, which were then succeeded by the shales and siltstones of the Mahantango Formation (Prave, Duke, and Slattery, 1996). Shoaling along the southeast basin margin and increased sediment input from the Acadian highlands created the multiple Mahantango deltas (Faill, Hoskins, and Wells, 1978; Dennison, 1985). Farther north in New York, the Mahantango Formation grades into the continental-facies Ashokan and Plattekill Formations, the oldest units of the nonmarine Catskill delta (Rickard, 1975). To the east, in the Green Pond syncline that crosses the New York-New Jersey border, coarser clastics (Esopus-equivalent) persisted from the Emsian throughout the Onesquethaw and the remainder of the Middle Devonian (Offield, 1967; Kirby, ms; Herman and Mitchell, 1991), presumably reflecting closer proximity to the source area.

The Middle Devonian came to a close with decreasing clastic input from the east, which allowed the thin Tully Limestone to occupy the eastern part of the basin, where it is a rather argillaceous carbonate. The Tully was the last (and strongest) of several such interruptions through the Middle Devonian. In the western part of the Appalachian basin, reactivation of the Waverly and Cincinnati arches produced the late Givetian Taghanic unconformity that truncated progressively older rocks to the southwest, down to the Onondaga Formation in eastern Kentucky, where it merges with the Wallbridge unconformity (Hamilton-Smith, 1993; Ettensohn, 1994). The Taghanic onlap continued to advance southwestward throughout the Frasnian. This late Middle Devonian arch resurgence probably represents a flexural-bulge response to a crustal loading in the active Acadian orogen to the east.

Acadian molasse—the Catskill delta.—During the Middle and Late Devonian, subsidence of the northern part of the basin accelerated relative to its descent during the Silurian and Early Devonian (Faill, 1985). (Although more recent time scales such as Gradstein and Ogg, 1996, portray longer Devonian durations, the relative Middle and Upper Devonian accelerations remain intact.) This increased subsidence was quite likely driven by the Acadian tectonism to the northeast in New England, and it provided an enlarged repository for the voluminous sediment shed from the Acadian highlands. Detrital white micas from Middle and Upper Devonian and Lower Mississippian beds in northern Ohio and central New York yield Early to Middle Devonian dates (Aronson and Lewis, 1994). This body of sediment, called the Catskill delta (Barrell, 1913, 1914), dominated the Appalachian basin throughout the Middle and Late Devonian. Its initiation is generally placed in the Emsian, with the deposition of the Needmore Shale (Dennison, 1985; Ettensohn, 1985). The delta system comprises both continental and marine

beds, with the latter constituting the larger fraction, especially in the western part. During the Late Devonian, siliciclastic sediment was deposited across the entire Appalachian basin, as far southwest as Tennessee and Georgia (Lundegard, Samuels, and Pryor, 1985), and across the Cincinnati arch into the Illinois and Michigan basins.

Basinal black shales in a deepened Appalachian basin at the beginning of the Late Devonian were followed by turbidite and shallow marine deposition in the east. As the marine beds advanced westward up the Taghanic onlap on the Waverly arch, nonmarine deposits prograded westward and southwestward over the marine beds. The absence of disconformities or unconformities (with one exception additional to the Taghanic) during the approximately 16 my duration of the Late Devonian (Gradstein and Ogg, 1996) suggests a relative tectonic quiescence in the central Appalachian orogen during this time. Yet, the increasing amount of sediment input to the basin, the general upward coarsening of grain size and quartz content with time (Epstein, Sevon, and Glaeser, 1974), the greater and more rapid subsidence of the basin (Faill, 1985), the spread of thick conglomeratic sequences such as the Foreknobs Formation in Maryland (for example, Van Tassell, 1987), and the westward/southwestward shift of the shore zone and continental facies, all attest to persistent uplift (and thus tectonism?) in the source areas to the east and northeast.

The lower part of the Catskill delta in the eastern part of the basin consists of shallow-marine, shore-zone, and low-energy alluvial deposits. Higher in the delta, sandstone/mudstone sequences of alluvial origin and thick- and very thick-bedded quartzites of braided stream origin are far more common (Epstein, Sevon, and Glaeser, 1974; Diemer, 1992). The Catskill delta system is, therefore, lithically varied, reflecting a multiplicity of depositional environments at any given time, which has resulted in a complex stratigraphy (Woodrow and others, 1988). Nonmarine, delta-plain facies were prevalent in the east (Sevon, 1985) and graded westward into marine facies (Ettensohn, 1985). The shore zone, the boundary between the marine and nonmarine environments, is a significant feature, because its changing nature and lateral shifts through time provide a record of the evolution of the delta system. This in turn is an interplay between sediment input to the basin (a reflection of the tectonics and erosion in the source area) and subsidence of the basin, which itself may be in part a response to crustal loading elsewhere.

The Catskill shore zones vary from sandy to muddy, having formed in estuarine, floodplain, and tidal-flat environments (Walker and Harms, 1971; Miller and Woodrow, 1991). The earliest (early Givetian) shore zones are preserved in east-central New York (Rickard, 1975; Bridge and Willis, 1994). With time, the shore zone migrated irregularly to the west and southwest, reflecting the growth of the continental portion of the delta, produced by the increase of terrestrial sediment volume and its excess over subsidence. The shore zone reached western Pennsylvania, central West Virginia, and west-central Virginia late in the Famennian before retreating eastward.

The eastward transgression of marine graywacke sandstone from the western part of the basin late in the Famennian may be related to a singular

event along the southeastern basin margin. Discontinuously along this margin, the Devonian-Mississippian Spechty Kopf Formation disconformably overlies the Catskill Formation. The lowermost Spechty Kopf contains an unusual sequence of lithologies (from the bottom: polymictic diamictite, pebbly mudstone, laminites, and parallel-bedded sandstones) (Epstein, Sevon, and Glaeser, 1974; Sevon, 1981). Most of the overlying beds of the Spechty Kopf and the overlying Pocono Formation consist of quartzitic sandstones containing low-angle tabular crossbeds and sharp basal contacts, indicating a high-energy, braided-stream environment (Epstein, Sevon, and Glaeser, 1974). The significance of the basal sequence is unclear. No similar sequence is present at this horizon to the west in the central or western part of the basin. However, although sedimentation appears to have continued without interruption, dark shales (such as the marine Riddlesburg Formation) are present that seem out-of-place with respect to the fluvial environments of the underlying Catskill Formation and the overlying Huntley Mountain Formation (personal communication, W. D. Sevon, 1997).

Sedimentation in much of the Appalachian basin continued largely uninterrupted into the Carboniferous. However, the Spechty Kopf disconformity at the top of the Catskill Formation, in the uppermost Devonian along the present southeast margin, provides a convenient horizon to mark the termination of the Catskill delta (*sensu stricto*).

Northern Appalachian basin.—The persistent input of large amounts of siliciclastic sediment into the basin and the rapid subsidence of the eastern part produced an exceptionally thick (2400 m), largely nonmarine sequence in eastern Pennsylvania (Epstein, Sevon, and Glaeser, 1974). This probably does not represent the thickest part of the Catskill delta because the youngest Catskill beds along the Catskill escarpment in eastern New York (the Slide Mountain sandstone and conglomerate) correlate with the upper middle of the section (upper part of the Long Run member, 1600 m above the Tully) along the Lehigh River (Sevon and others, 1989). Yet vitrinite-reflectance measurements of coalified plant material from the Gilboa Formation (Tully equivalent) in eastern New York suggest that the Gilboa was buried at one time by 6.5 km of rock (Friedman and Sanders, 1982). If the overlying Carboniferous strata there were as thick as what is preserved in the anthracite basin of eastern Pennsylvania (2.5 km, Wood, Trexler, and Kehn, 1969) (which they probably were not), then the Upper Devonian thickness in eastern New York must have been on the order of 4 km (assuming no Permian or younger strata, but see below).

The persistent great thickness and coarseness of the Upper Devonian sediments northeastward to the erosional limit again raises the question as to the northern limit of the Appalachian basin during this time. Several lines of evidence indicate that the basin continued much farther to the northeast: (1) Sediment input lobes along the present southeast margin of the basin from Maryland to New York (Sevon, 1985; Sevon and others, 1989, p. 38) indicate that significant amounts of sediment were derived from areas to the southeast—there is no suggestion of a northern limit of the basin (say, for example, by the presence of input lobes above the Helderberg escarpment southwest of

Albany, New York with south- or southwest paleocurrent directions). (2) Fluid-inclusion data from Lower and Middle Ordovician rocks along the Champlain Valley imply a former depth of burial of 5 to 7 km (Friedman, 1987). (3) The Acadian orogeny was most intense from Connecticut to Vermont, and it would be expected that a large fraction of the debris eroded from the Acadian highlands would be carried westward and would accumulate in a basin at the foot of the highlands (in eastern New York), unless some unknown elevated area diverted the sediment southwestward toward southern New York and Pennsylvania. The Adirondack massif was probably not emergent then (Isachsen, 1975; Miller and Lakatos, 1983; Schofield and others, 1997) and thus would not have been able to divert sediment transport. (4) Isopachs of Lower and Middle Devonian rocks in New York trend north-northeast, directly toward the Adirondack massif, with no suggestion of divergence of thickness or facies around the massif (Rickard, 1989). (5) The Devonian rock fragments in the St. Helens Island breccia in Montreal implies deposition in the Quebec basin at least into the Middle Devonian.

These lines of evidence suggest that during the Devonian the Appalachian basin persisted uninterrupted across the Adirondack area and presumably joined with the Quebec basin and St. Lawrence trough. If so, the Appalachian basin in the Adirondack area may very well have accumulated the major portion (at least of the coarse fraction) of the westward transported sediment eroded from the Acadian highlands, all of which has since been removed and probably deposited on the Atlantic continental margin largely during the Late Jurassic and Miocene (Poag, 1992). From this, one could infer that the northern and central parts of the Appalachian basin remained a single continuous basin in the Devonian, and that the fundamental boundary between the northern and central Appalachians (CNAB) had yet to make its appearance in this basin.

Source areas for the Catskill delta.—No Acadian deformation has been conclusively demonstrated in the north-central Appalachian basin, nor has any Acadian tectonism been discerned in the pre-basin rocks to the southeast (Faill, 1985). Similarly, the absence of any significant metamorphism or deformation in the southern Appalachian internides (other than possibly in the Talladega belt, Tull and others, 1988) indicates either that uplift or highland elevations southeast of the central and southern basin were not very large, or that the high-grade Acadian internides lie farther east under the present Coastal Plain deposits. Yet the large volume of sediment, particularly in the north-central basin, demands a large source area.

The Acadides in New England would have been sufficiently large, and a large river system could have carried the sediment southwestward, parallel to the orogen, much as the Ganges and Brahmaputra Rivers parallel the Himalayas before joining and turning south to feed the Bengal delta. However, the sediment-input patterns along the southeast margin do not suggest delivery of sediment through a single (albeit possibly complex) river system. Indeed, numerous (as many as 12 from New York to Virginia) local sediment-dispersal systems have been identified along the present southeastern exposures of the basin (Sevon, 1985). The variability among these systems with

respect to their age and the sediment they supplied indicates that they were independent of one another and that the source area for each was nearby. Furthermore, this conclusion is supported by the first (earliest) occurrence of abundant detrital muscovite in the proximal basin rocks (in the Upper Devonian Clarks Ferry member of the Catskill Formation) in eastern Pennsylvania (Epstein, Sevon, and Glaeser, 1974). This suggests that at this time large areas of micaceous schist (such as the Wissahickon schist in the exposed Piedmont or for that matter any of the New England schists that extend under Long Island) became exposed in one or more of the source areas.

Farther to the southwest in the southern Appalachian basin, the accumulation of a considerable thickness of Late Devonian and Early Carboniferous siliciclastic sediment along the eastern margin suggests that later, additional source areas developed east of there. This southwestward spread of activity possibly reflects a southwestward shift of Acadian tectonism and mountain building through time (Rodgers, 1967; Dennison, 1985; Etensohn, 1985). An alternative hypothesis to explain this apparent southward shift of activity is that the Appalachian basin was displaced sinistrally along an orogen-parallel shear zone, offsetting the New York/Pennsylvania Appalachian basin sediments from their initial place next to the Acadian highlands in New England. Although sinistral displacements of large magnitude occurred between Laurentia and Baltica/Armorica (Kent and Keppie, 1988; McKerrow, 1988), this movement was largely completed by the Middle Devonian. No evidence for post- (or pre- for that matter) Middle Devonian sinistral shear in the central Appalachian orogen has been described.

THE CARBONIFEROUS APPALACHIAN BASIN (LATE PHASE)

The Carboniferous succession in the north-central Appalachian basin records a basin tectonism more complex than that in the Devonian or Silurian. Vertical movements, probably as flexural-bulge responses to tectonism outside (east of) the basin (Etensohn, 1994), apparently caused accumulation and then removal of substantial amounts of Mississippian and lower Pennsylvanian sediment (fig 3, Edmunds, 1993). The basin was far more stable in the latter part of the Pennsylvanian, during which eustacy and climate were the principal controls on the depositional environments. The vertical movements, along with the sealevel variations and climatic changes, created a complex Carboniferous stratigraphy throughout the various parts of the north-central Appalachian basin and caused the development of several regional unconformities (Edmunds and others, 1979; Edmunds, 1993; 1996).

Early Carboniferous.—The distribution of depositional environments in the central Appalachian basin that were extant at the end of the Late Devonian persisted into the Mississippian. Alluvial environments in eastern Pennsylvania graded laterally into deltaic, estuarine, and marine environments to the west in western Pennsylvania and Ohio and to the southwest in West Virginia to Kentucky. The high-energy environment in the northeast produced the coarse-grained braided-stream deposits of the Pocono Formation and its more distal equivalents, the Burgoon Formation (Epstein, Sevon,

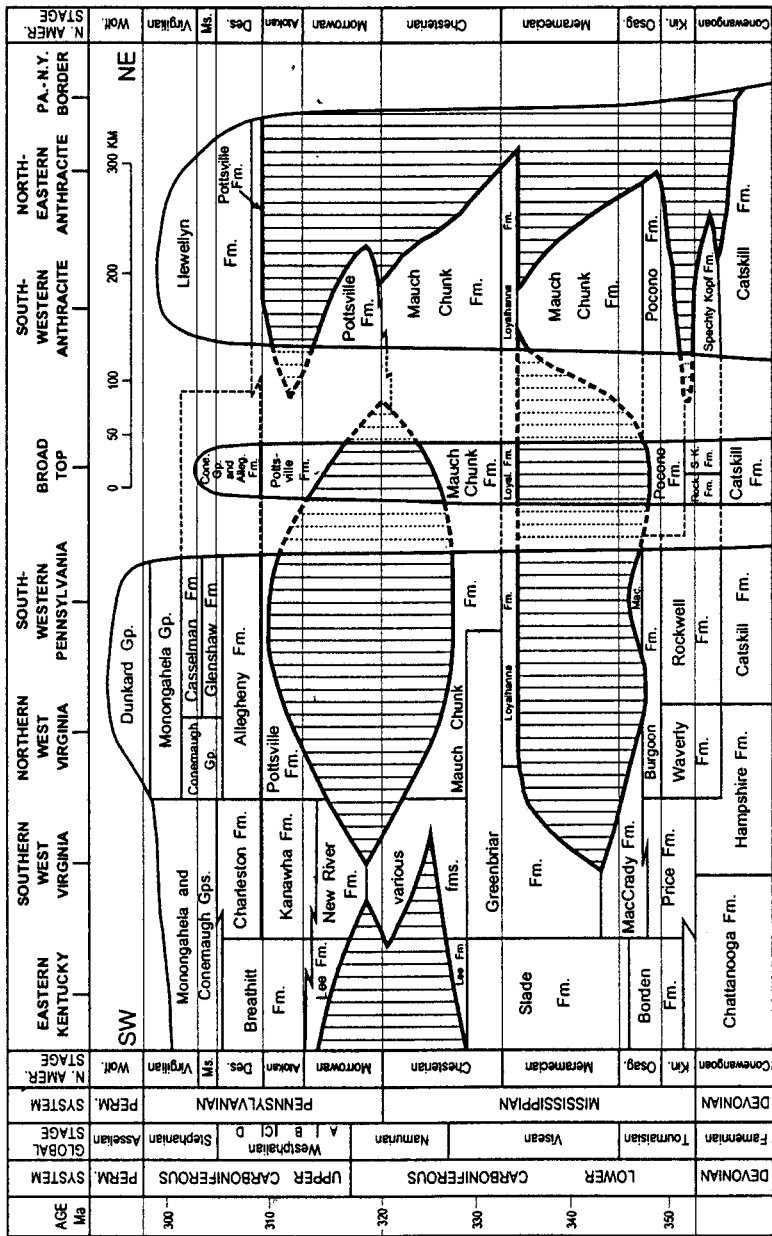


Fig. 3. Carboniferous correlation chart along the central Appalachian basin, from the Pennsylvania-New York border southwestward to eastern Kentucky (see fig. 1 for location). Heavy lines enclosing vertical lines represent unconformities within the Carboniferous. Stage name abbreviations: Kin—Kinderhookian; Osag—Osagian; Des—Desmoinesian; MS—Missourian; Wolf—Wolfcampian; Fam—Famennian; Tour—Tournaisian; Steph—Stephanian. SK—Speckty Kopf.

and Glaeser, 1974) and the low-energy Huntley Mountain Formation that underlies the Burgoon. This large volume of quartzose sediment was probably in response to increased Kinderhookian (early Tournaisian) tectonism to the east beyond the basin margins (a southward-migrated "Acadian" orogeny?) and was concurrent with rapid subsidence, particularly in the central Appalachian basin's northeastern part (eastern and central Pennsylvania and possibly east-central New York).

These units were succeeded in the middle Osagean (late Tournaisian) by the Mauch Chunk Formation (fig. 3), a thick, deltaic red-bed sequence somewhat similar to the continental portion of the Catskill delta. However, much of the Appalachian basin was uplifted in the early Meramecian (early Visean); a Meramecian arch reached from northern Pennsylvania (or farther north) to eastern Kentucky (Edmunds, 1993, 1996). During the middle and late Meramecian, most of the Mauch Chunk and stratigraphically equivalent rocks were eroded from a large part of the basin (fig. 3), except along the eastern margin where red-bed deposition apparently continued uninterrupted.

The decrease in maximum grain size of the sediment entering the basin from the east during the mid-Osagean coincided with a climatic change from wet to semi-arid. A lowering of the tectonic highland source area could cause a grain-size reduction, but apparently there was no reduction in sediment volume: post-Osagean thicknesses in the basin are comparable to pre-Osagean ones. A eustatic sealevel rise augmented the middle and late Meramecian onlap of the Greenbrier limestone toward the northeast (Carney and Smosna, 1989), where it graded into the sandy, strongly cross-bedded Loyahanna limestone that exhibits (where presently preserved) basin-axial long shore paleocurrent directions (Edmunds, 1993; 1996). The Loyahanna quartz-sand fraction may have had an aeolian provenance from Ohio, northwestern Pennsylvania, and the craton farther to the northwest, which persisted as a positive area.

By the early Chesterian (late Visean), sediment input from the eastern source area must have increased because the Mauch Chunk delta spread westward over the Loyahanna into southwestern Pennsylvania and western Maryland, grading into the marine upper Greenbrier (and equivalent units) interval that dominated the basin in West Virginia and beyond (Brezinski, 1989; Edmunds, 1993, 1996). The Mauch Chunk delta appears to have continued to prograde southwestward into West Virginia throughout the remainder of the Chesterian (Namurian) and into the Morrowan (late Namurian) (fig. 3), interfingering extensively with marine and marginal marine units there and in eastern Kentucky (Englund and Thomas, 1990).

It is difficult to posit what tectonism, if any, was occurring east of the basin during the Mississippian because of limited exposure in the central Appalachian Piedmont and the absence of any clearly defined Early Carboniferous metamorphism or tectonism there. In contrast, the Alleghany orogeny was just beginning in the southern Appalachian internides (Dallmeyer and others, 1986); terrane convergence associated with a thermal event (about 360-340 Ma) in the Carolina slate and Charlotte belt may have created

a peripheral bulge, the Meramecian arch. Despite this activity, much of the southern Appalachian basin was dominated throughout the Early Carboniferous by shallow marine to supratidal carbonates that lay west and southwest of the Price delta of central Virginia (Milici and others, 1979; but see also Yeilding and Dennison, 1986). The fairly limited amount of siliciclastic sediments along the present southeast margin of the Mississippian outcrop belt (for example, the Price delta) suggests that whatever tectonism was occurring in the orogen to the east was not producing a large amount of terrigenous sediment in the Appalachian basin.

It is unlikely that activity in the New England Appalachians was having any causative effect on the north-central part of the basin. The closest Early Carboniferous tectonism is represented by local basins in the Canadian Maritimes and eastern Maine that contain Late Devonian to Pennsylvania sediments (Belt, 1968). These basins apparently formed in response to a regional dextral transpressive tectonism (Bradley, 1982; Durling and Marillier, 1993; Langdon and Hall, 1994; but see also Hamblin and Rust, 1989). Lefort and Van der Voo (1981) attribute their development to strike-slip movement generated by the approaching Gondwanan (Africa) plate. The basins are neither late Acadian nor early Alleghany structures because their tectonic settings are entirely different from both Acadian and (central and southern) Alleghany orogeneses. Whether this Early Carboniferous tectonism extended south of the Maritimes as far as the central Appalachians, hidden though it may be under the Coastal Plain, is simply not known; it seems to have no representation in the intervening New England Appalachians. The apparent absence of comparable structures in the central and southern Appalachians is another contrast between the northern and central/southern parts of the orogen, even though the apparent southern limit of these Mississippian basins is far north of the New York recess ("promontory"). Be that as it may, the vertical movements (unconformities) and facies shifts in the central Appalachian basin and the southeast provenance of coarse-grained sediment strongly suggest that Early Carboniferous tectonism (early Alleghany in the southern internoles) was occurring nearby.

Toward the end of the Mississippian, the easternmost part of the Mauch Chunk delta in the central Appalachian basin began to change from a low-energy alluvial-plain to a high-energy braided-stream environment in which quartzose, coarse-grained, crossbedded sandstones were deposited, interspersed with very low energy peat-swamp deposits. This change in the latest Chesterian (Namurian) has been attributed to a climatic shift from semi-arid back to wet, tropical conditions (Edmunds, 1993, 1996), but the increase in coarse sediment also suggests that uplift in a source area to the east may have been a contributing factor. This Pennsylvanian high-energy facies spread westward in the early Morrowan in the form of the Pottsville Formation (fig. 3; Meckel, 1967), forcing the low-energy Mauch Chunk facies ahead of it across the basin. However, the ultimate western extent of these alluvial clastics is not known because of the subsequent erosion in this part of the basin.

Late Carboniferous.—Rapid subsidence in the present northeasternmost part of the central Appalachian basin continued into the Late Carboniferous, during which a considerable thickness of coarse-grained Pottsville sediments accumulated in eastern Pennsylvania (Wood, Trexler, and Kehn, 1969). Farther to the north and northeast, erosion has removed whatever equivalent sediments that may have been deposited in east-central and northeastern New York (fig. 3). At the southwest end of the central Appalachian basin, in the Pocahontas basin of southern West Virginia and western Virginia, deposition appears to have continued through this time interval with only brief interruptions (Miller, 1974; Wanless, 1975; Englund, 1979; Donaldson and Shumaker, 1981).

The western part of the basin, which extended from central New York southwestward to northern West Virginia, underwent uplift during Early Morrowan (Late Namurian) time possibly as a reactivation of the earlier Meramecian uplift in this area. The bulge apex apparently lay in western Pennsylvania, where the subjacent rocks were more deeply eroded (down to the Burgoon Formation and into Upper Devonian strata in western New York and northwestern Pennsylvania) than elsewhere in the basin. The consequent erosion was previously believed to be part of the continent-wide Mississippian-Pennsylvanian unconformity at the Chester/Morrow boundary, caused by a major eustatic fall in sealevel. However, the erosion in the western part of the central Appalachian basin post-dates this unconformity, and the Morrowan uplift is now considered to be a result of a northwestward-migrating peripheral bulge in response to the approach of Gondwana (Donaldson and Shumaker, 1981; Beaumont, Quinlan, and Hamilton, 1987; Ettensohn and Chestnut, 1989).

This sub-regional Morrowan erosion event may be an indication that the Appalachian basin began to evolve differentially along its length, perhaps for the first time since the Late Silurian. That is, the history of the basin to the north may have begun to diverge at this time from that of the central and southern Appalachian basin. Specifically, following the Morrowan uplift, a southwest-draining fluvial system developed in the western part of the basin (Rice and Schwietering, 1988; Beuthin, 1994; Archer and Greb, 1995), a significant shift in the direction of sediment distribution. Coarse, quartzose sediment in the form of the Sharon Conglomerate (Olean Conglomerate farther east) now entered the basin from the north rather than across the basin from the southeast. This sediment was carried in the paleoriver system southwestward, filling the paleovalleys along the eastern side of the Morrowan arch, grading into the quartzose sandstones of the New River Formation in West Virginia (Beuthin, 1994) and farther southwestward into the Lee and Crab Orchard Mountains Formations in Kentucky and Tennessee (Rice and Schwietering, 1988) and even as far as the Ouachifa foreland (Donaldson and Eble, 1991). The Morrowan bulge was gradually covered during the Atokan by the Connoquenessing member of the Pottsville Formation and by the late Atokan Mercer Formation where the Connoquenessing is absent (Edmunds, 1996).

The southwestward distribution of the Sharon sediments is interesting in its own right, but its significance was greatly enhanced by another event. During the early Atokan, an uplift developed in northeastern and north-central Pennsylvania (fig. 3). This at-first-glance more areally restricted unconformity appears to have been a separate uplift event, perhaps unrelated to the more widespread Morrowan peripheral bulge to the west. This Atokan unconformity is most strongly evident in the northern and middle anthracite basins, where much of the Mississippian section and even the uppermost Upper Devonian Catskill Formation was eroded, progressively downsection to the north and northeast (Sevon, 1969; Edmunds, 1988).

The severity of this erosion in the northern Anthracite region was so great that it is possible that areas to the north in central and eastern New York may also have been involved. Indeed, if central and eastern New York were eroded to such an extent during the Atokan, this area would have provided an ingress of sediment into the basin. This access zone would have allowed sediment from New England to bypass the higher proximal parts of the basin that had existed along the east margin since the Ordovician. Access from the Canadian shield would also have been possible. Indeed, by the late Atokan, sediment in the eastern part of the basin (at least in northeastern Pennsylvania) was also being derived from the north. Sedimentation (in the form of the Sharp Mountain member of the Pottsville Formation) resumed in northeastern Pennsylvania above the Atokan erosion surface (fig. 3). Trough-crossbed measurements indicate a northern source (Robinson and Prave, 1995), which was a distinct change from the predominant southeast source for the lower two Pottsville members (Meckel, 1967; Wood, Trexler, and Kehn, 1969).

The northern source area was apparently quite large. The distribution of U-Pb ages of zircons within the quartzose clasts of the Sharp Mountain member is quite broad, ranging from 2.1 Ga to 380 Ma (Gray and Zeitler, 1997). The large proportion of ages between 1200 and 900 Ma indicates that Grenville rocks were providing a major fraction of the sediment. The Superior province farther west may have supplied the clasts with the oldest zircons. The generally euhedral zircons with dates of 450 to 400 Ma suggests that the Late Ordovician to Silurian plutons in New England were emergent in the Late Carboniferous and thereby may have contributed to the Sharp Mountain sediments.

However, Late Carboniferous tectonism in New England is not well understood. Local basins containing Pennsylvanian sediments, such as the Narrangansett (Mosher, 1983; Skehan, Rast, and Mosher, 1986) and the Norfolk (Cazier, 1987), developed in southeastern New England at the beginning of the Late Carboniferous (although the Avalon terrane on which they formed may not yet have docked with Laurentia). The anatectic Sebago and Effingham plutons in southern Maine/New Hampshire were emplaced at 325 Ma (Aleinikoff, Moench, and Lyons, 1985). An extensive high-grade metamorphism associated with these batholiths lasted only 20 my (Lux and Guidotti, 1985); this fairly rapid cooling may reflect Pennsylvanian uplift of at least this part of New England, which could then have provided sediment to the Appalachian basin to the west. These limited events, though, were

pre-Alleghany, because the main impress of Alleghany deformation, metamorphism, and magmatism in New England would wait until the Permian.

Sediments deposited above the Morrowan and Atokan unconformities in the north-central Appalachian basin are lithically quite variable, vertically and laterally (see, for example, Donaldson and Eble, 1991). They include muds, sands, conglomerates, lime beds, and extensive peat deposits, the last being quite rare in older rocks. This varied lithic assemblage accumulated throughout the Pennsylvanian and well into the Permian. The distinctive characteristic of this part of the stratigraphic section is the presence of numerous metamorphosed peat deposits—that is, coal beds. These peat deposits were raised to bituminous coal rank largely by burial metamorphism throughout much of the basin in the Allegheny Plateau province and the non-folded rocks of the interior craton regime; the anthracitization of the coals in eastern Pennsylvania was a separate metamorphism superimposed on the earlier one (Levine and Davis, 1989).

The peat deposits and associated sediments were formed on a regional west-to-northwest sloping alluvial plain that graded laterally to the west and southwest into a shallow marine setting. The coarser-grained quartzose beds so common on the southeast side of the basin reflect proximity to a source area. The general west- and northwest movement of sediment on this alluvial plain is reflected by the gradual reduction of grain size and quartz-content. This coal-bearing sequence was divided by early workers into the Lower Productive (Allegheny Group) and Upper Productive (Monongahela Group) which contain thicker, mineable coals. These were overlain respectively by the Lower Barren (Conemaugh Group) and the Upper Barren (Dunkard Group), which contain fewer, thinner, generally uneconomical coals (fig. 3). This subdivision reflects allogenic, basin-wide sedimentation factors that controlled the appearance of limestones, marine units, and average coal thickness; autogenic factors controlled local depositional aspects, including vertical and lateral distribution of individual lithosomes (Edmunds and others, 1979). In general, allogenic factors tended to dominate on the lower coastal (delta) plain in the west, whereas autogenic factors were stronger in the high-energy upper delta plain and alluvial plain in the east. In addition, the autogenic factors dominated sedimentation during the early Pennsylvanian and gave way to more allogenic factors during the late Pennsylvanian and early Permian as the low-energy lower delta plain environments became more widespread (for example, Skema and Lentz, 1994).

Post-unconformity peat deposition began in the western part of the basin with the covering by the Mercer strata of the remaining emergent part of the Morrowan erosion surface. In the Anthracite region, a few scattered, lenticular coals are present below the unconformities, in the lower and middle members of the Pottsville Formation. Most of the coals in this region, though, occur in the Sharp Mountain member and in the overlying Llewellyn Formation, which encompass all the preserved rocks above the Pottsville Formation (fig. 3).

Whatever tectonic activity that was occurring during the Late Carboniferous in the internides to the southeast or elsewhere along the orogen had

only minor effect on the central Appalachian basin. The presence of the Fire Clay and other tonsteins in the Atokan rocks of eastern Kentucky (Lyons and others, 1992; Rice and others, 1994) with a mean $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum of 311 Ma (Kunk and Rice, 1994) indicates that volcanic activity had commenced nearby, probably in the Carboniferous (Hercynian) magmatic arc (Sinha and Zietz, 1982) to the east near the Laurentian margin. The occurrence of possible tonsteins in Desmoinesian and Missourian (late Westphalian and early Stephanian) beds (Allegheny and Conemaugh Groups) in Pennsylvania (personal communication, V. W. Skema, 1995) suggests that this volcanism was persistent and widespread.

Yet, the Appalachian basin, aside from the coarse- to very coarse grained sediment input from the northeast, was relatively quiescent for the remainder of the Late Carboniferous, particularly in comparison to the vertical peripheral-bulge movements during the Early and early Late Carboniferous. The extremely low relief across the Appalachian basin allowed repeated, widespread marine incursions of the Midcontinent sea (Heckel, 1995). Influx of coarse detritus and deposition of fluvial sandstone sequences punctuated basin sedimentation a number of times, particularly in the northeast. However, during most of this time interval, peat swamps developed on the broad interfluves between through-flowing streams (Sholes, Edmunds, and Skema, 1979; Skema, Sholes, and Edmunds, 1982). Farther to the southwest, the basin accumulated a number of fluvial-to-marine sequences (Greb and Chestnut, 1996) in which peat swamps developed on abandoned delta-lobes behind barrier-beach sandstones (Englund, Windolph, and Thomas, 1986).

The shifting shallow marine and delta-plain environments that began during the late Atokan marine transgression in the western part of the basin persisted through the middle Desmoinesian under a fairly wet, tropical climate (Cecil and others, 1985; Cecil, 1990), during which the lower Allegheny Group sediments were deposited. A gradual change to a semi-arid climate during the Desmoinesian led to the appearance of recurrent lakes on the upper delta plain in which widespread fresh-water limestones were deposited. It was also during this time that the numerous thinner peats characteristic of the Conemaugh Group were formed.

The gradual shift from high-energy fluvial systems to low-energy environments of quiet embayments and lakes during the Virgilian is reflected by the thick, wide-spread coals (Pittsburgh, Waynesburg) of the Monongahela Group. The climate remained semi-arid, but occasional wet intervals led to the accumulation of these very thick peat deposits. The diminution of wet intervals during the early Permian resulted in fewer and thinner coals in the Dunkard Group.

The Dunkard Group contains the youngest Paleozoic rocks in the central Appalachian basin and is now preserved only in a fairly small region in West Virginia, southeastern Ohio, and southwestern Pennsylvania. Even within this small area marked lithic differences exist between the sequences in central West Virginia and those to the north, differences that reflect a divergence in the tectonism in the internides to the southeast. The fluvial-

lacustrine-deltaic paleo-environments in the north grade laterally to the south into sandier, more energetic upper-delta-plain environments (Rendina, ms; W. D. Martin, ms). The northwest paleocurrent directions present over much of the basin veer northward in the northern end of the basin. This suggests that during the early Permian, the major sediment source was the internides of the southern Appalachians (central Virginia and southward), and that the central Appalachian internides were providing a significantly smaller amount of sediment. This pattern suggests that Alleghany orogenesis in the southern Appalachians was earlier than in the central Appalachians.

Implications from the Carboniferous Appalachian basin.—The large volume of coarse-grained, quartzose sediment represented by the Pottsville Formation in the north-central Appalachian basin indicates renewed vigorous erosion in the highland area to the east. This, in conjunction with the Morrowan and Atokan unconformities, suggests that perhaps some docking was occurring at the end of the Mississippian or early in the Pennsylvanian. Specifically, this could have been the time of accretion of the Goochland, Savannah River, or Roanoke Rapids terranes in the southern Appalachian internides (Rankin, 1994). Certainly, the protracted igneous and metamorphic activity to the south (Sinha and Zietz, 1982; Secor, Snoke, and Dallmeyer, 1986) indicate that Alleghany tectonism had begun during the Late Carboniferous, at least in the southern Appalachian internides. The penetrative deformation and plutonism there during the Pennsylvanian (315-294 Ma, the second phase of Dallmeyer and others, 1986) would probably have provided a sediment source for the Appalachian basin, as seen in the Dunkard Group in central West Virginia. In contrast, local metamorphic overprinting in southern New England (indicated by U-Pb titanite dates of 290-287 Ma, Tucker and Robinson, 1990) would suggest that the Avalon terrane may not have docked with Laurentia (Laurussia) until the end of the Carboniferous or later.

It is not known where the southeast margin of the central Appalachian basin lay at any given time following the Taconic orogeny, except that it lay southeast of the present Blue Mountain front (and Green Pond syncline) from New York to West Virginia, and the Massanutten syncline in Virginia, which presently contain the southeasternmost exposures of Appalachian basin rocks. The basin margin, undoubtedly shifted in position through time in response to source area uplifts, volume of sediment input to the basin, and possible uplift and erosion of the basin margin itself. However, the coarseness of the various quartzose stratigraphic units of the Middle and Late Paleozoic suggests that the fall line was at those times no more than a few tens of kilometers from the present southeast margin (Pelletier, 1958; Yeakel, 1962; and Meckel, 1967).

Regardless of whether the Appalachian basin ever covered the Reading Prong or the Piedmont, the early crests of the Taconic highland probably consisted of Lower Paleozoic shelf, slope, and basin deposits of the Laurentian margin and Theia, and blocks of Grenville-age Reading Prong-like rocks, that had been tectonically stacked above the presently exposed Piedmont and Reading Prong rocks (Faill, 1997a). The earliest Appalachian basin deposits, then, were derived from the higher parts of the stack of thrust sheets,

parts that had never been significantly metamorphosed. This is reflected by the absence of post-Grenville ages in the detrital zircons from the earliest clasts of the Shawangunk Formation (Gray and Zeitler, 1997). The greenschist- to amphibolite-facies mineral assemblages, particularly in the Piedmont, produced during the Taconic regional metamorphism imply fairly deep burial. It wasn't until late in the Devonian that these higher-grade Taconic rocks became exposed, that large (1–2 mm) detrital muscovite flakes became a common component in Upper Devonian sandstones, and that identifiable metamorphic rock fragments appeared as clasts (as in the Spechty Kopf Formation at Jim Thorpe) (Epstein, Sevon, and Glaeser, 1974). These aspects indicate that considerable uplift (perhaps as much as 10 km or more) and erosion of the source area to the southeast had removed much of the higher parts of the Taconic thrust stack by then.

The Atokan erosion in northeastern Pennsylvania and by implication across much of New York State raises some interesting points. Data from fluid-inclusions, organic maturation, clay diagenesis, and stable isotopes indicate that Lower Devonian rocks in New York appear to have been buried by 4.5 to 6.0 km of overlying strata (Friedman, 1987; Sarwar and Friedman, 1995). Presumably this thick cover was not present at the end of the Atokan erosion. If the cover consisted solely of Upper Devonian and Mississippian rocks, this part of the stratigraphic section would have been considerably larger than the maximum thickness present in eastern Pennsylvania. And it would have required complete removal during the Atokan to allow sediment from New England to enter the Appalachian basin through New York. It is far more likely that the cover accumulated after the Atokan, during the late Pennsylvanian, Permian, and perhaps even earliest Triassic (as will be discussed in Faill, 1997b). That the accumulation was later than the Atokan is supported by apatite fission-track dates across New York that range from 236 to 155 Ma (Johnsson, 1986). This indicates that at least 3 km of cover was present until the Late Triassic to Middle Jurassic.

A large part of eastern Laurentia was covered from the Early Paleozoic by the Appalachian orogen and the Appalachian basin. These Laurentian cratonic rocks were thereby removed as a potential source of sediment. Indeed, throughout much of the Paleozoic, the voluminous westward flow of sediment from the southeast probably blocked any contribution from whatever part of the craton that was emergent to the northwest. This pattern may have changed in the Late Paleozoic, as indicated by the northern source for the Sharon and equivalent units in the western part of the basin. The large proportion of Grenville and Superior dates in the zircons in the Sharp Mountain member of the Pottsville Formation (Gray and Zeitler, 1997) provides clear evidence of this. And vitrinite reflectance data from western New York suggest that the post-Devonian cover actually thinned toward the east (Gerlach and Cercone, 1993; Sarwar and Friedman, 1995). This apparent emergence of the craton may have been a consequence of an Alleghany peripheral bulge.

Finally, I conclude, from the evidence that the Appalachian basin offers, that the Alleghany orogeny in the north-central Appalachians did not

commence until well into the Early Permian. The basin was the site of a regional alluvial plain and adjacent shallow sea for much of the Pennsylvanian and Early Permian, an environment in which paleoslopes remain very low. For example, the Missourian transgression of the estuarine Mill Creek (Ames) Limestone (Ashburner, 1886; Chow, 1951; Eggleston and Edmunds, 1991) as far eastward as the anthracite region attests to an extremely low paleoslope across the basin at this time. The great thickness and lateral persistence of the late Virgilian (late Stephanian) Pittsburgh and Waynesburg coals also reflects a stable period of very low sediment input and low slope within the Appalachian basin. The northern Dunkard rocks similarly indicate continued tectonic inactivity to the east. Had folding begun in the basin in the Late Pennsylvanian, relief-sensitive units such as estuarine and lacustrine limestones would have been seriously affected. Had deformation and uplift begun in the internides, the resulting sediment would have appeared in the northern Dunkard rocks, as surely as the southern Dunkard rocks reflect the earlier Alleghany tectonism in the southern Appalachians.

INTERIM SUMMARY

The Late Ordovician Taconic orogeny created the Appalachian orogen and the Appalachian basin on the eastern part of Laurentia. The Early Permian (for the north-central Appalachians) Alleghany orogeny brought the Theic Wilson cycle to a close and transformed much of the Appalachian orogen into what we see today. The intervening Silurian, Devonian, and Carboniferous history of the north-central Appalachian orogen is best recorded in the continental Appalachian basin, which received and mostly preserved the sediment that was shed from the southeastern internides and which reflects to some degree the tectonic activity that occurred there.

The gradual reduction in volume and grain-size of the sediment from the southeast highlands shrank the Early Silurian delta, allowing marine carbonate and paralic environments to encroach over the Appalachian basin from the west. This relative tectonic quiescence persisted to the end of the Early Devonian.

The introduction of siliciclastic debris, albeit fine-grained, signaled the beginning of another period of active tectonism. The Acadian orogeny, so active in New England, may have extended as far south as the north-central Appalachians, but no direct deformational or metamorphic evidence is presently exposed here. However, the increasingly large amount of detritus that built the Catskill delta across the basin attests to a lengthy period of uplift and erosion in the sources areas and greater and more rapid subsidence in the basin, during the Middle and particularly the Late Devonian.

Continued influx of coarse- to fine-grained siliciclastic material throughout the Carboniferous implies continued tectonism and resulting uplift in the internides. But now the basin itself was involved in vertical tectonism, most potently expressed by two regional unconformities during the Early Carboniferous. Early in the Late Carboniferous, another uplift, this time to the north of Pennsylvania, created a major unconformity, presumably across New York; thereafter, much of the coarse sediment to the basin entered through

this new "lowland." The latter part of the Late Carboniferous, and the earliest Permian, was relatively quiet for the north-central Appalachian basin, in which widespread organic deposits (the "coal measures") were able to accumulate in a very-low-relief lower-delta-plain environment. This was the "quiet" before the Alleghany orogenic "storm" that soon followed.

ACKNOWLEDGMENTS

I appreciate the numerous constructive criticisms, suggestions, and comments by Mary Beth Gray, Donald M. Hoskins, Peter T. Lyttle, Richard P. Nickelsen, William D. Sevon, C. Gil Wiswall, and especially by John Rodgers on an early version of this manuscript. The critical reviews and helpful comments on a revised version by John Rodgers, Donald U. Wise, William D. Sevon, Robert C. Smith, II, and an anonymous reviewer were also very much welcomed.

I thank James H. Dolimpio and John G. Kuchinski of the Pennsylvania Geological Survey for the excellent drafting of the figures and Caron E. O'Neil, also of the Pennsylvania Geological Survey, for editing the illustrations.

This work is part of an ongoing Pennsylvania Geological Survey project, the Tectonic Map of Pennsylvania. An early phase of this project was supported by the U.S. Geological Survey under Contract No. 14-08-0001-16342.

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