

BASIN-REBOUND ORIGIN FOR THE "TUSCARORA UNCONFORMITY" IN SOUTHWESTERN VIRGINIA AND ITS BEARING ON THE NATURE OF THE TACONIC OROGENY

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ABSTRACT. The Tuscarora Sandstone (Late Ordovician-Early Silurian) in southwestern Virginia can be divided into two sedimentologically distinct units: a regionally extensive "upper" Tuscarora Sandstone and a regionally restricted "lower" Tuscarora Sandstone. The regionally traceable "Tuscarora unconformity" occurs at the base of the "upper" Tuscarora Sandstone and splits the Martinsburg-Shawangunk clastic wedge into two parts. This unconformity corresponds to the earlier identified Cherokee and Taconic Discontinuities in the central Appalachians. Based on the nature of the lacuna, regional comparisons, and paleotectonic setting, we conclude that the "Tuscarora unconformity" probably did not develop as a consequence of the end-Ordovician glacio-eustatic event. Isostatic flexural rebound of the Taconic orogen and its adjacent foredeep, following cessation of thrusting, and erosional and tectonic thinning of the orogen, is favored, instead, as the causal mechanism for this regional unconformity. The "Tuscarora unconformity" may separate two distinct phases of thrusting and thrust-load induced foredeep subsidence in the development of the Taconic orogen and its foreland. The two phases of thrusting might tentatively be correlated with two separate phases of terrane accretion within the central Appalachians. The Ordovician-Silurian boundary in southwestern Virginia probably falls within the lacuna associated with the "Tuscarora unconformity."

INTRODUCTION

The Tuscarora Sandstone (Late Ordovician-Early Silurian) forms part of the Martinsburg-Shawangunk clastic wedge (Thomas, 1977), which corresponds to the fill of a peripheral foreland basin/foredeep. Development of the foredeep and evolution of the clastic wedge are related to the Taconic orogeny in the central Appalachians. The Tuscarora Sandstone conformably overlies the red beds of the Juniata Formation and unconformably overlies the Martinsburg Formation or the Oswego Sandstone in the southeastern parts of the Valley and Ridge (fig. 1). This unconformable contact between the Martinsburg Formation and Tuscarora Sandstone is a clear disconformity (Juniata Formation and Oswego Sandstone missing), which can be traced throughout the central Appalachians. The disconformity changes into an angular unconformity in easternmost Pennsylvania (Pavlides, Boucot, and Skidmore, 1968; Rodgers, 1971). This unconformity separates Sloss's (1988) Tippecanoe I

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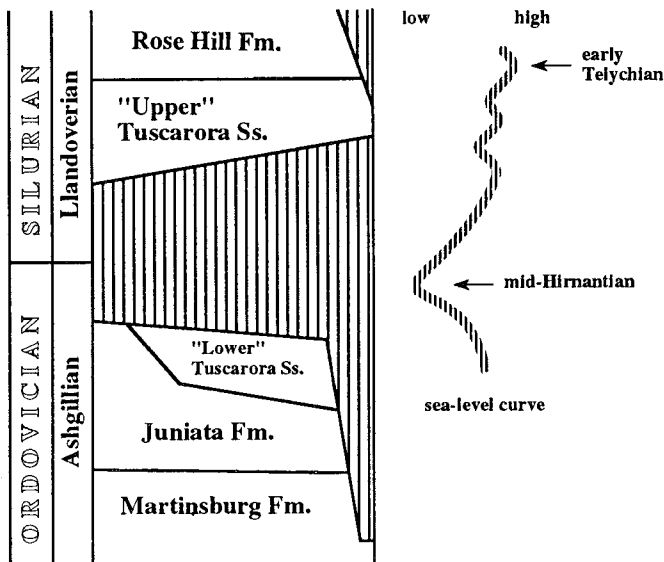


Fig. 1. Interpretive correlation chart for Late Ordovician/Early Silurian stratigraphic units in southwestern Virginia (modified from Dennison and others, 1992). Vertical axis represents time; sealevel curve is based on Johnson and others (1991).

from Tippecanoe II subsequence and has been referred to as the Taconic Discontinuity (Wheeler, 1963) or the Cherokee Discontinuity (Dennison and Head, 1975). Dennison (1976) emphasized the role of the end-Ordovician glacio-eustatic event in the origin of the unconformity with a component of tectonic uplift in northern Virginia and Pennsylvania (Dennison and Head, 1975; Dennison, 1970, 1976).

The Tuscarora Sandstone and its lithostratigraphic equivalents are exposed in several Alleghanian thrust sheets within the Valley and Ridge. Outcrop exposures of good to excellent quality in southwestern Virginia (fig. 2), predominantly along road cuts, provide access to the stratigraphic units of the Martinsburg-Shawangunk clastic wedge and their contacts for a detailed sedimentologic and stratigraphic study (Dorsch, ms). Our goal with this short contribution is to show, emphasizing stratigraphic data, that the unconformity so prominently displayed within the southeastern parts of the Valley and Ridge province is actually of regional significance, and that the observations are more consistent with a tectonic interpretation, as opposed to a glacio-eustatic interpretation, for the origin of this regional unconformity. The interpretation of a tectonic mechanism (isostatic basin rebound) for the origin of the unconformity has significant implications for the nature and timing of the Taconic orogeny in the central Appalachians. This regional tectonic unconformity was referred to as the "Tuscarora unconformity" (Dorsch,

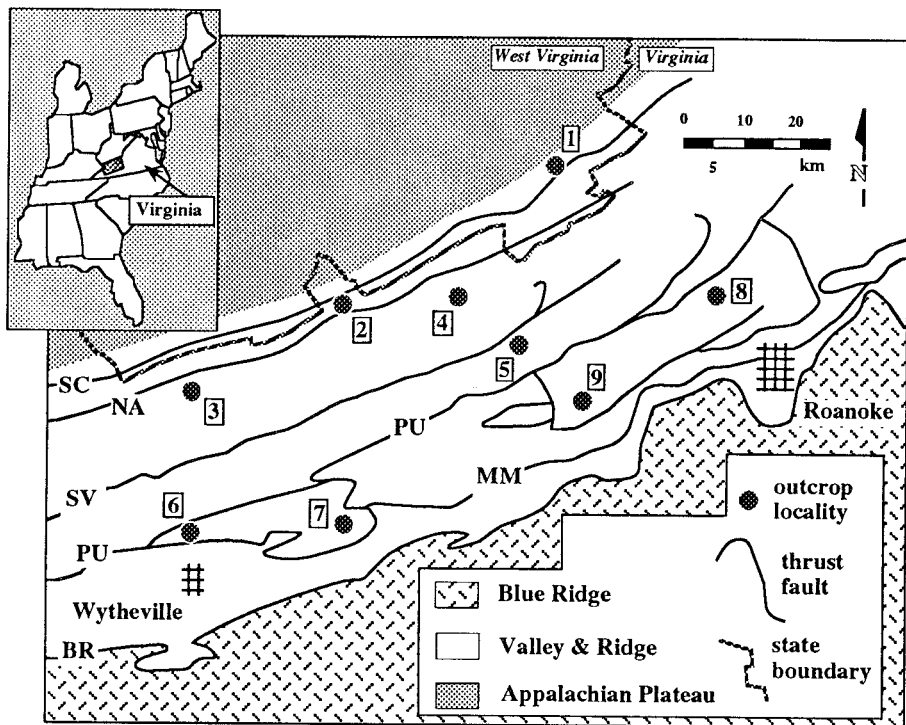


Fig. 2. Location map of the study area in southwestern Virginia. Outcrop localities are: 1—Gap Mills; 2—Narrows; 3—South Gap; 4—Cascades; 5—Gap Mountain; 6—Cove Mountain; 7—Draper Mountain; 8—Catawba Mountain; 9—Fagg. Major thrust faults include: SC—Saint Clair; NA—Narrows; SV—Saltville; PU—Pulaski; MM—Max Meadows; BR—Blue Ridge.

Driese, and Bambach, 1990), following its stratigraphic position within the Tuscarora Sandstone throughout most of the study area. The "Tuscarora unconformity" is developed within the Taconic foredeep and corresponds to the Cherokee Discontinuity/Taconic Discontinuity.

In a perceptive abstract, Chapple (1973) tried to place the sequence of events associated with the Taconic orogeny, as outlined by Rodgers (1971), within the framework of plate tectonics. Chapple was the first to point out that the "classical" Taconic unconformity of New York and New Jersey (developed during the "Hudson Valley phase" of Rodgers, 1971) is related to slow uplift and erosion following the cessation of subduction of Laurentian continental crust.

"TUSCARORA UNCONFORMITY": REGIONAL EXTENT

In the southeastern part of the Valley and Ridge of southwestern Virginia (fig. 2, outcrops at Catawba Mountain and Fagg), the Tuscarora

Sandstone rests at different stratigraphic levels of the Martinsburg Formation, marking the "Tuscarora unconformity." The Tuscarora Sandstone commences with a massive bed of conglomeratic sandstone/sandy conglomerate (except at the Catawba Mountain locality, where about 3 m of medium-grained sandstone is intercalated between the Martinsburg Formation and the conglomerate) and is succeeded upward by thick-bedded, white (pebbly) quartzarenite (Bambach, 1987). At the South Gap and Narrows localities (fig. 2), thinner bedded, fine-grained quartzarenite with thin mudstone partings occurs in the upper part of this unit, which is informally known as the "upper" Tuscarora Sandstone (Bambach, 1987; Dorsch, Driese, and Bambach, 1990).

The "upper" Tuscarora Sandstone constitutes a fining- and thinning-upward succession of predominantly trough cross-stratified sandstone. The thinner bedded sandstone beds in the upper intervals at the South Gap and Narrows localities (fig. 2) display hummocky cross-stratification (Dorsch, ms). The trace-fossil suite is dominated by *Skolithos*, *Monocraterion*, and *Arthropycus* but also includes some examples of *Arenicolites*, *Planolites*, *Rusophycus*, and *Phycodes*. Body fossils are absent, except for occurrences of acritarchs in some of the interbedded mudstone and siltstone beds (G. Wood, personal communication, 1992). The "upper" Tuscarora Sandstone is interpreted as marginal-marine, storm-dominated deposits of the upper to lower shoreface. Interbedded fairweather deposits were eroded away by successive storm events and, therefore, are rare (Dorsch, ms). The stacking of facies within the upward fining and thinning "upper" Tuscarora Sandstone is interpreted to reflect a complete transgressive stratigraphic succession (retrogradational parasequence; Dorsch, ms).

The contact between the "upper" Tuscarora Sandstone and the overlying Rose Hill Formation is distinct and conformable. Mudstone interspersed with thin sandstone beds of the Rose Hill Formation, interpreted as shallow-marine, offshore, storm-dominated deposits, abruptly overlies sandstone beds of different facies of the "upper" Tuscarora Sandstone. This prominent contact between the two stratigraphic units is interpreted as a marine flooding surface (Dorsch, ms).

The "upper" Tuscarora Sandstone with its distinctive basal conglomeratic sandstone bed can easily be traced throughout the study area (Bambach, 1987) and generally increases in thickness to the northwest (fig. 3). In the central and northwestern outcrop belts (fig. 2), the "upper" Tuscarora Sandstone overlies the "lower" Tuscarora Sandstone with a sharp, erosional contact (figs. 3 and 4), and at the most distal locality (Gap Mills) the "upper" Tuscarora Sandstone overlies the Juniata Formation.

The "lower" Tuscarora Sandstone is lithologically distinctly different from the "upper" Tuscarora Sandstone. It is characterized by yellowish-weathering, thin- to medium-bedded quartzarenite with numerous mudstone interbeds (Bambach, 1987). The sandstone beds are characterized

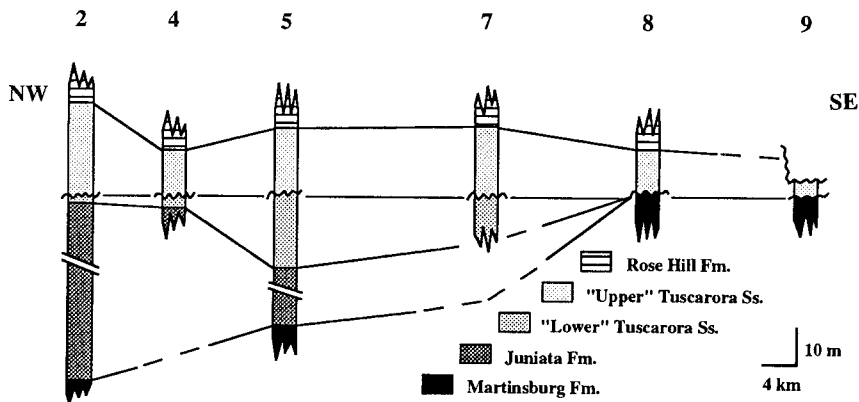


Fig. 3. Lithostratigraphic cross section from distal outcrops in the northwest to proximal outcrops in the southeast. Wavy line indicates "Tuscarora unconformity"; top of Fagg section is truncated by a Devonian unconformity. Numbers above the stratigraphic columns refer to outcrop localities depicted in figure 2. At the Narrows (2) and Gap Mountain (5) localities, 60 m of Juniata Formation are not depicted in the stratigraphic columns, as indicated by the gap in the respective stratigraphic columns.

by trough cross-stratification (one example of hummocky cross-stratification occurs at the Cove Mountain locality, fig. 2) and abundant *Rusophycus*, *Cruziana*, *Monocraterion*, *Skolithos*, *Planolites*, and *Arthropycus* trace fossils (Dorsch, ms). The "lower" Tuscarora Sandstone is interpreted as storm-dominated, shallow-marine deposits. The sandstone beds represent tempestites, whereas the interbedded mudstone beds represent fairweather deposits (Dorsch, ms). The "lower" Tuscarora Sandstone caps a coarsening-upward succession, which started in the Martinsburg Formation.

The "lower" Tuscarora Sandstone has a clear intertonguing stratigraphic relationship with the Juniata Formation. Northwest-oriented paleocurrent trends and an overall coarsening of the "lower" Tuscarora Sandstone toward the southeast indicate sediment derivation from a southeastern source area (Hayes, ms; Whisonant, 1977; Dorsch, ms). The "lower" Tuscarora Sandstone is interpreted as a northwestward prograding quartz-rich sand body, which succeeded deposition of finer grained sediment of the Juniata Formation and is interpreted to represent a facies equivalent of the upper part of the Juniata Formation (Dicchio, 1985; Dorsch, ms). The observed thickness of the "lower" Tuscarora Sandstone (fig. 3) is controlled by original depositional geometry (probably a wedge-shaped lithosome, tapering to the northwest, away from the source area) and the magnitude of erosional removal beneath the "upper" Tuscarora Sandstone.

The "Tuscarora unconformity" is developed at the contact between the regionally extensive "upper" Tuscarora Sandstone and the various underlying units (Martinsburg Formation, "lower" Tuscarora Sandstone,



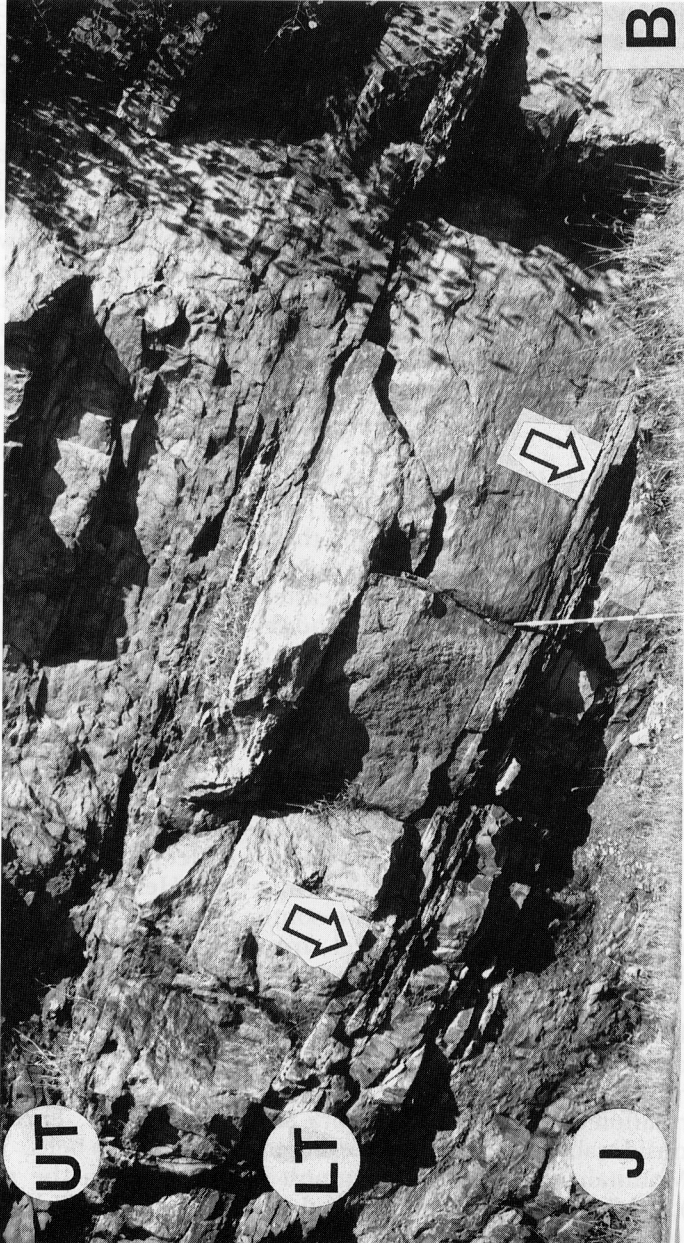


Fig. 4. The "Tuscarora unconformity" in outcrop. Intersection trace of unconformable surface with outcrop face indicated by arrows; stratigraphic units are: J—Junata Formation, LT—"lower" Tuscarora Sandstone, UT—"upper" Tuscarora Sandstone; staff is 1.20 m long. (A) Outcrop locality at South Gap; (B) Outcrop locality at Narrows.

Juniata Formation; figs. 3 and 4). Reconnaissance observations and published stratigraphic data (Diecchio, 1985) indicate that the "Tuscarora unconformity" within the Taconic foreland molasse is of regional extent and can be traced throughout the Valley and Ridge from Virginia to Pennsylvania (Bambach, 1987; Dennison and others, 1992). Folk (1960), in fact, subdivided the Tuscarora Sandstone of the eastern panhandle of West Virginia similarly. The lacuna associated with the "Tuscarora unconformity" is largest in the southeastern outcrop belt, where a minimum of 150 m of section is missing (fig. 3, Fagg locality), based on correlation of key beds within the Martinsburg Formation (Bambach, 1987). The lacuna decreases in magnitude to the northwest, concomitant with an increase in the combined thickness of Juniata Formation and "lower" Tuscarora Sandstone. The temporal break associated with the "Tuscarora unconformity" is difficult to assess, because of the absence of body fossils. Dennison and others (1992), nevertheless, estimate a maximum of 11 Ma not represented by strata in the southeastern outcrop belt.

"TUSCARORA UNCONFORMITY": A CASE AGAINST EUSTASY

The Late Ordovician glacio-eustatic sealevel drop and rise were emphasized as the dominant factor in the origin of the "Tuscarora unconformity" (Bambach, 1987) and of the earlier described, correlative Cherokee Discontinuity within the southeastern Valley and Ridge (Dennison, 1976). Several arguments indicate, however, that a tectonic mechanism might be a better and more viable explanation for the nature of the "Tuscarora unconformity" within the Taconic foredeep rather than a purely glacio-eustatic mechanism.

The magnitude of the lacuna associated with the "Tuscarora unconformity" is given as a minimum of 150 m (Fagg locality, fig. 3; Bambach, 1987). An estimated sealevel drop of only about 70 m associated with the end-Ordovician glacio-eustatic sealevel drop (Brenchley, 1989) can explain the removal of 150 m of foredeep fill, because of isostatic amplification (see for example, Angevine, Heller, and Paola, 1990). Assuming that the lacuna in the southeastern outcrop belt was created exclusively by eustatic sealevel drop, foredeep deposits of a similar thickness should have been removed, and a lacuna of comparable magnitude should have been developed in outcrops farther northwest (for example at the Gap Mountain locality). At the Gap Mountain locality, the unconformity should rest within the Martinsburg Formation, yet the Martinsburg Formation is complete and is overlain by a thick section of Juniata Formation and "lower" Tuscarora Sandstone (fig. 3). This indicates that considerably less section is missing in these outcrop belts.

Cove Mountain, the southwesternmost outcrop within the study area (fig. 2), exhibits the thickest preserved section of "lower" Tuscarora Sandstone (46.70 m; Dorsch, ms). The "lower" Tuscarora Sandstone is bound at the top by the Devonian Wallbridge Discontinuity, which removed, among other stratigraphic units, the "upper" Tuscarora Sand-

stone and the "Tuscarora unconformity" (Dennison and others, 1992). The thickness of the preserved "lower" Tuscarora Sandstone at Cove Mountain can be interpreted to indicate a small magnitude for the lacuna associated with the "Tuscarora unconformity." To the southwest of the Cove Mountain locality, the "lower" and "upper" Tuscarora Sandstone, as defined farther to the northeast, and the "Tuscarora unconformity" are absent. The stratigraphic interval above the Upper Ordovician red-bed succession is occupied, instead, by the Clinch Sandstone (Dorsch, ms).

These observations show a decrease toward the southwest in the magnitude of the lacuna associated with the "Tuscarora unconformity" and a drastic change in the overall stratigraphic character of the deposits above the Juniata Formation. Cove Mountain, furthermore, is the outcrop locality of the study area positioned farthest from the site of maximum crustal loading during the Taconic orogeny. This site is believed to have been in present-day northern Virginia, Maryland, and southern Pennsylvania (Beaumont, Quinlan, and Hamilton, 1988).

In eastern Tennessee, the end-Ordovician glacio-eustatic sealevel drop and rise are well documented (Gogola, ms; Driese and others, 1991). The exposure surface created during sealevel drop is indicated by the development of vertic paleosols (Driese and Foreman, 1992), whereas the eustatic sealevel rise, closely succeeding in time (Brenchley, 1989), is expressed by the "basal transgressive sandstone" (Gogola, ms). The lacuna associated with these sealevel changes is of considerably smaller magnitude than the lacuna observed in southwestern Virginia (Dorsch and others, 1991). Time of exposure and extent of erosion were far less in eastern Tennessee than in southwestern Virginia (Gogola, ms). The "upper" Tuscarora Sandstone, onlapping onto the exposure surface in southwestern Virginia (fig. 3), is unlike the "basal transgressive sandstone," which overlies the paleosols in eastern Tennessee. The "upper" Tuscarora Sandstone represents a complete transgressive succession (retrogradational parasequence) from basal nearshore deposits to lower shoreface deposits at the top (Dorsch, ms). The "basal transgressive sandstone" in eastern Tennessee, in contrast, represents a thin (≤ 3 m) condensed amalgam of nearshore to shallow-marine deposits formed during erosional shoreface retreat (Gogola, ms; Driese and others, 1991). The stratigraphic relationships in eastern Tennessee indicate a relative sealevel rise with pronounced erosion and low sediment supply (Cant, 1991). The situation in southwestern Virginia, in marked contrast, indicates a relative sealevel rise with creation of the necessary accommodation space for preservation of the complete transgressive facies succession. The preservation of a complete transgressive shallow-marine facies succession is considered to involve pronounced and continuous tectonic subsidence for creation of the necessary accommodation space and ample sediment supply to the depositional site (Hobday and Tankard, 1978; Bourgeois, 1980; Hein, 1987; Cant, 1991). This indicates that the

depositional realm of the Tuscarora Sandstone in southwestern Virginia was tectonically active.

Tectonic activity during deposition of the Tuscarora Sandstone and during development of the "Tuscarora unconformity" is not surprising, considering the paleotectonic setting. The Tuscarora Sandstone forms part of the Taconic molasse and the "Tuscarora unconformity" developed within this molasse, which is related to the Taconic orogeny in the central Appalachians. The end-Ordovician glacio-eustatic sealevel event left a detectable trace within the stratigraphic succession of eastern Tennessee. Tennessee was affected by the already terminated mid-Ordovician Blountian orogeny (Drake and others, 1989; Blountian phase of the Taconic orogeny: Rodgers, 1953, 1971) and was probably not affected by the Taconian crustal-loading episode in the central Appalachians during the end-Ordovician and Early Silurian.

The nature of the lacuna associated with the "Tuscarora unconformity" in southwestern Virginia and the marked differences to the stratigraphic situation in Tennessee can be explained only partly by a simple eustatic sealevel drop and rise. The stratigraphic and sedimentologic relationships in southwestern Virginia, especially in comparison to the observations in eastern Tennessee, seem to be more consistent with a tectonic mechanism for the origin of the "Tuscarora unconformity."

"TUSCARORA UNCONFORMITY": ISOSTATIC REBOUND AS CAUSATIVE MECHANISM

The Taconic peripheral foreland basin/foredeep may have originated through the downbending of continental lithosphere in front of advancing thrust sheets of the growing Taconic orogen (Chapple, 1973; Jacobi, 1981; Quinlan and Beaumont, 1984). Peripheral-bulge retreat toward the orogen and isostatic basin-rebound are two possible tectonic mechanisms for the development of unconformities within foreland-basin fills (Cant and Stockmal, 1989). Both mechanisms operate as thrusting and thrust-loading come to a stillstand (Quinlan and Beaumont, 1984; Cant and Stockmal, 1989). (1) Following the cessation of thrusting, the peripheral bulge migrates toward the orogen (for a temperature-dependent viscoelastic lithosphere model; Quinlan and Beaumont, 1984) during viscoelastic relaxation of the bending stresses. This leads to uplift and erosion associated with the migrating peripheral bulge, concomitant with deepening of the foredeep near the orogenic load (Quinlan and Beaumont, 1984). The resulting foredeep unconformity shows a maximum lacuna in the distal-central foredeep, with a conformity (no lacuna) developed within the proximal foredeep (Cant and Stockmal, 1989). (2) Erosional and/or tectonic thinning of the orogen, following cessation of thrusting, leads to a reduction of the lithospheric load and to flexural isostatic rebound of both the orogen and the adjacent foredeep as an isostatic response to this unloading (Jamieson and Beaumont, 1988; Quinlan and Beaumont, 1984). The resulting unconformity covers the whole foredeep with the associated lacuna

steadily increasing in magnitude toward the orogen, the site of maximum isostatic uplift (Cant and Stockmal, 1989).

As outlined above, the "Tuscarora unconformity" in southwestern Virginia covers the whole exposed foredeep, with its lacuna increasing in magnitude toward the orogen to the east/southeast. Evidence for crustal thinning of the Taconic orogen is provided by the metasediments of the Quantico and Arvonian Formations (Late Ordovician-Early Silurian ?) of the Virginia Piedmont (Brown, 1970; Seiders and others, 1975; Pavlides and others, 1980; Glover, 1989). These formations are contained in successor basins formed by extensional tectonism (active rifting, Glover, 1989; see below for an alternative hypothesis), which were rapidly inundated by marine waters.

The nature of the lacuna within the foreland molasse, together with the evidence for crustal thinning within the internides of the Taconic orogen, points toward isostatic basin-rebound as the most likely causative mechanism for the "Tuscarora unconformity" in southwestern Virginia (and for the remainder of Taconic foredeep). If the affected lithosphere behaved according to the temperature-dependent viscoelastic model (Quinlan and Beaumont, 1984), a combination of earlier peripheral-bulge retreat and succeeding flexural isostatic rebound can be envisioned. But even in this case, the component of flexural rebound had to be the dominant causative mechanism in order to explain the geologic situation encountered in southwestern Virginia. The thick section of "lower" Tuscarora Sandstone preserved at the Cove Mountain locality (fig. 2), mentioned above, might indicate less flexural isostatic rebound. This might reflect the distance of this locality from the locus of maximum crustal loading during the Taconic orogeny situated in present-day northern Virginia, Maryland, and southern Pennsylvania (Beaumont, Quinlan, and Hamilton, 1988), which also was the probable locus of maximum flexural isostatic rebound.

Flexural isostatic rebound of the foredeep during a phase of tectonic quiescence established a depositional plane sloping away from the orogen toward the west-northwest. The creation of necessary accommodation space for the upper part of the Martinsburg-Shawangunk clastic wedge can be explained by a renewed phase of thrusting within the orogen and thrust-load induced subsidence within the adjacent foredeep. Renewed basin subsidence, furthermore, provided the conditions for the development and preservation of the complete transgressive facies succession of the "upper" Tuscarora Sandstone. The end-Ordovician glacio-eustatic sealevel event almost certainly left its record within the sediments ("lower" Tuscarora Sandstone) of the Taconic foredeep. Sedimentological evidence, however, was removed by erosion during isostatic basin-rebound.

Based on sedimentological studies in Ontario, Middleton, Rutka, and Salas (1987) concluded that the deposition of the Whirlpool Sandstone (Early Silurian) was not affected primarily by the end-Ordovician sealevel drop and rise. Basin rebound can conceivably include the

mechanism for the establishment of the postulated northwest sloping depositional plane for the fluvial lower Whirlpool Sandstone. The succeeding transgression and concomitant deposition of the marine upper Whirlpool Sandstone, then, could have been accomplished during the second phase of thrust loading, causing a reorientation of the depositional plane toward the south/southeast (Middleton, Rutka, and Salas, 1987; Quinlan and Beaumont, 1984).

The lacuna associated with the "Tuscarora unconformity" is expected to display its largest magnitude within the exposed most proximal deposits of the Taconic foredeep in eastern Pennsylvania and New Jersey, if the mechanism of flexural isostatic rebound is indeed the causative mechanism for the origin of this unconformity. The more proximal foredeep deposits, furthermore, can possibly provide the basis for a quantitative evaluation of foredeep sedimentation, the role of tectonism, and the influence of eustasy. An evaluation of the stratigraphic situation in Pennsylvania, however, is beyond the scope of this study.

"TUSCARORA UNCONFORMITY": IMPLICATIONS FOR THE DEVELOPMENT OF
TACONIC OROGEN AND FOREDEEP

The interpretation of flexural isostatic rebound of the Taconic foredeep as the causative mechanism for the development of the "Tuscarora unconformity" has significant implications for the evolution of the Taconic orogen and its associated foredeep (fig. 5). Correlation of phases of thrusting and load-induced subsidence to phases of terrane accretion is attempted, similar to the analysis by Cant and Stockmal (1989) for the Alberta foredeep. This correlation is based on present outlines of Appalachian tectonics (that is, Drake and others, 1989; Horton, Drake, and Rankin, 1989; Hatcher, 1989). We emphasize, however, that different opinions exist concerning the exact nature of terranes in the central Appalachians and their timing of accretion (Drake and others, 1989; Horton, Drake, and Rankin, 1989; Glover, 1989). Assignment of specific terranes to phases of thrusting and foredeep subsidence is therefore tentative, awaiting more detailed investigations into the tectonic history of the central Appalachian internides.

The pre-foreland flysch stage in the development of the Taconic foredeep (fig. 5A) is characterized by hemipelagic sedimentation within a deep-marine foredeep (basal Martinsburg Formation; McBride, 1962; Shanmugam and Lash, 1982; Drake and others, 1989). Rapid subsidence of the Laurentian continental margin was accomplished by downbending of continental and transitional crust in front of the growing Taconic orogen to the southeast (present coordinates). The foredeep was bounded toward the craton by a peripheral bulge (Jacobi, 1981). The orogen remained below sealevel and displayed pronounced lateral translation (subduction of transitional and thinned continental crust: A-subduction *sensu* Bally, 1989).

During continued convergence, the orogen grew partially above sealevel, due to its climbing up the continental-margin ramp and to the

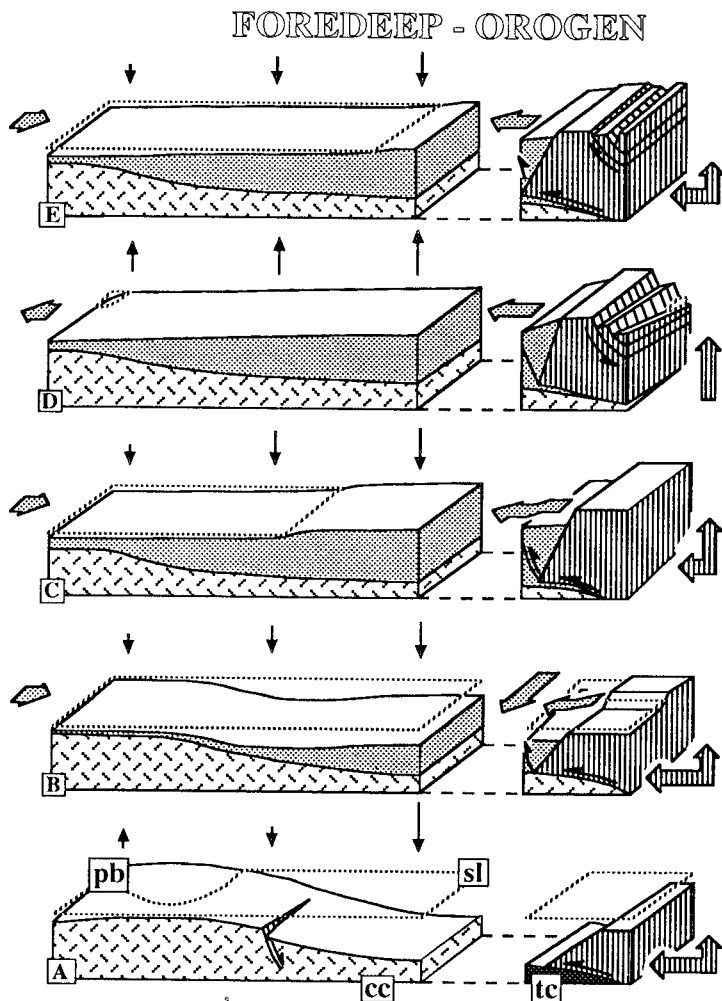


Fig. 5. Schematic summary of sequential development of the orogen-foredeep couplet during the Taconic orogeny in the central Appalachians, integrating the proposed phase of isostatic basin rebound. The model incorporates ideas of Ricci Lucchi and Ori (1984) and Ricci Lucchi (1986, 1990); compare also to Cant and Stockmal (1989). Stages include: A—pre-foreland flysch (late Middle Caradocian): basal Martinsburg Formation; B—foreland flysch (Late Caradocian-Early Ashgillian): Martinsburg Formation and Reedsville Shale; C—foreland molasse I (Ashgillian-earliest Llandoveryan): uppermost Martinsburg Formation, Oswego Sandstone, Juniata Formation, "lower" Tuscarora Sandstone; D—basin rebound (?latest Ashgillian-earliest Llandoveryan); E—start of foreland molasse II (Llandoveryan): "upper" Tuscarora Sandstone. Horizontally ruled arrows indicate relative magnitude of lateral translation of the orogen versus topographic uplift; stippled arrows indicate dominant dispersal system and sediment derivation; thin arrows above the block diagrams indicate relative magnitude of foreland subsidence and uplift. Abbreviations: cc—continental crust; tc—transitional crust; sl—sea level; pb—peripheral bulge. Foredeep and clastic wedge/foredeep fill (stippled) is on the left side of each block diagram, orogen is on the right side. See text for details.

incorporation of continental-slope and -rise deposits into the orogen. The subsiding deep-marine foredeep received sediment-gravity-flow deposits ("turbiditic" Martinsburg Formation; McBride, 1962; Lash, 1988), while distal and lateral shallow-marine areas were dominated by storm deposits ("tempestitic" Martinsburg Formation and Reedsville Shale; Kreisa, 1981). This foreland-flysch stage (fig. 5B) was characterized by a prominent longitudinal dispersal system (McBride, 1962; Lash, 1988).

The transition to the foreland-molasse stage is indicated by the change to a transverse dispersal system (fig. 5C). The orogen was raised appreciably above sealevel following the subduction of thicker continental crust, internal deformation of the orogen, and incorporation of proximal foredeep deposits into the orogen. Sedimentation rate outpaced subsidence rate leading to filling of the foredeep with orogen-derived clastic sediment (uppermost Martinsburg Formation, Oswego Sandstone, Juniata Formation, "lower" Tuscarora Sandstone; fig. 5C).

Thick continental crust choked the A-subduction zone and terminated thrusting and thrust-load induced subsidence. Erosion and extensional tectonism thinned the orogen and initiated flexural isostatic rebound of the orogen and the adjacent foredeep, resulting in an erosional surface covering the foredeep and sloping away from the orogen (fig. 5D). This stage of isostatic rebound, following cessation of thrusting, can be interpreted to mark the completed accretion of a terrane. In the central Appalachians, the Chopawamsic island arc and associated accretionary complex to the northwest, together with lateral correlatives, constitutes the most likely candidate for this phase of terrane accretion (Williams and Hatcher, 1983; Wehr and Glover, 1985; Drake and others, 1989; Horton, Drake, and Rankin, 1989). It was speculated that the Quantico and Arvonias successor basins of the Virginia Piedmont were created by extensional collapse of the Taconic orogen (Dorsch, 1992). Extensional orogenic collapse occurred during rearrangement of the plate tectonic regime and establishment of a new subduction zone, following (and during late stages of) accretion of the Chopawamsic island arc. Rapid gravitational collapse of the Taconic orogen is believed to have been triggered by now dominating internal body forces after termination/reduction of external compressive forces in the wake of cessation/slowing of plate convergence.

Resumed sedimentation within the foredeep can be linked to a renewed phase of thrusting within the orogen and concomitant subsidence of the foreland area (fig. 5E). During this stage, the erosional surface, established during basin rebound, was converted back to a southeast-sloping depositional plane. The retrogradational parasequence of the "upper" Tuscarora Sandstone overlapped earlier onto the erosion surface during onset of this phase of reorientation. Continued subsidence provided the accommodation space for the remainder of the Martinsburg-Shawangunk clastic wedge. This second phase of thrusting and load-induced foredeep subsidence can be related to collision and accretion of a second terrane, outboard of the already accreted

Chopawamsic island arc. This outboard terrane, probably the Goochland microcontinent and its correlatives, reactivated earlier thrusts upon collision and pushed the earlier accreted island arc and accretionary complex farther toward the craton.

Multiple and successive accretion of terranes during the Taconic orogeny is not surprising considering that the most likely modern analogue for the Ordovician-Silurian Iapetus ocean is the southwest Pacific, with its myriad of plate tectonic elements. The New Guinea orogen, in particular, might constitute an analogue for the evolution of the Ordovician-Silurian Taconic orogen. Multiple and successive accretion of terranes are believed to be responsible for the development of the New Guinea orogen and its adjacent foredeep (Pigram and Davies, 1987). The notion of multiple phases of terrane accretion during the Taconic orogeny, as deduced from the foredeep fill of the central Appalachians, corroborates the findings of Tucker and Robinson (1990) and Tremblay (1992) obtained within the internides of the northern Appalachians.

CONCLUSIONS

1. Based on sedimentologic characteristics, the Tuscarora Sandstone can be subdivided into two distinct units: a regionally restricted "lower" Tuscarora Sandstone and a regionally extensive and ubiquitous "upper" Tuscarora Sandstone. The "Tuscarora unconformity" is developed at the base of the "upper" Tuscarora Sandstone.

2. The "Tuscarora unconformity" within the Taconic foreland molasse is of regional significance and splits the Martinsburg-Shawangunk clastic wedge into two parts. This unconformity correlates with the Taconic Discontinuity (Wheeler, 1963) and the Cherokee Discontinuity (Dennison and Head, 1975).

3. Isostatic basin-rebound is favored over glacio-eustasy as the causative mechanism for the "Tuscarora unconformity." Following completed terrane accretion (Chopawamsic island arc and accretionary complex) and cessation of thrusting, erosional and tectonic unloading of the orogen caused isostatic uplift of both the orogen and the adjacent foredeep. This led to development of a regionally extensive erosional surface within the foredeep. Vestiges of tectonic thinning of the orogen might be preserved in the extensional successor basins (Arvonian and Quantico basins) within the Virginia Piedmont. Effects of the end-Ordovician glacio-eustatic sealevel changes were cut out by erosion during the epeirogenic uplift within the central Appalachians.

4. Creation of accommodation space for the upper part of the Martinsburg-Shawangunk clastic wedge and preservation of the complete transgressive facies succession (retrogradational parasequence) of the "upper" Tuscarora Sandstone can be linked to another phase of load-induced subsidence within the foreland area. This renewed phase of tectonic deepening of the foredeep might be related to accretion of a

second terrane (Goochland microcontinent ?), outboard of the earlier accreted terrane, and to associated thrusting.

5. The "Tuscarora unconformity" developed within the Taconic foreland molasse, closely following and contemporaneous with the formation of successor basins by extensional collapse (?) within the internides of the Taconic orogen. The unconformity separates two distinct phases of terrane accretion, thrusting, and load-induced foredeep subsidence during the Taconic orogeny. The second phase of Taconic load-induced subsidence occurred in the Early Silurian.

6. The preserved "lower" Tuscarora Sandstone was deposited before the end-Ordovician glacio-eustatic event and the start of basin rebound, thus placing the onset of Tuscarora sedimentation into the Late Ordovician. The Ordovician-Silurian boundary probably falls within the lacuna associated with the "Tuscarora unconformity." The boundary might be most closely approximated within the distal (that is, basinal) outcrops, where the lacuna is of smallest magnitude.

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REFERENCES

- Angevine, Ch. L., Heller, P. L., and Paola, C., 1990, Quantitative sedimentary basin modeling: American Association of Petroleum Geologists, Continuing Education Course Notes 32, 132 p.
- Bally, A. W., 1989, Phanerozoic basins of North America, *in* Bally, A. W., and Palmer, A. R., editors, *The Geology of North America—An Overview*: Boulder, Colorado, Geological Society of America, *The Geology of North America*, v. A, p. 379–446.
- Bambach, R. K., 1987, The Ordovician-Silurian unconformity in western Virginia and adjacent West Virginia: *Appalachian Basin Industrial Associates*, v. 13, p. 2–14.
- Baumont, C., Quinlan, G., and Hamilton, J., 1988, Orogeny and stratigraphy: Numerical models of the Paleozoic in the eastern interior of North America: *Tectonics*, v. 7, p. 389–416.
- Bourgeois, J., 1980, A transgressive shelf sequence exhibiting hummocky stratification: The Cape Sebastian Sandstone (Upper Cretaceous) southwestern Oregon: *Journal of Sedimentary Petrology*, v. 50, p. 681–702.
- Brenchley, P. J., 1989, The Late Ordovician extinction, *in* Donovan, S. K., editor, *Mass Extinctions—Processes and Evidence*: New York, Columbia University Press, p. 104–132.

- Brown, W. R., 1970, Investigations of the sedimentary record in the Piedmont and Blue Ridge of Virginia, in Fischer, G. W., Pettijohn, F. J., Reed, J. C., and Weaver, K. N., editors, *Studies of Appalachian geology: Central and southern*: New York, Interscience Publishers, p. 335-349.
- Cant, D. J., 1991, Geometric modelling of facies migration: Theoretical development of facies successions and local unconformities: *Basin Research*, v. 3, p. 51-62.
- Cant, D. J., and Stockmal, G. S., 1989, The Alberta foreland basin: Relationship between stratigraphy and Cordilleran terrane-accretion events: *Canadian Journal of Earth Sciences*, v. 26, p. 1964-1975.
- Chapple, W. M., 1973, Taconic orogeny: Abortive subduction of the North American continental plate? [abstract]: *Geological Society of America Abstracts with Programs*, v. 5, p. 573.
- Dennison, J. M., 1970, Silurian stratigraphy and sedimentary tectonics of southern West Virginia and adjacent Virginia: *Appalachian Geological Society, Field Conference Guidebook: Charleston, West Virginia, Appalachian Geological Society*, p. 2-33.
- , 1976, Appalachian Queenston delta related to eustatic sea-level drop accompanying Late Ordovician glaciation centered in Africa, in Bassett, M. G., editor, *The Ordovician System*: Cardiff, University of Wales Press and National Museum of Wales, p. 107-120.
- Dennison, J. M., Bambach, R. K., Dorobek, S. L., Filer, J. K., and Shell, J. A., 1992, Silurian and Devonian unconformities in southwestern Virginia, in Dennison, J. M., and Stewart, K. G., editors, *Geologic Field Guides to North Carolina and Vicinity: Chapel Hill, North Carolina*, University of North Carolina at Chapel Hill, Department of Geology, *Geologic Guidebook No. 1*, p. 79-105.
- Dennison, J. M., and Head, J. W., 1975, Sealevel variations interpreted from the Appalachian basin Silurian and Devonian: *American Journal of Science*, v. 275, p. 1089-1120.
- Diecchio, R. J., 1985, Post-Martinsburg Ordovician stratigraphy of Virginia and West Virginia: Virginia Division of Mineral Resources Publication 57, 77 p.
- Dorsch, J., 1992, Extensional basin formation during collapse of the Taconic orogen: A hypothesis for the Arvonian and Quantico successor basins of the central Appalachian Piedmont [abstract]: *Geological Society of America Abstracts with Programs*, v. 24, p. 17.
- , ms, 1993, Tectonics and sedimentation of the Taconic molasse in southwestern Virginia: Ph.D. thesis, University of Tennessee, Knoxville, 249 p.
- Dorsch, J., Driese, S. G., and Bambach, R. K., 1990, Basin rebound origin for the "Tuscarora unconformity" in southwestern Virginia: Evidence for a two-stage accretionary history during the Taconic orogeny? [abstract]: *Geological Society of America Abstracts with Programs*, v. 22, p. A45.
- Dorsch, J., Driese, S. G., Gogola, A. R., Bolton, J. C., and Bambach, R. K., 1991, Tectonic vs. eustatic unconformities: Examples from Upper Ordovician and Lower Silurian rocks, southern Appalachians [abstract]: *Geological Society of America Abstracts with Programs*, v. 23, p. 23.
- Drake, A. A., Jr., Sinha, A. K., Laird, J., and Guy, R. E., 1989, The Taconic orogen, in Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., editors, *The Appalachian-Ouachita Orogen in the United States*: Boulder, Colorado, Geological Society of America, *The Geology of North America*, v. F-2, p. 101-177.
- Driese, S. G., Fischer, M. W., Easthouse, K. A., Marks, G. T., Gogola, A. R., and Schoner, A. E., 1991, Model for genesis of shoreface and shelf sandstone sequences, southern Appalachians: Palaeoenvironmental reconstruction of an Early Silurian shelf system, in Swift, D. J. P., Oertel, G. F., Tillman, R. W., and Thorne, J. A., editors, *Shelf Sand and Sandstone Bodies: Geometry, Facies and Sequence Stratigraphy*: International Association of Sedimentologists Special Publication 14, p. 309-338.
- Driese, S. G., and Foreman, J. L., 1992, Paleopedology and paleoclimatic implications of Late Ordovician vertic paleosols, Juniata Formation, southern Appalachians: *Journal of Sedimentary Petrology*, v. 62, p. 71-83.
- Folk, R. L., 1960, Petrography and origin of the Tuscarora, Rose Hill, and Keefer Formations, Lower and Middle Silurian of eastern West Virginia: *Journal of Sedimentary Petrology*, v. 30, p. 1-58.
- Glover, L., III, 1989, Tectonics of the Virginia Blue Ridge and Piedmont: International Geological Congress, 28th, Washington, D.C., *Field Trip Guidebook T363*, 59 p.
- Gogola, A. R., ms, 1990, Depositional and diagenetic history of the Lower Silurian basal transgressive sandstone in the southern Appalachians: M.S. thesis, University of Tennessee, Knoxville, 142 p.

- Hatcher, R. D., Jr., 1989, Tectonic synthesis of the U.S. Appalachians, in Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., editors, *The Appalachian-Ouachita Orogen in the United States*: Boulder, Colorado, Geological Society of America, *The Geology of North America*, v. F-2, p. 511–535.
- Hayes, A. W., ms, 1974, Origin of the Tuscarora Formation (Lower Silurian), southwestern Virginia: Ph.D. thesis, Virginia Polytechnic Institute and State University, Blacksburg, 162 p.
- Hein, F. J., 1987, Tidal/littoral offshore shelf deposits—Lower Cambrian Gog Group, southern Rocky Mountains, Canada: *Sedimentary Geology*, v. 52, p. 155–182.
- Hobday, D. K., and Tankard, A. J., 1978, Transgressive-barrier and shallow-shelf interpretation of the lower Paleozoic Peninsula Formation, South Africa: *Geological Society of America Bulletin*, v. 89, p. 1733–1744.
- Horton, J. W., Drake, A. A., Jr., and Rankin, D. W., 1989, Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Appalachians, in Dallmeyer, R. D., editor, *Terranes in the Circum-Atlantic Paleozoic Orogens*: Geological Society of America Special Paper 230, p. 213–246.
- Jacobi, R. D., 1981, Peripheral bulge—a causal mechanism for the Lower/Middle Ordovician unconformity along the western margin of the northern Appalachians: *Earth and Planetary Science Letters*, v. 56, p. 245–251.
- Jamieson, R. A., and Beaumont, C., 1988, Orogeny and metamorphism: A model for deformation and pressure-temperature-time paths with applications to the central and southern Appalachians: *Tectonics*, v. 7, p. 417–445.
- Johnson, M. E., Kaljo, P. D., and Rong, J.-Y., 1991, Silurian eustasy, in Bassett, M. G., Lane, P. D., and Edwards, D., editors, *The Murchison symposium: Proceedings of an international conference on the Silurian System: Special Papers in Palaeontology* 44, p. 145–163.
- Kreisa, R. D., 1981, Storm-generated sedimentary structures in subtidal marine facies with examples from the Middle and Upper Ordovician of southwestern Virginia: *Journal of Sedimentary Petrology*, v. 51, p. 823–848.
- Lash, G. G., 1988, Sedimentology and evolution of the Martinsburg Formation (Upper Ordovician) fine-grained turbidite depositional system, central Appalachians: *Sedimentology*, v. 35, p. 429–447.
- McBride, E. F., 1962, Flysch and associated beds of the Martinsburg Formation (Ordovician), central Appalachians: *Journal of Sedimentary Petrology*, v. 32, p. 39–91.
- Middleton, G. V., Rutka, M. A., and Salas, C. J., 1987, Depositional environments in the Wirlpool Sandstone Member of the Medina Formation, in Duke, W. L., editor, *Sedimentology, Stratigraphy, and Ichnology of the Lower Silurian Medina Formation in New York and Ontario*: Society for Sedimentary Geology (SEPM), Eastern Section, 1987 Annual Field Trip Guidebook, p. 31–45.
- Pavlidis, L., Boucot, A. J., and Skidmore, W. B., 1968, Stratigraphic evidence for the Taconic orogeny in the northern Appalachians, in Zen, E.-An, White, W. S., Hadley, J. B., and Thompson, J. B., Jr., editors, *Studies of Appalachian geology: Northern and maritime*: New York, Interscience Publishers, p. 61–82.
- Pavlidis, L., Pojeta, J., Jr., Gordon, M., Jr., Parsley, R. L., and Bobyarchick, A. R., 1980, New evidence for the age of the Quantico Formation of Virginia: *Geology*, v. 8, p. 286–290.
- Pigram, C. J., and Davies, H. L., 1987, Terranes and the accretion history of the New Guinea orogen: *BMR Journal of Australian Geology and Geophysics*, v. 10, p. 193–211.
- Quinlan, G. M., and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the eastern interior of North America: *Canadian Journal of Earth Science*, v. 21, p. 973–996.
- Ricci Lucchi, F., 1986, The foreland basin system of the northern Apennines and related clastic wedges: A preliminary outline: *Giornale di Geologia*, v. 48, p. 165–185.
- 1990, Turbidites in foreland and on-thrust basins of the northern Apennines: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 77, p. 51–66.
- Ricci Lucchi, F., and Ori, G. G., 1984, Orogenic clastic wedges of the Alps and Apennines [abstract]: *American Association of Petroleum Geologists Bulletin*, v. 68, p. 798.
- Rodgers, John, 1953, *Geologic map of East Tennessee with explanatory text*: Tennessee Division of Geology Bulletin 58, part II, 168 p.
- 1971, The Taconic orogeny: *Geological Society of America Bulletin*, v. 82, p. 1141–1178.

- Seiders, V. M., Mixon, R. B., Stern, T. W., Newell, M. F., and Thomas, C. B., Jr., 1975, Age of plutonism and tectonism and a new minimum age limit on the Glenarm Series in the northeast Virginia Piedmont near Occoquan: *American Journal of Science*, v. 275, p. 481-511.
- Shanmugam, G., and Lash, G. G., 1982, Analogous tectonic evolution of the Ordovician foredeeps, southern and central Appalachians: *Geology*, v. 10, p. 562-566.
- Sloss, L. L., 1988, Tectonic evolution of the craton in Phanerozoic time, in Sloss, L. L., editor, *Sedimentary Cover—North American Craton: U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America*, v. D-2, p. 25-51.
- Thomas, W. A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: *American Journal of Science*, v. 277, p. 1233-1278.
- Tremblay, A., 1992, Tectonic and accretionary history of Taconian oceanic rocks of the Quebec Appalachians: *American Journal of Science*, v. 292, p. 229-252.
- Tucker, R. D., and Robinson, P., 1990, Age and setting of the Bronson Hill magmatic arc: A re-evaluation based on U-Pb zircon ages in southern New England: *Geological Society of America Bulletin*, v. 102, p. 1404-1419.
- Wehr, F., and Glover, L., III, 1985, Stratigraphy and tectonics of the Virginia-North Carolina Blue Ridge: Evolution of a late Proterozoic hinge zone: *Geological Society of America Bulletin*, v. 47, p. 1497-1526.
- Wheeler, H. E., 1963, Post-Sauk and pre-Absaroka Paleozoic stratigraphic patterns in North America: *American Association of Petroleum Geologists Bulletin*, v. 47, p. 1497-1526.
- Whisonant, R. C., 1977, Lower Silurian Tuscarora (Clinch) dispersal patterns in western Virginia: *Geological Society of America Bulletin*, v. 88, p. 215-220.
- Williams, H., and Hatcher, R. D., Jr., 1983, Appalachian suspect terranes, in Hatcher, R. D., Jr., Williams, H., and Zietz, I., editors, *Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158*, p. 33-53.