

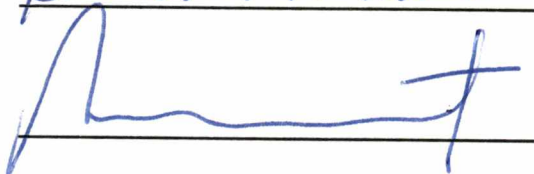
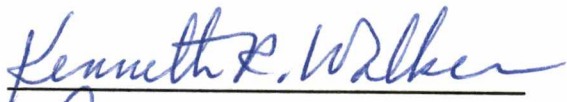
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I am submitting herewith a dissertation written by Joachim O. Dorsch entitled "Tectonics and Sedimentation of the Taconic Molasse of Southwestern Virginia." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geology.

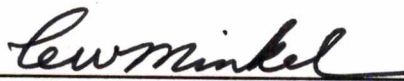


Dr. Steven G. Driese, Major Professor

We have read this dissertation
and recommend its acceptance:



Accepted for the Council



Associate Vice Chancellor
and Dean of the Graduate School

**TECTONICS AND SEDIMENTATION OF THE TACONIC
MOLASSE IN SOUTHWESTERN VIRGINIA**

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Joachim Oskar Dorsch
December 1993

DEDICATION

to my *parents*: für ihr Vertrauen und stete Unterstützung

and to *Ana Lúcia De Carvalho Cruz*: por tudo o que ela fez

Eventually, all things merge into one, and a river runs through it.
The river was cut by the world's great flood and runs over rocks
from the basement of time. On some of the rocks are timeless
raindrops. Under the rocks are the words,
and some of the words are theirs.
I am haunted by waters.

Norman Maclean

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Much of the strenuous work was ameliorated by the "old gang" and their companionship, especially Tim Davis (and Sally), Jeff Connelly (and Kelly), apartmentmate and "*Computer Wizard*" Ian Richards (and Maria), Keith Roberson (and Jennifer), Linc Foreman (and Kathy). Add to this fine assortment of individuals the aforementioned members of the Sandbar and sprinkle it with Chris Olson (and Kelly).

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And now, please read the *Dedication* again.

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The dissertation was finished under the tropical climate of East Stadium Hall during the June-August '93 heat-&-humidity extravaganza: imagine what could have been done under more comfortable climatic conditions!

ABSTRACT

A detailed sedimentologic and stratigraphic examination of the Juniata Formation, Tuscarora Sandstone, and Rose Hill Formation (Upper Ordovician to Lower Silurian) revealed new insights on the process sedimentology and regional stratigraphic architecture of these units, exposed within Alleghanian thrust sheets of the Appalachian Valley and Ridge in southwestern Virginia. The examined stratigraphic units are part of the Martinsburg-Shawangunk clastic wedge, which represents the fill of a peripheral foredeep formed during the Taconic orogeny in the central Appalachians. The stratigraphic units succeed the Martinsburg Formation and mirror the secular development of the Taconic orogen.

The regional "Tuscarora unconformity" bisects the Martinsburg-Shawangunk clastic wedge. It separates a regionally extensive and sedimentologically distinct "upper" Tuscarora Sandstone from various subjacent stratigraphic units, including the regionally restricted "lower" Tuscarora Sandstone. 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 (extensional collapse?) unloading of the orogen caused isostatic uplift of both the orogen and adjacent foredeep. This led to development of a regionally extensive erosional surface within the foredeep. Vestiges of tectonic thinning of the orogen are preserved in the extensional successor basins (Arvonian and Quantico basins) within the Virginia Piedmont. Creation of accommodation space for the upper part of the Martinsburg-Shawangunk clastic wedge 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.

The Juniata Formation and "lower" Tuscarora Sandstone beneath the "Tuscarora unconformity" represent storm-dominated deposits of a shallow-marine foredeep. Identified shallow-marine hydrodynamic zones range from the middle shoreface to the offshore marine. The "lower" Tuscarora Sandstone is interpreted as a wedge-shaped sediment body, which constitutes the lithostratigraphic equivalent of the upper Juniata Formation in more proximal outcrop belts. The thick section of shallow-marine deposits of the Juniata Formation and "lower" Tuscarora Sandstone implies a delicate balance between

creation of accommodation space (subsidence predominantly through tectonic loading, supported by sediment compaction and loading) and sediment supply. The sandier-upward trend from the upper Martinsburg Formation through the "lower" Tuscarora Sandstone probably reflects a combination of increase in relief of the orogen and change in source-rock lithologies. A cyclic organization is not readily apparent within the Juniata Formation and "lower" Tuscarora Sandstone.

The "upper" Tuscarora Sandstone, situated above the "Tuscarora unconformity," represents predominantly storm-dominated deposits of the upper shoreface to the offshore transition zone. The "upper" Tuscarora Sandstone constitutes a continuous transgressive facies succession, which is bound at the base by a sequence boundary ("Tuscarora unconformity") and at the top by a (maximum) marine-flooding surface, along which the storm-dominated deposits of the Rose Hill Formation commence. The "upper" Tuscarora Sandstone, furthermore, forms a transgressive systems tract composed of a single retrogradational parasequence (except at the most distal outcrop locality). Development and preservation of this transgressive facies succession is believed to be related to an episode of load-induced flexural subsidence within the Taconic foredeep. Gradual and continuous subsidence created accommodation space at a rate which outpaced the rate of ample sediment supply.

On a regional scale (central Virginia to northern Alabama/Georgia), the uppermost Ordovician to Lower Silurian stratigraphic units above the Upper Ordovician red-bed succession in the central and southern Appalachians can be subdivided into the distinctly different 'White Sandstone Lithosome' (Tuscarora Sandstone, Poor Valley Ridge Sandstone Member of the Clinch Sandstone, and some beds/bedsets within the Rockwood Formation) and 'Heterolithic Lithosome' (Rose Hill Formation, Rockwood Formation, and Hagan Shale Member of the Clinch Sandstone). In southwestern Virginia, the 'White Sandstone Lithosome' dominates, whereas in extreme southwestern Virginia and eastern Tennessee, the 'Heterolithic Lithosome' dominates. The latter commences with the 'basal transgressive sandstone' and encapsulates the more exotic 'White Sandstone Lithosome'.

The 'White Sandstone Lithosome', contrary to ruling opinion, is not a simple, homogeneous and uniform quartzarenite blanket, but is divisible into separate components. Each component possesses its distinct tie to different developmental stages of the Taconic orogen in the central Appalachians and to eustatic sea-level changes.

Detritus for the "lower" Tuscarora Sandstone was shed from the growing Taconic orogen and was deposited within the foredeep during thrust-load induced foredeep

subsidence. The glacio-eustatic sea-level events during the Hirnantian (latest Ordovician) are thought to be reflected in the Whirlpool Sandstone (subsurface of southern Ohio and parts of West Virginia), whose stratigraphic position and glacio-eustatic origin corresponds to that of the 'basal transgressive sandstone' (extreme southwestern Virginia to northern Alabama/Georgia). Detritus for the Whirlpool Sandstone was derived from erosion of "lower" Tuscarora Sandstone during glacio-eustatic sea-level drop.

Flexural isostatic uplift/rebound converted part of the Taconic foredeep from an active depositional site to an active erosional site. In the area of uplift (denudation area), evidence for the Hirnantian glacio-eustatic sea-level events was cut out, and the produced erosional detritus (derived predominantly from the "lower" Tuscarora Sandstone) was redistributed radially away from the denudation area into parts of the foredeep not affected by rebound, and into areas at the fringe of the foredeep and beyond (parking area and fill area). The 'White Sandstone Lithosome' in extreme southwestern Virginia and eastern Tennessee (Poor Valley Ridge Sandstone and bedsets within the Rockwood Formation) is interpreted to be part of this redistributed material, which interrupted the normal, mud-dominated sedimentation in that area. The "Clinton" sandstone in the subsurface of southern Ohio is regarded as a lithostratigraphic equivalent. The quartz-rich detritus was reworked and distributed within the fill area by the ambient storm system. The isolated bedsets of the 'White Sandstone Lithosome' within the Rockwood Formation, demarcating the farthest spread of this lithosome, might represent forced regressions.

Renewed compressional tectonism and active foredeep subsidence converted the foredeep back to a depositional site, thereby gradually shutting off supply of white quartz sand to peripheral areas. Transgressive reworking of erosional detritus covering the denudation area, together with new sediment contribution from the Taconic orogen during this new phase of thrusting, provided the detritus for the "upper" Tuscarora Sandstone. Deposition of the 'White Sandstone Lithosome' within the active foredeep was terminated by rapid marine flooding during the ? early Telychian eustatic sea-level rise.

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CHAPTER 1

INTRODUCTION

GEOLOGIC FRAMEWORK

The Taconic orogeny affected the eastern margin of Laurentia diachronously from the Middle Ordovician to the Early Silurian (Rodgers, 1971; Williams and Hatcher, 1983). The Taconic orogeny is believed to be related to southeastward (present coordinates) subduction of Iapetan oceanic crust beneath an array of island arcs and microcontinents, and to the succeeding collision of Laurentia with these terranes (Chapple, 1973; St. Julien and Hubert, 1975; Thomas, 1977; Hatcher, 1978; Hiscott, 1978; Hatcher and Odom, 1980; Rowley and Kidd, 1981; Jacobi, 1981; Williams and Hatcher, 1983; Wehr and Glover, 1985). An often-cited modern analogue for this tectonic scenario is the eastern Indonesian archipelago, with the Banda Arc overriding the Sahul Shelf, the passive continental margin of Australia (Zen, 1967; Hiscott, 1978; Shanmugam and Walker, 1980; Rowley and Kidd, 1981).

A recent hypothesis proposes continent-continent collision between Laurentia and Gondwana as the main cause for the Taconic orogeny (Dalla Salda and others, 1992a, b). This hypothesis aims to explain the abrupt termination of the Taconic orogen at the Alabama promontory and the occurrence of lower Paleozoic carbonate-platform rocks of Laurentian affinity within the southern central Andes. A continent-continent collision for the Taconic orogeny, however, does not preclude the collision of smaller terranes prior to the terminal "event" (I. Dalziel, pers. comm., 1992). A test for the Laurentia-Gondwana continental collision hypothesis for the Taconic orogeny, especially based on the tectonics of the Taconic internides, is still pending.

A series of peripheral foreland basins/foredeeps developed diachronously upon the Laurentian continental crust from present-day Alabama to Newfoundland (Hiscott and others, 1986; Shanmugam and Lash, 1982), reflecting the evolution of the Taconic orogen. The foredeeps (a foredeep "refers to a basement depression and has no morphologic-bathymetric connotation": Bally and Oldow, 1984, page 121) originated primarily due to loading of Laurentian lithosphere, resulting in the rapid downbending of the former passive

continental margin of Laurentia in front of the orogen (Chapple, 1973; Jacobi, 1981; Quinlan and Beaumont, 1984). Block faulting associated with lithospheric flexure may have contributed to the rapid inception of the foredeeps (Chapple, 1973; Jacobi, 1981; Shanmugam and Walker, 1983; Bradley and Kidd, 1991). The foredeep fills (clastic wedges) evolved from deep-marine to shallow-marine and terrestrial clastic sediments (for example, Hiscott and others, 1986).

In the central Appalachians, the fill of the Taconic foredeep constitutes the Upper Ordovician to Upper Silurian Martinsburg-Shawangunk clastic wedge (Thomas, 1977). During the Late Ordovician to Early Silurian, this clastic wedge (Figure 1-1) developed from deeper water hemipelagites (basal Martinsburg Formation; McBride, 1962; Shanmugam and Lash, 1982), through foreland flysch ("turbiditic" Martinsburg Formation; McBride, 1962; Lash, 1988), to foreland molasse (uppermost Martinsburg Formation, Oswego Sandstone, Juniata Formation, Tuscarora Sandstone, Rose Hill Formation). The evolution of the foredeep fill mirrors the sequential development of the Taconic orogen in the central Appalachians with respect to changing plate-tectonic conditions (see Chapter 2). The sediment for the foredeep fill was derived from the Taconic orogen to the southeast (for example, Amsden, 1955; Yeakel, 1962; Pettijohn, 1970; Dennison, 1970; Hayes, 1974; Whisonant, 1977). The locus of maximum lithospheric loading, flexural subsidence, and thickness of the foredeep fill (clastic wedge) is situated in present-day southern Pennsylvania, Maryland, and northern Virginia (Beaumont and others, 1988). In areas more distal from this locus, the Martinsburg Formation is not represented by deep-water deposits, but consists of storm-dominated, shallow-marine deposits ("tempestitic" Martinsburg Formation, Reedsville Shale; Kreisa, 1981). These distal areas, including the study area in southwestern Virginia, experienced less flexural subsidence primarily due to increased distance from the main load.

A similar, but slightly older foredeep (Middle Ordovician), developed to the southwest in the southern Appalachians, with the locus of maximum subsidence and thickness of the foredeep fill centered in Tennessee (Thomas, 1977; Beaumont and others, 1988). This foredeep and its fill (here referred to as the Blount foredeep and the Sevier-Bays clastic wedge, respectively) display a similar sequential development as the Taconic foredeep and the Martinsburg-Shawangunk clastic wedge of the central Appalachians (Rodgers, 1967, 1971; Thomas, 1977; Shanmugam and Lash, 1982; Shanmugam and Walker, 1980, 1983; Read, 1980; Drake and others, 1989). The Blount foredeep and

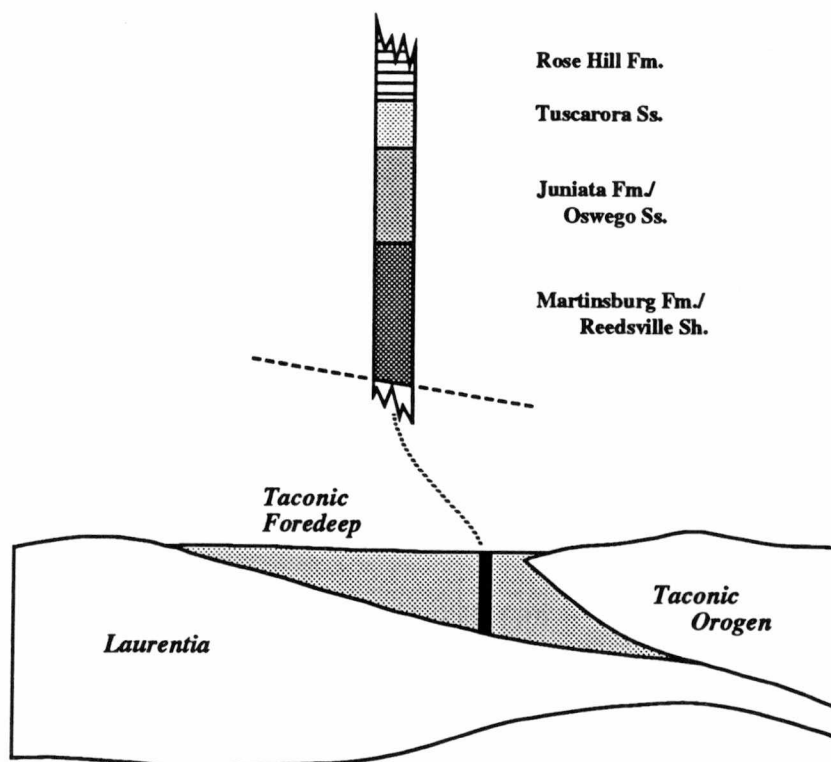


Figure 1-1. Schematic drawing of the Taconic foredeep-orogen couplet showing the Martinsburg-Shawangunk clastic wedge (foredeep fill) up to the Lower Silurian. The schematic stratigraphic column provides the lithostratigraphic nomenclature of the Upper Ordovician through Lower Silurian part of the clastic wedge. The stippled line indicates the base of the clastic wedge. Drawing is not to scale.

Sevier-Bays clastic wedge are related to the Blountian phase of the Taconic orogeny (Rodgers, 1953, 1971) or Blountian orogeny (Drake and others, 1989).

STRATIGRAPHY

The focus of the field-based research for this dissertation was the stratigraphic interval comprised by the Juniata Formation, the Tuscarora Sandstone, and the Rose Hill Formation (Figure 1-2). The light-colored Tuscarora Sandstone is split into a lithologically distinct "upper" and "lower" Tuscarora Sandstone (Figure 1-2; see Chapter 2). The "upper" Tuscarora Sandstone is of regional extent and is bound at its base by the "Tuscarora unconformity", which bisects the Martinsburg-Shawangunk clastic wedge. The "upper" Tuscarora Sandstone unconformably overlies Martinsburg Formation, Juniata Formation and, in the central part of the Valley and Ridge, "lower" Tuscarora Sandstone. Recognition of the subtle, yet regionally extensive "Tuscarora unconformity," and definition of "upper" and "lower" Tuscarora Sandstone occurred recently (Bambach, 1987; Dorsch and others, 1990; see Chapter 2). The unconformity is interpreted as a basin-rebound unconformity, which developed during a lull in Taconic compressional tectonism (Dorsch and others, 1990; see Chapter 2). The most prominent stratigraphic break within the uppermost Ordovician and Lower Silurian deposits of the study area clearly resides within the Tuscarora Sandstone.

Biostratigraphic data for age assignment of the different lithostratigraphic units are available only for the Martinsburg Formation and the Rose Hill Formation. The red-bed succession of the Juniata Formation is considered to be Ashgillian (Twenhofel and others, 1954; Diecchio, 1985; Dennison and others, 1992). The "lower" Tuscarora Sandstone interfingers with the Juniata Formation and caps a coarsening-upward trend, which started within the Martinsburg Formation. The "lower" Tuscarora Sandstone is regarded as a northwestward prograding quartzarenitic wedge, which replaced deposition of red sediment. This stratigraphic unit is believed to constitute a facies equivalent of the upper part of the Juniata Formation (see Chapter 4). Sedimentological evidence for the Hirnantian (latest Ashgillian) glacio-eustatic sea-level changes, such as paleosols, a widespread, thin transgressive sheet sandstone (related to erosional shoreface retreat), and a small lacuna (for example, Driese and others, 1991), are well developed from eastern Tennessee to northern Alabama and Georgia. The stratigraphic setting in southwestern Virginia is radically

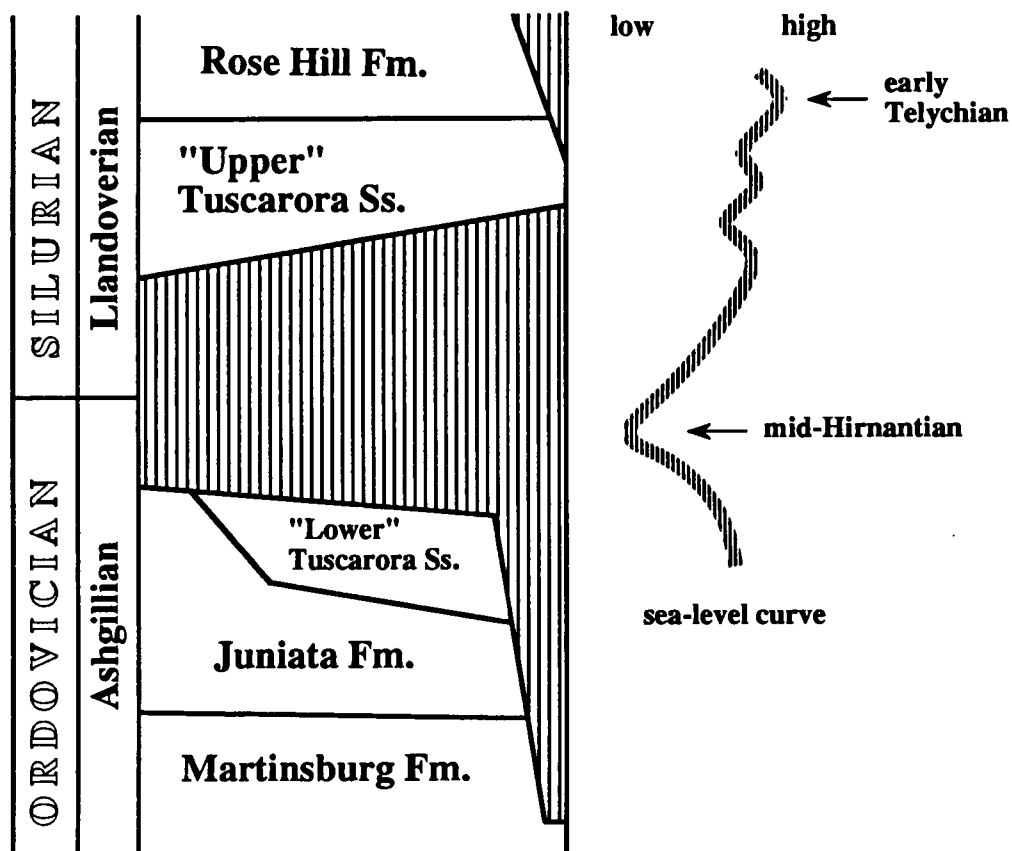


Figure 1-2. Interpretive correlation chart for Late Ordovician/Early Silurian stratigraphic units in southwestern Virginia (modified from Dennison and others, 1992). Vertical axis represents time; sea-level curve is based on Johnson and others (1991).

different, and similar evidence for glacio-eustasy cannot be detected within the Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia. Strata recording the Hirnantian glacio-eustatic sea-level changes probably were deposited in southwestern Virginia, but were removed during regional uplift of the foredeep and development of the subaerial exposure surface, which later became the "Tuscarora unconformity" following deposition of the "upper" Tuscarora Sandstone (see Chapters 2 and 5). A minimum age for the onset of deposition of "lower" Tuscarora Sandstone can be inferred, therefore, as earlier than the Hirnantian glacio-eustatic sea-level changes. The "upper" Tuscarora Sandstone onlaps the subaerial exposure surface created during isostatic basin rebound. The extent of the lacuna, however, cannot be constrained biostratigraphically (Dennison and others, 1992). In the southeastern part of the Valley and Ridge of southwestern Virginia, the unconformity cuts down into the Martinsburg Formation ("lower" Tuscarora Sandstone, entire Juniata Formation, and part of the Martinsburg Formation are missing), and a minimum of 150 m of section were removed (Bambach, 1987) during isostatic basin rebound. A long time break associated with the "Tuscarora unconformity" is implied, at least in the southeastern Valley and Ridge. The sharp contact between the "upper" Tuscarora Sandstone and the Rose Hill Formation can be placed into the Late Llandoveryan (Lampiris, 1975; R. Bambach, pers. comm., 1992), and might be related to a documented eustatic sea-level rise during the early Telychian (Johnson and others, 1991).

FIELD AREA AND METHODS

The field area is situated in the Valley and Ridge of southwestern Virginia. It stretches from Wytheville to Roanoke along structural strike, and to the Virginia-West Virginia state line in the northwest (Figure 1-3). The Juniata Formation, the Tuscarora Sandstone and the Rose Hill Formation are contained within several southeast-dipping thrust sheets, which dismembered the remnants of the original Martinsburg-Shawangunk clastic wedge during the late Paleozoic Alleghanian orogeny. The usage of 'proximal' and 'distal' refers to the present-day exposures of Taconic foredeep deposits within the Valley and Ridge. Proximal refers to outcrops close to the Blue Ridge in the southeast, whereas distal refers to outcrops close to the Cumberland Plateau in the northwest. Truly distal and proximal deposits of the Taconic foredeep may be concealed beneath the Cumberland

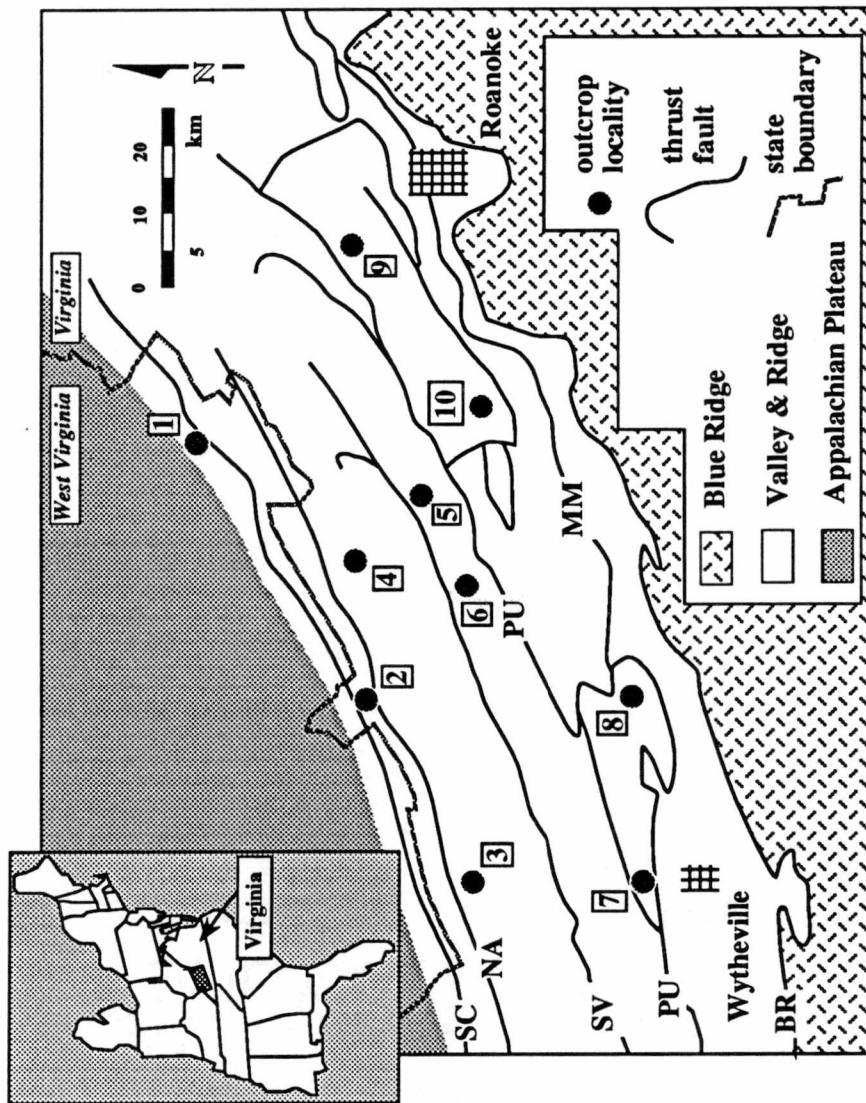


Figure 1-3. Location map of the study area in southwestern Virginia. Outcrop localities are: 1 - Gap Mills; 2 - Narrows; 3 - South Gap; 4 - Cascades; 5 - Gap Mountain; 6 - McCoy; 7 - Cove Mountain; 8 - Draper Mountain; 9 - Catawba Mountain I, II; 10 - Fagg I, II. Major thrust faults include: SC - Saint Clair; NA - Narrows; SV - Saltville; PU - Pulaski; MM - Max Meadows; BR - Blue Ridge.

Plateau to the northwest (distal deposits) and beneath the crystalline thrust sheets to the southeast (proximal deposits) of the Valley and Ridge.

Field work involved the detailed measurement of outcrop sections on a bed-by-bed basis. Overall, more than 700 m were logged from the lithologically distinctly different Juniata Formation, Tuscarora Sandstone and Rose Hill Formation (Appendix 1). The different outcrop sections are predominantly located along road cuts. They provide excellent to good exposures of the stratigraphic units, including their contacts. The location of the outcrop sections were restored to their approximate original spatial configuration prior to Alleghanian deformation, using (as of now) unpublished balanced geologic cross sections by William M. Dunne and Brent A. Couzens (University of Tennessee-Knoxville). A copy of the palinspastic base map is provided in Appendix 4.

Measurement of outcrop sections involved the recording of grain size and other textural criteria, rock color, physical and biogenic sedimentary structures, and bedding characteristics (Appendix 1). More than 600 directional measurements were collected (Appendix 2). In addition, appropriate lithologic intervals of all three lithostratigraphic units were sampled for analysis for "acritarchs", totaling 110 samples (Appendix 3). Analysis for "acritarchs" was carried out by Dr. Gordon Wood of Amoco Production Company in Houston, Texas. As of now, only preliminary results of these latter investigations are available, because of time constraints imposed by more pressing company commitments. More than 200 samples of different lithologies were taken in the field and examined in detail in the laboratory, after slabbing and polishing. The samples were studied using the binocular microscope and hand lens; 135 samples were retained for thin section preparation and for microscopic petrographic analysis to be carried out at a later point in time.

Based on the data obtained in the field and laboratory, the outcrop sections were subdivided into distinct and recurring facies and their variants. The facies/variants and their association formed the basis for a process-sedimentologic interpretation of the paleoenvironments of the lithostratigraphic units under study. The directional measurements were evaluated statistically using an unpublished computer program by Maher and Dott (1979).

Earlier studies on parts of the Martinsburg-Shawangunk clastic wedge in southwestern Virginia focused on different aspects of provenance, sedimentary petrography and paleoenvironmental interpretation. The ("tempestitic") Martinsburg Formation was measured and analyzed in considerable detail by Kreisa (1980, 1981), Kreisa and Bambach

(1982), Kreisa and Springer (1987), and Springer and Bambach (1985). The stratigraphic units studied for this dissertation received earlier attention by Hayes (1974), Lampiris (1975), Whisonant (1977), Hunter (1970), Kreisa (1980, 1982), and Diecchio (1985). The "Keefer Sandstone" of southwestern Virginia, situated above the stratigraphic interval of this study, was examined by Lampiris (1975), and Lightner and Whisonant (1983).

THE CHAPTERS

The dissertation is composed of different chapters focusing on different aspects of the stratigraphy and sedimentology of the lithostratigraphic units under study. Some overlap between chapters is unavoidable. Each chapter, however, is self-contained and can be read (and understood) without the help of the other chapters.

Chapter 2 establishes the "Tuscarora unconformity", its regional extent, and the two informal members of the Tuscarora Sandstone ("lower" and "upper" Tuscarora Sandstone) in southwestern Virginia. Literature descriptions and reconnaissance investigations indicate the extent of this unconformity throughout the Valley and Ridge of the central Appalachians. Chapter 2, furthermore, proposes isostatic basin rebound as the most likely causative mechanism for the "Tuscarora unconformity", and outlines the possible implications for the nature of the Taconic orogeny in the central Appalachians.

Chapter 3 reviews the lithostratigraphic framework from central Virginia to northern Alabama/Georgia. It outlines the possible influence of foredeep tectonism (related to the tectonics of the Taconic internides) and eustasy on the development of the regional stratigraphic pattern, and on the origin of the widespread white quartzarenite blanket (Tuscarora Sandstone, Poor Valley Ridge Sandstone Member of the Clinch Sandstone, Whirlpool Sandstone and "Clinton" sandstone) in particular.

Chapters 4 and 5 detail the sedimentology of the Juniata Formation/"lower" Tuscarora Sandstone and "upper" Tuscarora Sandstone, respectively, and their paleoenvironmental interpretations. For each segment of the foredeep stratigraphy, inferences about foredeep behavior are drawn. For the "upper" Tuscarora Sandstone, deposited during a crucial time in foredeep development, a detailed sequence stratigraphic framework is proposed and the influencing mechanisms for development of that framework are outlined.

Stratigraphy and sedimentology of the Rose Hill Formation are not laid out in a separate chapter. The paleoenvironments conform to those proposed by Cotter (1983a, 1988, 1990) for the Rose Hill Formation in Pennsylvania and, especially for the hematitic intervals, by Hunter (1970). The process-sedimentology of the Rose Hill Formation, furthermore, is closely similar to that of the heterolithic Rockwood and Red Mountain Formations, published recently by Driese (1988), Driese and others (1991) and Bolton (1992).

The results put forward in the chapters of this dissertation are based upon observations on rocks in the field and in the laboratory. Observations provided in the chapters and in the appendices are already a condensate of the full observational data contained in the field notebooks. There are obviously limitations in the extent to which observations are possible. Some involve the prowess of the worker to observe and the knowledge of the worker of what to observe. Others are imposed by the nature of the stratigraphic record and its myriad of gaps, the perceived uniqueness of some geologic processes with respect to human experience, the inaccessibility of modern analogue examples and, not the least important of which in the Appalachian Valley and Ridge, the accidental provision of outcrops by the Alleghanian orogeny and the State Highway Department. Because of the limitations to obtain observable facts, much of the geological knowledge is obtained "only by means of speculative mental processes" (Davis, 1913).

Inferences drawn from observations provided in this dissertation, interpretations based on these observations, and speculations emanating from these observations and interpretations naturally might be controversial. It is hoped that the reader critically evaluates for her/himself the interpretations and the observations in which they root. Much is accomplished, if the reader agrees with the results, even more, if she/he disagrees and is stimulated to adroitly conceive her/his own interpretations and speculations.

The realization of the limitations in geological science and the speculative aspects involved in geological research to overcome these limitations, the challenge derived from knowing of these limitations and the resulting desire to push the boundaries of geologic knowledge, and the realization of the proximity of the next error are well expressed by Ampferer (1906):

Auf zweifachen Wegen hat die Geologie tiefen Einfluss auf die moderne Weltanschauung geübt, indem sie einmal das wundervoll verschlungene Wurzelwerk alles organischen Lebens aus unbekannter Tiefe erhob und weiteres uns im steinernen,

scheinbar starren Antlitz der Erde eine Fülle von bewegten oder beweglichen Zügen verstehen lehrte. Der Macht dieser Anregungen aber steht ein ungeheures Feld zur wissenschaftlichen Erforschung gegenüber, das in solcher Weite, solcher Unerschöpflichkeit vor den Augen keiner anderen Wissenschaft sich breitet.

Die steten Erschütterungen und Erweiterungen unserer Zeit-, Raum- und Kraftvorstellungen hat die Geologie mit der Astronomie gemeinsam, von der sie sich jedoch durch die Nähe und Anschaulichkeit ihrer Schauplätze unterscheidet. In keiner anderen Wissenschaft aber ist der Schatz der gesicherten Beobachtungen im Vergleich zum Unerforschten, zur Unendlichkeit des Möglichen so bescheiden wie hier und nirgends gehört daher die Hypothese, die Theorie so zum unumgänglichen täglichen Werkzeug des Forschers.

Das mag für viele den Anlass zu einer geringeren Schätzung bedeuten und gibt der Geologie als Wissenschaft den äusserlichen Anschein des Vergänglichen und Ungefestigten - für den Forscher jedoch kann nach meiner Einsicht nur eine tiefere Lust daraus entspringen, indem die Beschäftigung mit dieser Wissenschaft Schritt für Schritt den schlummerlosen, vollen Einsatz alles geistigen Erkennens fordert, soll anders das Ziel des Strebens rein und klar auf Näherung der Wahrheit gerichtet sein.

So scheint uns hier neben der Fülle des Erreichten vor allem der unermüdlich achtsame, stete Entscheid zwischen nahem und nächstem Irrtum als besonders wertvolles und vornehmes Gepräge dieses Denkens, welches von jeder Mechanisierung, Sensation und allgemeinen Verbreiterung entehrt wird.

Wenden wir uns nun unserer Aufgabe zu.

Let us stand on the shoulders of a giant and go to work!

CHAPTER 2

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

PREAMBLE

The unconformable contact between the Martinsburg Formation and Tuscarora Sandstone in the southeastern parts of the Valley and Ridge 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 and others, 1968; Rodgers, 1971). This unconformity separates Sloss's (1988) Tippecanoe I 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 goal of this chapter 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 and others, 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 (Figure 1-3, 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 ca. 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 (Figure 1-3), 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 and others, 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 (Figure 1-3) display hummocky cross stratification (see Chapter 5). 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 (see Chapter 5). The stacking of facies within the upward fining and thinning "upper" Tuscarora Sandstone is interpreted to reflect a complete transgressive stratigraphic succession (retrogradational parasequence; see Chapter 5).

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 (see Chapter 5).

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 (Figure 2-1). In the central and northwestern outcrop belts (Figure 1-3), the "upper" Tuscarora Sandstone overlies the "lower" Tuscarora Sandstone with a sharp, erosional contact (Figures 2-1 and 2-2), 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 by trough cross stratification (one example of hummocky cross stratification occurs at the Cove Mountain locality; Figure 1-3), and abundant *Rusophycus*, *Cruziana*, *Monocraterion*, *Skolithos*, *Planolites*, and *Arthropycus* trace fossils (see Chapter 4). 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 (see Chapter 4). The "lower" Tuscarora Sandstone caps a coarsening-upward succession, which commenced 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, 1974; Whisonant, 1977; see Chapter 4). 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; see Chapter 4). The observed thickness of the "lower" Tuscarora Sandstone (Figure 2-1) 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.

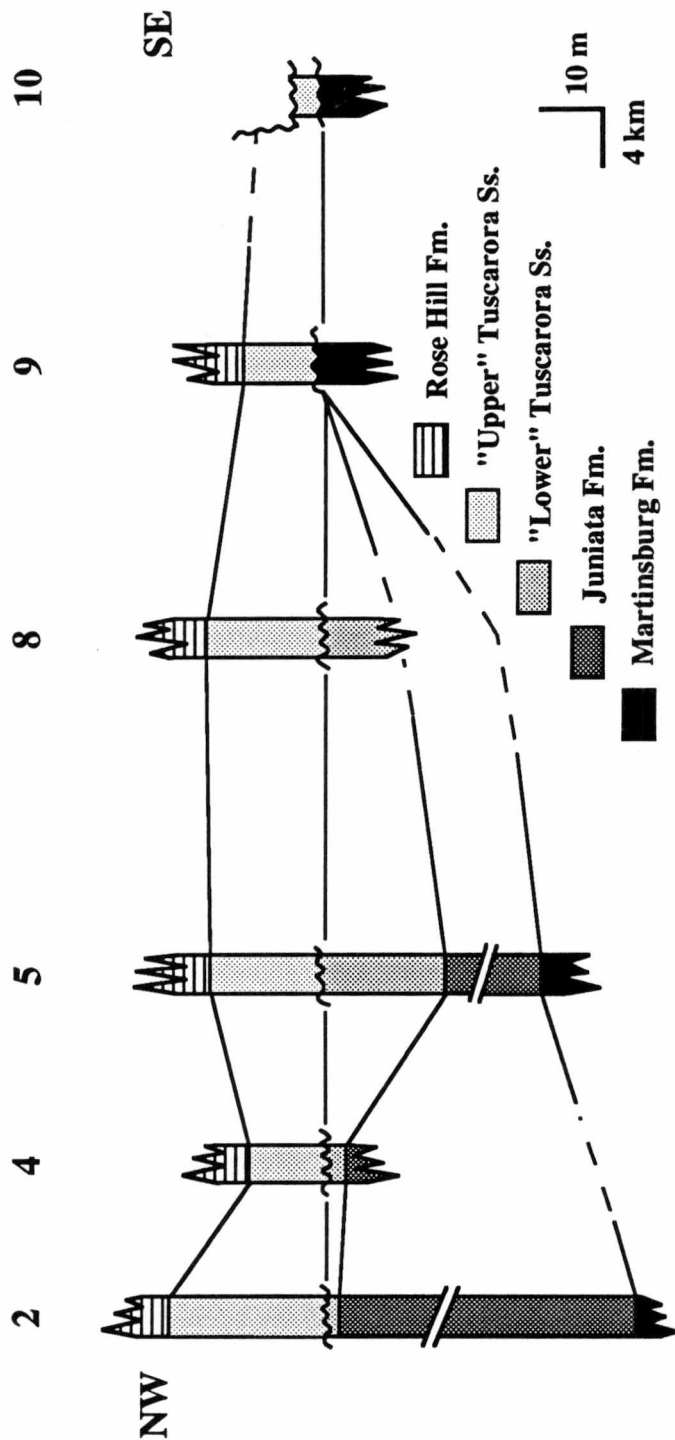
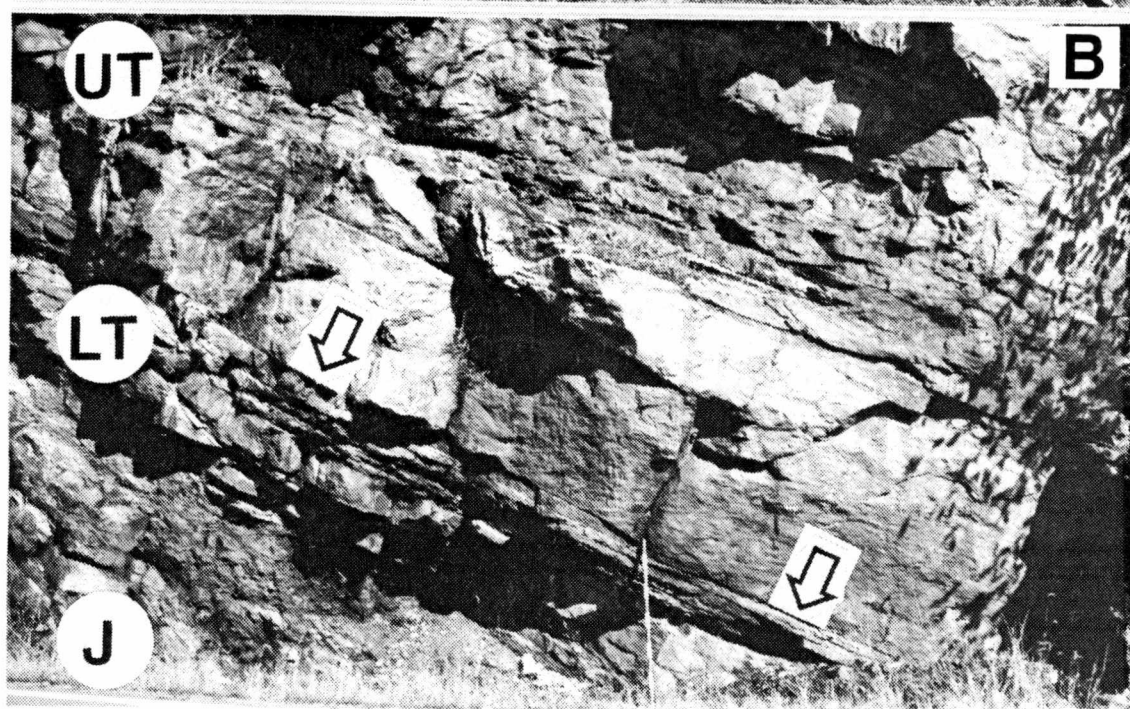
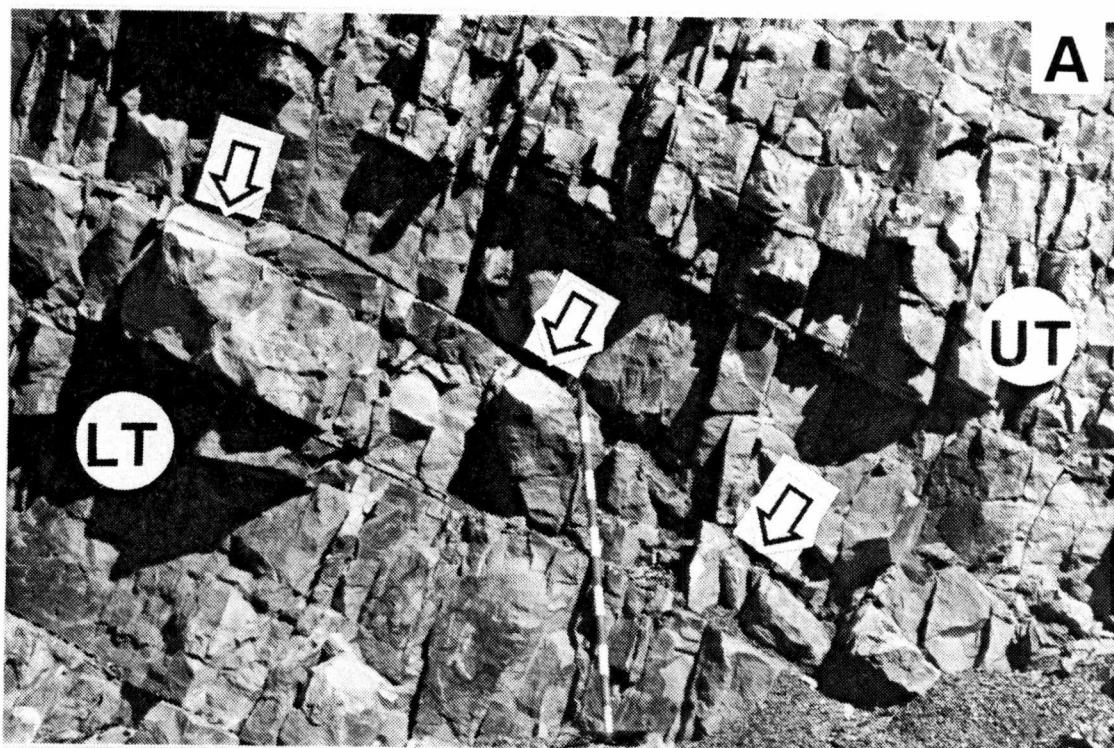


Figure 2-1. Lithostratigraphic cross section from distal outcrops in the northwest to proximal outcrops in the southeast. Wavy line indicates "Tuscarora unconformity"; top of Fagg section is truncated by Devonian unconformity. Outcrop localities are: 2 - Narrows, 4 - Cascades, 5 - Gap Mountain, 8 - Draper Mountain, 9 - Catawba Mountain, 10 - Fagg; for location of the outcrops refer to Figure 1-3. 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.

Figure 2-2: The "Tuscarora unconformity" in outcrop. Intersection trace of unconformable surface with outcrop face indicated by arrows; stratigraphic units are: J - Juniata Formation, LT - "lower" Tuscarora Sandstone, UT - "upper" Tuscarora Sandstone; staff is 1.20 m long with 10 cm divisions. (A) Outcrop locality at South Gap; (B) Outcrop locality at Narrows.



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, Juniata Formation; Figures 2-1 and 2-2). 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 (Figure 1-3, 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, estimated 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 sea-level 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 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, Figure 1-3; Bambach, 1987). An estimated sea-level drop of only about 70 m associated with the end-Ordovician glacio-eustatic sea-level drop (Brenchley, 1989) can explain the removal of 150 m of foredeep fill, because of isostatic amplification (see for example, Angevine and others, 1990). Assuming that the lacuna in the southeastern outcrop belt was created exclusively by eustatic sea-level 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 (Figure 2-1). This indicates that considerably less section is missing in these outcrop belts.

Cove Mountain, the southwesternmost outcrop within the study area (Figure 1-3), exhibits the thickest preserved section of "lower" Tuscarora Sandstone (46.70 m). The "lower" Tuscarora Sandstone is bound at the top by the Devonian Wallbridge Discontinuity, which removed, among other stratigraphic units, the "upper" Tuscarora Sandstone 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 (see Chapter 3).

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 and others, 1988).

In eastern Tennessee, the end-Ordovician glacio-eustatic sea-level drop and rise are well documented (Gogola, 1990; Driese and others, 1991). The exposure surface created during sea-level drop is indicated by the development of vertic paleosols (Driese and Foreman, 1992), whereas the eustatic sea-level rise, closely succeeding in time (Brenchley, 1989), is expressed by the "basal transgressive sandstone" (Gogola, 1990). The lacuna associated with these sea-level 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, 1990). The "upper" Tuscarora Sandstone, onlapping onto the exposure surface in southwestern Virginia (Figure 2-1), 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 (see Chapter 5). 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, 1990; Driese and others, 1991). The stratigraphic relationships in eastern Tennessee indicate a relative sea-level rise with pronounced erosion and low sediment supply (Cant, 1991). The situation in southwestern Virginia, in marked contrast, indicates a relative sea-level 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 sea-level 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 sea-level 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 metasedimentary rocks of the Quantico and Arvonias 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 (Figure 1-3), 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 and others, 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 sea-level 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 and others (1987) concluded that the deposition of the Whirlpool Sandstone (Early Silurian) was not affected primarily by the end-Ordovician sea-level drop and rise. Basin rebound can conceivably comprise 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 and others, 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

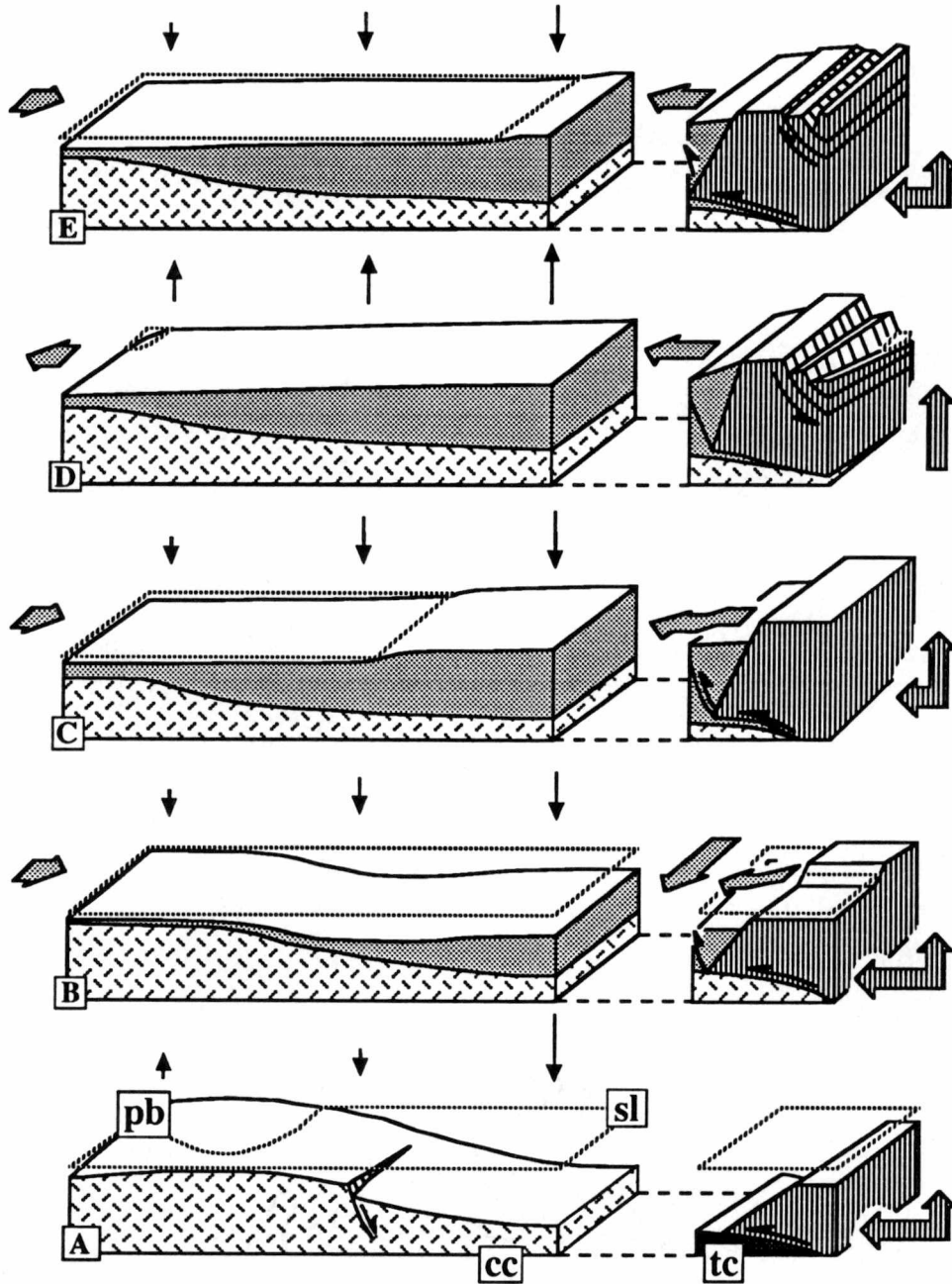
The interpretation of flexural isostatic rebound of the Taconic foredeep as the causative mechanism for the development of the "Tuscarora unconformity" has significant implications for the evolution of the Taconic orogen and its associated foredeep (Figure 2-3). Correlation of phases of thrusting and 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 (i.e., Drake and others, 1989; Horton and others, 1989; Hatcher, 1989). I 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 and others, 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 (Figure 2-3A) 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 sea level 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 sea level, due to its climbing up the continental-margin ramp and to the 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),

Figure 2-3: 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 vs. 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.

FOREDEEP - OROGEN



while distal and lateral shallow-marine areas were dominated by storm deposits ("tempestitic" Martinsburg Formation and Reedsville Shale; Kreisa, 1981). This foreland-flysch stage (Figure 2-3B) 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 (Figure 2-3C). The orogen was raised appreciably above sea level 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; see discussion in Chapter 3; Figure 2-3C).

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 (Figure 2-3D). 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 and others, 1989). I have 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 (Figure 2-3E). 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 analog 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 analog 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.

CHAPTER 3

THE TACONIC FOREDEEP AS SEDIMENT SINK AND SEDIMENT EXPORTER: IMPLICATIONS FOR THE ORIGIN OF THE WHITE QUARTZARENITE BLANKET (UPPER ORDOVICIAN-LOWER SILURIAN) OF THE CENTRAL AND SOUTHERN APPALACHIANS

PREAMBLE

This chapter focuses on the regionally extensive quartzarenite blanket (Tuscarora and Clinch Sandstones; Figure 3-1) of the central and southern Appalachians. This quartzarenite blanket is contained within the Martinsburg-Shawangunk clastic wedge (Thomas, 1977), which represents the fill of a foredeep associated with the Taconic orogeny in the central Appalachians. I attempt to show that this blanket is not homogeneous, but is composed of genetically distinct components, instead. Each of these components is thought to be linked to distinct stages in the evolution of the Taconic orogen and its adjacent foredeep, and also to eustatic sea-level fluctuations. During the course of this coupled orogen-foredeep evolution, quartz-rich detritus was either clearly confined within the Taconic foredeep, reached the basin fringe, or at times may have spilled over into areas adjacent to the active foredeep. This interpretation sheds new light upon the regional stratigraphy of the area of overlap between the central and southern Appalachians, and redefines the stratigraphic relationship between the Clinch and Tuscarora Sandstones. The results also contribute to the continuing discussion of the tectonics of the central Appalachians and its manifestation within the foreland area. Of significance for foredeeps in general is the emphasis that "homogeneous" sandstone blankets might hide a more complex evolutionary history not only with respect to eustatic sea-level changes, but also with respect to the tectonics of the orogen and the resulting behavior of the foredeep.

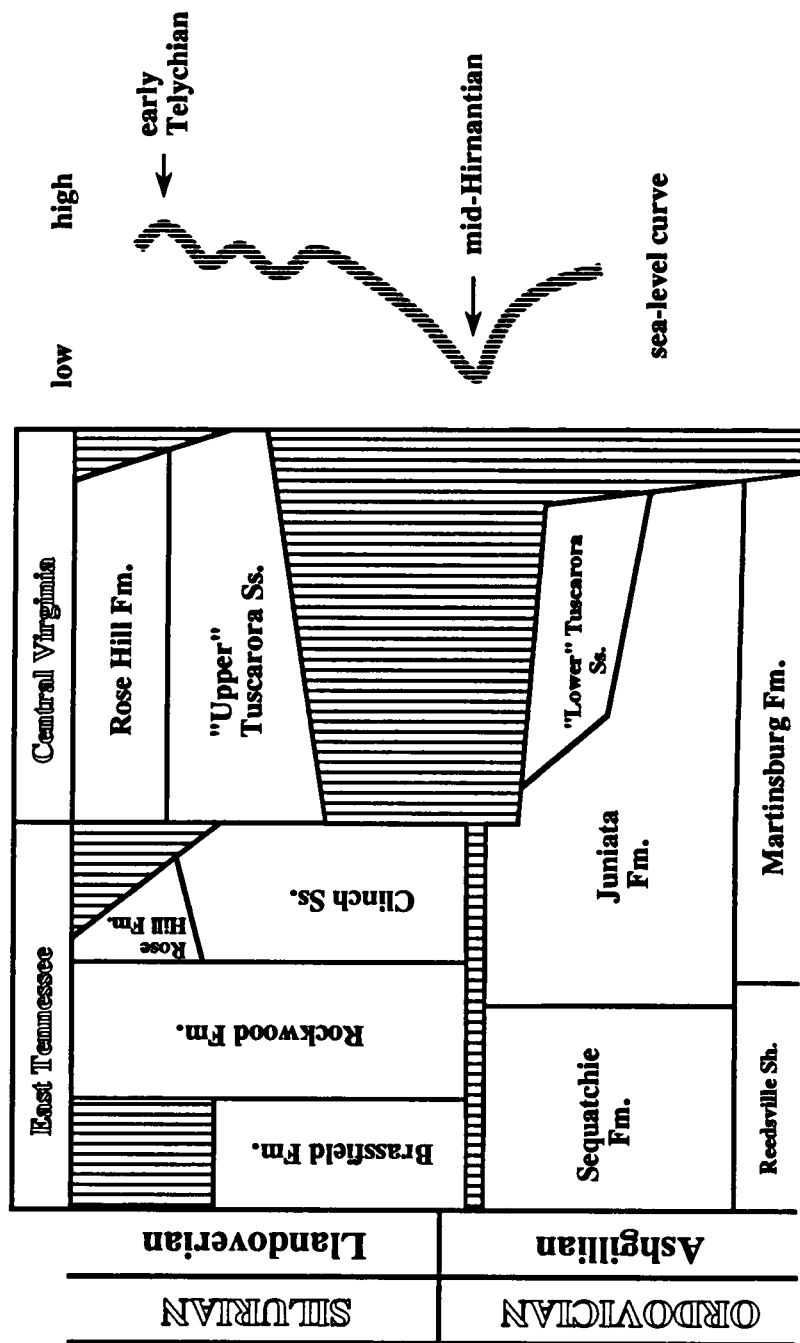


Figure 3-1. Interpretive correlation chart for Upper Ordovician/Lower Silurian stratigraphic units from southwestern Virginia to eastern Tennessee. Sea-level curve is based on Johnson and others (1991). Lacunae are indicated by vertical ruling.

REGIONAL STRATIGRAPHY AND SEDIMENTOLOGY

The following paragraphs concisely summarize the stratigraphy and present a succinct sedimentologic interpretation of the uppermost Ordovician to Lower Silurian deposits (Figure 3-1) in southwestern Virginia and extreme southwestern Virginia/eastern Tennessee. More detailed process-sedimentologic interpretations of the discussed stratigraphic units are provided in Chapters 4 and 5 for southwestern Virginia, and by Driese (Driese, 1988, Driese and others, 1991) for eastern Tennessee. Significant gaps in preserved strata are caused by the "Tuscarora unconformity" in southwestern Virginia, and the Devonian Wallbridge Discontinuity in Virginia and Tennessee (Figure 3-1). These unconformities cut out parts of the "lower" Tuscarora Sandstone, Juniata Formation, and Martinsburg Formation ("Tuscarora unconformity"), and parts of the "lower" and "upper" Tuscarora Sandstone, Clinch Sandstone, and Rose Hill Formation (Wallbridge Discontinuity).

Southwestern Virginia

Tuscarora Sandstone. The Upper Ordovician to Lower Silurian clastic deposits of southwestern Virginia (Figure 3-1) are part of the Taconic foreland molasse. The Tuscarora Sandstone unconformably overlies the Martinsburg Formation in the southeastern (proximal) outcrop belts (Figure 3-2; outcrops at Fagg and Catawba Mountain), and conformably overlies the Juniata Formation in the medial and northwestern (distal) outcrop belts, except at the Gap Mills locality (Figure 3-2). It was discovered recently that the prominent unconformity at the base of the Tuscarora Sandstone in the proximal outcrop belt can be traced throughout the Valley and Ridge (Bambach, 1987; see Chapter 2). This unconformity, named the "Tuscarora unconformity" by Dorsch and others (1990), rests within the Tuscarora Sandstone in the medial and distal outcrop belts (except at the Gap Mills locality), and divides the Tuscarora Sandstone into the sedimentologically distinct "lower" and "upper" Tuscarora Sandstone (Bambach, 1987; Dorsch and others, 1990; see Chapter 2; Figure 3-3A).

The "lower" Tuscarora Sandstone intertongues with red beds of the Juniata Formation, and is considered a facies equivalent of the upper Juniata Formation (see Chapter 4). The present distribution of the "lower" Tuscarora Sandstone reflects original depositional geometry (decreasing thickness away from the source area in the southeast/east)

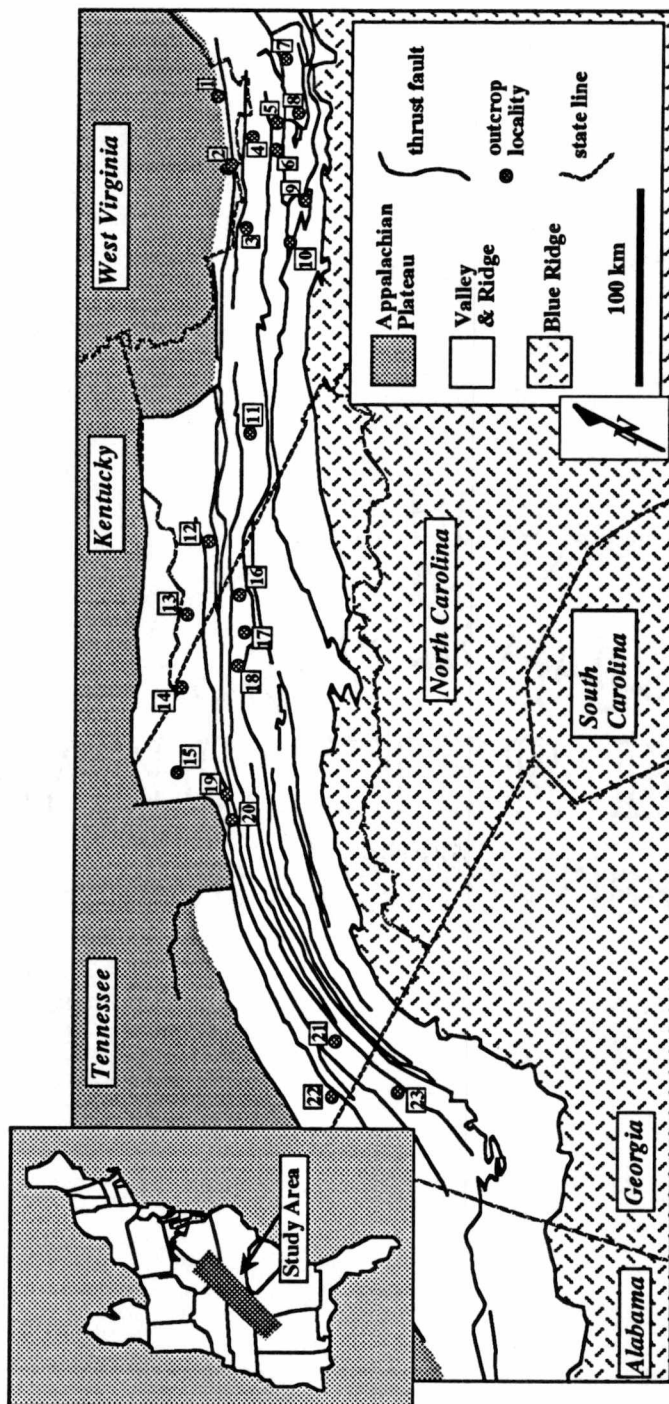
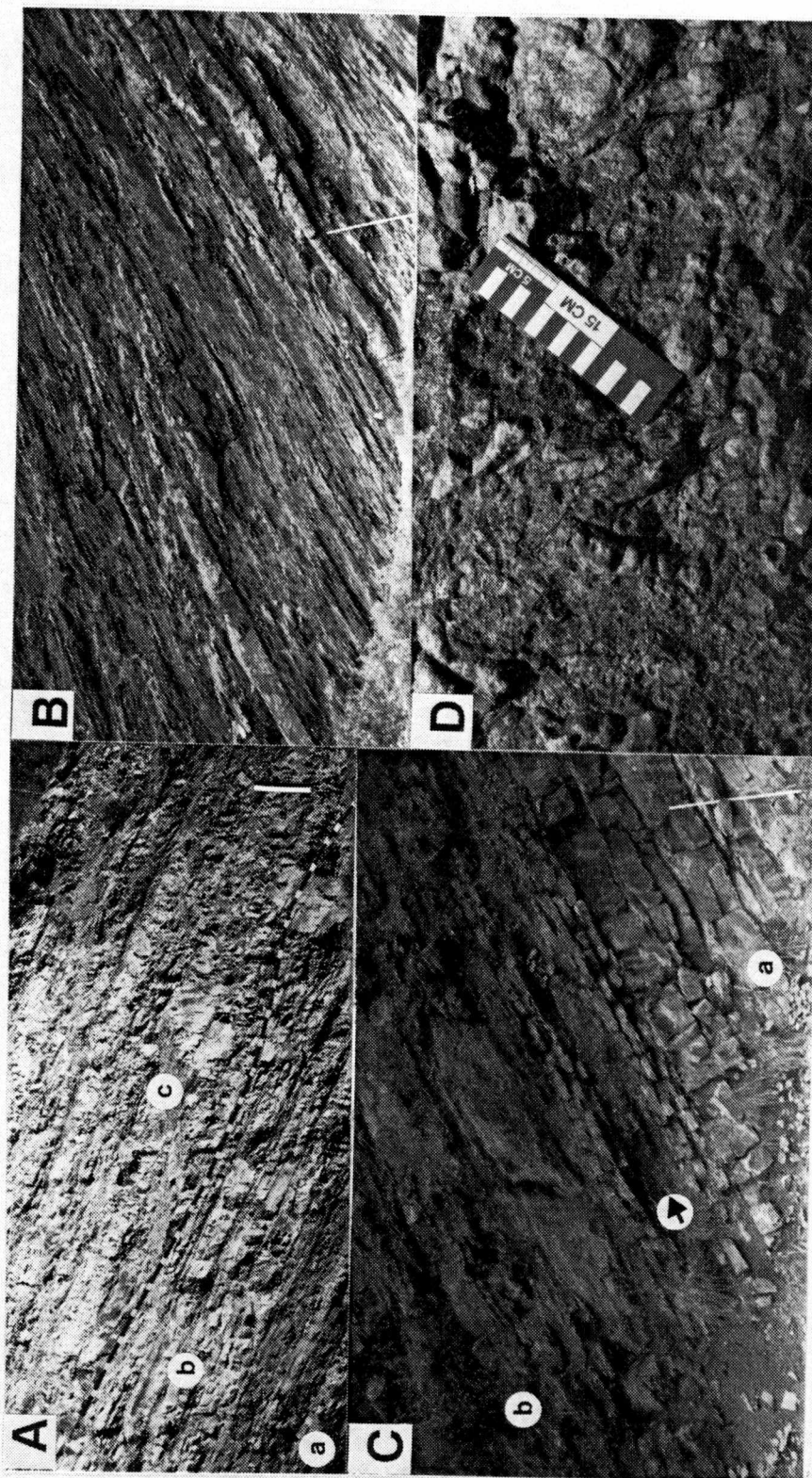


Figure 3-2. Location map of the study area in the Appalachian Valley and Ridge from southwestern Virginia to southeastern Tennessee. Outcrop localities are: 1 - Gap Mills, 2 - Narrows, 3 - South Gap, 4 - Cascades, 5 - Gap Mountain, 6 - McCoy, 7 - Catawba Mountain, 8 - Fagg, 9 - Draper Mountain, 10 - Cove Mountain, 11 - Little Moccasin Gap, 12 - Stickleyville (Powell Mountain), 13 - Hagan, 14 - Cumberland Gap, 15 - La Follette, 16 - Little War Gap, 17 - Flat Gap, 18 - Beans Gap, 19 - Lone Mountain, 20 - Melton Lake, 21 - Green Gap (Whiteoak Mountain), 22 - Tiftonia, 23 - Ringgold.

Figure 3-3: Field appearance of the stratigraphic units and the two lithosomes. (A) Juniata Formation (a), "lower" Tuscarora Sandstone (b) and "upper" Tuscarora Sandstone (c) at South Gap, southwestern Virginia; stippled line indicates location of the "Tuscarora unconformity"; scale bar is approx. 4 m. (B) Rose Hill Formation at South Gap, southwestern Virginia; sandstone beds encased in mudstone represent tempestites; staff is approx. 1.30 m. (C) Marine-flooding surface (at arrow) separating "upper" Tuscarora Sandstone (a) from overlying Rose Hill Formation (b) at South Gap, southwestern Virginia; arrow indicates coarse-grained interval (very coarse quartz grains, phosphatic pebbles, complete bioturbation) immediately above the flooding surface; staff is 1.50 m. (D) Bedding-plane view of top of "upper" Tuscarora Sandstone at McCoy, southwestern Virginia; overlying mudstone and shale of the Rose Hill Formation is weathered away, exposing the bedding surface covered by large (unidentified) burrows; the contact between the two stratigraphic units corresponds to the marine-flooding surface. (E) Clinch Sandstone at Stickleyville (Powell Mountain), extreme southwestern Virginia; the contact between the Poor Valley Ridge Sandstone Member (a) and the subjacent Hagan Shale Member (b) is indicated by the arrow; scale bar is approx. 2.0 m. (F) Contact between Hagan Shale (a) and Sequatchie Formation (b) at Lone Mountain, eastern Tennessee; the distinct contact is indicated by the arrow and corresponds to a glacio-eustatic sequence boundary; the basal transgressive sandstone (c) forms the base of the Hagan Shale; the top portion of the Sequatchie Formation is composed of bioturbated greenish and maroon mudstone with intercalated calcarenite beds; paleosols are developed at this stratigraphic position in more proximal outcrop belts to the southeast; staff is 1.20 m. (G) Middle part of the Rockwood Formation at Melton Lake, eastern Tennessee; a thick unit of Poor Valley Ridge Sandstone-type bedset (outlined by the arrows) is inserted into the mudstone-dominated heterolithic Rockwood Formation; the upper 50 cm of this bedset is formed by oolitic ironstone associated with a marine-flooding surface; the upper arrow marks three-dimensional small dunes developed and preserved on top of the ironstone bed; staff is 1.60 m.



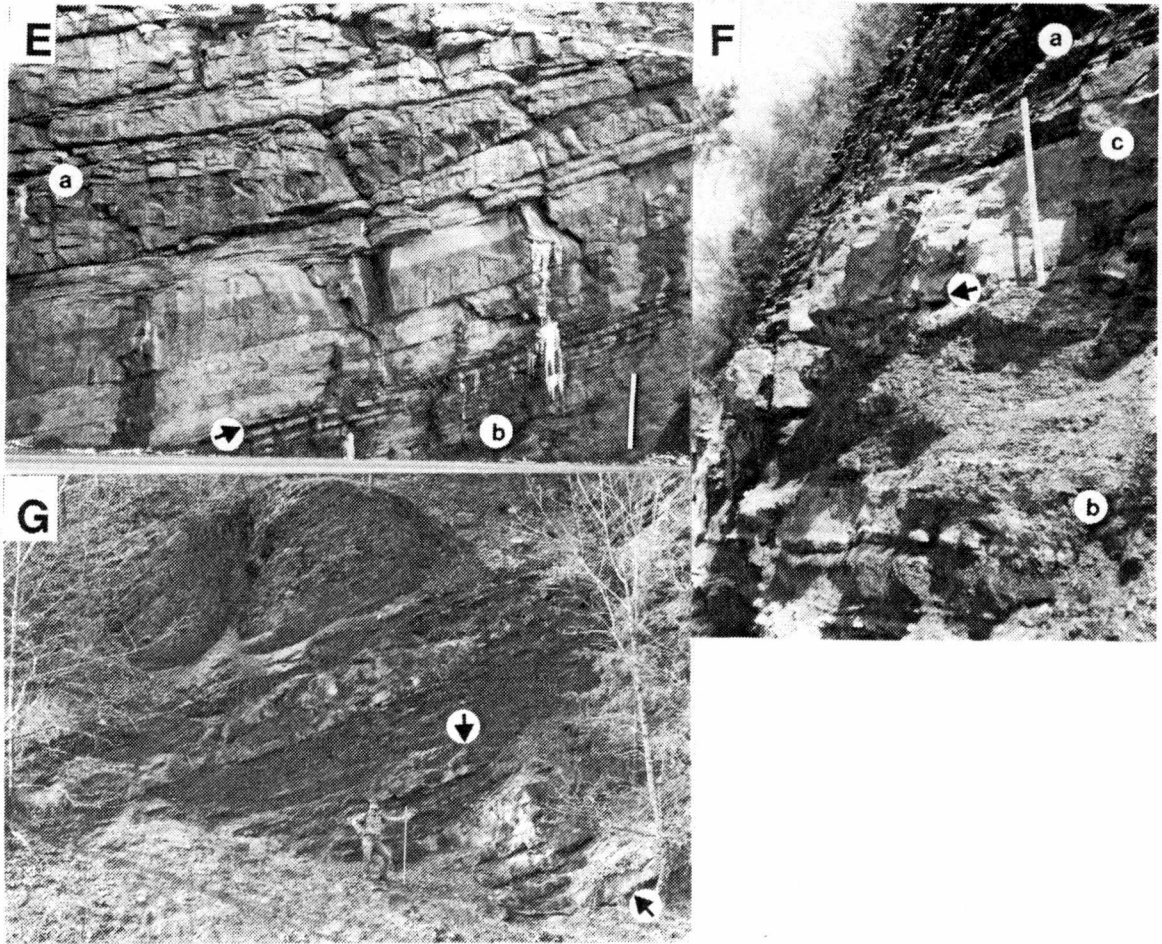


Figure 3-3 continued

and magnitude of erosional removal beneath the "upper" Tuscarora Sandstone (see Chapters 2 and 4). The "lower" Tuscarora Sandstone is a predominantly medium- to thick-bedded, medium- to coarse-grained, partly pebbly, yellowish white quartzarenite. Greenish gray mudstone and siltstone are interbedded with the sandstone. Stratification is dominated by trough cross stratification. One example of hummocky cross stratification occurs in fine-grained sandstone at the Cove Mountain locality. Paleocurrent indicators are directed toward the west to north (see Chapter 4; Whisonant, 1977). The "lower" Tuscarora Sandstone is devoid of body fossils, but trace fossils are very abundant. The trace fossil suite is dominated by *Monocraterion*, *Skolithos* and *Rusophycus*, but *Cruziana*, *Planolites*, and a few examples of *Arthropycus* also occur. Some intervals of this stratigraphic unit are completely bioturbated.

The "upper" Tuscarora Sandstone overlies with a clear disconformity Martinsburg Formation, "lower" Tuscarora Sandstone, or Juniata Formation (Figure 3-1), and thins from distal outcrop belts in the northwest toward proximal outcrop belts in the southeast (Bambach, 1987; Dorsch and others, 1990; see Chapter 2). Throughout the Valley and Ridge, a conglomeratic sandstone to sandy conglomerate marks the onset of the "upper" Tuscarora Sandstone. At Catawba Mountain, however, ca. 3 m of medium-grained, white sandstone is sandwiched between the conglomerate and the Martinsburg Formation (see Chapter 5). The "upper" Tuscarora Sandstone is characterized by medium- to thick-bedded, clean, white, (pebbly) coarse- to medium-grained quartzarenite. Thin, dark-gray to grayish black siltstone, fine-grained sandstone, and mudstone beds occur sparingly. At distal outcrop belts, thinner bedded, fine-grained quartzarenite with thin mudstone beds comprise the upper part of this stratigraphic unit. The lower, coarser grained part of the "upper" Tuscarora Sandstone exhibits predominantly trough cross stratification, with paleocurrent indicators directed toward the west and north (Whisonant, 1977; see Chapter 5), much like the paleocurrent indicators for the "lower" Tuscarora Sandstone. The upper, finer grained part of this stratigraphic unit is composed of hummocky cross-stratified beds, which are amalgamated to varying degrees (see Chapter 5). Body fossils are absent, except for occurrences of acritarchs in rare mudstone and siltstone beds, and a few brachiopods at the top of the stratigraphic section at Narrows. Trace fossils are abundant with *Arthropycus*, *Monocraterion*, *Skolithos*, *Arenicolites*, and a few *Rusophycus* and *Phycodes* dominating the lower part, whereas *Skolithos* is dominant in the upper part of the "upper" Tuscarora Sandstone.

Hayes (1974) documented that the Tuscarora Sandstone in southwestern Virginia constitutes almost exclusively mature to supermature siliceous quartzarenite. The framework-grain population is dominated by monocrystalline and polycrystalline quartz, and feldspar is virtually absent; although lithic fragments occur, they do not constitute a significant portion of the framework-grain population. Gravel within the Tuscarora Sandstone is composed of vein quartz and of polycrystalline quartz with sutured subgrain boundaries (Hayes, 1974). Of special importance for provenance interpretations are lithic fragments and their stratigraphic distribution, as exemplified by a suite of sandstone samples taken from the tunnel through East River Mountain along I-77, along strike to the southwest of the Narrows outcrop (Figure 3-2; Hayes, 1974). Sedimentary lithic fragments (chert, siltstone, indurated mudstone) occur in the "lower" Tuscarora Sandstone and are absent in the "upper" Tuscarora Sandstone. Polycrystalline quartz with prominent sutured subgrain boundaries, interpreted as metamorphic lithic fragments, occurs throughout the Tuscarora Sandstone, but increases in abundance up section (Hayes, 1974). Schistose lithic fragments (stretched polycrystalline quartz with either muscovite or biotite) occur in the upper half of the "upper" Tuscarora Sandstone at the tunnel section.

The "lower" Tuscarora Sandstone of southwestern Virginia constitutes the upper segment of a coarsening-upward succession, which started within the Martinsburg Formation. This can be best appreciated at the Cove Mountain locality, where the thickest section of "lower" Tuscarora Sandstone is preserved. The "lower" Tuscarora Sandstone also displays a coarsening trend toward the southeast/east, the inferred location of the source area (see for example, Butts, 1940; Amsden, 1955; Pettijohn, 1970; Dennison, 1970; Hayes, 1974; Whisonant, 1977). Based on stratification types and trace fossils, the "lower" Tuscarora Sandstone is interpreted as storm-dominated shallow marine deposits seaward of the shoreface. The coarsening-upward succession might have shallowed to subaerial conditions, but potential sedimentological evidence for subaerial exposure is not preserved due to erosional removal beneath the "upper" Tuscarora Sandstone (see Chapter 4).

The "upper" Tuscarora Sandstone in southwestern Virginia is interpreted as storm-dominated upper to lower shoreface deposits. This fining- and thinning-upward unit represents a complete transgressive sequence (transgressive systems tract, retrogradational parasequence; Dorsch and Driese, 1992a; see Chapter 5) onlapping onto a subaerial erosion surface. The sequence boundary ("Tuscarora unconformity") at the base of the "upper" Tuscarora Sandstone and the transgressive surface are amalgamated and no deposits of a lowstand systems tract are preserved (see Chapter 5).

Rose Hill Formation. The Rose Hill Formation conformably overlies the "upper" Tuscarora Sandstone along a marked and distinct contact. This Formation represents a heterolithic stratigraphic unit of olive-brown or maroon-red mudstone with intercalated sandstone and siltstone (Figure 3-3B). The intercalated sandstone beds are either fine-grained, thin- to very thinly bedded and tobacco-brown to maroon-red, or coarser grained, rarely more than thin- to medium-bedded, and maroon-red. The maroon-red lithologies are predominantly hematitic. The finer grained, sharp-based sandstone beds are dominated by hummocky cross stratification and wave-ripple cross stratification. They are typically scattered throughout mudstone intervals. Some beds contain a basal bioclastic lag and display pronounced normal grain-size grading. The coarser grained sandstone beds exhibit high-angle cross stratification and constitute the principal components of sandstone-dominated intervals within the Rose Hill Formation. Both sandstone and mudstone exhibit different degrees of bioturbation up to complete obliteration of any stratification. Fossils are abundant throughout the Rose Hill Formation and include brachiopods, ostracodes, trilobites, crinoid ossicles, some graptolites, tentaculites and acritarchs. Lampiris (1975) also mentions gastropods, cephalopods and pelecypods as occurring in the Rose Hill Formation. Identifiable trace fossils comprise *Planolites*, *Skolithos*, *Monocraterion*, some *Chondrites*, *Teichichnus*, *Rusophycus* and *Cruziana*.

The Rose Hill Formation is composed of shallow-marine deposits of deeper water than the "upper" Tuscarora Sandstone. The fine-grained hummocky cross-stratified sandstone beds represent tempestites of varying distality from the source area, whereas the coarser grained, high-angle cross-stratified sandstone beds probably represent storm-dominated deposits more proximal to the shoreline. All of the sandstone beds are contained within mudstone and shale, which constitute the fairweather deposits between storm events. The distinct contact between the Rose Hill Formation and the Tuscarora Sandstone throughout the study area is interpreted as a marine-flooding surface (see Chapter 5; Figure 3-3C, D).

Chronostratigraphic Framework. Biostratigraphic data for the Tuscarora Sandstone are absent, because of a lack of body fossils. The "lower" Tuscarora Sandstone interfingers with the Juniata Formation which succeeds the *Orthorhynchula* zone at the top of the Martinsburg Formation. The Juniata Formation is customarily placed into the Ashgillian (Figure 3-1; Butts, 1940, Twenhofel and others, 1954, Diecchio, 1985, Springer and Bambach, 1985, Dennison and others, 1992). Evidence for the Hirnantian (latest

Ashgillian; Figure 3-1) glacio-eustatic sea-level events, which are so prominently developed in eastern Tennessee (see below), cannot be detected in the preserved strata of the Juniata Formation and "lower" Tuscarora Sandstone. Sedimentological evidence for these events probably was developed in southwestern Virginia, but was eroded away during development of the subaerial exposure surface, which later became the "Tuscarora unconformity" upon deposition of the "upper" Tuscarora Sandstone (see Chapters 2 and 5). Deposition of the preserved "lower" Tuscarora Sandstone, therefore, had to start before the early Hirnantian, providing a minimum lower age limit for the Tuscarora Sandstone (Figure 3-1).

The magnitude of the lacuna associated with the "Tuscarora unconformity" can only be estimated (Dennison and others, 1992; R. Bambach, pers. comm., 1992), because dateable fossils are missing. The marine-flooding surface marking the contact between the Tuscarora Sandstone and the Rose Hill Formation (Figure 3-3C) is placed into the early Telychian (Late Llandoveryan; Figure 3-1; Lampiris, 1975; R. Bambach, pers. comm., 1992). Rapid transgression and development of the marine-flooding surface at the base of the Rose Hill Formation in southwestern Virginia, therefore, can be related to the documented eustatic sea-level rise in the earliest Telychian (Figure 3-1; Johnson and others, 1991).

Eastern Tennessee And Extreme Southwestern Virginia

The Silurian stratigraphy of extreme southwestern Virginia and northeastern Tennessee was summarized most recently by Miller (1976). The Clinch Sandstone of extreme southwestern Virginia is differentiated into a lower Hagan Shale Member and an upper Poor Valley Ridge Sandstone Member (Miller and Fuller, 1954; Figure 3-3E). To the southeast, in the outcrop belt closest to the Blue Ridge, Miller (1976) used Clinch Sandstone (undifferentiated) without its bipartite division developed in outcrops to the northwest. The lithostratigraphic term Rockwood Formation was applied in outcrop belts to the west and southwest of the Clinch Sandstone (differentiated and undifferentiated; Miller, 1976). In contrast to Miller (1976), Driese (1987, 1988, unpublished report) applied the bipartite nomenclature of the Clinch Sandstone also in the southeastern-most Silurian outcrop belt in Tennessee (outcrops at Beans Gap, Flat Gap, Little War Gap; Figure 3-2). He further extended the Rockwood Formation into outcrop belts, whose Silurian strata were previously referred to by Miller (1976) as Hagan Shale and Poor Valley Ridge Sandstone.

The following synopsis of the stratigraphy and sedimentology of the Clinch Sandstone, the Rose Hill Formation, and the Rockwood Formation in eastern Tennessee and

extreme southwestern Virginia is taken from Driese (1987, 1988, unpublished report) and Driese and others (1991), unless indicated otherwise.

Clinch Sandstone. The Clinch Sandstone with its lower and upper member occurs in extreme southwestern Virginia (outcrops Little Moccasin Gap, Stickleyville, Hagan; Figure 3-2) and in the southeastern outcrop belts in eastern Tennessee (outcrops Little War Gap, Beans Gap, Flat Gap; Figure 3-2). The Clinch Sandstone grades into the Rockwood Formation toward the west and southwest (Rodgers, 1953; Dennison and Boucot, 1974; Miller, 1976; Driese, 1987, 1988). The Poor Valley Ridge Sandstone Member is markedly different from the underlying Hagan Shale Member: the Poor Valley Ridge Sandstone is dominated by coarser grained, light-colored, quartzarenitic sandstone, whereas the Hagan Shale is comprised of mudstone and shale interbedded with sandstone (Figure 3-3E, F).

The Hagan Shale Member of the Clinch Sandstone unconformably overlies the Juniata Formation (Figures 3-1, 3-3 F). It is a heterolithic stratigraphic unit with pronounced bioturbation up to complete obliteration of any primary sedimentologic features. Gray-green mudstone, siltstone and shale volumetrically dominate over sandstone. Brownish-gray sandstone is predominantly thin-bedded, fine- to very fine-grained, and displays horizontal stratification, wave-ripple cross stratification, and hummocky cross stratification. Hematitic-red sandstone beds occur sparingly. Trace fossils encountered include *Planolites*, *Palaeophycus*, *Chondrites*, and locally *Cruziana* and *Rusophycus*. In the upper part of the Hagan Shale some bioturbated, medium-grained sandstone with relict trough cross stratification occurs. These sandstone beds exhibit abundant *Skolithos* and *Monocraterion* traces.

The Poor Valley Ridge Sandstone Member of the Clinch Sandstone conformably overlies the Hagan Shale Member. The Poor Valley Ridge Sandstone is predominantly composed of light-grey, medium- to very coarse-grained quartzarenite. Thin lags of granules and pebbles cap a few sandstone beds. Interbedded siltstone and mudstone are of minor importance volumetrically. The sandstone beds are mostly medium- to thick-bedded, and display prominent, commonly compound, medium- to large-scale planar-tabular and trough cross stratification. Some beds of finer grained sandstone exhibit ripple cross stratification or horizontal stratification. At Beans Gap (Figure 3-2), thin mudstone layers drape some of the trough-shaped foresets. Paleocurrent readings from high-angle cross stratification throughout the Poor Valley Ridge Sandstone indicate a paleoflow direction to the northwest and west. The trace fossil assemblage includes abundant *Skolithos*,

Diplocraterion, *Planolites*, *Palaeophycus*, *Arthropycus*, and *Rusophycus*. Body fossils, on the other hand, are absent, except for a few poorly preserved brachiopods in extreme southwestern Virginia (Miller and Fuller, 1954). Some beds within the Poor Valley Ridge Sandstone are almost completely bioturbated and appear "massive". At Stickleyville, very fine- to fine-grained, thin- to medium-bedded, red sandstone occurs locally in the upper part of this member. The sandstone beds are wave ripple cross-stratified and horizontally stratified. These beds are lavishly bioturbated and exhibit polygonal desiccation cracks.

The sandstones of the Hagan Shale Member and the Poor Valley Ridge Sandstone Member can also be differentiated petrographically (Figure 3-4; based on Schoner, 1985, Marks, 1987, and Fischer, 1987). The framework-grain population of medium-, fine-, and very fine-grained sandstone samples of the Poor Valley Ridge Sandstone Member is exclusively quartz (predominantly monocrystalline quartz) for 95% of the analyzed samples, and feldspar is virtually absent. Gravel horizons, found only in the Poor Valley Ridge Sandstone, are made up exclusively of vein quartz. Schoner (1985) furthermore observed an upward increase in both textural (degree of roundness, grain-size sorting) and compositional (modal percentage of monocrystalline quartz) maturity within the Clinch Sandstone at Beans Gap.

The Hagan Shale Member represents offshore storm-sandstone beds (tempestites) dispersed within fairweather mudstone. The depositional environment was similar to that of the Rose Hill Formation of southwestern Virginia (see above), the Rose Hill Formation of extreme southwestern Virginia, and the Rockwood Formation of eastern Tennessee (see below). The Poor Valley Ridge Sandstone is interpreted to represent northwest-migrating, marine, subaqueous dunes. Episodic storm currents were responsible for offshore-directed bedform migration away from the shoreface. Water depth for the dunes of the Poor Valley Ridge Sandstone was shallower than for the storm and fairweather deposits of the Hagan Shale. Preserved desiccation cracks at the top of the Poor Valley Ridge Sandstone at Stickleyville indicate filling of the available accommodation space and intermittent subaerial emergence on coastal sandflats. Shallower water might also be indicated by mudstone-draped foresets in some beds at Beans Gap, indicating probable tidal influence.

Rose Hill Formation. The Rose Hill Formation conformably succeeds the Poor Valley Ridge Sandstone Member of the Clinch Sandstone. In most outcrops, however, the Rose Hill Formation is missing due to erosional removal beneath the Devonian Wallbridge

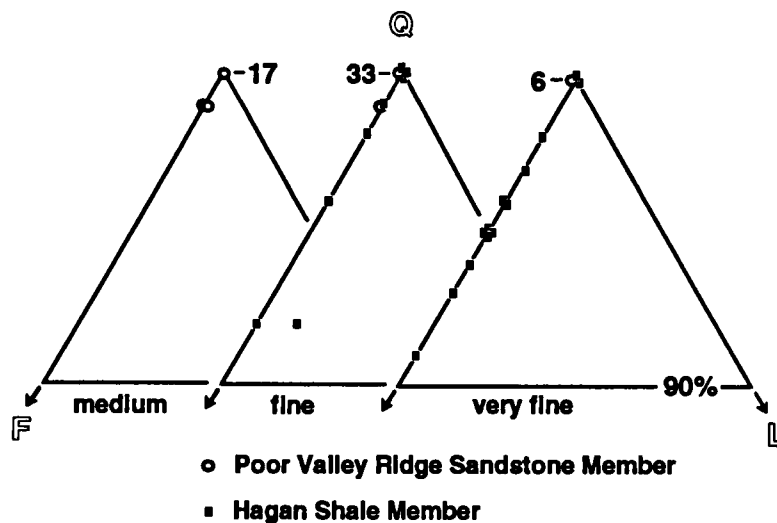


Figure 3-4. QFL-diagrams for medium-, fine-, and very fine-grained sandstone samples from the Poor Valley Ridge Sandstone Member and Hagan Shale Member of the Clinch Sandstone. Modal percentages of framework grains for sandstone samples were obtained by point counting (300 points per thin section). Only the >90%-quartz area of the QFL-diagrams is shown. Numbers at the Q-apex indicate multiple sample plots. Based on Schoner (1985), Marks (1987), and Fischer (1987).

Discontinuity, or due to erosion associated with the present-day land surface. Where remnant deposits of the Rose Hill Formation are present, such as at the Little Moccasin Gap, Hagan, or Stickleyville outcrop localities (Figure 3-2), the Formation is very similar in character to the Rose Hill Formation of southwestern Virginia (Miller, 1976). Fossils include brachiopods, ostracodes, pelecypods, and trilobites (Miller and Fuller, 1954). As in southwestern Virginia, the Rose Hill Formation is a heterolithic unit with thin-bedded tempestites interbedded with mudstone or shale. Coarser grained and thicker bedded hematitic sandstone beds occur at different levels within the Formation. Bioturbation is ubiquitous and in some cases has caused complete obliteration of any physical stratification.

Rockwood Formation. The Rockwood Formation is the lateral (to the west and southwest) lithostratigraphic equivalent of the Clinch Sandstone and the Rose Hill Formation (Rodgers, 1953; Dennison and Boucot, 1974). The lithostratigraphic term is applied in areas where the sandstone succession of the Poor Valley Ridge Sandstone Member of the Clinch Sandstone is not identifiable as a separate and mappable lithostratigraphic unit. In these areas (outcrops at Cumberland Gap, Green Gap, Melton Lake, and Lone Mountain; Figure 3-2) the Hagan Shale Member of the Clinch Sandstone and the Rose Hill Formation join due to pinch-out of the Poor Valley Ridge Sandstone Member of the Clinch Sandstone, and form the Rockwood Formation (Miller, 1976).

The Rockwood Formation is a heterolithic succession of dominantly gray-green shale and mudstone, interbedded with sandstone, siltstone, some sandy calcarenite, and rare hematitic-red sandstone. Sharp-based, dark-brown sandstone beds are mostly fine- to very fine-grained, and thin- to medium bedded. Stratification is dominated by hummocky cross stratification, wave-ripple cross stratification and horizontal stratification. Basal bioclastic lags, normal grain-size grading, and gutter casts at the base of sandstone beds are common. At certain levels within the Rockwood Formation, hummocky cross-stratified sandstone beds become medium- to thick-bedded and amalgamated, and form sandstone-dominated intervals of variable thickness. Hematite-cemented, fine- to coarse-grained sandstone and calcarenite occur scattered throughout the Formation (Driese and Bolton, 1990). Fossils are abundant and include brachiopods, pelmatozoans, bryozoans, and trilobites. They are mostly encountered as fragments comprising the bioclastic lags of some sandstone beds. Trace fossils are dominated by *Planolites*, *Chondrites*, and *Palaeophycus*. Bioturbation is ubiquitous, but never destroys shale fabric or sandstone stratification.

Light-colored, medium- to coarse-grained, and predominantly medium- to thick-bedded sandstone beds with prominent high-angle cross stratification occur within the middle part of most Rockwood stratigraphic sections (Figure 3-3G). The bedsets rest with sharp-erosive contact on mudstone interspersed with tempestites, and are commonly capped by a hematitic sandstone bed. The bedsets are overlain in turn by interbedded mudstone and tempestites. At Green Gap, most of the sandstone beds are stained red (Easthouse and Driese, 1988). These sandstone beds are reminiscent of the sandstone facies, which constitutes the bulk of the Poor Valley Ridge Sandstone Member of the Clinch Sandstone and, likewise, indicate paleocurrent flow toward the northwest and west.

The Rockwood Formation is interpreted as storm-dominated, shallow-marine deposits. Offshore mud deposition within the Early Silurian epicontinental seaway was episodically interrupted by storms, producing the heterolithic succession of fairweather mudstone and shale punctuated by sandy tempestites. The bedsets of Poor Valley Ridge-like sandstone most likely represent shallow-marine shoreface deposits.

'Basal Transgressive Sandstone'. The base of the Hagan Shale Member of the Clinch Sandstone and the base of the Rockwood Formation are marked by a distinctive, thin (≤ 3 m), dark-brown sandstone, informally termed the 'basal transgressive sandstone' (Gogola, 1990; Driese and others, 1991; Figure 3-3F). This unit is regionally extensive and can be traced from extreme southwestern Virginia, through eastern Tennessee, into northern Georgia and Alabama, where it resides at the base of the heterolithic Red Mountain Formation (Gogola, 1990; Bolton, 1992). The sandstone is very fine- to fine-grained, with local concentrations of sand- to pebble-sized phosphate grains, chert grains, Juniata or Sequatchie Formation lithiclasts, quartz grains, fossil fragments (brachiopods, bryozoans, pelmatozoans), and some glauconite (Gogola, 1990). The sandstone is complex internally, displays high-angle cross stratification and wave-ripple cross stratification, and is bioturbated to varying degrees (up to 100%; Gogola, 1990). The 'basal transgressive sandstone' is overlain by shale with interbedded thin tempestites of the Hagan Shale (Figure 3-3F) or Rockwood Formation in eastern Tennessee and extreme southwestern Virginia. The unit overlies the Juniata or Sequatchie Formation, which display evidence of subaerial emergence and erosion. Vertisol-like paleosols are developed in the top part of estuarine to tidal-flat deposits of the Juniata Formation at Beans Gap and Stickleyville (Driese and Foreman, 1992; Figure 3-2). The 'basal transgressive sandstone' truncates the paleosols, and

marine burrows reach down from the overlying transgressive sandstone sheet into the upper part of the decapitated paleosols (Driese and Foreman, 1991).

The 'basal transgressive sandstone' represents a regionally extensive, transgressive sandstone sheet, which is thought to have developed during erosional shoreface retreat (Gogola, 1990). The sandstone sheet is considered to constitute an amalgam of shoreface to proximal inner offshore deposits (Gogola, 1990). Complete bioturbation and authigenic glauconite and phosphate point to a low sedimentation rate. The coarser grains and most of the finer sediment are considered to be eroded and reworked material from the underlying red beds of the Juniata and Sequatchie Formations. The sandstone sheet can be termed a condensed transgressive lag. The overlying deposits of the Hagan Shale Member or the Rockwood Formation represent more distal offshore environments, in marked contrast to the shallow-marine environments represented by the 'basal transgressive sandstone' (Gogola, 1990).

Chronostratigraphic Framework. The Juniata Formation and the Sequatchie Formation are regarded as middle and late Ashgillian in age (Rodgers, 1953; Twenhofel and others, 1954; Miller and Fuller, 1954; Milici and Wedow, 1977), whereas the Clinch Sandstone with its two members and the Rockwood Formation are placed into the Llandoveryan (Butts, 1940; Rodgers, 1953; Berry and Boucot, 1970). The 'basal transgressive sandstone' and the underlying exposure surface are thought to be related to the glacio-eustatic sea-level events in the Ashgillian (Gogola, 1990; Dorsch and others, 1991; Driese and others, 1991; Figure 3-1). Biostratigraphic data from outcrops close to the Appalachian Plateau indicate that strata underlying the 'basal transgressive sandstone' reach into the upper Ashgillian, whereas strata directly above the 'basal transgressive sandstone' can be placed into the lowermost Llandoveryan (Gogola, 1990; Driese and others, 1991). The development of paleosols and subaerial exposure surfaces in the top part of the Juniata and Sequatchie Formations, therefore, can be correlated with the end-Ordovician eustatic sea-level fall linked to glaciation centered in present-day northern Africa (Sougy and Lécorché, 1963; Debyser and others, 1965; Bennacef and others, 1971). The 'basal transgressive sandstone', then, can be regarded as evidence for the swiftly ensuing eustatic sea-level rise due to ablation of the Saharan glaciers. These glacio-eustatic sea-level events occurred from the beginning of the Hirnantian to the mid-Hirnantian (Branchley, 1989; Figure 3-1). The 'basal transgressive sandstone' as a condensed transgressive lag is diachronous. The degree of diachroneity, however, can be regarded as small, because the

glacio-eustatic sea-level rise in the mid-Hirnantian is believed to have been rapid (Brenchley, 1989). The 'basal transgressive sandstone', therefore, might be considered as a *practical* chronostratigraphic marker, similar to some condensed shell deposits in the Miocene of Maryland (Kidwell, 1989). In addition, the 'basal transgressive sandstone' constitutes a convenient lithostratigraphic marker for the (approximate) placement of the Ordovician-Silurian systemic boundary throughout the southern Appalachians (Gogola, 1990; Driese and others, 1991). The chronostratigraphic placement of this systemic boundary, however, has to be sought in the lowermost part of the Rockwood Formation, Hagan Shale Member, and Red Mountain Formation. The exact temporal extent of the lacuna associated with the regional disconformity between Ashgillian red beds and the 'basal transgressive sandstone' cannot be ascertained, due to the paucity of adequate biostratigraphic data. The close temporal proximity of glacio-eustatic sea-level fall and rise within the Ashgillian (Brenchley, 1989; Brenchley and Storch, 1989), and the limited biostratigraphic data from outcrops close to the Appalachian Plateau (Gogola, 1990), however, makes it highly probable that the time not recorded by rock is rather small.

Biostratigraphic data from the Rockwood Formation indicate that it spans most of the Llandoveryan (Easthouse and Driese, 1988). The original temporal extent of this lithostratigraphic unit remains unknown, because it is truncated by the present-day erosion surface. Lack of biostratigraphic information renders it impossible to assign an age to the transition from Hagan Shale Member to Poor Valley Ridge Sandstone Member of the Clinch Sandstone. The Rose Hill Formation in extreme southwestern Virginia and eastern Tennessee seems to commence earlier than the Rose Hill Formation in southwestern Virginia. Occurrences of *Eocoelia hemisphaerica* within the lowermost Rose Hill Formation at Little Moccasin Gap (Miller 1976) and Hagan (Miller and Fuller, 1954, R. Bambach, unpublished data, pers. comm., 1992) indicate that deposition of Rose Hill Formation started before the Telychian (and before the earliest Telychian eustatic sea-level event), probably in the late to middle? Aeronian (based on the range of *E. hemisphaerica* as given by Bassett, 1989).

DEFINITION AND EXTENT OF REGIONAL LITHOSOMES

The stratigraphic units, which overlie the Upper Ordovician red-bed succession throughout the central and southern Appalachians, can be grouped into a 'White Sandstone

Lithosome' and a 'Heterolithic Lithosome' (Dorsch and Driese, 1992b). Both lithosomes are distinct in their characteristics (Table 3-1) and are of regional extent.

In southwestern Virginia, the Upper Ordovician red-bed succession is overlain by, and grades into, the 'White Sandstone Lithosome', which is split into two parts by the "Tuscarora unconformity" (Figure 3-5). The 'White Sandstone Lithosome' is succeeded by the 'Heterolithic Lithosome' along a distinct and sharp contact. Further to the southwest, in extreme southwestern Virginia and eastern Tennessee, a lower 'Heterolithic Lithosome' occurs between the Upper Ordovician red-bed succession and the onset of the 'White Sandstone Lithosome'. The 'Heterolithic Lithosome' commences with the 'basal transgressive sandstone' throughout the area (Figure 3-5). The 'White Sandstone Lithosome' in extreme southwestern Virginia and eastern Tennessee is completely encased within the 'Heterolithic Lithosome', which overall is the dominant lithosome in these areas. The contact between the two lithosomes is conformable (distinct to gradational) vertically, and intertonguing and pinching-out laterally. The regional distribution of the two lithosomes is depicted, furthermore, in three stratigraphic cross sections constructed perpendicular to structural strike (Figure 3-6). The thickness of the 'White Sandstone Lithosome' in southwestern Virginia (Figure 3-6, section A-A') is severely influenced by erosional removal of strata prior to deposition of the upper part of the lithosome. The 'White Sandstone Lithosome' in northeastern Tennessee (Figure 3-6, section B-B') does not contain the "Tuscarora unconformity" and thins markedly toward the northwest, where it pinches out into the 'Heterolithic Lithosome'. The present-day erosion surface and the Devonian Wallbridge Discontinuity renders it impossible to depict the remaining parts of the Silurian stratigraphic interval. It is reasonable to assume, however, that the 'Heterolithic Lithosome' extended to the southeast, eventually covering the 'White Sandstone Lithosome'. The cross section in southeastern Tennessee (Figure 3-6, section C-C') reveals that the 'White Sandstone Lithosome' thins markedly from the northeast to the southwest, and continues to thin toward the northwest/west.

The stratigraphic cross sections clearly show that the 'White Sandstone Lithosome' in Tennessee and extreme southwestern Virginia occurs as an oddity within the 'Heterolithic Lithosome', which otherwise dominates the exposed Lower Silurian stratigraphic interval. The cross sections also portray the markedly different stratigraphic relationships of the two lithosomes to each other and to the underlying red-bed succession, when the areas of southwestern Virginia (and to the northeast) and extreme southwestern Virginia/eastern Tennessee are compared.

Table 3-1. Salient distinguishing characteristics of the 'White Sandstone Lithosome' and the 'Heterolithic Lithosome'. See text for discussion.

'White Sandstone Lithosome'	'Heterolithic Lithosome'
sandstone-dominated (>90%)	mudstone-dominated, with interbedded sandstone, siltstone (<35%)
coarser grained	finer grained
white quartzarenite	darker colored
high-angle cross stratification	wave-ripple cross stratification, HCS, planar stratification
"lower" and "upper" Tuscarora Sandstone Poor Valley Ridge Sandstone Member beds/bedsets within Rockwood Formation	Hagan Shale Member Rockwood Formation Rose Hill Formation

Figure 3-5: Representative measured sections of the stratigraphic interval overlying the Upper Ordovician red-bed succession from southwestern Virginia to eastern Tennessee. The sections portray the distribution of the 'Heterolithic Lithosome' and 'White Sandstone Lithosome'. For location of sections please see numbered outcrops in Figure 3-2. Legend: a - 'Heterolithic Lithosome'; b - 'White Sandstone Lithosome'; c - interfingering of 'Heterolithic Lithosome' with 'White Sandstone Lithosome'; d - location of 'basal transgressive sandstone'; e - present-day erosion surface; f - unconformity, T = "Tuscarora unconformity", D = Wallbridge Discontinuity; g - covered interval. Some measured sections have section omitted (in m) for ease of illustration.

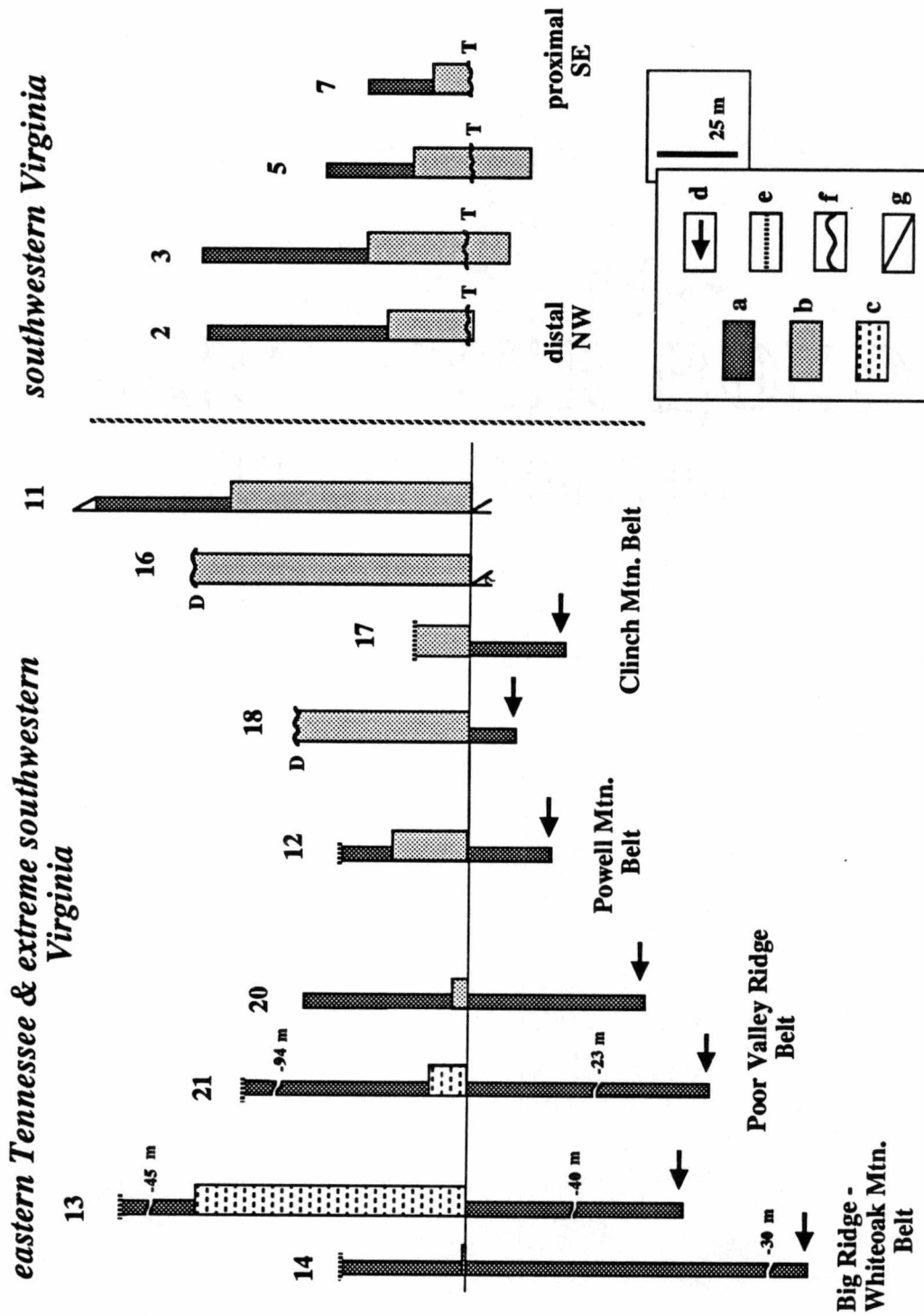
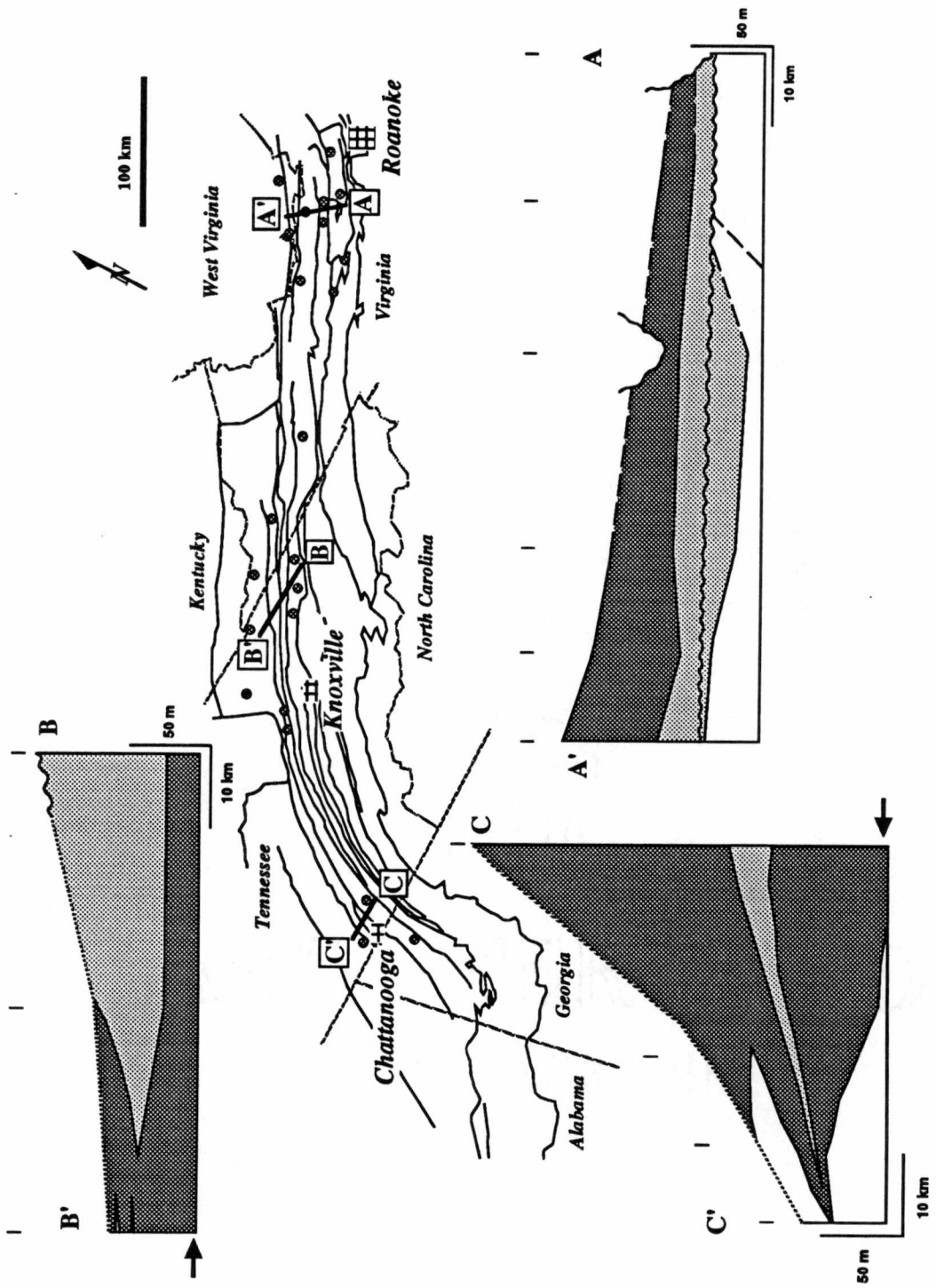


Figure 3-6: Stratigraphic cross sections (on palinspastic base) displaying the stratigraphic relationship and the distribution of the 'Heterolithic Lithosome' and the 'White Sandstone Lithosome'. Locations of cross sections are indicated on the base map. For identification of outcrop localities please see Figure 3-2. Symbols and patterns on the stratigraphic cross sections correspond to those used in Figure 3-5 (please see legend to Figure 3-5). Areas of cross sections left unpatterned correspond to red-bed succession or carbonate rocks. Palinspastic base for section A-A' based predominantly on balanced cross sections by Couzens and Dunne (unpublished data), palinspastic base for sections B-B' and C-C' provided by Roeder and Witherspoon (1978).



ISOSTATIC BASIN REBOUND AND ITS INFLUENCE ON THE ORIGIN OF THE 'WHITE SANDSTONE LITHOSOME'

The Taconic foredeep in the central Appalachians and its foredeep fill, the Martinsburg-Shawangunk clastic wedge, evolved sequentially, closely tied to the evolution of the Taconic orogen. This coupled orogen-foredeep evolution is the expression of the prevailing plate tectonic regime during the Late Ordovician to Early Silurian along the eastern (present coordinates) Laurentian continental margin (see Chapter 2). The Taconic foredeep evolved from a deep-marine underfilled stage, to a shallow-marine/terrestrial underfilled or overfilled stage. This scenario is typical for peripheral foredeeps which develop on thinned continental crust of former passive continental margins loaded by a growing orogen (Dickinson, 1974). Figure 2-3 schematically illustrates part of this sequential development, as expressed in the evolution of the Martinsburg-Shawangunk clastic wedge from foreland flysch to foreland molasse (*sensu* Ricci Lucchi and Ori, 1984).

Of particular interest for our discussion is a phase of flexural isostatic rebound of the foredeep, which is believed to be manifest prominently in the "Tuscarora unconformity." The "Tuscarora unconformity" is interpreted here to represent a rebound unconformity which developed following the completed accretion of (an) outboard terrane(s) to Laurentia (see Chapter 2). Completed accretion lead to cessation of convergence and thrusting, which halted load-induced foredeep subsidence. During the ensuing phase of rearrangement of the plate tectonic regime, erosion and extensional tectonism thinned the orogen, resulting in flexural uplift of the orogen and its adjacent foredeep as an isostatic response to the negative load (Figure 2-3D; Dorsch, 1992; see Chapter 2). Within the foredeep, relative magnitude of flexural uplift decreased radially away from the locus of maximum loading (Beaumont and others, 1988). At present, quantification of the relative proportions of erosion and extensional tectonism for thinning of the orogen is not available. The magnitude and distribution of flexural uplift within the foredeep, however, are considered not to be affected by a change in the relative proportions of these two factors (Jamieson and Beaumont, 1988). The erosional surface within the foredeep, created during isostatic rebound, was covered during resumption of deposition of Tuscarora Sandstone ("upper" Tuscarora Sandstone), giving rise to the "Tuscarora unconformity" (Figure 2-3E). This renewed phase of foredeep sedimentation is thought to be primarily related to resumed load-induced foredeep subsidence, caused by accretion of another terrane(s) to the ocean-

facing side of the orogen (Dorsch, 1992; see Chapter 2), in concert with eustatic sea-level rise during the Early Silurian (Johnson and others, 1991).

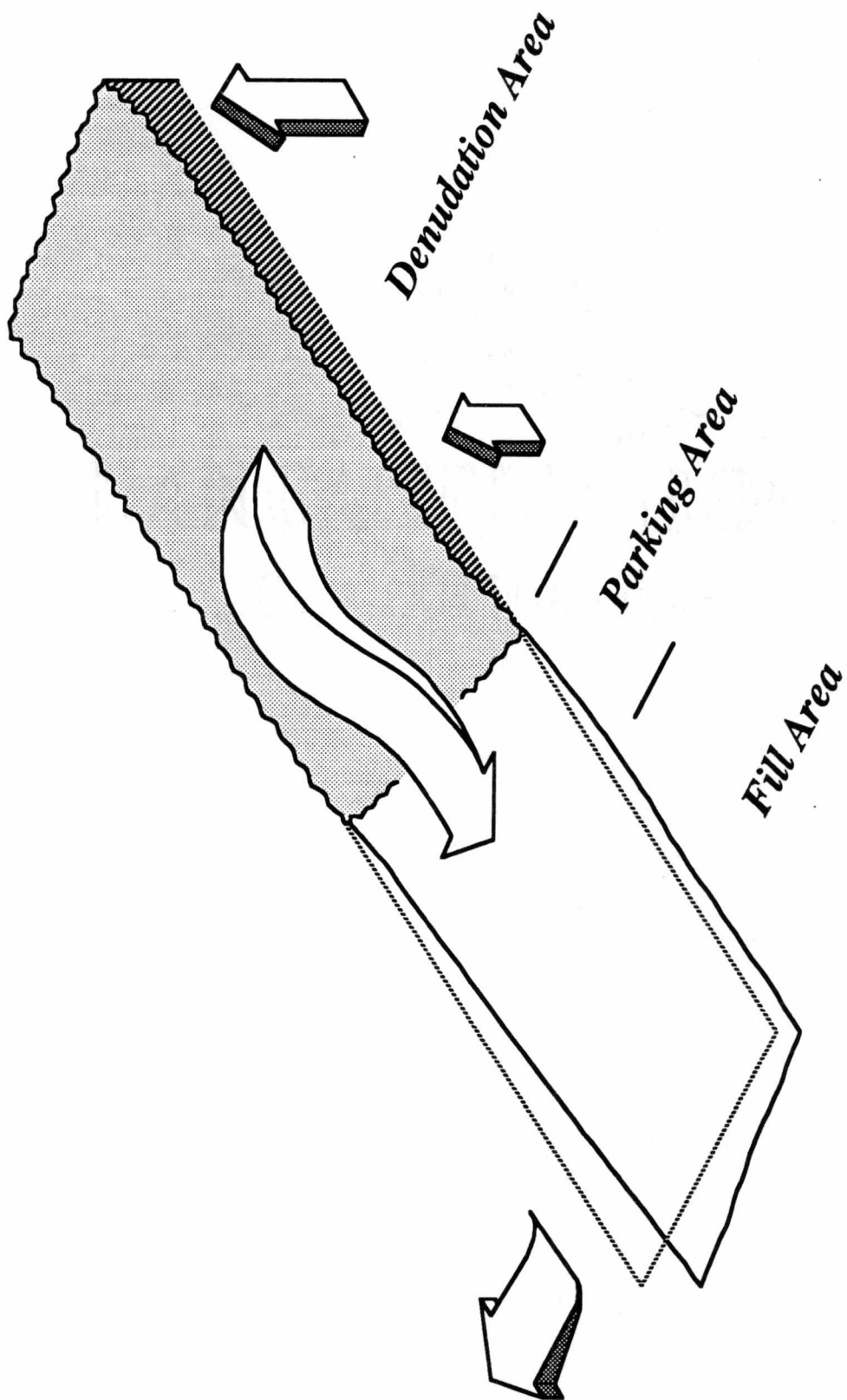
Flexural uplift of part of the foredeep as an isostatic response to erosional (Beaumont, 1981; Stockmal and others, 1986), or erosional and extensional thinning of the orogen (Jamieson and Beaumont, 1988; Beaumont and others, 1988), can be viewed as an integral part in the evolution of an orogen-foredeep couplet following cessation of compressional tectonism. Several authors pointed out that this phase finds its expression in a regional unconformity developed within the foredeep fill/clastic wedge (Heller and others, 1988; Jamieson and others, 1988; Cant and Stockmal, 1989).

Exposed more proximal parts of the Taconic foredeep reveal that erosion associated with isostatic basin rebound cut down into the Martinsburg Formation (Bambach, 1987; Diecchio, 1985; Dennison and Head, 1975). Erosion provided detritus for deposition away from the erosional sites. Erosional detritus was mainly derived from "lower" Tuscarora Sandstone and, therefore, is expected to be rich in quartz. Based on the recognition of the "Tuscarora unconformity" and its geodynamic interpretation, I propose that erosional detritus produced during flexural uplift of part of the Taconic foredeep constituted the material for the more "distal" parts of the 'White Sandstone Lithosome' in extreme southwestern Virginia and eastern Tennessee (Dorsch and Driese, 1992b).

The model of flexural isostatic rebound of part of the Taconic foredeep, and cannibalization and redistribution of foredeep deposits during a lull in compressional tectonism, corresponds to a general model of foredeep behavior outlined previously by Heller and others (1988). These authors attributed the spreading of coarse-grained sediment to flexural isostatic rebound of the orogen and the adjacent proximal foredeep, during what they termed the post-orogenic phase. Proximal foredeep deposits were eroded and redistributed toward the distal part of the foredeep and beyond, while an erosional surface was cut in the more proximal foredeep (Heller and others, 1988).

Figure 3-7 outlines the conceptual model of sediment derivation for the 'White Sandstone Lithosome' in extreme southwestern Virginia and eastern Tennessee. Flexural isostatic rebound of part of the Taconic foredeep established an erosional surface (denudation area, Figure 3-7) which sloped radially away from the locus of maximum uplift situated in present-day southern Pennsylvania, Maryland, and northern Virginia (Beaumont and others, 1988). In southwestern Virginia, this denudation surface was inclined toward the southwest and west. Flexural uplift of part of the foredeep terminated deposition of Tuscarora Sandstone ("lower" Tuscarora Sandstone), and lead to erosion of predominantly

Figure 3-7: Conceptual model of sediment derivation for the 'White Sandstone Lithosome' in extreme southwestern Virginia and eastern Tennessee. Vertical arrows indicate relative magnitude of isostatic basin rebound (flexural uplift); wavy line and stipple pattern outline area of active erosion (denudation area); broken line depicts sea level and frames area of active sedimentation (parking area, fill area); large horizontal arrow indicates route of detritus supply from area of uplift and erosion into area of available accommodation space; small horizontal arrow indicates movement direction of subaqueous bedforms within the accommodation space due to ambient storm conditions. Model was inspired by Ricci Lucchi's model (1987) for derivation of Apenninic megaturbidites but, naturally, is strongly modified.



"lower" Tuscarora Sandstone, but also of Juniata Formation, Oswego Sandstone, and Martinsburg Formation. The part of the foredeep designated as the "denudation area" was converted from an active depositional site (= sediment sink) to an active erosional site (= sediment exporter). Erosional detritus was shed along the paleoslope from the denudation area into a "parking area" and a "fill area" in the more distal parts of the Taconic foredeep not affected by flexural uplift, at the fringe of the foredeep, and beyond. The detritus was remolded into northwest-migrating subaqueous 2D- and 3D-dunes by the ambient storm system, and was redistributed into and within the fill area. The accommodation space of fill and parking area is thought to have been created by the overall eustatic sea-level rise commencing in the mid-Hirnantian, and lasting through the Early Silurian (Brenchley, 1989; Johnson and others, 1991). This accommodation space was not destroyed by tectonism, because it was beyond the reach of flexural isostatic rebound.

The present-day distribution of the denudation area is outlined by the occurrence of the "Tuscarora unconformity", whereas the parking area is a rather narrow belt marginal to the area covered by the "Tuscarora unconformity". The fill area is represented by the area beyond the occurrence of the "Tuscarora unconformity", where the 'White Sandstone Lithosome' is wedged as an oddity into the 'Heterolithic Lithosome' (Figures 3-5, 3-6). In this area distant from the sites of the active Taconic orogeny, the 'Heterolithic Lithosome' represents the "normal" sedimentation, which was abruptly interrupted by the incursion of sediments of the 'White Sandstone Lithosome'.

Detritus was likely not only shed toward the southwest into present-day Tennessee, but also along the paleoslope toward the west, northwest, and north, radially away from the area of maximum flexural isostatic uplift. A 'White Sandstone Lithosome' with similar stratigraphic relationships to the surrounding deposits, as described from the outcrops of extreme southwestern Virginia and eastern Tennessee, is expected to appear in a north/northwest direction.

Figure 3-8 (from Lukasik, 1988) is a lithostratigraphic cross section depicting the Lower Silurian stratigraphic relationships in the subsurface of southern Ohio, which correspond to the ones in eastern Tennessee and can be traced into western West Virginia (Lukasik, 1988; Coogan, 1991). The 'White Sandstone Lithosome' encompasses the "Clinton" sandstone, a drillers' term for sandstones in the subsurface of Ohio, which is equivalent to the Tuscarora Sandstone further to the east in West Virginia (Lukasik, 1988). In southern Ohio, the 'Heterolithic Lithosome' consists of the Cabot Head Shale and Lulbeugrud Shale, and displays an intimate interfingering relationship with the 'White

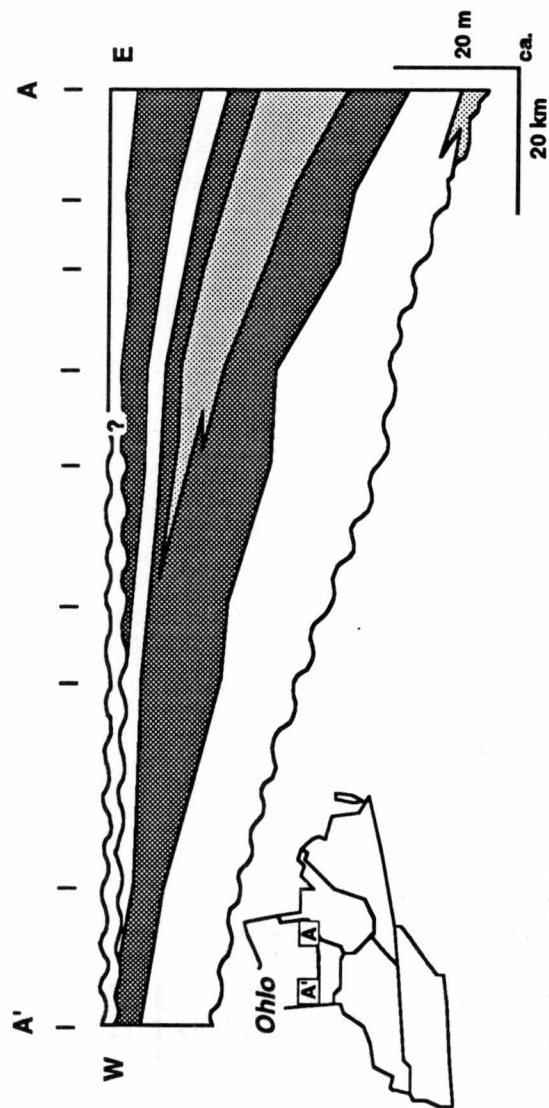


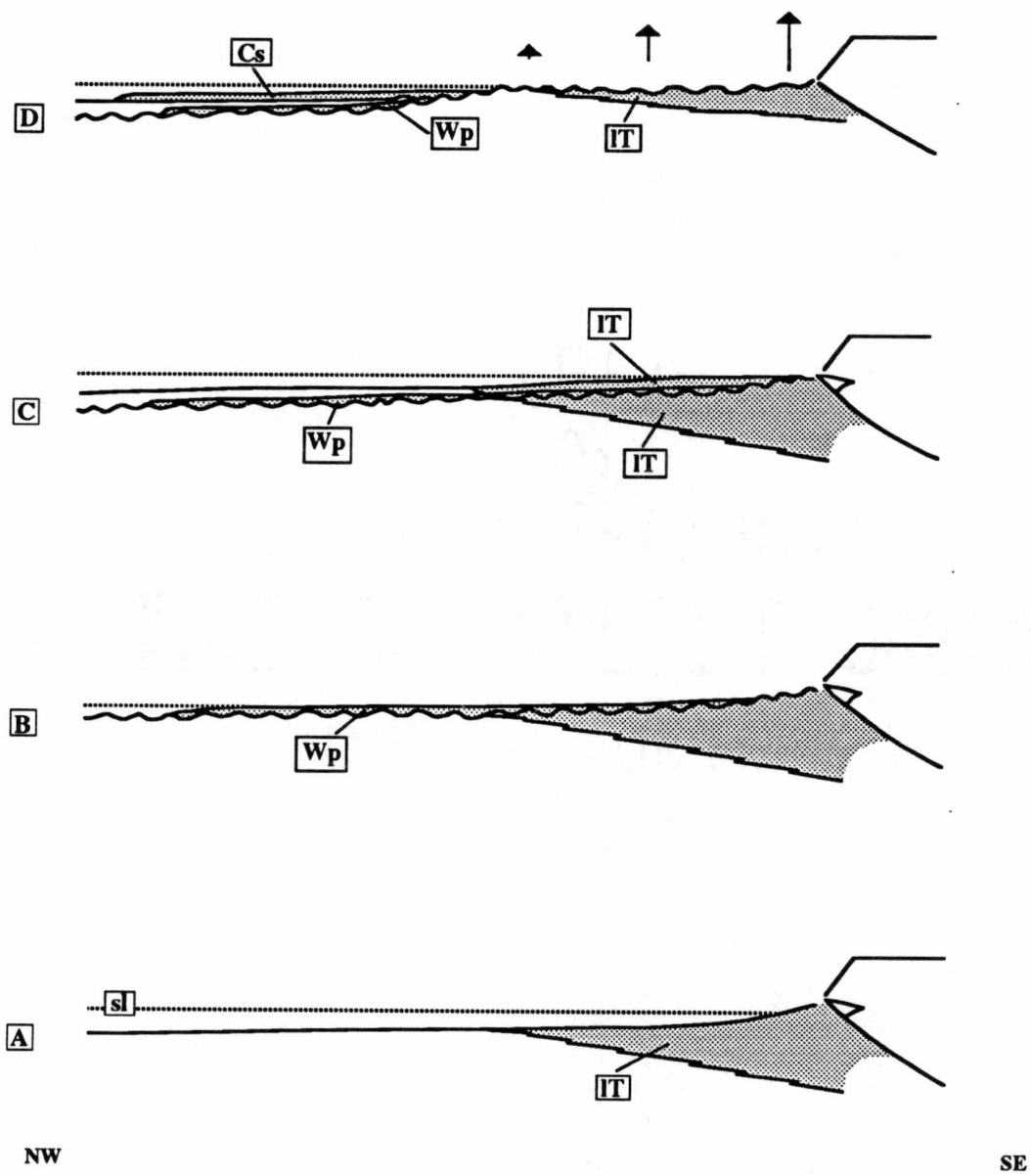
Figure 3-8. Stratigraphic cross section showing the distribution of the 'Heterolithic Lithosome' and 'White Sandstone Lithosome' in the subsurface of southern Ohio. Compare to stratigraphic cross sections in Figure 3-6. Dense stipple pattern depicts the 'Heterolithic Lithosome', the lighter stipple pattern depicts the 'White Sandstone Lithosome'. The unpatterned areas within the cross section correspond to carbonate deposits and indicate the interfingering of the distal portion of the the Martinsburg-Shawangunk clastic wedge with non-clastic-wedge deposits (from Lukasik, 1988, his Figure 10).

Sandstone Lithosome' (Lukasik, 1988). The 'White Sandstone Lithosome' thins toward the west/northwest, away from the source area (denudation area) developed within part of the Taconic foredeep further to the southeast/east.

A small unit of 'White Sandstone Lithosome' occurs in the cross-section below the main part of the 'White Sandstone Lithosome' and the 'Heterolithic Lithosome' (Figure 3-8). This is the distal end of the Whirlpool Sandstone, which overlies the Upper Ordovician red-bed succession (here Queenston Shale) along a regional disconformity, and interfingers with the Brassfield Formation (Lukasik, 1988). The occurrence of the Whirlpool Sandstone along a disconformity above red beds corresponds to the location of the 'basal transgressive sandstone' in extreme southwestern Virginia and eastern Tennessee. We believe that the origin of the Whirlpool Sandstone, like that of the 'basal transgressive sandstone', is related to the Hirnantian glacio-eustatic sea-level events (Figure 3-9).

Glacio-eustatic sea-level drop is responsible for creation of the subaerial exposure surface on top of the red-bed succession. It also made quartzarenite beds of the "lower" Tuscarora Sandstone within the more proximal foredeep available to erosion. During sea-level fall, quartz-rich detritus prograded toward the northwest, closely following the retreating shoreline. Beyond the depositional limit of the "lower" Tuscarora Sandstone, the quartz-rich detritus came to rest on top of the red-bed succession (Figure 3-9B). During subsequent glacio-eustatic sea-level rise, the quartz-rich deposits were (partially) reworked and covered by fine-grained clastic or non-clastic deposits. Within the more proximal foredeep, deposition of "lower" Tuscarora Sandstone resumed (Figure 3-9C). Outcrop studies in New York and Ontario revealed that the lower part of the Whirlpool Sandstone represents deposits of braided streams, whereas the upper part represents shallow-marine deposits (Middleton and others, 1987). Applied to the subsurface occurrence of the Whirlpool Sandstone, the lower part of the Whirlpool Sandstone might represent the progradational phase of spreading of erosional detritus of the "lower" Tuscarora Sandstone during glacio-eustatic sea-level fall, whereas the upper marine portion might correspond to the subsequent glacio-eustatic sea-level rise. The disconformity beneath the Whirlpool Sandstone corresponds to a sequence boundary overlain by lowstand (braided stream) deposits (Brett and others, 1990). The fluvial deposits, in turn, are overlain by marine deposits along a transgressive surface (Brett and others, 1990). It is possible, however, that the intervening fluvial deposits were completely removed during sea-level rise, and that sequence boundary and transgressive surface are amalgamated. Coogan (1990), in a different model, interprets the Whirlpool Sandstone in the subsurface of Ohio to represent

Figure 3-9: Highly schematized diagram showing the development and distribution of the Whirlpool Sandstone along a southeast to northwest transect (approximately from southwestern Virginia to Ohio). Abbreviations: sl - sea level, IT - "lower" Tuscarora Sandstone, Wp - Whirlpool Sandstone, Cs - "Clinton" sandstone; stippled area: components of the 'White Sandstone Lithosome'; arrows indicate relative magnitude of isostatic basin rebound (flexural uplift). A - foredeep sedimentation: "lower" Tuscarora Sandstone interfingers with red-bed succession of the Juniata Formation; B - Hirnantian glacio-eustatic sea-level fall; C - Hirnantian glacio-eustatic sea-level rise; D - flexural isostatic rebound of part of the foredeep. See text for discussion.



progradational deposits which interrupted the glacio-eustatic sea-level rise, and not to be related to the initial glacio-eustatic sea-level fall. Coogan paints a more complicated picture of stratigraphic effects of the Hirnantian glacio-eustatic sea-level changes, but his interpretation of well-log data appears to match the Hirnantian eustatic sea-level curve developed by Branchley (1989). Whether the Whirlpool Sandstone is associated with the initial eustatic sea-level fall or represents an interruption of the succeeding eustatic sea-level rise, depends on the placement of the Upper Ordovician Cherokee Discontinuity (Lukasik, 1988; Coogan, 1990; Brett and others, 1990).

The 'basal transgressive sandstone' of eastern Tennessee and extreme southwestern Virginia is not a white quartzarenite sheet, simply because "lower" Tuscarora Sandstone was not available as a detritus source in this area. The "lower" Tuscarora Sandstone of the Taconic foredeep terminated by interfingering with red beds of the Juniata Formation somewhere to the southwest of present-day Wytheville, VA. The Whirlpool Sandstone as evidence for the Hirnantian glacio-eustatic sea-level changes was cut out from the more proximal parts of the Taconic foredeep during isostatic basin rebound, and is preserved today only in the more distal parts of the foredeep which were beyond the effects of isostatic rebound (Figure 3-9D).

The 'White Sandstone Lithosome' along a southeast-northwest transect in the central Appalachians consists, therefore, of the "lower" and "upper" Tuscarora Sandstone in the main part of the foredeep, and of the two northwestward excursions of the Whirlpool Sandstone and the "Clinton" sandstone/Tuscarora Sandstone. The latter is encased within the 'Heterolithic Lithosome', and can be considered as the stratigraphic equivalent of the Poor Valley Ridge Sandstone Member of the Clinch Sandstone and of the white, coarser grained quartzarenite beds within the Rockwood Formation of extreme southwestern Virginia and eastern Tennessee. Like its brethren in eastern Tennessee and extreme southwestern Virginia, this stratigraphic unit is interpreted to represent redeposited erosional detritus produced during a phase of flexural isostatic rebound (Figure 3-7).

DISCUSSION

Recognition of the "Tuscarora unconformity" in southwestern Virginia and its interpretation as an isostatic rebound unconformity (see Chapter 2) provided the impetus for a new look at the regional stratigraphic relationships above the Upper Ordovician red-bed succession in the central and southern Appalachians. Flexural uplift of foredeep deposits, erosion, and redistribution of the detritus, as outlined in the model above and by Heller and others (1988), can account for the occurrence of the 'White Sandstone Lithosome' within the 'Heterolithic Lithosome' in eastern Tennessee, extreme southwestern Virginia, and in the subsurface of Ohio. This stratigraphic relationship is in marked contrast to the distribution of the same two lithosomes throughout the rest of Virginia.

Derivation of the quartz-rich detritus for the Poor Valley Ridge Sandstone Member of the Clinch Sandstone and for similar but thinner sandstone tongues within the Rockwood Formation in eastern Tennessee and extreme southwestern Virginia, can be linked to the phase of flexural isostatic uplift within southwestern Virginia (and to the northeast). Based predominantly on paleocurrent information, the source for the quartz-rich detritus in eastern Tennessee and extreme southwestern Virginia was commonly sought to the southeast of the present-day outcrop belt (for example, Amsden, 1955; Dennison, 1970; Whisonant, 1977). The lithologic similarity of the Tuscarora and Clinch sandstones, nevertheless, lead some authors to suspect a common source area, located to the northeast in Virginia (present-day Massanutten synclinorium; Driese and others, 1991).

Paleocurrents

A major difficulty with the notion of a northeastern source area for the quartzarenite in eastern Tennessee was the absence of any southwest-directed paleocurrent indicators within the Tuscarora Sandstone (Whisonant, 1977). Our model, however, indicates that the Tuscarora Sandstone is not homogeneous, but split into two distinct parts by the "Tuscarora unconformity". In this model, the subaerial surface indicated by the "Tuscarora unconformity" (denudation area, Figure 3-7) was the site of the dispersal system, probably braided rivers. Deposits of the dispersal system were reworked during transgression of the sea onto the denudation area, completely obliterating any evidence of the former dispersal system and its paleocurrent indicators. The amalgamation of transgressive surface with the "Tuscarora unconformity" was pointed out earlier (see above, and Chapter 5). The detritus shed into the parking and fill area (Figure 3-7) was overprinted by the ambient storm

system, and was reworked completely into northwest-migrating subaqueous bedforms. This caused the destruction of any paleocurrent indicators within the quartz-rich deposits of eastern Tennessee and extreme southwestern Virginia bearing witness for a northeastern source area. The storm system, as reconstructed by Driese and others (1991), was the dominant influencing force on the sedimentation pattern during the Early Silurian in the southern and central Appalachians. It is responsible for the consistent west-to-north-directed paleocurrent indicators found in the "lower" and "upper" Tuscarora sandstones (see Chapters 4 and 5; Whisonant, 1977) and in the Poor Valley Ridge Sandstone (Driese, 1988; Driese and others, 1991). The storm system clearly favored the preservation of exceptional high-magnitude storm deposits over day-to-day fairweather deposits.

Coarse Sandstone Tongues of the Rockwood and Red Mountain Formations

The extension of the 'White Sandstone Lithosome' as discrete tongues into the Rockwood Formation is attributed to regression (Driese and others, 1991). Sharp-based bedsets of shoreface sandstone rest within deeper marine, offshore mudstone intercalated with tempestites, and are commonly capped by a hematitic sandstone bed (Driese, 1988; Driese and others, 1991; Figure 3-3G). The emplacement of these shoreface bedsets can be related either to ample sediment supply exceeding the available accommodation space during relative sea-level rise or stillstand (normal regression, *sensu* Posamentier and others, 1992), or to relative sea-level fall and concurrent loss of accommodation space (forced regression, *sensu* Posamentier and others, 1992). The hematitic beds topping the shoreface-sandstone bedsets mark rapid marine flooding and the return to an offshore depositional setting. Based on sedimentology, ichnology and scant biostratigraphic information, Easthouse and Driese (1988) explained the sudden occurrence of a coarser grained sandstone tongue within the Rockwood Formation at Green Gap (Whiteoak Mountain; Figure 3-2) by relative sea-level fall, and tentatively linked this event to the eustatic sea-level fall in the Llandovery C₂₋₃. It is likely that the 'Heterolithic Lithosome' in eastern Tennessee (predominantly the Rockwood Formation) was strongly influenced by eustatic sea-level changes as recorded for the Llandoveryan from different continents by Johnson and others (1991).

A more detailed discussion of the importance of normal versus forced regressions in the emplacement of the shoreface-sandstone bedsets within the Rockwood Formation is hampered at the moment by the lack of biostratigraphic data, and the resulting inability to correlate the sandstone tongues across the multitude of thrust sheets with certainty. The

present-day erosion surface and the Devonian Wallbridge Discontinuity, furthermore, are responsible for the fragmentary record of the 'Heterolithic Lithosome' within eastern Tennessee. Eastern Tennessee and extreme southwestern Virginia, nevertheless, promise to be a fertile ground for testing and investigating the concept and the stratigraphic implications of forced regressions. Efforts to address these questions are currently under way.

Lighter colored, coarser grained, and typically high-angle cross-stratified sandstone tongues can be found encased within heterolithic deposits of the Llandoveryian Red Mountain Formation of northwestern Georgia and northeastern Alabama (Chowns and McKinney, 1980; Chowns, 1989; Bolton, 1992). These sandstone tongues are reminiscent of the Poor Valley Ridge-like sandstone tongues resting within the Rockwood Formation of eastern Tennessee. The 'basal transgressive sandstone' is present in most of the outcrops in northwestern Georgia and northeastern Alabama, and marks the base of the heterolithic Red Mountain Formation (Gogola, 1990; Bolton, 1992). The increased thickness of the coarser grained sandstone tongues within the Red Mountain Formation, and their distance from the rebound area in southwestern Virginia makes it highly unlikely that the quartz-rich detritus was funnelled down to Georgia and Alabama. We believe, instead, that a second input center (a point source?) was present in this part of the southern Appalachians. The spread of the coarser grained sandstone tongues might be related to eustatic sea-level drops during the Llandoveryian. Mixing of detritus supplied from the rebound area in Virginia with detritus supplied from the source area in present-day Alabama and Georgia is likely. The spread of detritus supplied by the two sources and the area of detritus mixing is currently not possible to estimate.

Provenance Relationships of the 'White Sandstone Lithosome'

Based on the presented stratigraphic relationships and their interpretation, and the available petrographic data (Hayes, 1974; Schoner, 1985; Marks, 1987; Fischer, 1987), the provenance relationships within the 'White Sandstone Lithosome' from southwestern Virginia to eastern Tennessee can be elucidated. The "lower" Tuscarora Sandstone was derived from the Taconic orogen (for example Folk, 1960; Pettijohn, 1970; Hayes, 1974; Whisonant, 1977; Figure 3-10), and is perceived to have formed a northwestward tapering wedge of light-colored, quartz-rich sandstone, interfingering with and overlying the red-bed succession of the Juniata Formation in southwestern Virginia (Figure 3-9A). The source terrain is believed to have included quartz-rich sedimentary deposits (Chilhowee Group) and

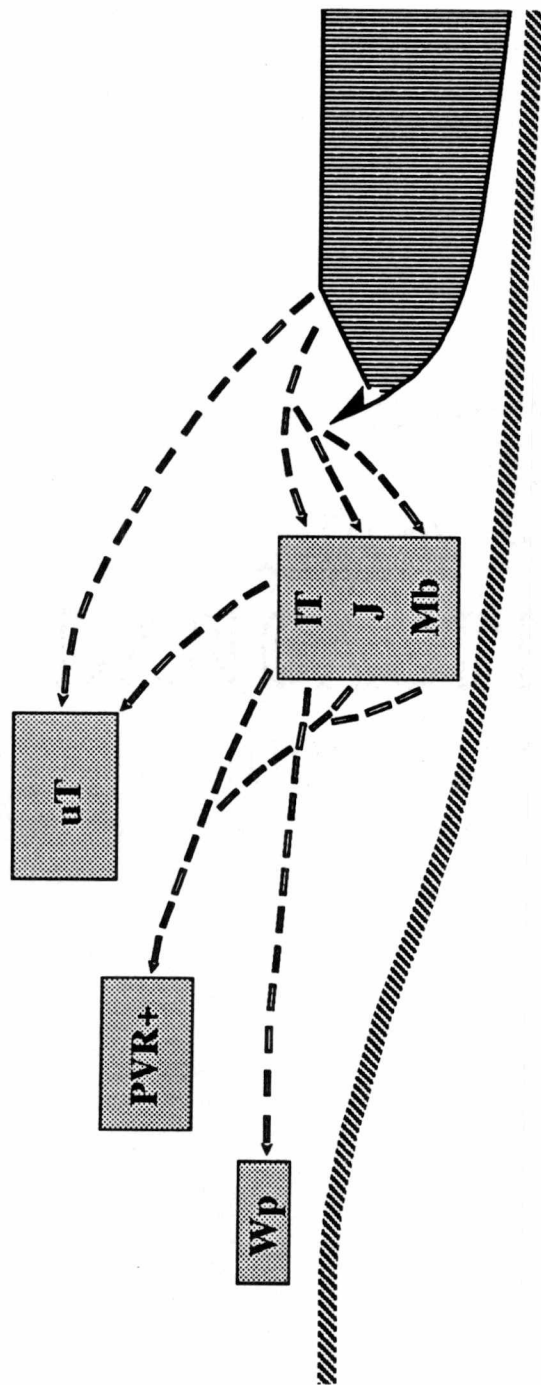


Figure 3-10. "Provenance web" portraying the inferred provenance relationships for the 'White Sandstone Lithosome' from southwestern Virginia to eastern Tennessee. The "lower" Tuscarora Sandstone (IT) is derived from the Taconic orogen, as are the Juniata Formation (J) and Martinsburg Formation (Mb). The "lower" Tuscarora Sandstone provided the detritus for the Whirlpool Sandstone (Wp) during glacio-eustatic sea-level fall; for the Poor Valley Ridge Sandstone Member of the Clinch Sandstone and the "Clinton" sandstone (PVR+), together with contributions from the Juniata and Martinsburg formations, during flexural isostatic uplift of part of the Taconic foredeep; and for the "upper" Tuscarora Sandstone (uT) during thrust-load induced transgression. The "upper" Tuscarora Sandstone, however, received its main share of detritus from the Taconic orogen during renewed thrusting.

various low-rank metamorphic units (Hayes, 1974; Whisonant, 1977; Folk, 1960) of the Taconic externides (fold-thrust belt) and internides. It is also possible that deposits of the "lower" Tuscarora Sandstone closest to the orogen were cannibalized, as the externides of the Taconic orogen grew cratonward and incorporated foredeep deposits. Reworking of "lower" Tuscarora Sandstone during glacio-eustatic lowering of sea level in the Ashgillian provided the detritus for the Whirlpool Sandstone (Figure 3-10), a quartzarenite tongue extending toward the northwest away from the source area in southwestern Virginia (Figure 3-9B). Flexural uplift of part of the Taconic foredeep made the "lower" Tuscarora Sandstone available as the principal detritus source for a second (or third) time. This time, detritus of the "lower" Tuscarora Sandstone was shed radially away from the locus of uplift into areas to the southwest, west, and northwest not affected by flexural uplift (Figure 3-9D), giving rise to such units as the Poor Valley Ridge Sandstone Member of the Clinch Sandstone in eastern Tennessee and extreme southwestern Virginia, and the "Clinton" sandstone in the subsurface of Ohio (Figure 3-10). The absence of polycrystalline quartz with sutured subgrain boundaries in the gravel and sand population of the Poor Valley Ridge Sandstone (Schoner, 1985) is in marked contrast to the "lower" Tuscarora Sandstone (Hayes, 1974), and can be attributed to destruction of these grains during transport from the erosional site in southwestern Virginia to the depositional site in eastern Tennessee. The occurrence of some red-colored sandstone and siltstone beds in the upper part of the Poor Valley Ridge Sandstone at Stickleyville (Marks, 1987; Driese, 1988; Driese and others, 1991) might indicate the influx and rare preservation of Juniata detritus, made available in southwestern Virginia as erosion breached through the "lower" Tuscarora Sandstone. Preservation and identification of detritus of the Martinsburg Formation (predominantly mudstone and coquinite limestone, Kreisa, 1981), also made available to erosion during isostatic flexural uplift, is highly unlikely. The "upper" Tuscarora Sandstone is believed to be composed of detritus of "lower" Tuscarora Sandstone, which was reworked during marine transgression onto the subaerial exposure surface created during flexural uplift (Dorsch and Driese, 1992a; see Chapter 5), and of new material supplied from the orogen during a renewed phase of thrusting (Figure 3-10). The influx of schistose lithic fragments (Hayes, 1974) might attest to this input of new material. Hayes (1974) interpreted his petrographic data from the Tuscarora Sandstone of southwestern Virginia to indicate an evolution from a predominantly sedimentary/low-rank metamorphic source to a predominantly crystalline (metamorphic and plutonic ?) source. Quartzarenite grains (as discrete lithic fragments) are conspicuously absent from the gravel and sand population of the Poor Valley Ridge

Sandstone and related sandstone tongues within the Rockwood Formation of extreme southwestern Virginia and eastern Tennessee (Schoner, 1985; Marks, 1987; Fischer, 1987). A possible explanation for this observation might be that the "lower" Tuscarora Sandstone was not lithified substantially at the time of erosion to provide quartzarenite detritus.

A Lithostratigraphic Boundary for the Tuscarora and Clinch Sandstones

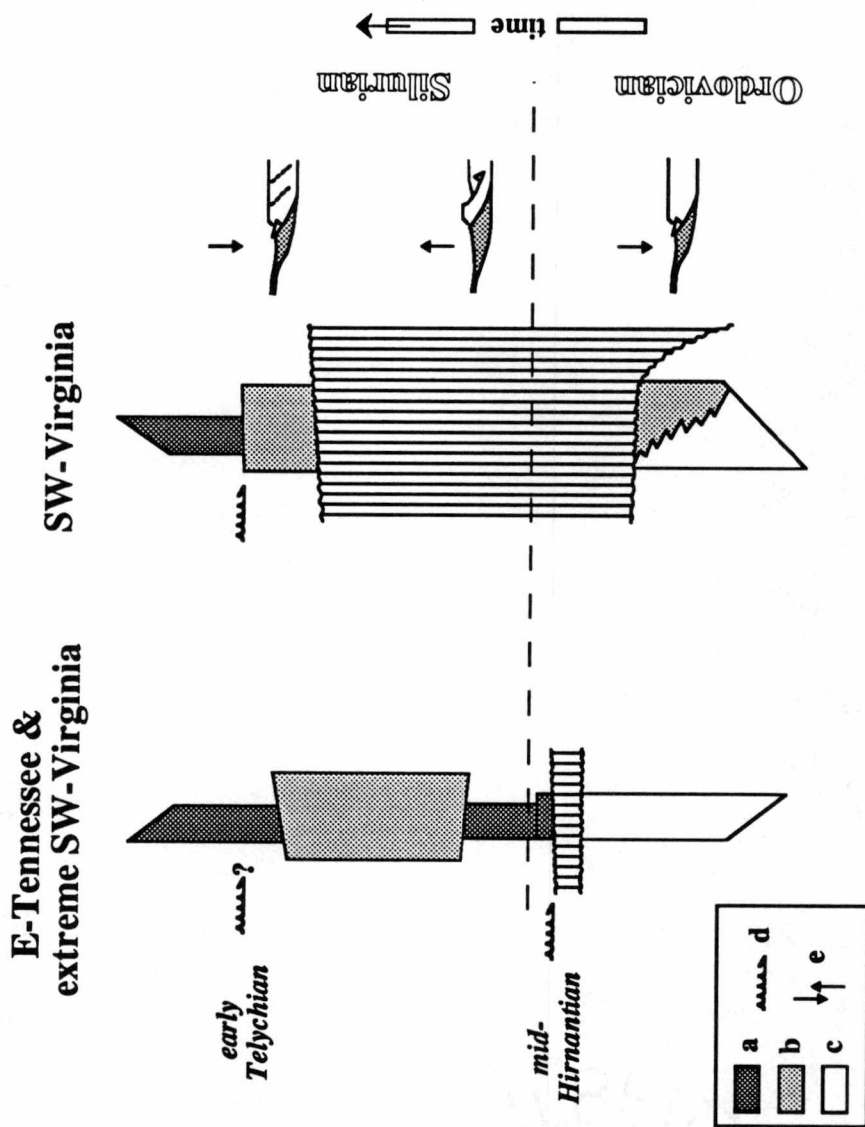
This new look at the regional stratigraphic relationships allows, furthermore, a more precise definition of the lithostratigraphic boundary between the Clinch and the Tuscarora Sandstones (Dorsch and Driese, 1993). Currently, the boundary between the two Formations is not clearly fixed and changes according to the respective worker (Butts, 1940; Whisonant, 1977). The most common usage is the one proposed by Dennison (1970) in which Clinch Sandstone is used to the southwest, and Tuscarora Sandstone is used to the northeast of the New River in southwestern Virginia. We would like to propose the usage of Tuscarora Sandstone within the area which is covered by the "Tuscarora unconformity" (the denudation area, Figure 3-7), and where the "lower" Tuscarora Sandstone interfingers with the red-bed succession of the Juniata Formation (if not eroded away). Clinch Sandstone is used in the area where the "Tuscarora unconformity" is absent, and where a part of the 'Heterolithic Lithosome' (Hagan Shale Member with 'basal transgressive sandstone') can be found beneath rocks of the 'White Sandstone Lithosome' (the fill area, Figure 3-7). As already mentioned above, the Clinch Sandstone has its lithostratigraphic equivalent in the subsurface of Ohio in the "Clinton" sandstone and the underlying Cabot Head Shale. In the Valley and Ridge of Virginia and Tennessee, the boundary between the Clinch and Tuscarora sandstones falls between the outcrops at Cove Mountain (Tuscarora Sandstone; outcrop locality 10, Figure 3-2) and Little Moccasin Gap (Clinch Sandstone; outcrop locality 11, Figure 3-2).

Tectono-stratigraphy of the Uppermost Ordovician to Lower Silurian Taconic Molasse

Figure 3-11 illustrates a new view of the chronostratigraphic relationship between the 'White Sandstone Lithosome' and the 'Heterolithic Lithosome' from southwestern Virginia to eastern Tennessee. It relates different parts of the lithosomes to distinct events in the evolution of the Taconic orogen.

Two regional lithostratigraphic marker beds/surfaces of inferred chronostratigraphic significance are developed in extreme southwestern Virginia/eastern Tennessee and southwestern Virginia, respectively. Both markers are thought to be related to rapid marine

Figure 3-11: Schematic chronostratigraphic diagram detailing the relationships between the two regional lithosomes above the Upper Ordovician red-bed succession. Abbreviations: a - 'Heterolithic Lithosome', b - 'White Sandstone Lithosome', c - Ordovician red-bed succession, d - marine flooding surface (as discussed in detail in the text; note diachroneity of marine flooding events indicated by the slightly sloping onlap surfaces), e - arrows indicating foredeep behavior (flexural subsidence or flexural isostatic uplift). Because firm biostratigraphic data are lacking for most of the studied stratigraphic interval, this chronostratigraphic framework has to be considered as provisional.



flooding. Biostratigraphic data, albeit limited, make a reasonable placement of the markers within the chronostratigraphic framework possible. They allow, furthermore, linkage of the regional flooding events to documented and well established eustatic sea-level curves of the Upper Ordovician and Lower Silurian (for example Brenchley, 1989; Johnson and others, 1991). Neither lithostratigraphic marker bed/surface is isochronous. Diachroneity, however, is considered to be minimal, even on the regional scale of observation, because marine flooding is inferred to have been rapid. In eastern Tennessee and extreme southwestern Virginia, the 'basal transgressive sandstone' (Figure 3-3F) overlies a subaerial exposure surface and is considered to reflect glacio-eustatic sea-level rise associated with ablation of Saharan glaciers in the mid-Hirnantian (Gogola, 1990; Dorsch and others, 1991; Driese and others, 1991). In southwestern Virginia, the marine-flooding surface developed on top of the "upper" Tuscarora Sandstone (Figure 3-3C) is interpreted to reflect the early Telychian eustatic sea-level rise (Dorsch and Driese, 1992a, b), as documented by Johnson and others (1991). Unequivocal identification of this latter flooding event within the Rockwood Formation and the remnants of the Rose Hill Formation of eastern Tennessee and extreme southwestern Virginia is not possible, because adequate biostratigraphic data in concert with sedimentologic data are lacking at present. Due to paucity or lack of dateable fossils, placement of the Ordovician-Silurian boundary and temporal extent of the lacunae (Figure 3-11) have to be considered as approximate.

Despite these limitations imposed by the paucity of biostratigraphic information, several hypotheses concerning the regional lithosomes and their relationship to the Taconic orogeny can be proposed. The 'White Sandstone Lithosome' is partitioned into three parts, with each part having its distinct tie to different developmental stages of the Taconic orogen (Figure 3-11). In southwestern Virginia, the 'White Sandstone Lithosome' (Tuscarora Sandstone) is split into two by the "Tuscarora unconformity" (Figure 3-3A). The "lower" Tuscarora Sandstone is thought to be related to active thrusting within the orogen and active foredeep subsidence due to thrust-loading. Quartz-rich detritus prograded away from the orogen and interfingered with red-colored sediment. Sediment of the "lower" Tuscarora Sandstone was confined within the Taconic foredeep which acted as a sediment sink. Conversion of part of the Taconic foredeep from a sediment sink to a sediment exporter took place during flexural uplift of part of the foredeep, as an isostatic response to thinning of the orogen. Flexural uplift caused erosion of previously deposited sediment, and redistribution of that detritus into parts of the foredeep not affected by flexural isostatic rebound and beyond the confines of the foredeep. This phase in the evolution of the

Taconic orogen is thought to be documented by the "Tuscarora unconformity" in southwestern Virginia, and by the redistributed erosional detritus, which constitutes the 'White Sandstone Lithosome' in extreme southwestern Virginia and eastern Tennessee (Poor Valley Ridge Sandstone, coarser grained sandstone tongues within Rockwood Formation; Figures 3-6; 3-11) and southern Ohio ("Clinton" sandstone; Figure 3-8). The whole foredeep was reestablished as a sediment sink following resumption of thrusting and thrust-load induced subsidence. Supply of quartz-rich detritus toward the distal foredeep and beyond was gradually shut off, and the detritus was confined within the more medial and proximal foredeep comprising the "upper" Tuscarora Sandstone.

The 'White Sandstone Lithosome' in eastern Tennessee and extreme southwestern Virginia is interpreted to owe its origin to tectonism within the Taconic foredeep of the central Appalachians, which in turn reflects the tectonic evolution of the Taconic orogen. This lithosome is completely encapsulated within the 'Heterolithic Lithosome' and interrupts, for a period, the complacent, mud-dominated, "normal" sedimentation in this area (Figure 3-6). This part of the 'White Sandstone Lithosome' is interpreted to correspond for a large measure to a lacuna within the outcrop sections of southwestern Virginia, a stratigraphic relationship already postulated by Heller and others (1988) to be expected in foredeeps. The 'Heterolithic Lithosome' is regarded to represent tectonically calm conditions during the latest Ordovician and Early Silurian in an area remote from active Taconic tectonism at the same time. Eastern Tennessee was the primary area affected by tectonism and active foredeep sedimentation (foreland flysch to foreland molasse; for example, Keller and Walker, 1980; Read, 1980; Shanmugam and Lash, 1982; Drake and others, 1989) during the earlier Blount orogeny (or Blount phase of the Taconic orogeny; Rodgers, 1953, 1971; Shanmugam and Lash, 1982; Drake and others, 1989). The 'Heterolithic Lithosome' in southwestern Virginia commenced later with the Rose Hill Formation, and might indicate similar, and calmer tectonic conditions (see also Folk, 1960).

The unconformity indicated by the paleosols in the Juniata Formation and by the overlying 'basal transgressive sandstone' represents a sequence boundary related to glacio-eustasy within the Ashgillian (Dorsch and others, 1991, Driese and others, 1991; Figure 3-3F). This unconformity was cut out in southwestern Virginia and superseded by the "Tuscarora unconformity". The "Tuscarora unconformity" represents a sequence boundary which owes its origin to tectonism, and is developed only in the area affected by flexural isostatic rebound (Dorsch and others, 1991; see Chapter 5).

Flexural uplift of part of the foredeep resulted in destruction of accommodation space and erosion at more proximal locations within the foredeep. This lead to redistribution of sediment into more distal parts of the foredeep, and even to export of sediment. This tectonic stimulus for sediment export complements sedimentary export through sediment bypassing. The latter occurs when rate of sediment delivery to the foredeep is greater than subsidence rate of the foredeep, and when the foredeep is filled above or near sea-level. Sediment bypassing and export, both laterally along the basin axis and/or transversely across the peripheral bulge, is accomplished either by pronounced currents within shallow-marine foredeeps (for example Taiwan straits, Covey, 1986), or by fluvial systems within non-marine foredeeps (for example Himalayan foredeep, Covey, 1986; Burbank and Beck, 1991; Late Cretaceous Idaho-Wyoming-Utah foredeep, Flemings and Jordan, 1989).

CONCLUSIONS

1. The uppermost Ordovician to Lower Silurian stratigraphic units above the Upper Ordovician red-bed succession in the central and southern Appalachian Valley and Ridge can be subdivided into the distinctly different 'White Sandstone Lithosome' (Tuscarora Sandstone, Poor Valley Ridge Sandstone Member of the Clinch Sandstone, and some beds/bedsets within the Rockwood Formation) and 'Heterolithic Lithosome' (Rose Hill Formation, Rockwood Formation, and Hagan Shale Member of the Clinch Sandstone). In southwestern Virginia, the 'White Sandstone Lithosome' dominates, which is divided by the "Tuscarora unconformity" into the "lower" and "upper" Tuscarora Sandstone, and is succeeded by the 'Heterolithic Lithosome'. In extreme southwestern Virginia and eastern Tennessee, the 'Heterolithic Lithosome' dominates, which commences with the 'basal transgressive sandstone' and encapsulates the more exotic 'White Sandstone Lithosome'.

2. The lithostratigraphic term Tuscarora Sandstone should be used within the area covered by the "Tuscarora unconformity" and/or where the "lower" Tuscarora Sandstone interfingers with the Juniata Formation. Clinch Sandstone, on the other hand, should be used within the area marked by the absence of the "Tuscarora unconformity" and by the presence of the 'White Sandstone Lithosome' contained within the 'Heterolithic Lithosome'.

3. In contrast to the commonly held view, the 'White Sandstone Lithosome' does not form a simple, homogeneous, and uniform quartzarenite blanket throughout the central and

southern Appalachians, but hides a more complex history. This lithosome is divisible into separate components, with each component having its distinct ties to different developmental stages of the Taconic orogen in the central Appalachians and to eustatic sea-level changes.

4. The detritus for the "lower" Tuscarora Sandstone was shed from the growing Taconic orogen and was deposited within the foredeep during thrust-load induced foredeep subsidence. The glacio-eustatic sea-level events during the Hirnantian (latest Ordovician) are thought to be reflected in the Whirlpool Sandstone (subsurface of southern Ohio and parts of West Virginia), whose stratigraphic position and origin corresponds to that of the 'basal transgressive sandstone' (extreme southwestern Virginia to northern Alabama/Georgia). Detritus for the Whirlpool Sandstone was derived from erosion of "lower" Tuscarora Sandstone during glacio-eustatic sea-level drop.

5. The "Tuscarora unconformity" (interpreted as an isostatic rebound unconformity) developed following a cessation in Taconic compressional tectonism. Flexural isostatic uplift/rebound converted part of the Taconic foredeep from an active depositional site to an active erosional site. In the area of uplift (denudation area), evidence for the Hirnantian glacio-eustatic sea-level events was cut out, and the produced erosional detritus (derived predominantly from the "lower" Tuscarora Sandstone) was redistributed radially away from the denudation area into parts of the foredeep not affected by rebound, and into areas at the fringe of the foredeep and beyond (parking area and fill area). The 'White Sandstone Lithosome' in extreme southwestern Virginia and eastern Tennessee (Poor Valley Ridge Sandstone and bedsets within the Rockwood Formation) is interpreted to be part of this redistributed material, which interrupted the normal, mud-dominated sedimentation in that area. The "Clinton" sandstone in the subsurface of southern Ohio is regarded as a lithostratigraphic equivalent. The quartz-rich detritus was overprinted and distributed within the fill area by the ambient storm system. The isolated bedsets of the 'White Sandstone Lithosome' within the Rockwood Formation, demarcating the farthest spread of this lithosome, might represent forced regressions.

6. The "upper" Tuscarora Sandstone is interpreted to be related to a new phase of compressional tectonism and active foredeep subsidence, in concert with eustatic sea-level rise in the Llandoveryan. The transgression reworked erosional detritus covering the denudation area, and thereby destroyed evidence of the distributive system. Most of the material for the "upper" Tuscarora Sandstone, however, is believed to have come from the Taconic orogen during this new phase of thrusting.

7. Taconic tectonism exerted a strong influence upon the origin of the 'White Sandstone Lithosome' within the central and southern Appalachians. Flexural isostatic uplift of part of the Taconic foredeep destroyed accommodation space and converted part of the foredeep from a sediment sink into a sediment exporter. Sediment export caused by tectonism (flexural isostatic uplift) complements sediment export through sediment bypassing, which is described from various shallow-marine and terrestrial foredeeps.

CHAPTER 4

THE JUNIATA FORMATION AND "LOWER" TUSCARORA SANDSTONE (UPPER ORDOVICIAN) OF SOUTHWESTERN VIRGINIA: STORM-DOMINATED, SHALLOW-MARINE SEDIMENTATION WITHIN THE TACONIC MOLASSE

PREAMBLE

The purpose of this study is to present a paleoenvironmental interpretation of the Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia (Figure 1-2). Previous paleoenvironmental investigations conducted on the Martinsburg-Shawangunk clastic wedge in Virginia concentrated on the analysis of defined lithostratigraphic units (for example, Hayes, 1974; Lampiris, 1975; Whisonant, 1977; Kreisa, 1980; Diecchio, 1985). It is apparent from recent investigations on the Martinsburg-Shawangunk clastic wedge in southwestern Virginia, however, that the most significant stratigraphic break resides within the Tuscarora Sandstone (Bambach, 1987; Dorsch and others, 1990, 1991; see Chapter 2). The Juniata Formation and "lower" Tuscarora Sandstone are genetically linked and connected to the subjacent Martinsburg Formation (Figure 1-1). Together, these stratigraphic units exhibit a general coarsening-upward trend, which started within the Martinsburg Formation. It is appropriate and warranted, therefore, to conduct a paleoenvironmental analysis on the combined Juniata Formation and "lower" Tuscarora Sandstone, but excluding the "upper" Tuscarora Sandstone.

Only a few earlier studies attempted a paleoenvironmental interpretation of the Juniata Formation and/or the Tuscarora Sandstone within southwestern Virginia or other parts of Virginia. Kreisa (1980, 1982) interpreted the lowermost Juniata Formation of southwestern Virginia as shoreface and beach deposits overlain by non-marine mudflat and coastal plain deposits of the middle and upper Juniata Formation. Diecchio (1985) pointed out the abundance of trace fossils within the Juniata Formation of Virginia. He depicted the Juniata Formation as deposits of broad coastal lowlands or delta plains covered by

shallowest marine waters at least part of the time (Diecchio, 1985). Hayes (1974) interpreted the deposits of the lower part of the Tuscarora Sandstone in southwestern Virginia to be predominantly of barrier island and coastal alluvial plain origin, whereas Lampiris (1975) envisioned fluvial deposits reworked into beach deposits during a transgression. Whisonant (1977) interpreted the same strata as deposits of a broad coastal plain dominated by rivers.

Based on a facies analysis of the Juniata Formation and the "lower" Tuscarora Sandstone, I argue that the Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia represent shallow-marine deposits of the Taconic foredeep, and that the ambient storm system during the Late Ordovician constituted the prime influence on facies development. The change in sediment caliber through time is interpreted to reflect a change in the type of sediment supplied from the Taconic orogen to the Taconic foredeep, and does not necessarily reflect a change in water depth. The persistent shallow-marine character of the studied preserved foredeep fill in southwestern Virginia indicates a delicate balance between creation of accommodation space and sediment supply. Documentation of a marine red-bed succession (Juniata Formation) in southwestern Virginia, furthermore, suggests that red coloration of sediment *per se* does not automatically indicate alluvial/non-marine deposits (Ziegler and McKerrow, 1975; Dorsch and Driese, 1992c).

FACIES DESCRIPTION AND INTERPRETATION

The Juniata Formation represents a red-bed succession and is characterized by maroon-red sandstone, siltstone and mudstone. The "lower" Tuscarora Sandstone, on the other hand, is represented by light-colored sandstone and thin greenish gray mudstone interbeds. The boundary between the two lithostratigraphic units is drawn only with difficulty. Because of the close genetic relationship between these two units, such a boundary serves only for mapping purposes, but has little relevance for paleoenvironmental interpretation.

The clastic succession of the Juniata Formation and "lower" Tuscarora Sandstone can be divided into several recurring facies and their attendant variants, which do not conform to any arbitrary lithostratigraphic boundary. The different facies and variants include: 1) an *amalgamated hummocky cross-stratified sandstone facies* (facies SH), 2) a *wave-ripple cross-stratified sandstone facies* (facies WX), 3) a *heterolithic facies* (facies H,

with variant H_A: *interbedded hummocky cross-stratified sandstone and background fines*, and variant H_B: *interbedded high-angle cross-stratified sandstone and background fines*), 4) a *scour facies* (facies SC), and 5) a *high-angle cross-stratified sandstone facies* (facies SX, with variant SX_A: *bedsets encased in amalgamated hummocky cross-stratified sandstone*, variant SX_B: *thick bedsets encased in heterolithic deposits*, and variant SX_C: *thick, continuous cross-stratified bedsets*).

Variants H_B, SX_B and SX_C have a gradational relationship with each other.

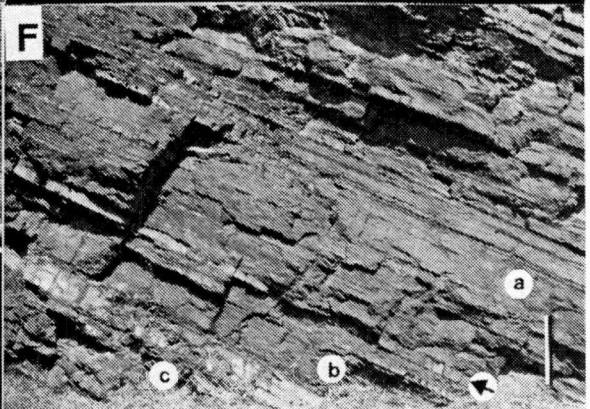
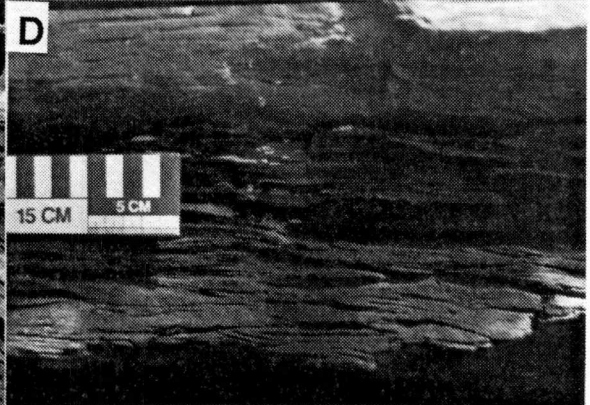
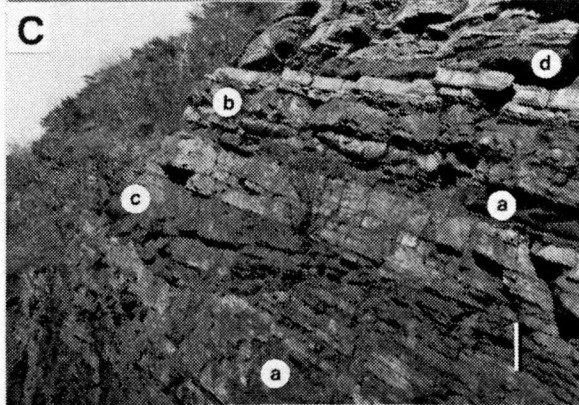
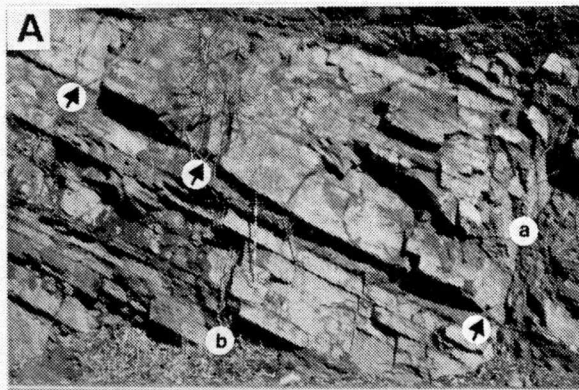
Distinctions between these different variants are based on the relative proportion of sand to background fines (usually silty mudstone or mudstone). Variant H_B constitutes thin discrete beds of high-angle cross-stratified sandstone set in abundant background fines (ratio sand:fines ranges up to 50:50); variant SX_B is made up of thicker bedsets of high-angle cross-stratified sandstone (either amalgamated sandstone beds with almost no background fines or beds separated by thin interbeds of background fines) set within the heterolithic facies; variant SX_C is represented by thick, continuous units of high-angle cross-stratified sandstone bedsets with little intercalated background fines ($\geq 85\%$ sand for thick outcrop sections). Figures 4-1 and 4-2 illustrate some of the sedimentological aspects of the different facies and variants as defined, whereas Table 4-1 provides a summary of the sedimentological characteristics and a process-sedimentologic paleoenvironmental interpretation of each facies and variant.

Description of Facies and Variants

Amalgamated Hummocky Cross-stratified Sandstone Facies. Facies SH is composed of fine- to very fine-grained sandstone. Medium-grained sandstone with abundant small maroon mudstone clasts and shell hash is very rare, as is the occurrence of silty mudstone/siltstone. Facies SH occurs as thick, amalgamated bedsets of sandstone (Figure 4-1A). A few thin maroon mudstone seams and aligned mudstone clasts make it possible to identify the outlines of beds now completely amalgamated. Notable are scour surfaces at the base of this facies and also within the amalgamated sandstone unit (Figure 4-1A). Relief on the scour surfaces reaches 25 cm at Narrows and up to 70 cm at South Gap (see Figure 1-3 for outcrop locations).

Stratification of facies SH is dominated by hummocky cross stratification. Swales up to 2 m wide seem to be preserved preferentially, but hummocks also occur (Figure 4-1B). Associated stratification types include wave-ripple cross stratification, either

Figure 4-1: Sedimentological features of the different facies and variants of the Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia. A) Facies SH (a) overlying facies WX (b), in the Juniata Formation at Narrows; note internal scour surface within facies SH indicated by the arrows; staff is 1.20 m. B) Detail of facies SH, Juniata Formation at Narrows; note convex-upward stratification within thick unit of amalgamated hummocky cross stratification; part of the hammer handle displayed is approx. 15 cm. C) Channel (c) incised into facies SH (a), note ball-and-pillow structure (b); facies SH is succeeded by facies WX (d), Juniata Formation at Narrows; scale bar is approx. 1.0 m. D) Detail of wave-ripple cross stratification, Juniata Formation at Narrows. E) Close-up view of ball-and-pillow structure developed in facies WX, Juniata Formation at South Gap. F) Variant H_A (a) succeeding facies WX (b) and SH (c), Juniata Formation at Narrows; note sharp-based tempestite bed (indicated by arrow) with distinct hummocky top; star indicates ball-and-pillow structure; scale bar is approx. 1.0 m. G) Distinctive sandstone bed (a) displaying low-angle trough cross stratification (*sensu* Nøttvedt and Kreisa, 1987) within variant H_A, Juniata Formation at Narrows; staff is 1.20 m. H) Appearance of variant H_B in outcrop, Juniata Formation at South Gap; staff is 1.20 m. I) Shallow asymmetric scour and fill (facies SC) developed within variant H_A, Juniata Formation at Narrows; scour base is outlined by arrows; staff is 1.20 m. J) Variant SX_B (a) sandwiched between two units of variant H_B (b), Juniata Formation at South Gap; staff is 1.20 m. K) Erosive base of a bedset of variant SX_C scouring into subjacent unit of variant SX_C, "lower" Tuscarora Sandstone at South Gap; staff is 1.20 m. L) Winnowed coarse lag strewn over top surface of thick unit of variant SX_C, "lower" Tuscarora Sandstone at Cove Mountain.



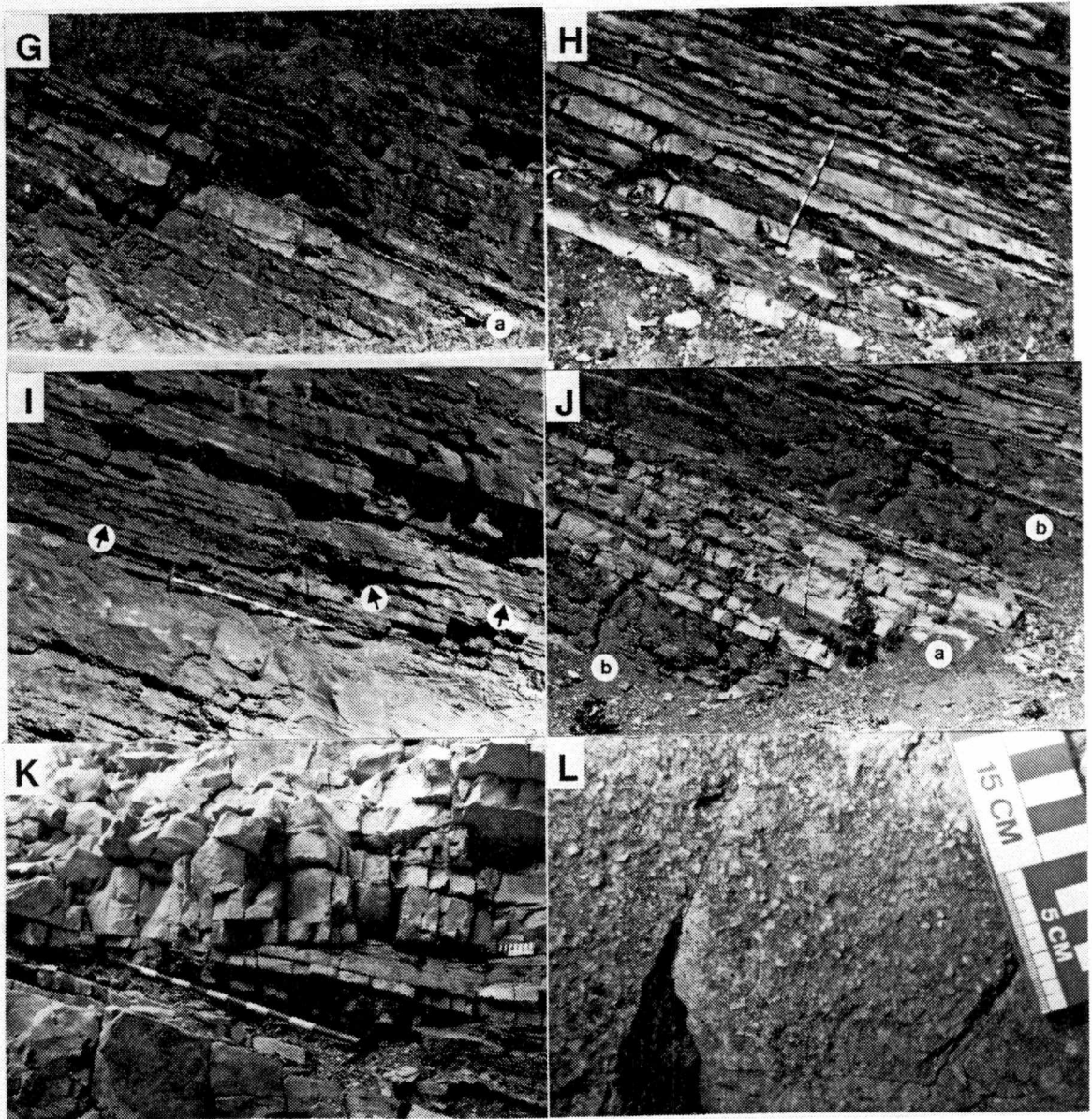


Figure 4-1 (continued)

Figure 4-2: Trace fossils encountered within the Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia. A) Completely bioturbated interval of maroon-red silty mudstone of variant H_B, Juniata Formation at South Gap; staff is divided into 10 cm increments. B) *Monocraterion* "trumpets" filled with maroon-red mudstone in greenish-gray sandstone bed of variant H_B, Juniata Formation at Narrows. C) Top of *Skolithos* burrows developed within variant H_B, Juniata Formation at Cove Mountain. D) Tops of mudstone-filled *Monocraterion* burrows within variant SX_B, Juniata Formation at Cove Mountain. E) *Cruziana* from the underside of a maroon-red sandstone bed of variant SX_B, Juniata Formation at South Gap. F) *Rusophycus* from the underside of a brownish-white sandstone bed of variant SX_C, "lower" Tuscarora Sandstone at South Gap.

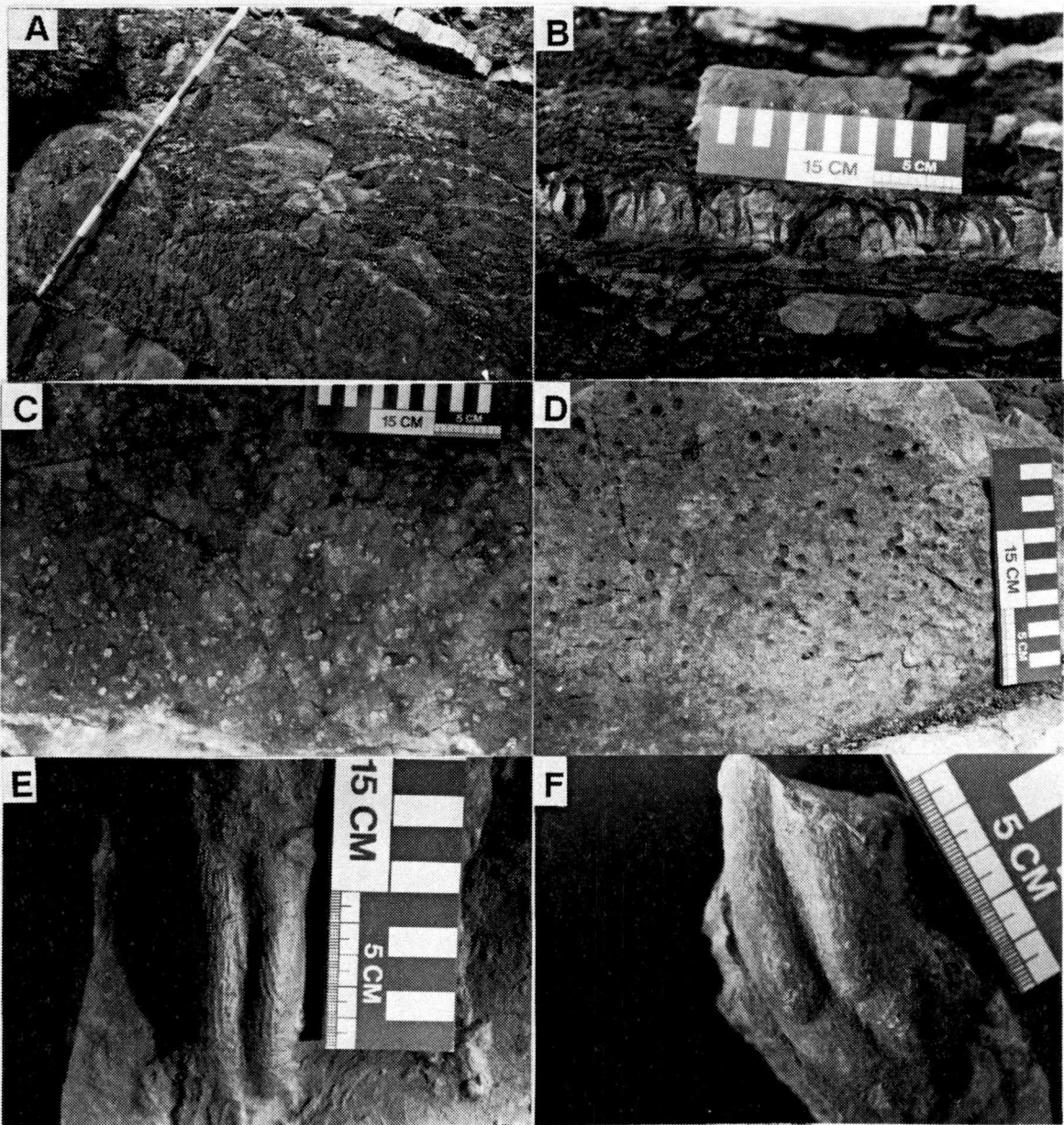


Table 4-1. Summary of the defining aspects of the different facies and variants of the Juniata Formation and "lower" Tuscarora Sandstone in southwestern Virginia, together with an interpretation of physical processes and paleodepositional environments.

Description	Interpretation
Amalgamated Hummocky Cross-stratified Sandstone Facies (facies SH)	
fine- to very fine-grained sandstone; amalgamated beds; hummocky cross stratification, some wave-ripple cross stratification, some ball-and-pillow structure; very rare medium-grained sandstone, planar cross stratification; few combined-flow ripple formsets; sparse bioturbation (<i>Skolithos</i> , <i>Cruziana</i> , <i>Rusophycus</i>)	suspension-load transport and settling; sandy storm deposits related to oscillatory-dominant combined flows; upper lower to middle shoreface
Wave-ripple Cross-stratified Sandstone Facies (facies WX)	
very fine- to fine-grained sandstone, mudstone clasts, some shell hash; wave-ripple and micro-hummocky cross stratification, ball-and-pillow structure; some symmetrical/combined-flow ripple formsets; abundant bioturbation (<i>Planolites</i> , <i>Rusophycus</i> , <i>Cruziana</i> , <i>Skolithos</i>)	suspension-load transport and settling; sandy storm and fairweather deposits, related to combined and oscillatory flows; ball-and-pillow structure due to cyclic wave loading; lower lower shoreface
Heterolithic Facies (facies H)	
interbedded sandstone and intensively bioturbated background sediment (muddy siltstone to mudstone); beds discrete, common lateral changes in thickness, sharp/erosional bases; variant H _A : very fine- to fine-grained sandstone, some mudstone clasts; hummocky and wave-ripple cross stratification; some symmetrical/interference-ripple formsets; extensive bioturbation (<i>Skolithos</i> , <i>Rusophycus</i> , <i>Monocraterion</i> , <i>Cruziana</i> , <i>Arenicolites</i> , <i>Planolites</i>); Variant H _B : fine- to medium-grained sandstone, rare granules/pebbles, abundant mudstone clasts; trough and ripple cross stratification, some planar cross stratification, rare wave-ripple cross stratification; some symmetrical/interference-ripple formsets, some winnowed top lags; extensive bioturbation (<i>Rusophycus</i> , <i>Monocraterion</i> , <i>Skolithos</i> , <i>Planolites</i> , <i>Cruziana</i> , <i>Arenicolites</i>)	suspension-load transport and settling (variant H _A and fairweather deposits), and offshore-directed unidirectional bedload transport (variant H _B), related to oscillatory-dominant to unidirectional-dominant combined flows; sandy storm deposits interbedded with finer grained fairweather deposits; large 3D-wave ripples (variant H _A), and subaqueous 3D-dunes and ripples (variant H _B) within the offshore-transition zone to offshore zones
Scour Facies (facies SC)	
shallow scours filled predominantly with heterolithic sediment; mostly fine- to very fine-grained sandstone, silty mudstone; micro-hummocky, wave-ripple and trough cross stratification; abundant bioturbation (<i>Skolithos</i> , <i>Monocraterion</i>)	offshore-directed unidirectional bedload transport, and suspension-load transport and settling; scours due to the effects of storm-enhanced distal rip currents and/or downwelling currents; shallow-marine offshore setting
High-angle Cross-stratified Sandstone Facies (facies SX)	
variant SX _A : medium-grained sandstone, some granules, abundant mudstone clasts; sharp/erosive bases, scouring; trough cross stratification; variant SX _B : fine- to coarse-grained sandstone, abundant mudstone clasts; amalgamated beds, sharp/erosive bases, some scouring; rare symmetrical-ripple formsets; trough cross stratification, some ripple and planar cross stratification; abundant bioturbation (<i>Skolithos</i> , <i>Monocraterion</i> , <i>Cruziana</i> , <i>Rusophycus</i> , <i>Planolites</i>); variant SX _C : medium- to very coarse-grained sandstone, dispersed granules/pebbles, abundant mudstone clasts, some interbedded silty mudstone; sharp/erosive bases, some scouring; some winnowed top lags; trough cross stratification, some ripple and planar cross stratification; abundant bioturbation (<i>Monocraterion</i> , <i>Rusophycus</i> , <i>Cruziana</i> , <i>Planolites</i> , <i>Arthropycus</i>)	offshore-directed unidirectional bedload transport, and suspension-load transport and settling, related to unidirectional-dominant combined flows; sandy storm deposits and some finer grained fairweather deposits; coalescing of 3D-, 2D-dunes and ripples to form larger scale sediment-storage bodies (variants SX _B and SX _C) within an offshore setting; variant SX _A represents 3D-dunes and ripples of rip-current channels cut into deposits of the middle and upper lower shoreface

succeeding hummocky cross stratification within beds, or furnishing the sole stratification type of separate beds. One single bed of medium-grained sandstone displays planar cross stratification in a set 20 cm thick. Some parts of facies SH exhibit ball-and-pillow structure, indicating the destruction of the original stratification by a process of soft-sediment deformation. Because of the scarcity of mudstone seams, features of bed bases and bed tops are rarely observable. A few examples of tool marks and one formset of symmetrical ripples (combined-flow type), however, were observed. Cross-stratification (combined-flow ripples and planar cross stratification) indicate paleoflow directed toward the northwest. Two readings on parting lineations give bidirectional results of 138°-318° and 68°-248°.

Facies SH is weakly bioturbated and contains only a small number of individual trace fossils, including *Skolithos*, *Cruziana* and *Rusophycus*. The scarcity of bioturbation is in marked contrast to the more bioturbated facies WX and variant H_A, which both overlie and underlie facies SH (Figure 4-3). A prominent channel deeply cuts into deposits of facies SH at Narrows, and is in turn overlain by deposits of facies SH (Figure 4-1C). The channel fill is inaccessible for direct observation, but seems to be made up of distinct sandstone beds. The crumbly appearance of the lower part of the channel fill might represent abundant bioturbation. Facies SH occurs within the lower reaches of the Juniata Formation at the Narrows, South Gap and Gap Mountain localities (Figure 4-3), and is not developed at the Cove Mountain locality.

Wave-ripple Cross-stratified Sandstone Facies. Facies WX is represented by very fine- and fine-grained sandstone and siltstone. Mudstone clasts usually are finely dispersed throughout some beds, but also form discrete and laterally discontinuous thin layers (<5 cm). Shell hash constitutes the basal parts of a few sandstone beds. Distinct sandstone beds reach a thickness of up to 27 cm (more commonly ≤10 cm) and display normal grading. Stratification types are dominated by wave-ripple cross stratification (Figure 4-1D) and micro-hummocky cross stratification. Planar stratification is found to a lesser degree. Notable are intervals up to 1.5 m thick exhibiting soft-sediment deformation, which can be described as ball-and-pillow structure (Figure 4-1E). Some beds of facies WX display small load casts and tool marks at bed bases, rare dish structures internally, and some symmetrical-ripple formsets (including combined-flow type) and micro-hummocks at bed tops. A few of the micro-hummocky cross-stratified and sharp-based sandstone beds are partly amalgamated. Directional measurements from facies WX are very sparse. One reading from a symmetrical-ripple formset gave a 68°-248° orientation for the ripple crest, and a

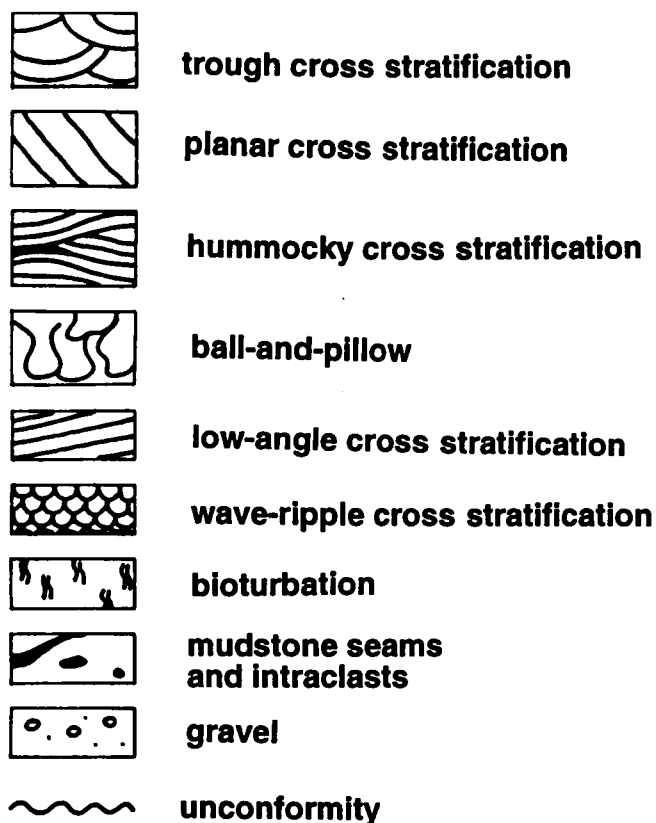


Figure 4-3: Measured stratigraphic sections of the Juniata Formation and "lower" Tuscarora Sandstone in southwestern Virginia. For location of outcrop localities refer to Figure 1-3. Abbreviations are as follows. Grain size: c - clay; f - fine sand; m - medium sand; cs - coarse sand; vc - very coarse sand; pb - pebble; trace fossils: AE - *Arenicolites*; AR - *Arthropycus*; CR - *Cruziana*; MO - *Monocraterion*; PL - *Planolites*; RU - *Rusophycus*; SK - *Skolithos*. Stratification types and some other sedimentologic features are explained in the legend; 'Corg-rich' refers to strata rich in organic matter; 'hcs' refers to the occurrences of hummocky cross stratification high in outcrop sections, 'lab' refers to the occurrence of lateral accretion bedding. The distribution of facies and variants are indicated along the measured sections. They include: SH - amalgamated hummocky cross-stratified sandstone; WX - wave-ripple cross-stratified sandstone; H_A - interbedded hummocky cross-stratified sandstone and background fines; H_B - interbedded high-angle cross-stratified sandstone and background fines; SC - scour; SX_A - bedsets encased in amalgamated hummocky cross-stratified sandstone; SX_B - thick bedsets encased in heterolithic deposits; SX_C - thick continuous cross-stratified bedsets.

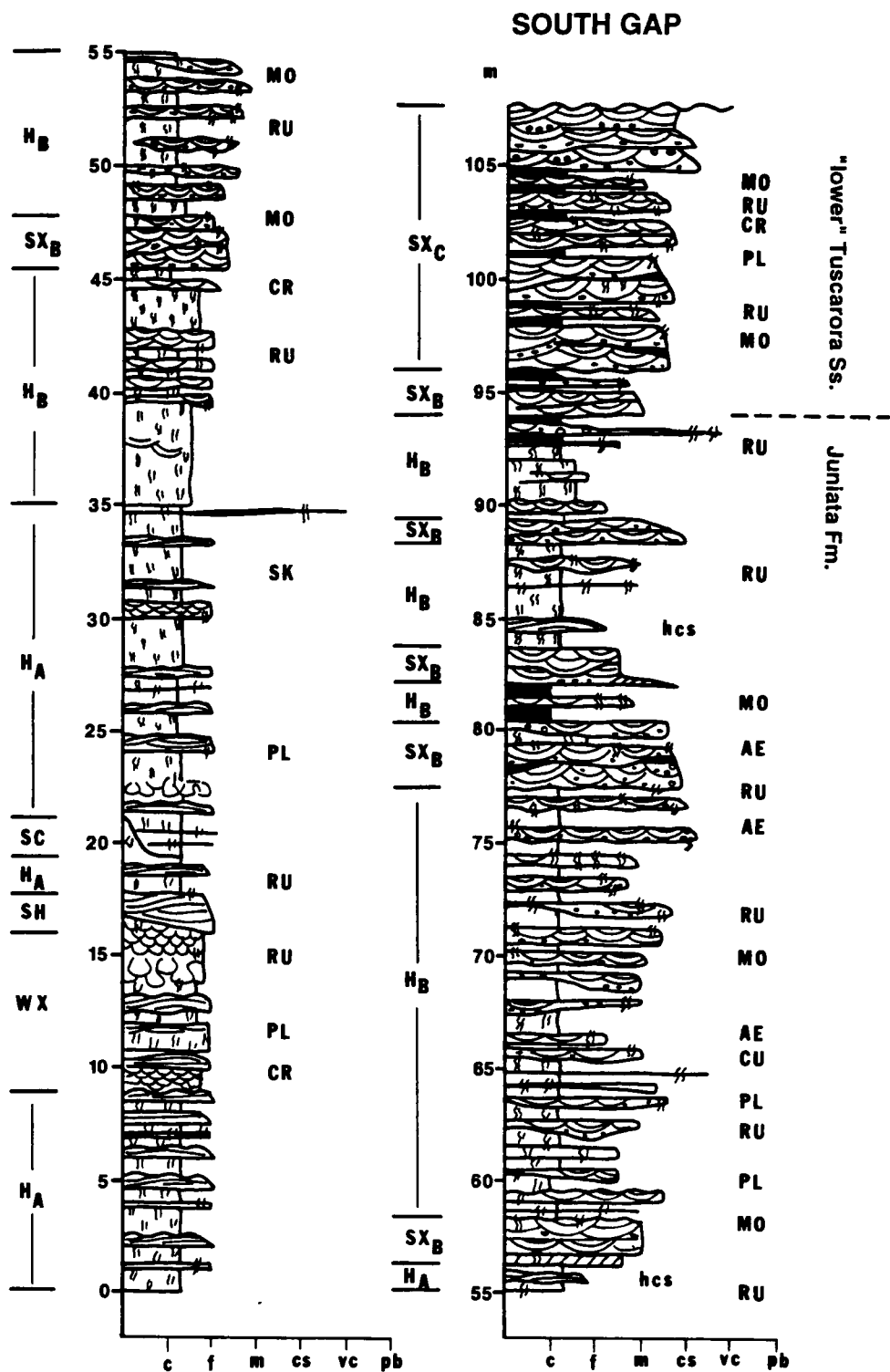


Figure 4-3 (continued)

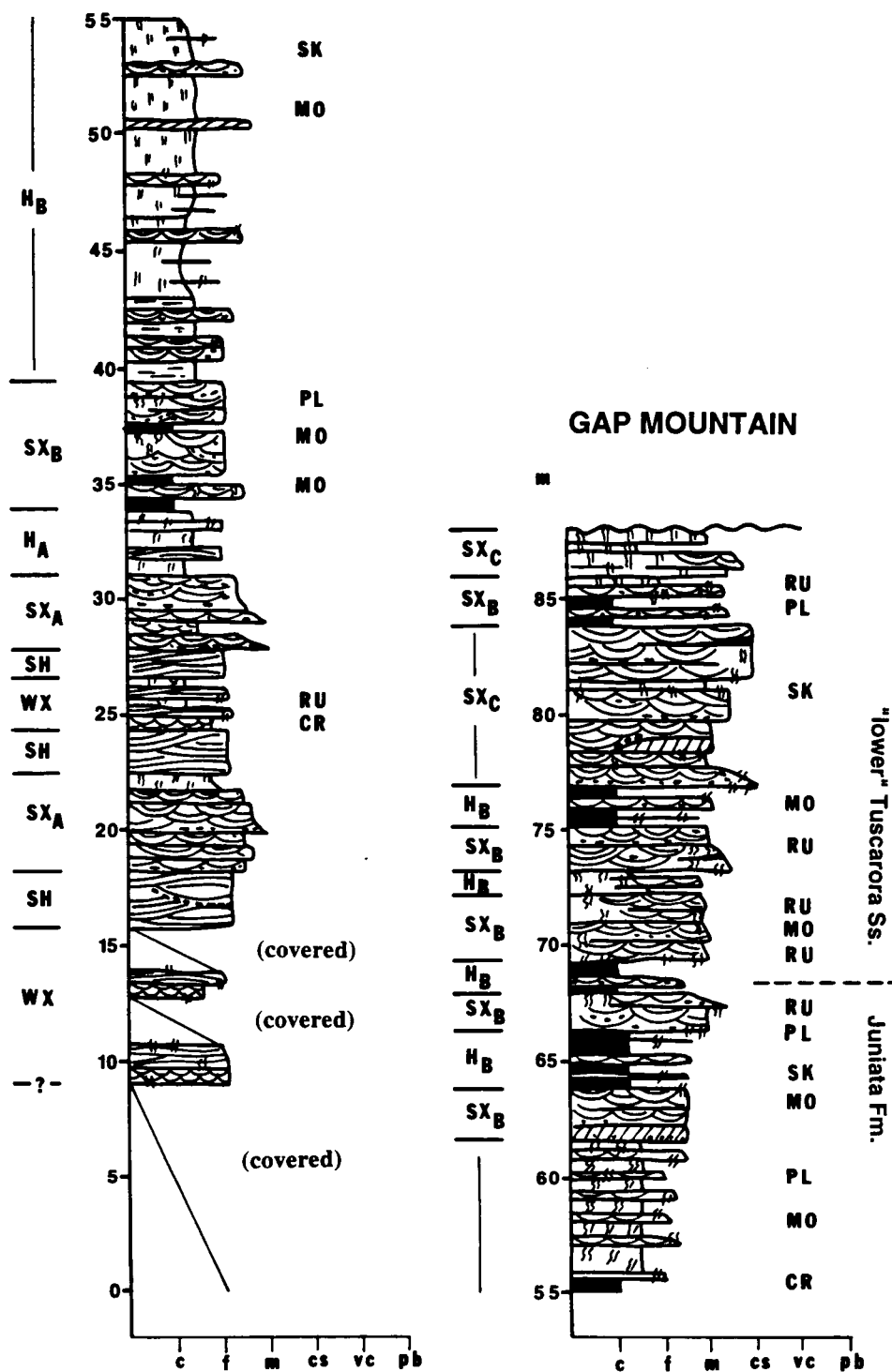


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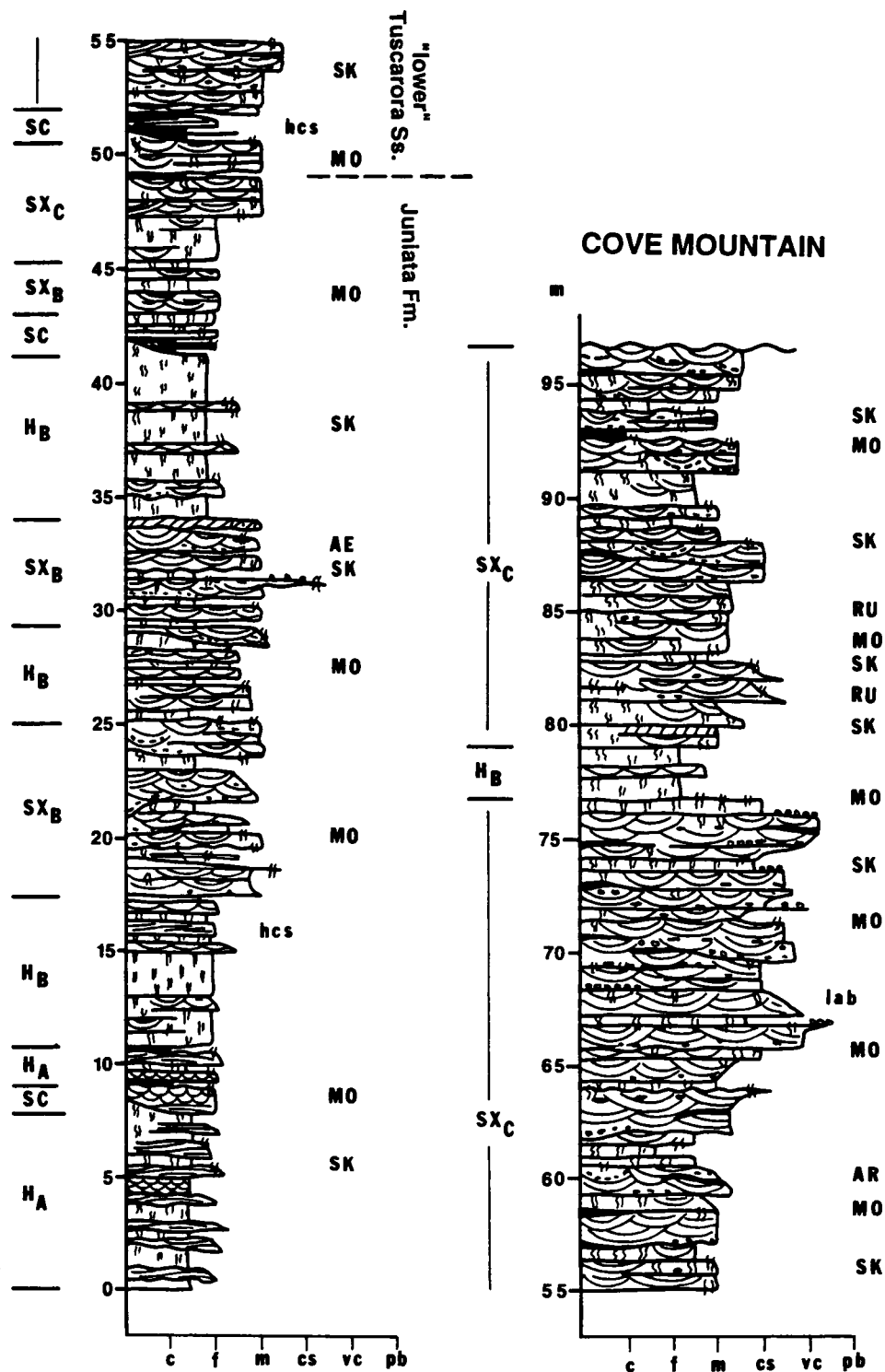


Figure 4-3 (continued)

paleoflow directed toward 321° was obtained from ripple cross stratification contained within a combined-flow symmetrical-ripple formset.

Bioturbation is more prevalent than in facies SH, but does not reach the degree displayed by variant H_A of the heterolithic facies. Nevertheless, some of the sandy/silty intervals are completely bioturbated. Trace fossils include *Planolites*, *Rusophycus*, *Cruziana*, and *Skolithos*. Facies WX occurs immediately beneath facies SH at the Narrows, South Gap and Gap Mountain localities, and above facies SH at the same outcrop localities except South Gap (Figure 4-3). Facies WX is not developed at Cove Mountain.

Heterolithic Facies. Facies H is characterized by discrete sandstone beds dispersed within a finer grained host sedimentary rock. The finer grained background fines predominate, but a ratio of 50:50 between sandstone beds and background fines is common. Background fines are relatively coarse-grained and are commonly muddy siltstone. In all outcrop sections, the background fines seem to become finer grained up section by the addition of more clay material; background fines of facies H, then, classify as silty mudstone to mudstone. Facies H can be differentiated into two separate variants based on the stratification type found in the sandstone beds: a variant H_A (interbedded hummocky cross-stratified sandstone and background fines) and a variant H_B (interbedded high-angle cross-stratified sandstone and background fines).

Variant H_A is made up of fine- to very fine-grained, discrete sandstone beds set within silty mudstone and rarely mudstone. Where maroon mudstone clasts and/or abundant shell hash are available, the sandstone beds become medium-grained. The sandstone beds are predominantly between 10 and 30 cm thick, with a minimum thickness of 3 cm. They commonly exhibit pronounced changes in thickness, including pinch-out, when traced laterally across the outcrop face. Amalgamation of adjacent beds is seen only rarely. Bed bases are sharp and undulatory-erosive, and display a few examples of tool marks, load casts and some gutter casts. Bed tops are distinct to indistinct, depending on the grain-size contrast between sandstone bed and background fines, and on the degree of bioturbation. The bed tops display some examples of symmetrical-ripple and interference-ripple formsets and, more commonly, micro-hummocks or hummocks (Figure 4-1F).

The sandstone beds of variant H_A are characterized by hummocky cross stratification and micro-hummocky cross stratification. Associated stratification types include wave-ripple cross stratification and planar stratification. One bed with abundant shell hash (*Lingula*) and mudstone clasts displays a single set of planar cross stratification.

At the Narrows locality, a peculiar 60 cm thick bed (Figure 4-1G) is dominated internally by very wide low-angle swales (in part accentuated by very thin mudstone seams) and draped erosive surfaces. Draping sand laminae can have a sigmoidal outline and thicken into swales. Dip of some of the draping laminae can reach up to 20°. Soft-sediment deformation features are rare within variant H_A, far less common than in facies WX.

Normal grading is observable in sandstone beds with an appropriate range of grain sizes. Directional readings obtained from variant H_A are summarized in Table 4-2.

The degree of bioturbation within variant H_A exceeds that of facies WX and SH. Background fines appear mostly massive, caused by complete bioturbation. Thinner sandstone beds seem to have been obliterated during biogenic activity, resulting in a relatively coarse mix of background fines and formerly discrete sandstone beds. Identifiable trace fossils are found associated with the less bioturbated discrete sandstone beds and include abundant *Skolithos*, *Monocraterion* and *Rusophycus*, rare *Arenicolites*, and some *Planolites*. Some of the sandstone beds, furthermore, contain escape burrows. Bioturbation seems to increase when proceeding up section. Variant H_A constitutes large intervals within the lower half of the Juniata Formation at all localities. At Narrows and South Gap, variant H_A can be found surrounding facies SH and WX (Figure 4-3).

Variant H_B of the Heterolithic Facies is characterized by fine- to medium/fine-grained sandstone beds encapsulated by background fines (Figure 4-1H). Rare dispersed granules and pebbles constitute the maximum grain size present. Mudstone clasts, either occurring dispersed within sandstone beds or as thin clast layers, are abundant. Shell hash can be found rarely. Stratification types of these sandstone beds are dominated by trough cross stratification in sets commonly ≤10 cm, but reaching up to 30 cm in thickness, and current-ripple cross stratification. Some occurrences of planar cross stratification, planar stratification and wave-ripple cross stratification are noted. A single hummocky cross-stratified sandstone bed occurs at the South Gap locality within a large interval of variant H_B. At the Narrows locality, a 66 cm thick sandstone bedset exhibits low-angle inclined bedding, which dips toward the northwest. The beds display low-angle stratification, which parallels the bed boundaries. A few thin mudstone seams separate some of the inclined beds. A part of this sandstone bedset is capped by hummocks.

Sandstone beds commonly range between 10 and 25 cm in thickness, with a maximum of 40 cm and a minimum of ≤5 cm. There is also some lateral change in bed thickness, including pinch-out, but it is not as pronounced as for variant H_A. Bases of

Table 4-2. Directional measurements from variant HA

<i>Sedimentary Structures</i>	<i>Directional Measurements</i>
gutter casts	82°-262°, 178°-358°, 64°-244°
tool marks	89°-269°, 127°-307°, 106°-286°
symmetrical-ripple crests	82°-262°, 66°-246°, 119°-296°, 60°-240°, 35°-215°, 53°-233°
parting lineations	103°-283°, 37°-217°, 107°-287°
combined-flow ripple foresets	345°, 355°, 11°, 251°, 272°

sandstone beds are sharp and undulatory-erosive/scoured. Some load casts, tool marks and a few pot casts also can be observed. Tops of sandstone beds display a few examples of symmetrical-ripple and interference-ripple formsets. In marked contrast to variant H_A, coarse-grained winnowed lags cap some of the sandstone beds of variant H_B.

Silty mudstone comprises most of the background fines, but "pure" mudstone occurs more often than in variant H_A. The massive appearance of most background fines is attributed to complete bioturbation (Figure 4-2A). The trace fossil suite of the sandstone beds is dominated by abundant *Rusophycus* and *Monocraterion* (Figure 4-2B), with *Skolithos* (Figure 4-2C), *Planolites*, and *Cruziana* also occurring. *Arenicolites* and discrete escape burrows, on the other hand, are rare. Variant H_B constitutes a major part of the upper half of the Juniata Formation and a minor part of the "lower" Tuscarora Sandstone (Figure 4-3), and it seems to develop out of variant H_A through coarsening of the average sand size. Variant H_B, furthermore, is intimately associated with variant SX_B.

Scour Facies. Facies SC is exemplified by shallow to deep scours and their associated fill. The relief of these scours is between 30 cm and 1.70 m. The scours occur within the lower part of the Juniata Formation at the Narrows (Figure 4-1I), South Gap and Cove Mountain localities, where they are associated with variant H_A. The scours also occur within the upper part of the Juniata Formation and the lower part of the "lower" Tuscarora Sandstone, where they are associated with variant SX_B and SX_C (at the Narrows and Cove Mountain localities). The fill of these scours is predominantly heterolithic (5 examples), with only once each occurrences of sandy and muddy fill. Commonly only one of the scour margins can be observed, because of the lateral limitations imposed by the outcrop.

Heterolithic scour fill is characterized by fine- to very fine-grained sandstone beds of 5 to 15 cm thickness set within background fines of silty mudstone. Where the scours are developed within variant H_A, the scour fill corresponds in character to the host sediment. Some of the sandstone beds are inclined conforming to the outline of the scour margin, but inclination decreases upward through the scour fill (Figure 4-1I). Stratification types include micro-hummocky cross stratification, wave-ripple cross stratification, current-ripple cross stratification, and also trough cross stratification. Ripple cross stratification and trough-axes indicate a paleoflow directed toward the west/northwest. One measured scour margin is oriented 113°-293°. Bioturbation is similar to the host sediment (including bioturbation up to 100%), and discrete *Skolithos* and *Monocraterion* burrows were identified. The example of muddy scour fill appears to be completely bioturbated and

occupies a ca. 30 cm deep and ca. 1.5 m wide scour, which is inaccessible for more detailed observations. Similar shallow scours are described by Duke and others (1991) from the Lower Silurian Medina Group of Ontario and New York.

The single example of sandy scour fill can be observed within the upper reaches of the Juniata Formation at the Narrows locality. The sandstone filling the scour (ca. 1.20 m deep) is medium/coarse- and medium/fine-grained. Maroon mudstone clasts are abundant. The sandstone fill is characterized by trough cross stratification, with sets reaching up to 20 cm in thickness. A scour margin is oriented 93° - 273° , and a measured trough-axis indicates a paleoflow directed toward 292° . Bioturbation could not be identified within this scour fill, whereas the sandy host sediment displays bioturbation.

High-angle Cross-stratified Sandstone Facies. Facies SX is the coarsest grained facies encountered within the Juniata Formation/"lower" Tuscarora Sandstone interval. It can be divided into variant SX_A (bedsets encased in amalgamated hummocky cross-stratified sandstone), which is closely related to facies SH, variant SX_B (thick bedsets encased in heterolithic deposits), which is associated with variant H_B of the heterolithic facies, and variant SX_C (thick continuous cross-stratified bedsets), which constitutes the uppermost, sandiest and coarsest grained variant within facies SX.

Variant SX_A occurs encased within facies SH and is best developed at the Gap Mountain locality. This variant is missing at the South Gap locality. The prominent channel, which cuts into facies SH at the Narrows locality (Figure 4-1C), is tentatively assigned to variant SX_A . Variant SX_A is characterized by predominantly medium-grained sandstone with abundant dispersed maroon mudstone clasts and some dispersed coarse quartz grains and even granules. Mudstone clasts reach a maximum of 4 cm in length and 1 cm in thickness. Some siltstone occurs capping intervals composed of variant SX_A . Variant SX_A reaches thicknesses of 3.21 and 2.70 m, and displays sharp-erosive lower and distinct upper boundaries to the surrounding facies SH. The sandstones are prominently trough cross-stratified in sets up to 30 cm thick, and also display current-ripple cross stratification. Measured trough axes ($n=8$) indicate a paleoflow directed toward the north-northwest (range from 341° to 19°).

Variant SX_B displays a wide range of grain sizes from fine to medium/coarse, with medium being the most common. Mudstone clasts are abundant, either dispersed within sandstone beds or as thin clast layers. The mudstone clasts are on the average 4 cm long, but molds of 7 cm length and 2 cm depth were observed. Sandstone beds are commonly

≤20 cm or ≤40 cm thick and reach a maximum of 90 cm at Cove Mountain. In general, the average bed thickness increases with increasing grain size, and thicker beds are commonly found higher in the outcrop sections within the Juniata Formation and "lower" Tuscarora Sandstone. Sandstone beds are either separated by thin mudstone interbeds or amalgamated to different degrees (Figure 4-1J). The latter is indicated by laterally discontinuous mudstone seams or interbeds. Bed bases are sharp-erosive and either flat or scoured. Scour relief is usually ≤10 cm, but reaches in one case up to 60 cm at Cove Mountain. Some bed bases also display load casts. Tops of sandstone beds are distinct and show examples of current-ripple and symmetrical-ripple formsets, and examples of micro-hummocks with no crest development. Larger scale undulatory bed tops might indicate larger bedforms.

Stratification types of sandstone beds are dominated by trough cross stratification. Sets are commonly ≤20 cm thick, but can reach up to 50 cm. The cross-sets are mutually intersecting with a width of up to 2 m. The size of the trough sets is positively related to the thickness of the sandstone bed containing the cross stratification. Occurring to a minor extent are ripple cross stratification and planar cross stratification (sets reaching up to 40 cm in thickness), and much more rarely planar stratification. Bioturbation is common, and trace fossils include abundant examples of *Skolithos*, *Monocraterion* (Figure 4-2D), *Cruziana* (Figure 4-2E), *Rusophycus*, and also *Planolites*.

Variant SX_B is clearly associated with variant H_B and can be found in all outcrops predominantly within the Juniata Formation, but also within the "lower" Tuscarora Sandstone. Variant SX_B replaces variant H_B when the sand content of an interval becomes dominant over interbedded background fines and the bedsets appear organized within a stretch of outcrop section. Typical examples of variant SX_B embedded within facies H are ≤2 m in thickness, and are made up of ≥80% of sandstone beds (Figure 4-1J).

Variant SX_C is best developed at the Cove Mountain locality, where it holds up most of the "lower" Tuscarora Sandstone (Figure 4-3). This variant can also be found in the "lower" Tuscarora Sandstone at Draper Mountain, Gap Mountain, and South Gap, and in the upper parts of the Juniata Formation at Narrows (Figure 4-3). Grain size of variant SX_C is predominantly medium to coarse, but can reach up to coarse/very coarse, and rarely down to fine. Quartz grains up to pebble-size can be detected within sandstone beds. Mudstone clasts are abundant, either dispersed within beds or concentrated in thin layers. Mudstone and siltstone constitute the rare interbedded fines.

Sandstone beds range from 10 to 40 cm in thickness, with an observed maximum of 60 cm. Sandstone beds usually are amalgamated to thicker bedsets, and bed outlines are indicated by aligned mudstone clasts and discontinuous mudstone seams. Bed bases are sharp-erosive and show some load casts. Undulatory bed bases can display a scour relief of up to 30 cm (Figure 4-1K). Bed tops are distinct and show some current-ripple formsets and coarse winnowed lags (Figure 4-1L). The thin winnowed lags often cap a normal grading trend within a bed. Larger scale undulatory tops of thicker bedsets at the Cove Mountain locality seem to indicate the presence of shallow channels/scours cutting the bedsets from above. Upon further inspection, however, these undulatory outlines appear to belong to larger scale bedforms, whose crest areas were decapitated by succeeding sandstone beds and whose intervening bedform troughs were preferentially preserved together with their fine-grained fill. At the Cove Mountain locality, one sandstone unit (ca. 1.10 m thick) displays inclined bedding. The separate beds are gently curved concave upwards and thin toward the base of the sandstone unit. The beds are trough cross-stratified and occasionally are separated by thin discontinuous mudstone seams.

Stratification is predominantly trough cross stratification, with mutually cross-cutting sets of ≤ 17 cm thickness (maximum 35 cm). Related stratification types include ripple cross stratification, planar cross stratification (sets up to 35 cm thick) and rare planar stratification. Bioturbation is prevalent, reaching 100% in a few intervals. The trace fossil suite is characterized by abundant *Monocraterion* and *Skolithos*, *Rusophycus* (Figure 4-2F), and some *Cruziana*, *Planolites* and *Arthropycus*.

Synopsis of Paleoflow Data

The directional measurements are treated separately for the Juniata Formation and "lower" Tuscarora Sandstone (Figure 4-4). Paleocurrents were obtained from trough axes (64% of the readings from Juniata Formation, 84% from "lower" Tuscarora Sandstone), planar cross stratification (18% from Juniata Formation, 10% from "lower" Tuscarora Sandstone), and current-ripple cross stratification (18% from Juniata Formation, 6% from "lower" Tuscarora Sandstone). The readings are predominantly from variant SX_C for the "lower" Tuscarora Sandstone, and predominantly from variants H_B and SX_B for the Juniata Formation.

The resultant mean vector azimuth for both stratigraphic units is directed toward the northwest, with a full range of paleocurrent readings from approximately southwest to north-northeast. These results are identical to those of Diecchio (1985) for the Juniata

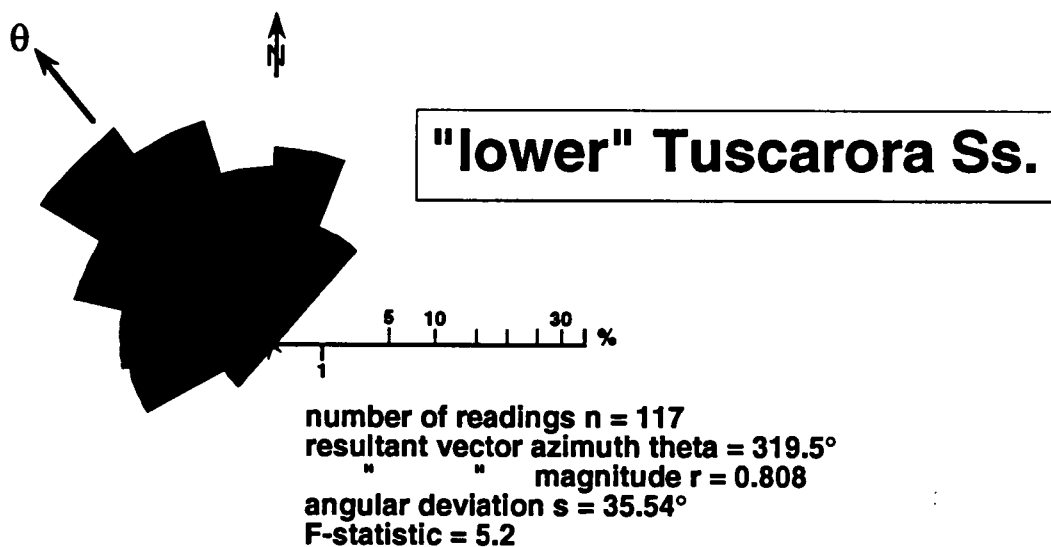
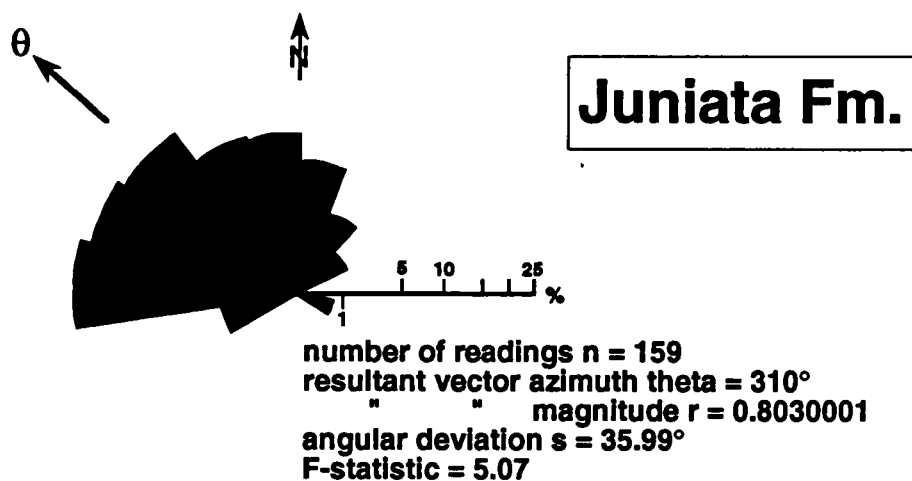


Figure 4-4. Paleocurrent rose diagrams (20° class intervals) for the Juniata Formation and "lower" Tuscarora Sandstone in southwestern Virginia. Vector-summation technique and statistical calculations were performed using an unpublished computer program by Maher and Dott (1979). Offshore is inferred to have been toward the west/northwest.

Formation, and Hayes (1974) and Whisonant (1977) for the Tuscarora Sandstone (see also Chapter 5). The data for the Juniata Formation are also similar to the paleocurrent data obtained by Kreisa (1980). The bidirectional paleocurrent pattern identified by Kreisa (1980) for one of his facies, which he interpreted as tidal in origin, however, could not be verified in the present study. The paleocurrents directed toward the northwest, west and north indicate flow down the inferred paleoslope (Hayes, 1974; Whisonant, 1977; Kreisa, 1980; Diecchio, 1985) away from the Taconic orogen to the southeast (present-day coordinates). Paleocurrents directed toward the north-northeast to northeast might indicate a flow component parallel to the orientation of the paleoslope.

Interpretation of Facies and Variants

Amalgamated Hummocky Cross-stratified Sandstone Facies. Thick continuous bedsets of amalgamated hummocky cross-stratified sandstone are interpreted as shoreface deposits of storm-dominated clastic shorelines (see, for example, Aigner and Reineck, 1982; Reineck and Singh, 1986; Brenchley, 1985; Brenchley and others, 1986; Johnson and Baldwin, 1986). These deposits usually can be found beneath high-angle cross-stratified and coarser grained sandstone units of the upper shoreface, and most likely represent deposits of the upper lower and middle shoreface (Harms and others, 1975; Reineck and Singh, 1986; Swift and others, 1987; Leckie and Krystinik, 1989; Cheel and Leckie, 1993). The scarcity of bioturbation is coincident with observations on modern shorefaces (Howard and Reineck, 1981; Reineck and Singh, 1986). The few trace fossils that are present are types that support the interpretation of a shallow-marine depositional setting. Finer grained fairweather deposits within amalgamated successions of hummocky cross-stratified sandstone beds are typically rare, because of erosional removal during successive storm events (Dott and Bourgeois, 1982; Duke, 1985). Some fairweather deposits are preserved in facies SH as thin, discontinuous mudstone seams and as a single bed of silty mudstone. The single sandstone bed exhibiting planar cross stratification is developed in medium-grained sand, which probably was too coarse for the development of hummocky cross stratification. The paleoflow direction indicated by this cross stratification indicates the presence of an offshore-directed unidirectional current at least part of the time beneath the upper shoreface.

Wave-ripple Cross-stratified Sandstone Facies. Facies WX is interpreted to represent deposits of the lower lower shoreface (see also Kreisa, 1980). Along a transect perpendicular to the paleoshoreline, facies WX is bordered by facies SH toward the shore and by variant H_A toward offshore. Deposition of facies WX occurred above mean fairweather wave base. The micro-hummocky cross-stratified sandstone beds represent storm sand layers (for example, Vos and Hobday, 1977; Hamblin and Walker, 1979; Dott and Bourgeois, 1982; Hunter and Clifton, 1982), whereas thicker intervals of wave-ripple cross-stratified sandstone/siltstone intervals with abundant bioturbation probably represent predominantly fairweather deposits (for example, De Raaf and others, 1977; Reineck and Singh, 1986; Elliott, 1986). The ubiquitous occurrence of soft-sediment deformation structures within facies WX is interpreted to reflect liquefaction of the sediment. Liquefaction might have been caused by increased pore pressures set up by cyclic loading due to storm waves (Doe and Dott, 1980). Given the inferred shoreface setting for facies WX, cyclic loading by storm waves appears preferable to cyclic loading by earthquakes (see also Dalrymple, 1979, 1980). The fine-grained nature of facies WX favors liquefaction, because release of excess pore pressure is retarded by the low permeability of the sediment (Doe and Dott, 1980). The degree of bioturbation, in some cases up to 100%, the association with other facies/variants, and the identifiable trace fossils support a shallow-marine interpretation for facies WX.

Heterolithic Facies. Heterolithic successions of discrete, predominantly hummocky cross-stratified sandstone interbedded with finer grained and bioturbated sediment (variant H_A) are commonly interpreted as shallow-marine deposits (see, for example, Harms and others, 1975; Vos, 1977; Bourgeois, 1980; Kreisa, 1981; Dott and Bourgeois, 1992; Hunter and Clifton, 1982). The sandstone beds are thought to represent deposits of separate short-lived and higher energy storms, whereas the intervening finer grained sediment is interpreted as having been deposited during longer lived, lower energy fairweather periods (see, for example, Vos and Hobday, 1977; Hamblin and Walker, 1979; Dott and Bourgeois, 1982; Hunter and Clifton, 1982). Hummocky and micro-hummocky cross stratification, parting lineation, sharp erosive bed bases with tool marks and gutter casts, escape burrows, bed tops with hummocks, symmetrical- and interference-ripple formsets, and pronounced lateral change in bed thickness are considered as distinguishing characteristics of shallow-marine storm sandstones (Seilacher, 1982; Goldring and Aigner, 1982; Dott and Bourgeois, 1982; Leckie and Krystinik, 1989; Seilacher and Aigner, 1991; Cheel and Leckie, 1993).

Variant H_A of the heterolithic facies, therefore, is interpreted to represent fairweather-dominated deposits intercalated with storm sandstones of the transition zone and offshore zone of a storm-influenced epicontinental sea.

The increased level of bioturbation in variant H_A relative to facies WX and SH supports placement of variant H_A in a depositional setting farther offshore from the shoreface deposits of facies WX and SH. A systematic increase in bioturbation away from the beach toward the open sea is documented from modern shallow-marine settings (Howard and Reineck, 1981; Aigner and Reineck, 1982; Reineck and Singh, 1986). The occurrence of completely bioturbated intervals indicates that ample time was available for organisms to modify and alter the primary fabric of the sediment (Howard, 1975). A shallow-marine depositional setting for variant H_A is supported, furthermore, by the trace fossil suite. *Skolithos*, *Monocraterion* and *Arenicolites* represent dwelling burrows of suspension-feeding organisms within a relatively high-energy, shallow-marine environment (Frey, 1975). Organisms responsible for the vertical burrows behaved opportunistically and swiftly reclaimed areas affected by storms following the convulsive events (Vossler and Pemberton, 1988; Frey, 1990). Organisms responsible for *Rusophycus* traces, on the other hand, might represent members of the resident population, which recolonized the same area during the lower energy fairweather periods (Frey, 1990; Cheel and Leckie, 1993). Shallow-marine storm deposits typically display a mix of trace fossils from the *Skolithos* and *Cruziana* ichnofacies (Frey, 1990; Cheel and Leckie, 1993).

Sand for the storm beds in the transition zone and offshore zone setting is believed to have been supplied from the shoreface by offshore-directed, oscillatory combined flows (Duke and others, 1991). The unidirectional current component can be related to coastal set-up and downwelling during storms (Duke, 1990; Duke and others, 1991) and to storm-enhanced rip currents. Offshore-directed foresets of combined-flow ripples within variant H_A (and facies WX and SH), and the rare planar foresets of coarser grained two-dimensional dunes, support the presence of an offshore-directed unidirectional current. The development of hummocky cross stratification is probably tied to the growth of large three-dimensional wave ripples. These bedforms originate through aggradation during waning oscillatory flows and strongly oscillatory-dominant combined flows, and through reworking involving storm and swell waves (Duke and others, 1991; Cheel and Leckie, 1992; 1993).

The peculiar 60 cm bed at the Narrows locality corresponds to the low-angle trough cross stratification (transverse section) described by Nøttvedt and Kreisa (1987). These

authors emphasize the close genetic relationship of this stratification type to hummocky cross stratification. They relate the origin of low-angle trough cross stratification to migration of a low-relief bedform in response to combined flow within a shallow-marine environment. Arnott and Southard (1990) referred to this stratification type as anisotropic hummocky cross stratification. Cheel and Leckie (1993) place it in the center of a continuum of stratification types, ranging from isotropic hummocky cross stratification to trough cross stratification, where the component of unidirectional flow steadily increases (see also Nøttvedt and Kreisa, 1987; Arnott and Southard, 1990; Duke and others, 1991).

Variant H_B represents subaqueous, predominantly three-dimensional dunes, which migrated in an offshore direction toward the west/northwest (and to a minor extent to the north), and apparently were scattered across the sea floor. A shallow-marine depositional setting for the discrete sandstone beds is indicated by the abundant bioturbation (up to 100%) and the shallow-marine trace fossil suite. This trace fossil suite is essentially the same as the one encountered in variant H_A . The sharp-based sandstone beds with erosional markings and some load casts indicate high flow velocities, episodic transport, and rapid and episodic deposition. They can be interpreted as event beds (Seilacher and Aigner, 1991), probably related to storms. The intervening and volumetrically dominant finer grained background sediment might represent suspension-settling deposits of fairweather periods. A shallow-marine environment and the link to storms is strengthened, furthermore, by the close kinship of variant H_B to variant H_A . Rare, discrete hummocky cross-stratified sandstone beds occur within variant H_B , and variant H_B alternates with variant H_A over an interval of outcrop section at the South Gap and Narrows localities (Figure 4-3). It appears that variant H_B developed out of variant H_A , and that the finer grained hummocky cross-stratified sandstone beds of variant H_A were replaced by coarser grained high-angle cross-stratified sandstone beds of variant H_B farther up in outcrop sections. The appearance of coarser grained winnowed lags on top of some of the sandstone beds is interpreted as a characteristic of shallow-marine sandstones (Levell, 1980; Reading, as cited in Byers and Dott, 1981), whereas the lateral impersistence of beds is considered typical of storm beds (Goldring and Aigner, 1982). The low-angle bedded bedset at the Narrows locality displays low-angle cross stratification, which is too low in dip to represent avalanche deposits. The sand body apparently grew in an offshore direction, but the exact nature of this shallow-marine sand body is presently unresolved.

The depositional setting for variant H_B is believed to have been the same as for Variant H_A . The stratification types point toward strong unidirectional currents and bed-

load transport within a shallow-marine, offshore setting. The presence of oscillatory flows is indicated by the occurrence of some symmetrical-ripple and interference-ripple formsets, and by the winnowed coarse-grained top lags. The sand might have been supplied to the subtidal setting by strong downwelling currents during storms and by storm-enhanced rip currents.

Scour Facies. The shallow scours are developed in a marine depositional setting as indicated by the bioturbated scour fill set within a bioturbated host sediment. The various facies and variants, which form the host for the scours and their fills, are also interpreted as shallow-marine, subtidal deposits (see above and below). The scarce directional measurements reveal that the scours are oriented in an offshore direction, perpendicular to the inferred paleoshoreline trend, and that bedforms contained within the scours migrated in the same direction.

The typical fill of the shallow scours is heterolithic and is dominated by the finer grained tail of the grain-size spectrum. The heterolithic character of the scour fills might indicate that deposition within the scour was accomplished over a period of time, with the sandstone beds reflecting higher energy depositional events alternating with lower energy suspension settling of silt/mud. It is also likely that a time lag existed between the erosive event responsible for the scour and the onset of deposition within the scour (Goldring and Aigner, 1982). Once the scour was cut it acted to funnel successive flows and depositional events. Goldring and Aigner (1982), furthermore, mention that scour structures (gutters to broader scours as in this example) characterized by an inferred distinct temporal separation of the cut and fill events, are typical of many interpreted shelfal deposits. The sand-filled scour in the upper part of the Juniata Formation at Narrows is similar in its characteristics to variant SX_A, except that it is not encased within amalgamated hummocky cross-stratified sandstone bedsets. The sandy fill reflects the availability of sand for the sediment-carrying current. The sand-filled scour might also represent an example where the cut and fill events were essentially contemporaneous.

Possible modern analogues from shallow-marine environments are described by Flood (1981), who reported estuarine erosional furrows which remained unfilled for several years. Cacchione and others (1984) described shallow scours oriented perpendicular to the shoreline from water depths up to 65 m off the coast of central California. They linked these and other reported (for example, Hunter and others, 1982) marine, shallow erosional

features and their sandy fill to the action of strong, offshore-directed downwelling currents during storms. The wave-ripple and micro-hummocky cross-stratified sandstone beds in scours set within a host sediment dominated by hummocky cross-stratified sandstone beds of the lower Juniata Formation seems to support a close relationship to storm currents. Similar shallow depressions in offshore water depth up to 30 m are interpreted by Reimnitz and others (1976), on the other hand, as due to the erosional and depositional activity of rip currents during severe storms. The profound effects of rip currents on shallow-marine sea bottoms even far offshore was recently summarized by Gruszczynski and others (1993).

In summary, the shallow scours within different facies/variants of the Juniata Formation and "lower" Tuscarora Sandstone are shallow-marine morphologic features. The cut and fill events most likely are related to storms. The scours and their fill are the result of strong storm-induced downwelling currents and/or manifestations of the more distal effects of severe storm-enhanced rip currents (Dorsch and Driese, 1992c). The sandy fill of one scour may reflect deposition closer to the ancient shoreline, but still in an offshore setting.

High-angle Cross-stratified Sandstone Facies. Variant SX_A is completely encased within deposits of facies SH, which was interpreted earlier (see above) as storm-dominated deposits of the middle to upper lower shoreface. Stratification and paleocurrent readings indicate migration of three-dimensional dunes and current ripples in an offshore direction. The most likely interpretation is that variant SX_A represents deposits of rip currents, which violently interrupted deposition of finer grained sand in the middle to upper lower shoreface. Rip currents introduced the coarser grained sand (and some silt) from the upper shoreface to the lower part of the shoreface. Because of outcrop limitations, it is not possible to judge whether variant SX_A at Gap Mountain constitutes laterally restricted scours or actually laterally extensive sandstone sheets. Laterally extensive sandstone sheets of rip-current deposits are described from ancient upper shoreface deposits by Vos and Hobday (1977), Clifton (1981), and Dorsch and Driese (1992a, see Chapter 5). These sandstone sheets formed by deposition of coarser grained sand within laterally migrating rip channels. Rip currents are more likely to leave their mark on the deposits of the upper shoreface (Cook, 1970; Vos, 1977; Reineck and Singh, 1986). They reach below the upper shoreface only under exceptional circumstances, such as during severe storms (for example, Seilacher, 1982). It is therefore likely that variant SX_A represents laterally restricted rip-current deposits introduced to the lower part of the shoreface during exceptional and more violent storms along a storm-dominated shoreline. The distinctive channel at the Narrows locality is

assigned to variant SX_A based on its occurrence within facies SH and on its apparent sandy fill. The channel clearly displays lateral margins and supports the argument against sandstone sheets. High-angle cross-stratified sandstone bedsets, associated with amalgamated hummocky cross-stratified sandstone bedsets and interpreted as rip-current deposits along a storm-dominated shoreline, were also described by Atkinson and others (1986) from the subsurface of the Miri Formation of Brunei.

Variant SX_B is interpreted as shallow-marine offshore deposits, like variant H_B of the heterolithic facies, with which it is closely related. Like the sandstone beds of variant H_B , the sandstone beds of variant SX_B are interpreted as storm beds. Stratification types indicate the former presence of subaqueous three-dimensional dunes, and to a much smaller extent of two-dimensional dunes and current ripples, which all migrated in an offshore direction predominantly toward the northwest and west. Bed-load transport is inferred to have occurred during higher energy conditions and involved migration and aggradation of fields of subaqueous bedforms (see Hein, 1987). Intervening finer grained deposits are interpreted to reflect predominantly suspension settling during lower energy fairweather conditions. The fairweather deposits, however, are mostly eroded away, resulting in different degrees of amalgamation of the sandstone beds. The more sandstone-rich intervals of variant SX_B , as compared to variant H_B , can be attributed to more frequent storms over a period of time, to more powerful storms and enhanced erosive power, or to a decrease in the rate of generation of accommodation space. The trace fossil suite of variant SX_B is very similar to the trace fossil suite found in variant H_B and H_A , supporting a shallow-marine interpretation for variant SX_B . Emplacement of sediment and migration of the sediment as bed load is related to powerful unidirectional currents. The concurrent presence of oscillatory water motion is indicated by the occurrence of symmetrical-ripple and micro-hummock formsets on top of some sandstone beds.

The sand-rich variant SX_C is interpreted to represent the coalescing of subaqueous bedforms, predominantly three-dimensional dunes, to larger scale sediment-storage elements within a shallow-marine setting. Bed-load transport predominantly toward the northwest was accomplished during storm periods, which were interrupted by suspension settling of finer sediment during fairweather periods. Undulatory outlines at the top of thicker bedsets of sandstone, which are capped by bioturbated finer sediment and are partly truncated by the following thicker sandstone bedset, indicate the rapid abandonment of larger sediment-storage elements. The shallow-marine setting is indicated by the trace fossil

suite and the extent of bioturbation, and by the occurrence of some winnowed coarse lags on bed tops. The inclined beds with thin mudstone seams within the "lower" Tuscarora Sandstone at the Cove Mountain locality depict lateral accretion deposits. This bedding style, however, seems not to be associated with the erosional lateral migration of a channel, but with episodic migration and aggradation of three-dimensional dunes along inclined depositional surfaces. Similar bedding styles were described by Johnson (1977) and Hein (1987) from Precambrian and Cambrian subtidal deposits, and were interpreted to indicate the sides of larger sediment-storage elements (shelf sand-ridges).

ASPECTS OF THE STRATIGRAPHY AND SEDIMENTOLOGY OF THE JUNIATA FORMATION AND "LOWER" TUSCARORA SANDSTONE IN SOUTHWESTERN VIRGINIA

Regional Lithostratigraphy

The Juniata Formation and "lower" Tuscarora Sandstone constitute part of the Taconic molasse. The formations conformably succeed the "tempestitic" Martinsburg Formation, which represents a lateral lithostratigraphic equivalent of the foreland flysch of the "turbiditic" Martinsburg Formation of the Taconic foredeep. The "lower" Tuscarora Sandstone of southwestern Virginia caps an uninterrupted coarsening-upward succession, which started within the Martinsburg Formation. The largest stratigraphic break is contained within the Taconic molasse, and is represented by the "Tuscarora unconformity" (Dorsch and others, 1990; 1991; see Chapter 2).

The Juniata Formation and "lower" Tuscarora Sandstone are closely related, and defining a lithostratigraphic boundary is difficult. In the present study, the boundary was drawn at the top of the last clearly maroon-red mudstone bed. "Lower" Tuscarora-type sandstone beds are intercalated within red beds of Juniata affinity and indicate the apparent intertonguing stratigraphic relationship of the two lithostratigraphic units.

Regional paleocurrent trends oriented toward the northwest and an increase in grain size toward the southeast reveal that the source area for the Taconic molasse was situated to the southeast (Amsden, 1955; Hayes, 1974; Whisonant, 1977; Kreisa, 1980; Diecchio, 1985; Figure 4-4; see Chapters 3 and 5). The "lower" Tuscarora Sandstone is interpreted as an overall coarser grained, quartz-rich sediment body derived from an orogenic source to the

southeast, which prograded toward the northwest away from the source area with time (Figure 4-5). The "lower" Tuscarora Sandstone can be considered to represent a lithostratigraphic equivalent of the upper Juniata Formation, much like the Oswego Sandstone represents a lithostratigraphic equivalent of the lower Juniata Formation in central and northern Virginia (Thompson, 1970a, b; Diecchio, 1985). The present-day distribution and observed thickness of the "lower" Tuscarora Sandstone (Figure 4-6) seems to be strongly influenced by its inferred original wedge-shaped outline (Figure 4-5) and by erosional removal associated with isostatic basin rebound prior to onset of deposition of the "upper" Tuscarora Sandstone (Dorsch and others, 1990, 1991; see Chapters 2 and 3; Figure 3-9). It is impossible to reconstruct the original distribution and thickness of the "lower" Tuscarora Sandstone, based on the present data.

Depositional Setting

Based on the stratification types, the association of different facies and variants, the pervasiveness of bioturbation, and the nature of the trace fossil suite, the Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia are interpreted to represent deposits of a shallow-marine epicontinental sea. The different facies and variants of the Juniata Formation and "lower" Tuscarora Sandstone conform to different hydrodynamic regimes within this epicontinental sea, ranging from the middle shoreface to offshore zones. The vast majority of the studied stratigraphic interval represents deposits of an offshore-marine setting. Stratification types and their interpretation indicate that the deposits of the shallow-marine epicontinental sea were strongly influenced by episodic storms, which interrupted more prolonged fairweather periods. The majority or all of the sharp-based sandstone beds can be designated as storm deposits (tempestites).

Fluvial, tidal, and delta plain environmental interpretations are not compatible with the observations of this study. Fluvial, and terrestrial environments in general, should be expected, however, in close vicinity to the southeast (presently not or only very poorly exposed) and to the northeast beyond the confines of the field area.

The heterolithic deposits indicate the presence of bed-load transport (high-angle cross stratification) and suspension-load transport (hummocky cross stratification, finer grained background sediment). Stratification types and bedding characteristics of sandstone beds of facies H are interpreted to represent sediment-storage bodies such as ripples and small to medium, simple, three-dimensional (and much less common two-

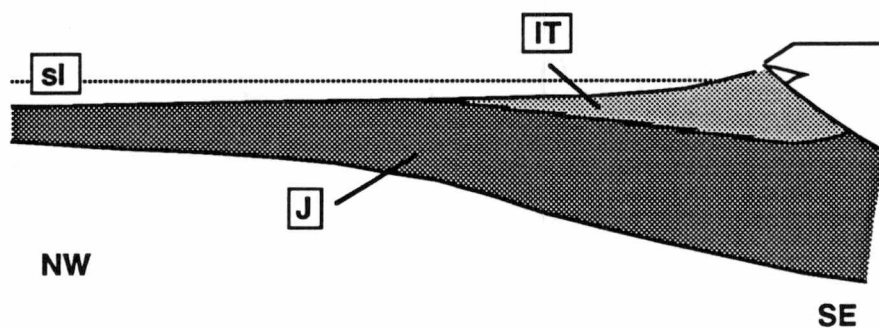
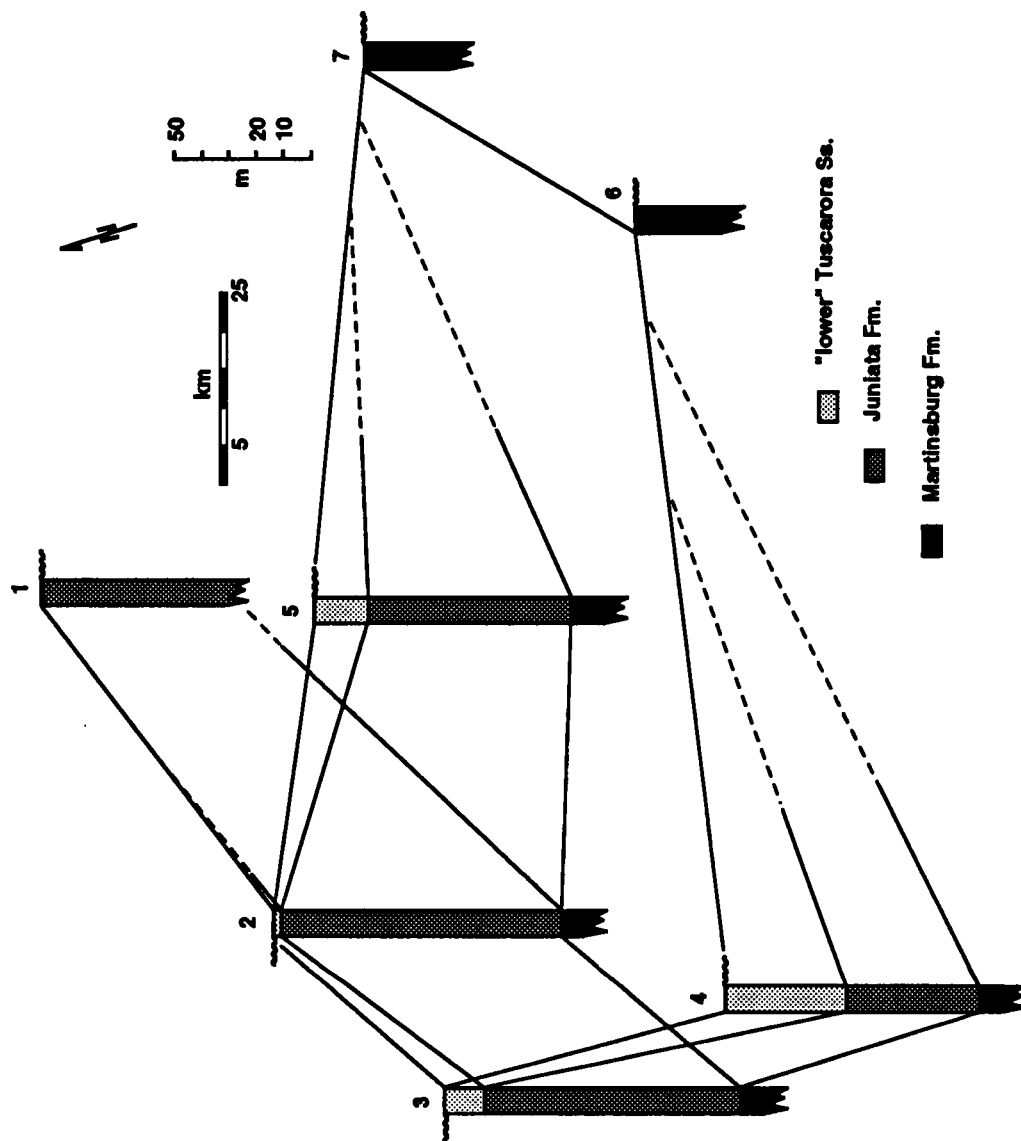


Figure 4-5. Highly schematized diagram showing the inferred stratigraphic relationship between "lower" Tuscarora Sandstone and Juniata Formation. Depicted is an instant in time before the onset of isostatic basin rebound. Orogen as source area is shown to the southeast. Abbreviations: IT - "lower" Tuscarora Sandstone; J - Juniata Formation; sl - sea level.

Figure 4-6: Stratigraphic correlation diagram for the Juniata Formation and "lower" Tuscarora Sandstone in southwestern Virginia drawn on a palinspastic base. Outcrop localities: 1 - Gap Mills; 2 - Narrows; 3 - South Gap; 4 - Cove Mountain; 5 - Gap Mountain; 6 - Fagg; 7 - Catawba Mountain. Refer to Figure 1-3 for location of outcrops. Wavy line indicates the "Tuscarora unconformity", except at Cove Mountain, where it represents the Devonian Wallbridge Discontinuity. Thickness data for the Gap Mills section are from Diecchio (1985) and Bambach (1987).



dimensional) subaqueous dunes. These sediment-storage bodies correspond to the ripples and megaripples of modern storm-dominated clastic shelves, as described, for example, by Swift and others (1983, 1986a) and Dalrymple and others (1992). The discrete nature of the sandstone beds and their common lateral termination over the width of the outcrop reflects sand starvation within the offshore-marine setting (for example, Hein and others, 1991), but not overall sediment starvation.

Variants SX_B and SX_C reflect bed-load transport and represent the coalescing and stacking of smaller sediment-storage bodies to form larger sediment-storage bodies. Units of variant SX_B and SX_C were consistently abandoned as active sediment-storage bodies, as indicated by strongly bioturbated sediment encasing variant SX_B , and topping units of variant SX_C and even preserving (some) ?dune formsets.

Whether the thick succession of stacked variant SX_C within the "lower" Tuscarora Sandstone at Cove Mountain represents large-scale subtidal sediment-storage bodies, such as shelf ridges, remains unresolved. In some aspects the "lower" Tuscarora Sandstone resembles the Gog Quartzite, where similar deposits were interpreted as shelf-ridge sands (Hein, 1987; Hein and others, 1991). A more detailed investigation of this question based on a larger regional coverage is needed, but is severely hampered by extensive erosional removal of "lower" Tuscarora Sandstone during isostatic basin rebound, especially in more proximal outcrop belts (Figure 4-6; see Chapter 2).

The current regime throughout deposition of the Juniata Formation and "lower" Tuscarora Sandstone seems to have been dominated by combined-flow currents. Abundant angle-of-repose cross stratification (variants H_B , SX_B , SX_C) indicates the presence of strong unidirectional currents accomplishing bed-load transport. Associated with this high-angle cross stratification, however, is evidence for oscillatory currents, such as coarse-grained winnowed lags on bed tops, some symmetrical and interference-ripple formsets, and rare wave-ripple cross stratification (in variant H_B). Facies and variants characterized by oscillatory-current dominated stratification types (facies SH and WX, variant H_A), on the other hand, display evidence for the presence of an unidirectional-flow component, such as combined-flow ripples and rare angle-of-repose cross stratification. A last indicator for the presence of combined-flow currents within the shallow-marine depositional realm is the alternation (and also interbedding) of units displaying unidirectional-current dominated and oscillatory-current dominated stratification types.

The transition from hummocky cross-stratified sandstone beds to high-angle cross-stratified sandstone beds within the heterolithic facies is noteworthy. Hummocky cross

stratification is developed within fine- and very fine-grained sandstone beds, whereas predominantly trough cross stratification is developed in coarser grained sandstone beds. The alternation of hummocky cross-stratified intervals and trough cross-stratified intervals in most of the outcrops (Figure 4-3), and the occurrence of some hummocky cross-stratified sandstone beds within trough cross-stratified sandstone intervals indicates that hydrodynamic conditions might have been similar, and that the change in available grain size was the prime determinant for the change in stratification type. The importance of grain size for the development of hummocky cross stratification was noted earlier by, among others, Duke (1985), Swift and others (1986a), Nøttvedt and Kreisa (1987), Dalrymple and others (1992), and Cheel and Leckie (1993). However, hummocky cross stratification formed in coarser grained psammitic deposits, albeit very uncommon, has been reported (Walker and others, 1983; Duke, 1985).

A second possibility for the change in stratification type involves the shift from strongly oscillatory-dominated combined-flow currents to strongly unidirectional-dominated combined-flow currents. As mentioned earlier, a shift away from strongly oscillatory-dominated combined-flow currents was invoked for the low-angle trough cross-stratified, fine-grained sandstone bed in variant H_A at Narrows. The influence on stratification type by the degree of partitioning of combined-flow currents between oscillatory and unidirectional components was emphasized by Swift and others (1986a), Nøttvedt and Kreisa (1987), Duke and others (1991), Myrow and Southard (1991), and Cheel and Leckie (1993).

If the degree of partitioning between the two flow components fluctuated considerably within the ambient combined-flow currents, trough cross stratification should also be expected within some of the finer grained sandstone beds of the heterolithic facies (Nøttvedt and Kreisa, 1987; Myrow and Southard, 1991; Duke and others, 1991). A shift toward strongly unidirectional-dominated combined-flow currents contemporaneous with the availability of coarser grain sizes appears to be a less plausible explanation. A change in available grain size during essentially the same hydrodynamic conditions (persistent combined-flow currents with *some* fluctuation in partitioning between the two flow components) appears to be a more likely explanation for the observed changes in stratification type within the heterolithic facies.

Supply of sediment to the shallow-marine setting was most likely accomplished by downwelling currents and powerful rip currents, both related to storm conditions. During storm conditions, the sea surface is set up against the shoreline triggering an offshore-

directed bottom current. This offshore-directed bottom-hugging current is powerful enough to entrain sediment and to transport it seaward from the upper shoreface (see, for example, Swift and others, 1983; 1986a, b; Nummedal, 1991). This downwelling circulation during storms is characteristic of storm-dominated shorelines and accomplishes much offshore-directed sediment transport (see, for example, Swift and others, 1983; Nummedal, 1991). The capacity and competence of the offshore-directed, steady unidirectional current can be enhanced considerably by the interaction with wave-induced currents. The combined shear stress exerted by these combined flows commonly exceeds the sum of the stress components of the separate flows (Grant and Madsen, 1979; Swift and others, 1986b; Nøttvedt and Kreisa, 1987; Nummedal, 1991).

The importance of rip currents as an agent for offshore sediment transport is often overlooked or underestimated. Gruszczynski and others (1993) documented the considerable erosional and depositional effects of modern rip currents, based on field experiments along the coast of the Baltic Sea and by summarizing cryptic Soviet literature. Rip currents are not confined to the upper regions of the water column, as commonly believed (for example, Nummedal, 1991), but can considerably affect the sea bottom (Reimnitz and others, 1976; Gruszczynski and others, 1993). The effects of rip currents, magnified substantially during storms, can be felt far offshore from the shoreline. Storm-enhanced rip currents are able to transport sediment from the nearshore far seaward (Gruszczynski and others, 1993; Swift and others, 1983) and might be invoked for the emplacement especially of the coarser grained sediment (for example, Leckie and Walker, 1982). The presence of storm-enhanced powerful rip currents and their importance for facies development was pointed out earlier for the Juniata Formation and the "upper" Tuscarora Sandstone (Dorsch and Driese, 1992a, c; see Chapter 5).

The paleocurrent readings obtained from high-angle cross stratification indicates migration of bedforms predominantly toward the northwest (variance from southwest to north) and a minor component toward the northeast (Figure 4-4). The migration directions are interpreted as predominantly offshore-directed, with a minor shore-parallel migration direction. Migration of bedforms within an offshore setting due to storm-generated shelf currents are reported from variable depths of modern shallow-marine settings (Boggs, 1974; Swift and others, 1983, 1986a, b; Luternauer, 1986; Dalrymple and others, 1992).

Offshore-marine settings are commonly strongly influenced by geostrophic veering of unidirectional currents into a shore-parallel direction (for example, Swift and others, 1986b). Geostrophic veering should be manifested especially in the orientation of the high-

angle cross stratification (Duke, 1990). Such a dominant shore-parallel geostrophic current, directed toward the southwest for the setting of the field area during the Late Ordovician (for example, Duke, 1990), is not detectable in the paleocurrent pattern of the Juniata Formation and "lower" Tuscarora Sandstone in southwestern Virginia (Figure 4-4). Only some of the paleocurrent indicators, especially in the "lower" Tuscarora Sandstone, might be interpreted to indicate geostrophic veering. Driese and others (1991) found good evidence for geostrophic veering in Lower Silurian shallow-marine rocks in eastern Tennessee.

Dalrymple and others (1992) explained the consistent sediment transport on the modern Atlantic shelf off Newfoundland as due to the interaction of intense wave-orbital motion and storm-generated unidirectional currents. The two flow components, aligned approximately parallel, augmented each other and, together with the weak Labrador current, generate a uniformly offshore-directed, strong combined-flow current system capable of moving sediment up to gravel size on the shelf floor. Geostrophic veering is apparently not detectable in the orientation of the resulting shelfal bedforms. A similar scenario of appropriately aligned storm-generated unidirectional and strong, prolonged oscillatory currents, and their mutual reinforcing might constitute the most probable explanation for the preferred offshore-directed paleocurrent pattern within the Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia. Whether a weak oceanic current was present and reinforced offshore-direct currents, as does the modern Labrador current off Newfoundland (Dalrymple and others, 1992), cannot be evaluated with the available data.

The red pigment for the maroon-red color of the Juniata Formation was most likely produced under oxidizing terrestrial weathering conditions along the front of the Taconic mountains. The oxidized and red sediment was transported to, and deposited within, the shallow-marine Taconic foredeep (Diecchio, 1985; Dorsch and Driese, 1992c). Rapid burial associated with high sedimentation rates within the foredeep, and low levels of organic productivity, might have caused the preservation of the maroon-red coloration (see for example, Ziegler and McKerrow, 1975). The grayish-green parts of some maroon-red mudstone and siltstone beds, and the more pervasive grayish-brown appearance of some sandstone beds can be explained by secondary decoloration, accomplished by percolation of reducing fluids preferentially through coarser grained beds. Secondary decoloration was also invoked for the Oswego Sandstone, which is believed to have been maroon-red originally (Thompson, 1970a, b; Diecchio, 1985). The interpretation of the maroon-red Juniata Formation as shallow-marine deposits points out the possible fallacy in using red

sediment color as a reliable indicator for terrestrial depositional environments (Ziegler and McKerrow, 1975; Dorsch and Driese, 1992c).

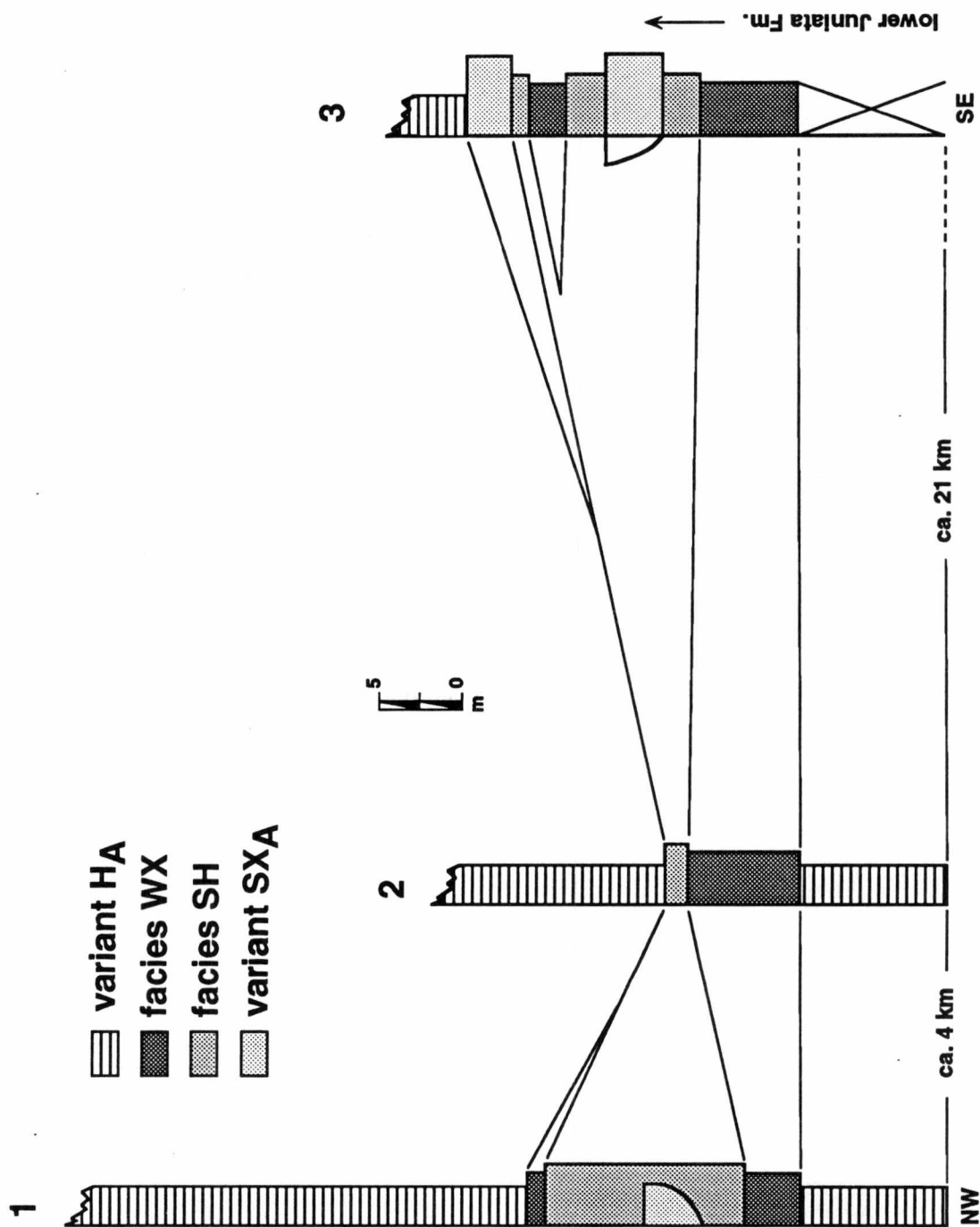
Foredeep Sedimentation

The Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia were deposited within the more distal part of a peripheral foredeep associated with the Taconic orogeny. From the Martinsburg Formation through the "lower" Tuscarora Sandstone, the shallowest depositional regime is encountered within the lowermost Juniata Formation. The depositional regime within the lowermost Juniata Formation shallowed from the offshore transition zone to the middle shoreface (Figure 4-7), and indicates that sediment supply outpaced the creation of new accommodation space. Succeeding this shallowing trend is a return into the offshore transition and offshore zones. The character of the deposits overlying the shallowest water facies (facies SH) and the absence of a sharp marine-flooding surface indicate that this return to deeper water was gradual and not accomplished by rapid marine flooding. The return to a deeper water setting might be related to an increase in the rate of subsidence. The increased subsidence rate was most likely the result of thrusting within the Taconic orogen and thrust-loading of the Laurentian continental crust, with sediment loading and compaction as probable additional factors. While eustatic sea-level rise as the sole cause for the deepening within the foredeep of southwestern Virginia is less likely, it cannot be ruled out completely, based on the data from the lowermost Juniata Formation within the field area.

Reineck and Schwerd (1984) invoked a third mechanism for a deepening from shoreface deposits to offshore/transition-zone deposits within a foredeep, based on observations within the Molasse Basin of Bavaria. Progradation of terrestrial environments into the foredeep results in lengthening of the transport distances and causes a reduction in competence and capacity of the fluvial delivery system. During steady-uniform subsidence, marine environments are able to overtop the decaying fluvial system in proximal areas and can retrograde toward the orogen (source area), placing transition-zone deposits over shoreface deposits in more intermediate areas. This mechanism would most likely entail a gradual return to deeper water, corresponding to the observations within the lowermost Juniata Formation.

Whatever the exact reason for reestablishment of transition zone-offshore zone water depths, the foredeep seemed to have remained shallow-marine, as far as can be judged from

Figure 4-7: Correlation of facies and variants within the lower Juniata Formation of southwestern Virginia. Outcrop localities are: 1 - Narrows, 2 - South Gap, 3 - Gap Mountain; refer to Figure 1-3 for location of outcrops.



the preserved deposits of the middle/upper Juniata Formation and "lower" Tuscarora Sandstone within southwestern Virginia. Progradational shoreline deposits or deposits indicating subaerial emergence are not recognized. Shallowing-upward into terrestrial depositional settings might have occurred. The stratigraphic record of this development, however, was removed by erosion during isostatic foredeep rebound (see Chapters 2, 3, and 5). Accumulation of thick shallow-marine deposits implies a balance between sediment supply and the creation of accommodation space (Cant and Hein, 1986). Based on the nature of the sedimentary basin, continual tectonic subsidence coupled with the effects of sediment loading and sediment compaction (Reynolds and others, 1991) is the most likely determinant for continuous creation of accommodation space. Subsidence was invoked earlier by Diecchio (1985) to explain the depositional pattern of the Juniata Formation of northern Virginia.

The stratigraphic succession of Juniata Formation and "lower" Tuscarora Sandstone displays a sandier-upward trend, and a general coarsening-upward trend of sandstone beds concomitant with fining of the interbedded background deposits. These trends might be ascribed to different causes, which probably acted in concert.

The trends might reflect an increase in the relief of the growing orogen adjacent to the foredeep, together with an attendant increase in erosion. Topographic uplift and increase in relief was related to growth of the orogen appreciably above sea-level. This was accomplished by lateral translation of the orogen up the Laurentian continental-margin ramp, internal deformation of the orogen, and accretion of sedimentary units (Figure 2-3). Accompanying this increase in relief should have been an increase in competence and capacity of the fluvial system delivering sediment to the marine part of the foredeep. Tied to topographic uplift of the orogen was a reduction of lateral translation of the orogen with time (Figure 2-3), which resulted in diminution of thrust-load induced foredeep subsidence. The combined effects of reduced tectonic subsidence and increased amounts of sediment shed from the orogen results in filling of a marine foredeep to subaerial conditions (Figure 2-3).

A second explanation for the two trends might be a secular change in the caliber of the source lithologies (Reading and Orton, 1991). The sandier-upward and coarser-sandstone-upward trends might reflect a change to coarser grained and more sand-rich lithologies within the source area, which were made available for erosion and transport to the marine part of the foredeep. A conceptualized stacking order of lithotectonic units of an arc-continent collisional orogen, the type envisioned for the Taconic orogen (see, for

example, Hatcher, 1978; Rowley and Kidd, 1981; Jacobi, 1981; Wehr and Glover, 1985; Drake and others, 1989), would show (from top to bottom): magmatic arc rocks, forearc deposits with (?) flooring ophiolite, oceanic accretionary prism, continental rise deposits, continental slope deposits (with continental basement slivers?), rift and drift deposits of a passive margin (with continental basement slivers), and older and more proximal foredeep deposits. The early sediment sources for the foredeep fill (Martinsburg Formation, Juniata Formation) might have included overall finer grained deposits of an oceanic accretionary prism and accreted continental slope and rise deposits. Subsequent source lithologies might have included passive margin deposits and foreland flysch deposits. The sand-rich passive margin deposits of the Chilhowee Group are commonly regarded as a major source for the Tuscarora Sandstone in Virginia (Hayes, 1974; Whisonant, 1977). Preliminary results by Hemming and others (1993) seem to indicate, furthermore, that much of the vein-quartz pebbles of the Tuscarora-equivalent Shawangunk Conglomerate might have been derived from the "plumbing system" of part of the foreland flysch, following its incorporation into the externides of the Taconic orogen and its availability as a sediment source.

The trends displayed by the Juniata Formation and "lower" Tuscarora Sandstone most likely reflect the combined effects of development of appreciable relief of the Taconic orogen above mean sea level and a change in caliber of the source lithologies. The effect of climatic change on the amount and type of sediment supplied to the marine foredeep cannot be evaluated at present for the Late Ordovician.

The Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia exhibit a paucity of apparent stratigraphic organization into repetitive 'cycles'. Continuous creation of abundant accommodation space together with efficient distribution of supplied sediment by a powerful current system within the shallow-marine foredeep might have prevented the development of a pronounced stratigraphic organization (Cant and Hein, 1986; Hein and others, 1991). This paucity of stratigraphic organization can be observed especially within the thick section of "lower" Tuscarora Sandstone at Cove Mountain, and is reminiscent of the Cambrian Gog Quartzite, which is also interpreted as a shallow-marine clastic succession (Hein, 1987). A few motifs, however, are developed in various outcrops.

Upward-fining motifs of <3 m thickness are developed within the "lower" Tuscarora Sandstone at South Gap. The motifs are composed of variants SX_B and rarely SX_C. The motifs commence with an erosional base and are capped by a thin unit of interbedded sandstone and mudstone, prior to deposition of the succeeding motif. Similar motifs appear not to be developed at other outcrop localities, and are conspicuously absent from the

thickest section of "lower" Tuscarora Sandstone at Cove Mountain. The upward-fining motifs at South Gap are interpreted to represent the migration and gradual abandonment of sediment-storage bodies, and are believed not to be related to eustatic sea-level rises and changes in water depth.

Within the upper Juniata Formation at Narrows, several coarsening- and thickening upward motifs are developed (Figure 4-8), reaching an average thicknesses of 4 m. The motifs are composed of a basal variant H_B , which gradually develops upward into variant SX_B . The motifs are capped by a distinct contact to the overlying variant H_B marking the onset of the next motif. The motifs are reminiscent of the progradational parasequences described by Van Wagoner and others (1990). These parasequences are thought to represent the filling of accommodation space, which was created by rapid eustatic sea-level rise. Each parasequence commences along a distinct marine-flooding surface, indicating rapid deepening, and exhibits a gradual shallowing-upward trend (for example, Van Wagoner and others, 1990). The motifs within the upper Juniata Formation at Narrows might represent such parasequences thought to be related to eustasy and changes in water depth. The motifs, however, cannot be correlated across the different thrust sheets and appear to be absent from more proximal outcrops to the southeast.

Regional correlation within the Juniata Formation and "lower" Tuscarora Sandstone is severely hampered by the combined effects of lack of biostratigraphic information and the uncertainty about the magnitude of erosional removal associated with isostatic basin rebound, especially perpendicular to structural strike. One could attempt to correlate 'Narrows-type' motifs within the upper Juniata Formation along strike toward the northeast within the more distal thrust sheet, and farther toward the northwest within parts of the foredeep now covered beneath rocks of the Cumberland Plateau. It is expected that similar motifs are developed at a similar stratigraphic position, should the motifs indeed reflect eustasy. The absence of these motifs in medial and more proximal outcrop belts could also reflect the suppression of the eustatic signal by abundant sediment supply. The eustatic signal, then, is recorded only within more distal portions of the foredeep, farther removed from the sediment source. A test for possible eustatic influence on the stratigraphic pattern within the upper Juniata Formation of the Taconic foredeep, however, must await further study on a broader regional scale.



Figure 4-8: Coarsening- and thickening-upward motif within the Juniata Formation at Narrows; deposits of variant H_B (a) grade upward into deposits of variant SX_B (b); staff is 1.20 m.

CONCLUSIONS

1. The Juniata Formation and "lower" Tuscarora Sandstone (Upper Ordovician) form part of the Taconic molasse, which is closely tied to the development of the Taconic orogen within the central Appalachians. The two formations develop out of the subjacent Martinsburg Formation and form an uninterrupted coarsening-upward succession. This succession is capped abruptly by the "Tuscarora unconformity", which constitutes the largest stratigraphic break within the Taconic molasse. The "lower" Tuscarora Sandstone is interpreted to represent a wedge-shaped sediment body, which constitutes the lithostratigraphic equivalent of the upper Juniata Formation within more proximal outcrop belts. The original distribution of the "lower" Tuscarora Sandstone is obscured by erosion associated with isostatic basin rebound.

2. The Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia are interpreted to represent deposits of a shallow-marine foredeep. The facies and variants of the two formations correspond to different hydrodynamic zones within the shallow-marine foredeep, ranging from the middle shoreface to the offshore-marine zone. Most of the two formations represent deposits of the offshore-marine setting. The ambient storm system was the prime determinant for facies development, subdividing the clastic deposits into storm deposits (tempestites) and fairweather deposits. The interpretation of the red-bed succession of the Juniata Formation as shallow-marine in origin emphasizes that red coloration *per se* is not an infallible indicator for a terrestrial depositional environment.

3. Sediment was supplied to the shallow-marine setting through storm-induced downwelling currents enhanced by the interaction with wave-generated currents, and through storm-enhanced rip currents. The bedforms and larger-scale sediment-storage bodies on the sea-floor migrated predominantly in an offshore-direction in response to a powerful and prolonged storm-generated combined-flow current system.

4. The persistence of a shallow-marine depositional setting throughout most of the stratigraphic interval and the development of a thick stratigraphic section of shallow-marine deposits implies a delicate balance between creation of accommodation space (subsidence: predominantly through tectonic loading, augmented by sediment compaction and sediment loading) and sediment supply. The sandier-upward trend displayed by the two formations (and the upper part of the subjacent Martinsburg Formation) might be the combined effect

of an increase in subaerial relief of the source area (orogen) and of a secular change in the caliber of the sedimentary rocks made available for erosion within the source area. Cyclic stratigraphic organization is not readily apparent within the Juniata Formation and "lower" Tuscarora Sandstone. This might be related to the continuous creation of accommodation space coupled with efficient distribution of the abundantly supplied sediment by the powerful storm-generated current system. In the most distal outcrop belt, fining-upward motifs within the upper part of the Juniata Formation might be linked to eustatic influence.

CHAPTER 5

THE "UPPER" TUSCARORA SANDSTONE (LOWER SILURIAN) OF SOUTHWESTERN VIRGINIA: A STORM-DOMINATED, SHALLOW- MARINE, RETROGRADATIONAL PARASEQUENCE RELATED TO TACONIC TECTONISM

PREAMBLE

Lower Silurian foredeep deposits related to the Taconic orogeny in the Appalachians have recently been interpreted via modern process-sedimentologic approaches in Pennsylvania (Cotter, 1983b: Tuscarora Sandstone) and in eastern Tennessee (Driese and others, 1991: Clinch Sandstone, Rockwood Formation). These studies expanded on earlier investigations, which focused on petrography and provenance determination (Folk, 1960; Yeakel, 1962). Cotter (1982, 1983b) modified earlier fluvial interpretations (Yeakel, 1962; Smith, 1970) for the Tuscarora Sandstone of Pennsylvania. He showed that this unit consists of an array of estuarine, beach, coastal flat, shallow-marine shelf, and braided-river deposits. The Clinch Sandstone and Rockwood Formation of eastern Tennessee were interpreted as shoreface to storm-dominated shallow-marine shelf deposits by Driese and others (1991). A comparable process-sedimentologic interpretation for equivalent deposits in Virginia (Tuscarora Sandstone) is lacking, despite previous stratigraphic, petrographic, and paleocurrent analyses (Dennison, 1970; Hayes, 1974; Lampiris, 1975; Whisonant, 1977; Diecchio, 1985; Bambach, 1987). Interpretations of depositional environments put forward for the Tuscarora Sandstone in southwestern Virginia include a broad coastal plain dominated by rivers (Whisonant, 1977), fluvial deposits reworked into beach deposits during a transgression (Lampiris, 1975), and a complex of alluvial coastal plain, tidal flat, barrier, and lagoonal environments (Hayes, 1974).

The present study provides a modern process-oriented interpretation for the "upper" Tuscarora Sandstone as it is exposed in southwestern Virginia. I intend to show that the "upper" Tuscarora Sandstone in southwestern Virginia represents storm-dominated

shallow/marginal-marine deposits. The stacking pattern of facies reveals, furthermore, that the "upper" Tuscarora Sandstone constitutes a single, complete transgressive facies succession, a stratigraphic architecture not commonly developed and preserved, and rarely described in the literature (Elliott, 1986; Cant, 1991). In sequence stratigraphic terms, the transgressive facies succession corresponds to an uninterrupted retrogradational parasequence, bound at its base by a sequence boundary ("Tuscarora unconformity") and at its top by a (maximum) marine-flooding surface (Van Wagoner and others, 1988; 1990). The retrogradational parasequence, furthermore, constitutes a transgressive systems tract. We would like to argue, finally, that the special circumstances for development and preservation of the retrogradational parasequence is most likely linked to active tectonism, which affected the Taconic foredeep during the Early Silurian. Eustasy, commonly regarded as the dominant, if not sole, determinant for the origin of parasequences, became dominant only during development of the marine-flooding surface capping the "upper" Tuscarora Sandstone.

FACIES DESCRIPTION AND INTERPRETATION

The "upper" Tuscarora Sandstone of southwestern Virginia is composed predominantly of hard, glassy, white quartzarenite (Hayes, 1974; Whisonant, 1977). This stratigraphic unit can be divided into four separate, but recurring facies: 1) a *gravelly facies* (facies G with variant G_A: *clast-supported pebble conglomerate*, and variant G_B: *gravelly sandstone*), 2) a high-angle cross-stratified sandstone facies (facies SX with variant SX_A: *cross-stratified sandstone (regional)*, and variant SX_B: *well-sorted cross-stratified sandstone with claystone seams*), 3) a *hummocky cross-stratified sandstone facies* (facies HS with variant HS_A: *amalgamated hummocky cross-stratified sandstone*, and variant HS_B: *hummocky cross-stratified sandstone and mudstone*), and 4) a *dark clastic facies* (facies DC). At the Narrows locality, the top of the "upper" Tuscarora Sandstone is occupied by a separately described 'transition complex'. Figures 5-1 and 5-2 illustrate some of the sedimentary aspects of each facies. Table 5-1 provides a synopsis of the sedimentary features of each facies, together with a process-sedimentologic and paleoenvironmental interpretation.

Figure 5-1: Sedimentologic features of the different facies and variants of the "upper" Tuscarora Sandstone. A) Variant G_A (clast-supported pebble conglomerate: a) sharply overlying subjacent sandstone bed along an erosive surface; the lag conglomerate grades upward into cross-stratified gravelly sandstone (variant G_B: b), Catawba Mountain II; staff is divided into 10 cm increments. B) Thick bed of trough cross-stratified sandstone (variant SX_A: a) scouring into subjacent siltstone to very fine-grained sandstone of facies DC (some beds of facies DC are indicated by stars), South Gap; staff is 1.20 m. C) Beds of trough cross-stratified sandstone (variant SX_B) of estuarine origin beneath conglomerate bed shown in A, Catawba Mountain II. D) Beds of hummocky cross-stratified sandstone (variant HS_B); note the 'pinch-and-swell' of the sandstone beds, hummocks at some bed tops, and mudstone interbeds, Narrows; staff is 1.20 m. E) Hummocky cross stratification (variant HS_A), South Gap; hammer for scale: length 32 cm. F) Facies DC (dark) sandwiched between two thick sandstone beds of variant SX_A (a); note thin sandstone beds of variant SX_A within facies DC, and cross sections of *Arthropycus* emanating from the white sandstone beds and mining the dark host sediment, South Gap; scale bar is approx. 10 cm.

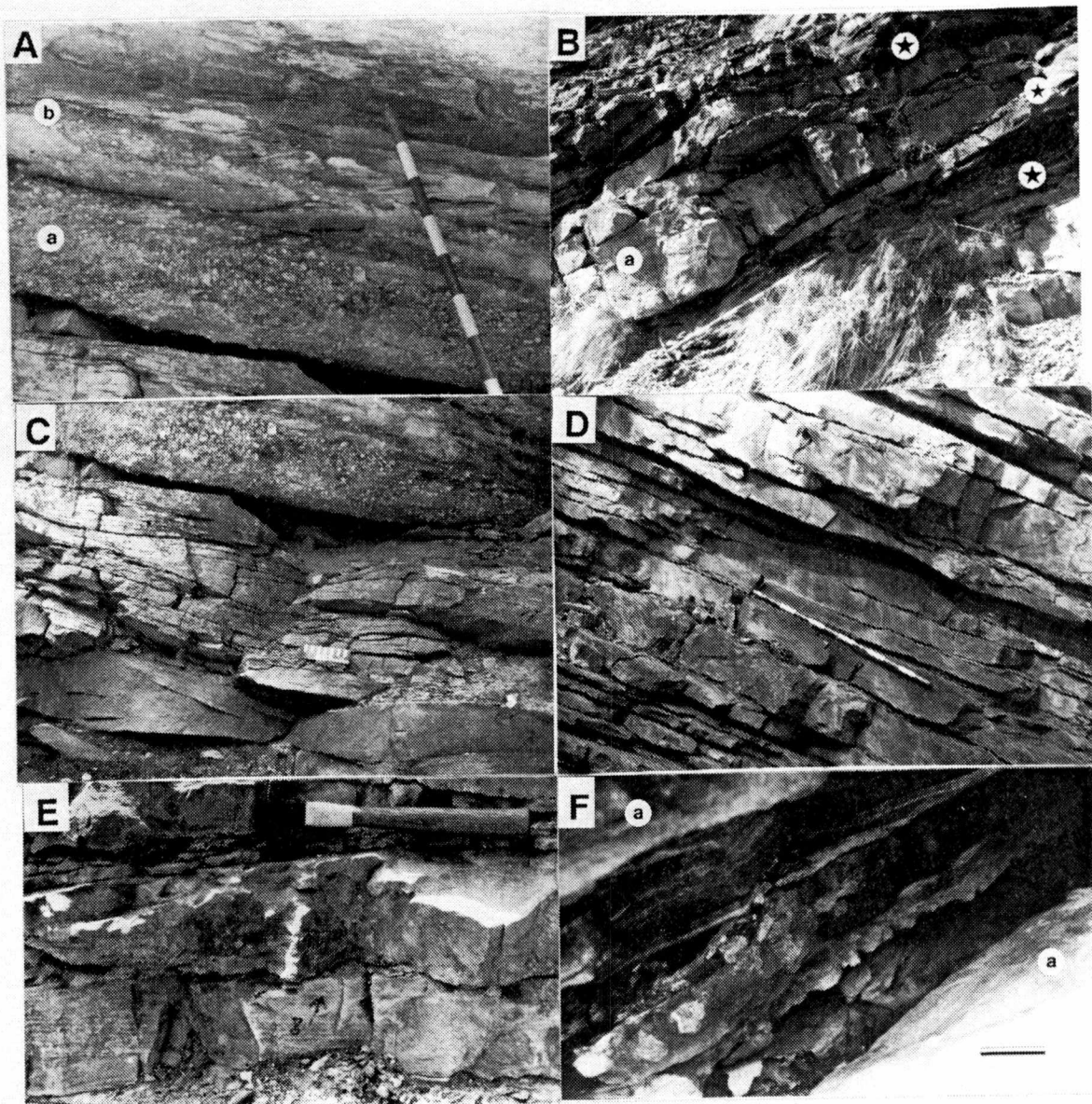


Figure 5-2: Trace fossils encountered within the "upper" Tuscarora Sandstone of southwestern Virginia. A) *Rusophycus*, at the base of lag conglomerate, variant G_A, Draper Mountain; B) *Skolithos*, producing 'pipe-rock', variant SX_A, Gap Mountain; C) *Arthropycus*, at the base of a sandstone bed of variant SX_A, South Gap; D) *Monocraterion* and *Arenicolites*, at top of a sandstone bed (weathered and cut piece), variant SX_A, South Gap; burrows are infilled with sediment of facies DC; E) *Rusophycus*, at base of estuarine sandstone bed, variant SX_B, Catawba Mountain I; F) *Skolithos*, burrow-top protrusions at the top of a hummocky cross-stratified sandstone bed, variant HS_B, Narrows.

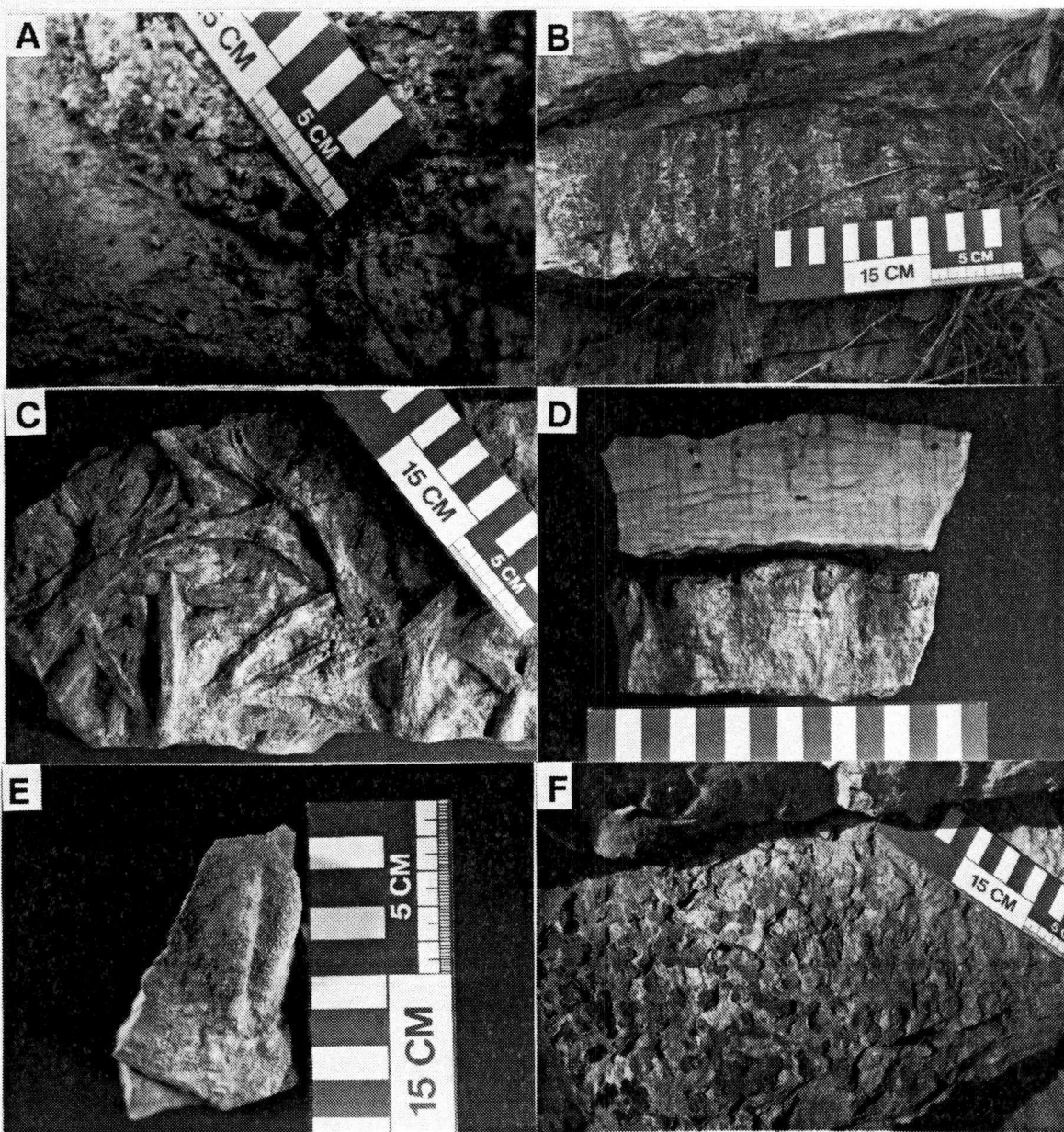


Table 5-1. Summary of defining aspects of the different facies of the "upper" Tuscarora Sandstone in southwestern Virginia, together with an interpretation of physical processes and paleodepositional environments for these facies

Description	Interpretation
Gravelly Facies (facies G)	
variant G_A: clast-supported pebble conglomerate; laterally discontinuous thin beds above a regional erosional surface; massive to crudely cross-stratified; sparse bioturbation (<i>Rusophycus</i>, ?<i>Phycodes</i>, <i>Arthropycus</i>) variant G_B: gravelly coarse- to medium-grained sandstone; trough cross stratification and some planar-tabular cross stratification; paleocurrents directed offshore; sparse bioturbation (<i>Arthropycus</i>)	unidirectional bedload transport; variant G_A: lag conglomerate associated with transgressive reworking within the surf zone; variant G_B: migration of subaqueous 3D- and 2D-dunes due to offshore-directed mean surf-zone bottom currents during storms; deposits of the upper upper shoreface
High-angle Cross-stratified Sandstone Facies (facies SX)	
variant SX_A: medium- to coarse-grained sandstone, rare granules; erosional bed bases; trough cross stratification, some ripple cross stratification and planar stratification; paleocurrents directed predominantly offshore, some longshore; extensive to moderate bioturbation (<i>Skolithos</i>, <i>Arthropycus</i>, <i>Monocraterion</i>, <i>Arenicolites</i>, <i>Planolites</i>) variant SX_B: medium-grained sandstone, some claystone seams; some scours; trough cross stratification, some planar-wedge cross stratification; varied paleocurrents, predominantly offshore; slight bioturbation (<i>Monocraterion</i>, <i>Rusophycus</i>, <i>Arthropycus</i>, <i>Planolites</i>);	unidirectional bedload transport; variant SX_A: migration of subaqueous 3D- and 2D-dunes mostly in an offshore direction and also in a longshore direction; predominantly deposits of laterally migrating shallow channels associated with storm-enhanced rip currents of the lower upper and middle shoreface; deposition also influenced by storm-return-flow currents; variant SX_B: migration of subaqueous 3D- and 2D-dunes; deposits of ebb-dominated tidal channels within an estuary
Hummocky Cross-stratified Sandstone Facies (facies HS)	
fine/medium- to very fine-grained sandstone; hummocky cross stratification, planar stratification; amalgamated beds; some mudstone interbeds (variant HS_A <<5%, variant HS_B ≤10%); some symmetrical ripples; extensive bioturbation (<i>Skolithos</i>, <i>Planolites</i>); acritarchs	sandy storm deposits related to oscillatory-dominant combined flows of the upper (variant HS_A) and lower (variant HS_B) lower shoreface; mudstone interbeds represent fairweather deposits from suspension settling
Dark Clastic Facies (facies DC)	
siltstone to very fine-grained sandstone, some silty mudstone; light-gray to dark-gray/black; as interbeds within variant SX_A; planar to wavy stratification; some soft sediment deformation (slumping); bioturbation abundant to slight (<i>Chondrites</i>, <i>Arthropycus</i>, the latter mining in from overlying sandstone beds); acritarchs	suspension settling; organic-rich fairweather deposits of the lower upper and middle shoreface; probably related to phytoplankton blooms and resultant oxygen deficiency
'transition complex'	
fine- to coarse-grained, thin sandstone beds, abundant mudstone; planar stratification, wave-ripple cross stratification, or massive; secondary mineralization; abundant bioturbation (<i>Skolithos</i>, <i>Planolites</i>), brachiopods	fairweather deposits of the offshore transition zone interspersed with sandy storm deposits

Gravelly Facies

Description. The gravelly facies (facies G) can be divided into a variant G_A (clast-supported pebble conglomerate) and a variant G_B (gravelly sandstone). Variant G_B is by far more common ($\geq 90\%$) in this facies than variant G_A ($\leq 10\%$).

Variant G_A is a clast-supported pebble conglomerate, composed of well-rounded, milky-white vein-quartz pebbles (Figure 5-1A). The pebbles are commonly 1.5 to 2 cm long (longest observable axis), and reach a maximum of 6 to 9 cm at the Catawba Mountain II locality. Sediment in the interstices between adjacent pebbles is comprised of coarse to very coarse sand and granules. Variant G_A is the coarsest grained deposit encountered within the "upper" Tuscarora Sandstone.

Beds composed of variant G_A are laterally discontinuous. Observed bed thicknesses are 15 to 40 cm (Catawba Mountain II locality), 8 cm (Draper Mountain locality), and 13 cm (Cascades locality) (Figure 5-3). At these localities, variant G_A occurs at the base of the facies G immediately above an erosional surface (Figures 5-1A, 2-3). Variant G_A occurs also as lenses and stringers within variant G_B . The bases of beds of variant G_A are sharp. The tops are gradational into variant G_B , due to an increase in sand concomitant with a decrease in pebble content (Figure 5-1A). Beds of this variant appear massive; faint planar cross stratification is indicated for a bed of this variant at the Catawba Mountain II locality. Lenses and stringers of variant G_A (thickness >1 pebble layer) contained within variant G_B commonly occur within the "deepest" parts of troughs or as short planar layers. Paleocurrent readings for variant G_A are not available.

Trace fossils within variant G_A are rare. They include, however, one example each of *Rusophycus* (Figure 5-2A) and ?*Phycodes* (at the Draper Mountain locality), and several examples of *Arthropycus* (at the Cascades and Draper Mountain localities).

Variant G_B represents gravelly sandstone, with a gravel content between 10 and 30%. Some examples of this variant contain gravel of slightly more than 30%, and can be designated as matrix-supported (granule-pebble) conglomerate. Sand is commonly coarse to medium in size, with very coarse and fine sand also occurring. Gravel is found dispersed within the sand, and is dominated by granules over pebbles (Figure 5-1A). Pebble layers of 1 pebble thickness occur within variant G_B along foresets and as planar layers. Observed maximum pebble sizes (longest observable axis) are 4.5 cm (Narrows locality), 2 cm (Gap Mountain locality), 4.9 cm (McCoy locality), and 2.4 cm (Fagg I locality). Mudstone layers are absent within variant G_B , but some holes originating from weathered out disc-shaped

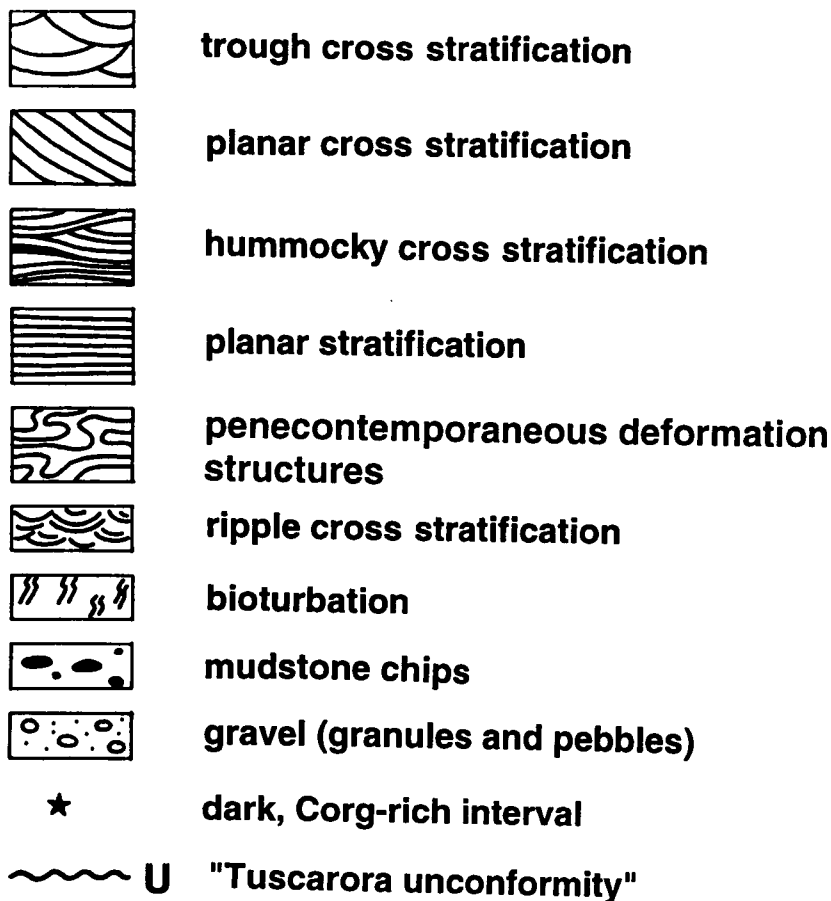
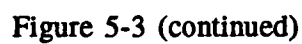
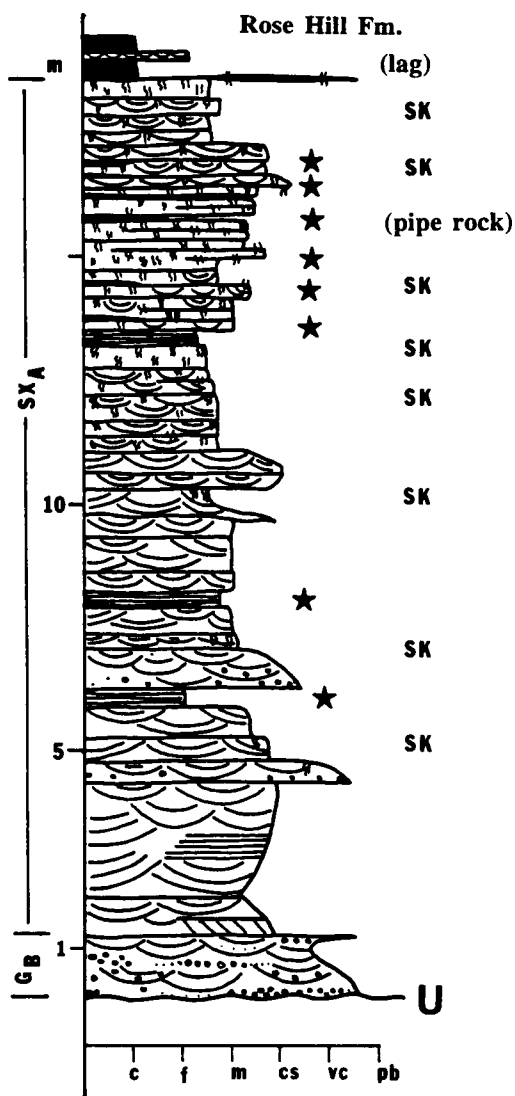


Figure 5-3: Measured stratigraphic sections of the "upper" Tuscarora Sandstone in southwestern Virginia. For location of outcrop localities refer to Figure 1-3. Abbreviations are as follows. Grain size: c - clay; f - fine sand; m - medium sand; cs - coarse sand; vc - very coarse sand; pb - pebble; trace fossils: AE - *Arenicolites*; AR - *Arthropycus*; MO - *Monocraterion*; PH - *Phycodes*; PL - *Planolites*; RU - *Rusophycus*; SK - *Skolithos*. Stratification types and some other sedimentologic features are explained in the legend; black "streaks" within sandstone intervals represent thin mudstone beds. Occurrence of dark clastic facies' (facies DC) in the measured sections is indicated by the star; bed thickness within this facies is too small to be portrayed in the sections. Other facies and variant designations include: G_A - clast-supported pebble conglomerate; G_B - gravelly sandstone; SX_A - cross-stratified sandstone (regional); SX_B - well-sorted cross-stratified sandstone with mudstone seams; HS_A - amalgamated hummocky cross-stratified sandstone; HS_B - hummocky cross-stratified sandstone and mudstone; 'TC' denotes the occurrence of the 'transition complex' at Narrows.

Rose Hill Fm.



Gap Mtn.



Cascades

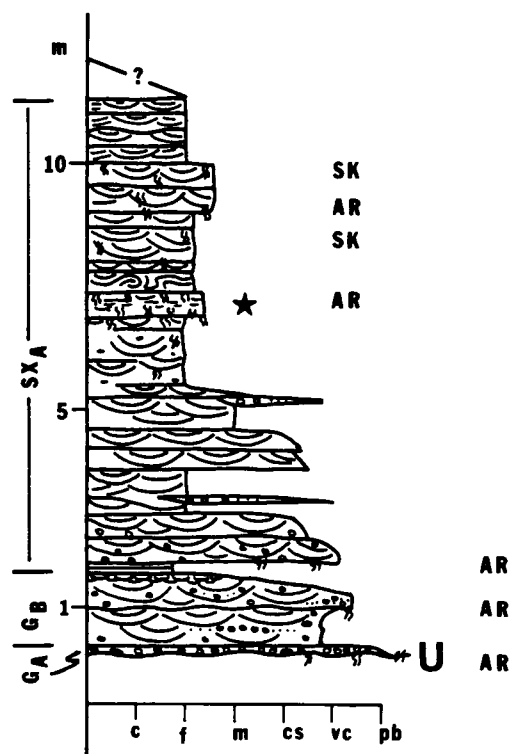


Figure 5-3 (continued)

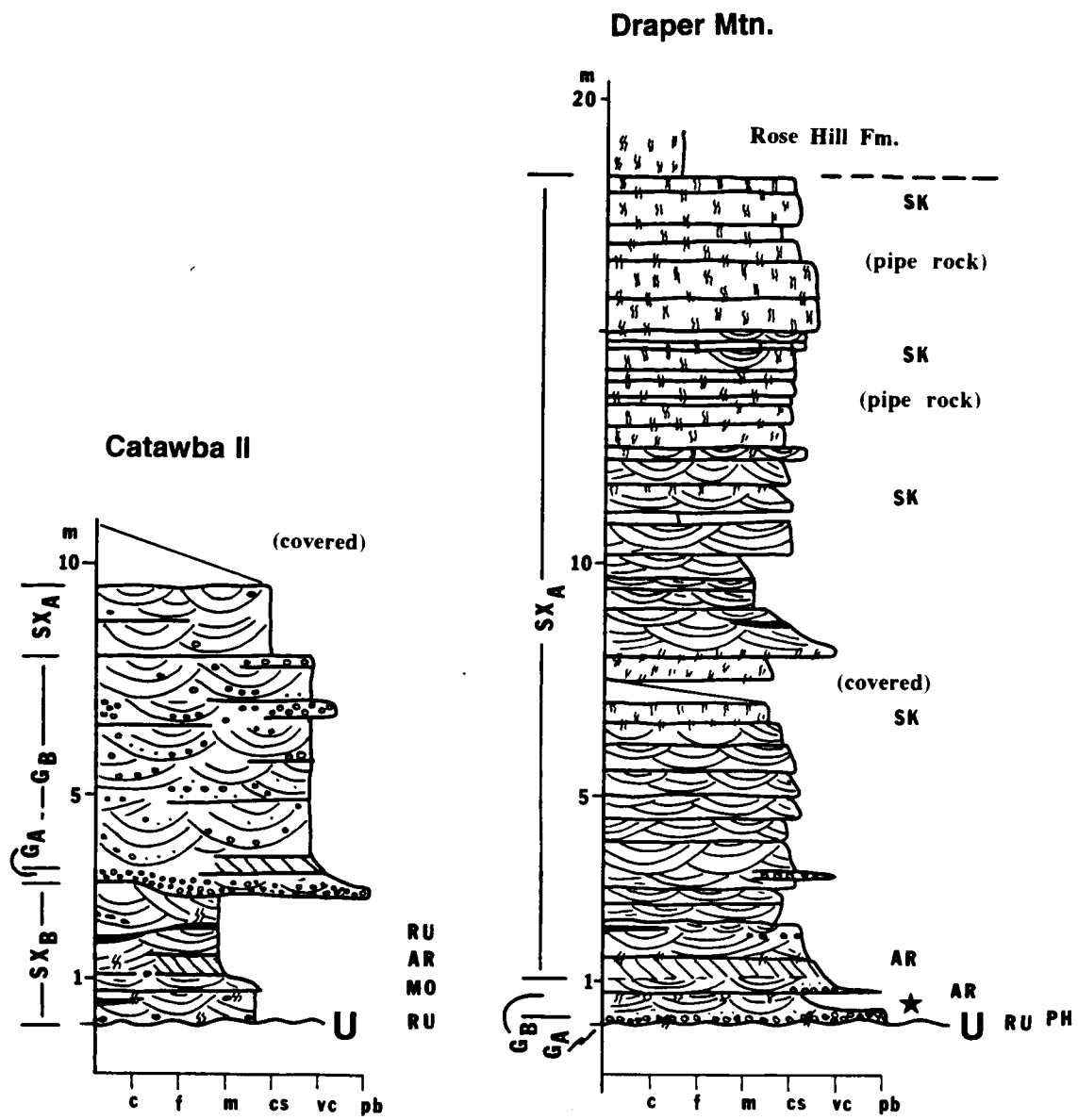


Figure 5-3 (continued)

intraclasts (up to 6 to 10 cm in diameter and 2 cm deep) and preserved mudstone intraclasts (commonly ≤ 2 cm in diameter) within the gravelly sandstone point towards the former presence of some mudstone layers. Variant G_B displays an upward-fining trend in outcrop (Figure 5-3), exemplified explicitly by a decrease in gravel (especially pebble) content.

In most outcrops, bedding within variant G_B is very hard to discern, because bed tops and bases are indistinct. At the South Gap locality, beds of this variant vary between 18 and 30 cm, and appear to reach 60 cm at other localities. Stratification is dominated by trough cross stratification, and in outcrop this variant commonly is characterized by mutually intersecting sets of trough cross strata (Figures 5-1A, 5-3). Observed sets are typically 10 to 30 cm thick and reach a maximum of 1.8 m in width. Trough-shaped foresets are generally outlined by granule/pebble layers. Planar-tabular cross stratification is by far less common. Where it is present, however, the sets are commonly of a larger scale than the sets of trough cross stratification. Observed thicknesses of planar cross-sets reach 50 cm (Narrows locality), and are commonly 10 to 15 cm at the South Gap locality. Trace fossils observed within variant G_B include only a few examples of *Arthropycus*.

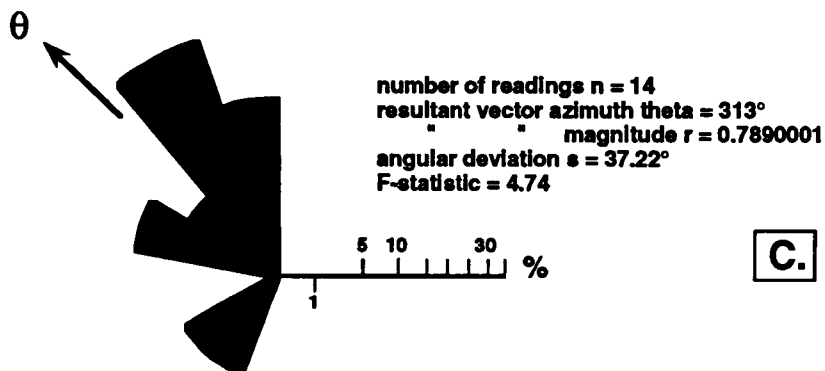
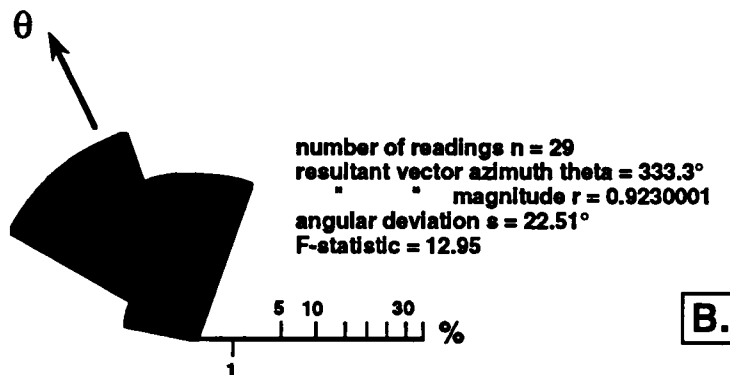
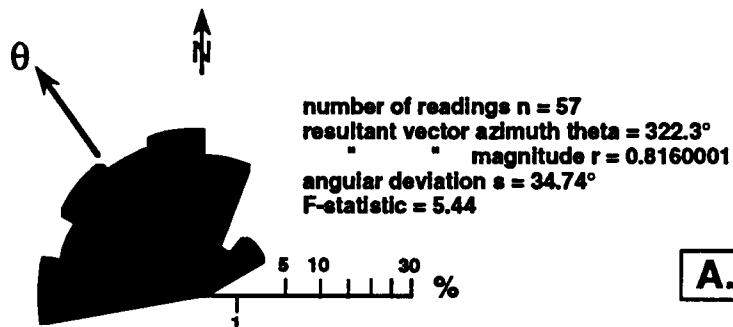
Paleocurrent measurements obtained within variant G_B ($n=29$) were obtained from trough cross stratification (93.1%) and from planar-tabular cross stratification (6.9%). Unidirectional paleoflow was directed in a tight cluster towards the northwest to north, with a resultant vector of 333.3° and an angular deviation of 22.51° (Figure 5-4B).

Facies G with its two variants forms the lower part of the "upper" Tuscarora Sandstone (except at the Catawba Mountain localities) and underlies deposits of facies SX (Figure 5-3). At the Draper Mountain locality, one thin bed of facies DC occurs within facies G (Figure 5-3).

Interpretation. The discontinuous beds of variant G_A (clast-supported pebble conglomerate), which rest directly on an erosional surface, are interpreted as lag deposits. The pebble lag formed by reworking of subjacent sediment within the surf zone during transgression (see below for a further discussion of the significance of the erosional surface). The occurrence of trace fossils within this lag deposit support a marine depositional setting. Lenses and stringers of variant G_A contained within variant G_B are related to bedform migration and the resulting stratification.

Deposits of variant G_B indicate the migration of three-dimensional dunes and, to a lesser extent, two-dimensional dunes. Migration of these bedforms was directed uniformly

Figure 5-4: Paleocurrent rose diagrams (20° class intervals) for the "upper" Tuscarora Sandstone in southwestern Virginia. Vector-summation technique and statistical calculations were performed using an unpublished computer program by Maher and Dott (1979). Rose diagrams are arranged in an idealized stratigraphic order: A - variant SX_A of the high-angle cross-stratified sandstone facies (situated above the wave-ravinement surface), B - variant G_B of the gravelly facies (situated above the wave-ravinement surface), C - variant SX_B of the high-angle cross-stratified sandstone facies (situated beneath the wave-ravinement surface). Shoreline orientation is inferred to have been from the northeast to the southwest, based on the orientation of symmetrical-ripple crest axes in the "upper" Tuscarora Sandstone (rare) and in the overlying Rose Hill Formation (very abundant). Offshore is towards the west/northwest.



in an offshore direction (Figure 5-4B). Trace fossils are rare except for the occurrence of *Arthropycus*. The beds of gravelly sandstone, however, are associated with variant G_A, and are overlain (throughout the study area) or sandwiched (at Catawba Mountain) by deposits of facies SX. All of these associated facies and variants show distinct trace fossils, indicating a marine depositional setting also for deposits of variant G_B. The grain size of variant G_B and its association with a transgressive lag (variant G_A) makes a nearshore depositional environment for this variant likely. I interpret the gravelly sandstone of this variant as deposits of the upper upper shoreface. The uniform paleocurrent orientation (Figure 5-4B) might indicate the presence of offshore-directed mean surf-zone bottom currents (Nummedal, 1991). These unidirectional currents accomplish offshore-directed bedload transport along the entire shoreline during storm conditions (Nummedal, 1991). The circulation pattern within the surf zone during storm conditions is distinctly different than the circulation pattern developed during fairweather conditions (Nummedal, 1991). A vertical flow segregation develops within the water column during storms, with pronounced offshore-directed flow near the bottom and onshore-directed flow near the surface (Nummedal, 1991). Rip currents are a less likely explanation for the paleocurrent pattern, because no longshore-oriented paleocurrent indicators can be detected, and the gravelly sandstone beds are not associated with scour surfaces (Hunter and others, 1979; Clifton, 1981). Onshore-directed paleocurrent indicators, pointing to reworking of upper shoreface deposits by shoaling waves during fairweather conditions (Clifton and others, 1971; Hunter and others, 1979; Hart and Flint, 1989), are also absent. Fairweather waves within the Taconic foredeep probably were not strong enough to rework the coarse-grained storm deposits, or successive storms might have obliterated all signs of fairweather periods. The material for the gravelly sandstone was derived predominantly from reworking of subjacent deposits.

High-angle Cross-stratified Sandstone Facies

Description. Facies SX (high-angle cross-stratified sandstone facies) is the volumetrically most abundant facies within the "upper" Tuscarora Sandstone in southwestern Virginia (Figure 5-3). It occurs as variant SX_A (cross-stratified sandstone (regional) gradationally above facies G, or is sandwiched between facies G and facies HS (Figure 5-3). At the Catawba Mountain localities, facies SX can be found, furthermore, between the superjacent facies G and the subjacent Martinsburg Formation (Figure 5-3), and is

designated as variant SX_B (well-sorted cross-stratified sandstone with claystone seams). Facies DC occurs characteristically as thin intervals within variant SX_A (Figure 5-3).

Variant SX_A is composed of light-colored, white sandstone. Mudstone interbeds are extremely rare. The sand size ranges predominantly from medium to coarse, with fine and very coarse sand also occurring in intervals. Dispersed gravel (mostly granules, rarely pebbles) can be found occasionally ($<10\%$). This facies displays an apparent fining-upward trend in outcrop (Figure 5-3). Intraclasts can be observed, but are less common than in facies G. Mud intraclasts are more common in deposits in which dark-colored deposits of facies DC are interbedded with the white sandstone. The color of the sandstone changes from white to greenish-yellow at the South Gap locality, where pods of marcasite can be detected within this facies. At the Gap Mountain locality, some sandstone beds of this facies appear dark gray to even black, which might be related to disseminated, dark-colored, fine-grained sediment of eroded interbeds of facies DC.

Bed thickness is variable and typically ranges between 15 and 45 cm, with a maximum of 80 cm. The thickness of beds decreases up section at all outcrop localities. Bases of beds are sharp and erosional. Beds lie erosively within intervals of facies DC, and relief of the scour can reach up to 25 cm (Figure 5-1B), provided that the interbedded facies DC is of sufficient thickness. Beds of 1 to 10 cm can also be detected within thicker intervals of facies DC. Tops of beds commonly are distinct, and in some instances display preserved bedforms, such as current ripples and three-dimensional dunes (crest spacing of 55 cm, height of 6 cm).

Stratification of the sandstone beds is dominated by trough cross stratification (Figure 5-3). Sets of trough-shaped cross strata are typically between 10 and 30 cm thick, and <10 cm in thinner beds. Single cross laminae are indicated by grain-size differences and by occasional dark or black streaks. These streaks might represent reworked finer grained facies DC. Planar-tabular cross stratification occurs rarely. Where present, sets of cross strata are generally ≤ 25 cm, and reach a maximum of 55 cm (Draper Mountain locality). Also present is current-ripple cross stratification, and very rarely planar stratification. Soft-sediment deformation can be observed at the Cascades locality, where a single bed (35 cm thick) with distinct top and base displays convolute stratification.

Paleocurrent readings from variant SX_A are abundant ($n=57$). A total of 82.5% of these readings were obtained from trough cross stratification, 10.5% from planar-tabular cross stratification, and 7.0% from ripple cross stratification. Paleoflow was unidirectional and directed towards the west, northwest, and north, with a resultant vector of 322.3° (Figure

5-4A). These results are similar to the paleocurrent data gathered from facies G (Figure 5-4B), but display a wider spread in the current readings.

The suite of trace fossils within facies SX is dominated by *Skolithos*. The sand-filled vertical *Skolithos* burrows can be so dense that any evidence of primary stratification is destroyed. Completely bioturbated sandstone intervals appear as typical 'pipe rock' (Figure 5-2B) and can be observed at the Draper Mountain and Gap Mountain localities (Figure 5-3). A second diagnostic trace fossil is *Arthropycus*, which can be found on the undersides of sandstone beds (Figure 5-2C). *Arthropycus* is commonly observed mining downward into subjacent interbeds of facies DC, creating a prominent contrast between *Arthropycus* traces filled with white, coarse sand, surrounded by gray, finer grained sediment. Other trace fossils include *Planolites*, *Monocraterion* and *Arenicolites*. The latter two occur at the tops of white sandstone beds and are typically infilled with finer grained sediment of facies DC (Figure 5-2D). Within facies SX, the degree of bioturbation increases up section, which can be documented for the outcrops at Draper Mountain and Gap Mountain (Figure 5-3).

At the Catawba Mountain localities (Figure 1-3), variant SX_B can be found beneath deposits of facies G (Figures 5-1C, 5-3). Variant SX_B is similar to variant SX_A, but possesses some noticeable differences. The sand in variant SX_B is better sorted (medium- to medium/fine) and contains no gravel. Mudstone intraclasts (a few mm to 2 cm thick, 1 cm to 4 cm long), however, are abundant. Variant SX_B is not associated with sediment of facies DC. Bioturbation is less dense than in most parts of variant SX_A. Only a few examples of mudstone-filled *Monocraterion*, *Rusophycus* (Figure 5-2E), *Arthropycus*, and some examples of ? arthropod scratch marks and *Planolites* can be found. *Skolithos* traces are conspicuously absent, and *Arthropycus* traces are far less common than in variant SX_A. As was the case for variant SX_A, variant SX_B exhibits prominent trough cross stratification with sets of cross strata 10 to 30 cm thick and up to 1.3 to 1.5 m wide (Figure 5-1C). The trough-shaped sets are mutually cross-cutting. A few examples of planar-wedge cross stratification (sets up to 35 cm thick) and some ripple cross stratification is associated with trough cross stratification. In contrast to variant SX_A, sets of cross strata are outlined by aligned mudstone clasts, and by some yellowish-brown discontinuous claystone/mudstone seams up to 1 cm thick. At Catawba Mountain II, a scour, infilled with trough cross-stratified sandstone and its base outlined by large mudstone clasts, can be found (Figure 5-1C).

Paleocurrent data (n=14) from variant SX_B at Catawba Mountain were obtained from trough cross stratification (64.3%) and from planar-tabular cross stratification (35.7%). Currents were directed towards the northwest and north (resultant vector = 313°), but there is also a distinct secondary mode directed towards the southwest (Figure 5-4C).

Interpretation. Stratification types within variant SX_A of the high-angle cross-stratified sandstone facies imply traction transport as three-dimensional dunes and current ripples, and to a much lesser degree as two-dimensional dunes. The trace fossil suite indicates that the sandstone beds represent shallow-marine deposits. At Narrows and South Gap, deposits of variant SX_A underlie hummocky cross-stratified sandstone and overlie gravelly sandstone (Figure 5-3). I interpret variant SX_A as deposits of the lower upper shoreface to middle shoreface, situated just offshore from variant G_B . Paleocurrent indicators are directed predominantly offshore, with a small secondary mode directed towards the northeast, parallel to the inferred shoreline trend (Figure 5-4A). Coarser grained sandstone beds with erosive/scoured bases and offshore-directed, high-angle cross stratification can be interpreted as deposits of rip currents. The laterally persistent erosive bases of the sandstone beds were most likely created by lateral migration of rip channels within the upper shoreface (Hunter and others, 1979; Clifton, 1981; DeCelles, 1987). Bars present between adjacent rip channels were eroded during lateral migration of the rip channels. The smaller secondary paleocurrent mode directed to the northeast can be related to the presence of longshore currents, which fed the rip channels. Longshore currents were generated by oblique wave approach along what was probably a straight paleoshoreline. Rip-current and longshore-current deposits, furthermore, are interpreted as storm deposits. Rip currents are enhanced in their activity during storm periods (Short, 1985), and can leave notable evidence of their activity within deposits of the upper shoreface (Clifton, 1981; Short, 1984; Dupre, 1984; Nummedal, 1991). Rapid emplacement of sand related to rip-current activity probably is responsible for convolute stratification in some of the sandstone beds. The absence of landward-directed cross stratification indicates that rip-current and longshore-current deposits were not reworked by shoaling waves during fairweather periods, a situation already encountered within the upper upper shoreface deposits of facies G. Fairweather deposits, nevertheless, are probably present and might be represented by deposits of facies DC (see below). The preservation of a few bedforms indicates that the reworking potential of waves during fairweather periods was low, and that the bedforms were

quickly mantled by fairweather deposits. High-angle cross-stratified sandstone beds with scoured bases within the shoreface might also be related to storm-return-flow currents (Siringan and Anderson, 1993), related to water-level set-up during storms. Both storm-related rip currents and storm-return-flow currents probably played a prominent role in providing sand for depositional settings farther seaward from the upper and middle shoreface.

A deepening-upward trend within variant SX_A is apparent. It can be inferred from an upward increase in bioturbation, and an upward decrease in both grain size and bed thickness (Figure 5-3) (Howard and Reineck, 1981). The animal responsible for producing the *Monocraterion* and *Arenicolites* burrows must have repopulated the tops of sand beds following storm events. The animals seem to have left their dwelling burrows in response to the onset of sedimentation of facies DC and the development of dysaerobic bottom conditions (see below). *Monocraterion* and *Arenicolites* burrows, therefore, are infilled with darker colored sediment of facies DC. *Arthropycus* traces are developed on the undersides of sandstone beds. The animal responsible for the *Arthropycus* feeding burrow mined along the interface between the light-colored storm sand and the subjacent dark-colored deposits of facies DC. The *Skolithos* dwelling burrows are best developed within the upper part of variant SX_A (Figure 5-3). The amount of time available for biogenic reworking of storm deposits seems to have been ample at times, judging from the development of 'pipe-rock' in the upper part of this variant (Howard, 1975).

The sandstone unit at Catawba Mountain (variant SX_B) shows evidence for migration of three-dimensional dunes, and to a lesser extent two-dimensional dunes, predominantly in an offshore direction. The few claystone/mudstone seams outlining sets of trough cross strata within sandstone beds indicate the temporary abandonment of dune migration and the suspension settling of clay. Abundant mudstone intraclasts point toward the former presence of more of these seams. The occurrence of a scour lined by mudstone intraclasts indicates the presence of channelized flow and the probable lateral migration of the scour. The trace fossils provide evidence for a marine or strongly marine-influenced depositional setting.

I interpret the sandstone of variant SX_B as estuarine in origin, confined to a narrow (?) incised "valley" at the base of the "upper" Tuscarora Sandstone. The high angle cross-stratified sandstone probably represents deposits of laterally migrating tidal channels, which even scoured into slightly older tidal-channel deposits. The predominantly offshore-

directed paleoflow (Figure 5-4C) indicates that the subaqueous dunes were confined to an ebb-dominated tidal channel. The secondary mode of paleoflow directed to the southwest (Figure 5-4C) is linked to planar cross stratification. It can be explained with the migration of two-dimensional dunes along minor erosion surfaces in response to an oblique and weaker counter (?) current (Clifton, 1982). The resulting sandstone interval shows planar cross stratification superimposed along reactivation surfaces onto more common trough cross stratification. Truly bidirectional paleoflow is not recorded within the preserved high-angle cross-stratified sandstone beds. Herringbone cross stratification, distinct tidal bundles, and heterolithic mudstone-dominated deposits are not observed at Catawba Mountain. Variant SX_B, however, represents merely a fragmentary record of estuarine deposits, because it is bound at the top and base by erosional surfaces. Finer grained estuarine deposits were probably present, but were removed by erosion. Erosion related to migration of tidal-inlet channels (lower erosional surface) removed older estuarine deposits, whereas subsequent erosional shoreface retreat (upper erosional surface) removed younger estuarine deposits and cut down into tidal-channel deposits (see below for a further discussion of the significance of these erosion surfaces).

As will be apparent from the discussion of the facies of the "upper" Tuscarora Sandstone, tidal deposits are otherwise absent from this stratigraphic unit, and facies indicate the dominance of waves and storms, instead. This paradox might be explained by the notion that overall weak tides within the marine foredeep might have been amplified within a straight estuary (Dalrymple and others, 1992) and, furthermore, that tidal action was effectively shielded within the estuary. Tidal currents, therefore, could have left their mark on estuarine deposits, while beyond the estuary storm/wave action completely overprinted weak tidal action along the shoreline. The Gironde estuary of southwestern France, for comparison, displays tidal activity within the confines of the estuary, whereas the Atlantic shoreline is wave-dominated (Allen and Posamentier, 1993).

Hummocky Cross-stratified Sandstone Facies

Description. Deposits of this facies occur only in the two most distal outcrop localities within the Valley and Ridge of southwestern Virginia (Narrows and South Gap localities, Figure 1-3). This facies can be divided into a variant HS_A (amalgamated hummocky cross-stratified sandstone) and a variant HS_B (hummocky cross-stratified sandstone and mudstone). Facies HS (hummocky cross-stratified sandstone facies) is

dominated by sandstone and contains only rare mudstone. Mudstone accounts for $<5\%$ in Variant A, and does not exceed 10% in Variant B. Grain size of the sandstone ranges from very fine to fine/medium sand, and in some instances to medium sand. Disc-shaped mudstone intraclasts with a maximum diameter of 3 cm occur occasionally within basal parts of sandstone beds. Overall, the beds display normal grain-size grading.

Bedding is well-defined within variant HS_B, where thin interbeds (a few cm to a rare maximum of 10 cm) of olive-gray mudstone separate sandstone beds (Figure 5-1D). Thickness of sandstone beds is generally 8 to 20 cm, but up to a maximum of 50 cm, where two or more beds are amalgamated. The sandstone beds display a pronounced change in thickness ('pinching-and-swelling') when traced along the outcrop face (Figure 5-1D), and individual beds thin and terminate rather abruptly. Intercalated thin mudstone beds commonly can be traced for up to several meters, but inevitably pinch out laterally (Figure 5-1D). Adjacent sandstone beds, then, verge and amalgamate. Bases of sandstone beds are sharp, undulatory-erosive, but do not show gutter casts. Tool marks are rare. Bed tops are distinct, and display hummocks and swales (Figure 5-1D). Spacing of hummocks commonly ranges from 0.8 to 1.1 m, with an observed maximum of 1.6 m. Symmetrical ripple-marks are rare; some preserved ripple bedforms are up to 2 cm in amplitude, show a spacing of 3 to 5 cm, and possess rounded crests.

Sandstone beds in variant HS_A are completely amalgamated and form bedsets of up to several meters in thickness. Individual bed boundaries are indicated by thin and highly discontinuous mudstone layers, and strings of aligned mudstone intraclasts, which indicate eroded mudstone interbeds. When identifiable, individual beds in variant HS_A seem to be thicker (20 to 40 cm) than in variant HS_B, but also display pronounced lateral changes in thickness ('pinch-and-swell'). Due to lack of interbedded mudstone, hummocks and swales at bed tops are difficult to identify, but the few examples discovered display a hummock-to-hummock spacing between 1.0 and 2.0 m. Some identifiable bed bases show broadly undulatory scouring into subjacent sandstone beds.

Internally, the sandstone beds are dominated by hummocky cross stratification (Figure 5-1E) and horizontal stratification, interrupted to different degrees by bioturbation (including escape burrows). Wave-ripple and current-ripple cross stratification occur rarely. Some beds appear massive, because their physical stratification is completely destroyed by bioturbation. Identifiable trace fossils include *Skolithos* (by far dominating) and *Planolites*. Dense populations of *Skolithos* can be observed on tops or undersides of sandstone beds (Figure 5-2F). Macrofossils are absent, but a few marine acritarch specimens were

recovered from mudstone interbeds (G. Wood, pers. comm., 1992). Measurement of paleocurrents within facies HS was difficult. At the South Gap locality, some tool marks are oriented 242-62°, and ripple cross stratification contained within preserved symmetrical-ripple bedforms indicates a ripple migration towards 325°. Crests of symmetrical ripple bedforms are oriented 206-26° (at South Gap) and 238-58° (at Narrows).

Facies HS constitutes the uppermost intervals of the "upper" Tuscarora Sandstone at the two most distal outcrop localities (Narrows and South Gap) exposed within the Valley and Ridge of southwestern Virginia (Figure 5-3). This facies is in erosional contact with subjacent beds of facies SX (Figure 5-3). The scoured contact can be observed in both outcrops, and the scour depth can reach up to 30 cm.

Interpretation. Hummocky cross stratification is considered to be a stratification type associated with the action of storms (for example, Harms and others, 1975; Hamblin and Walker, 1979; Bourgeois, 1980; Kreisa, 1981; Dott and Bourgeois, 1982). Sand is transported by oscillatory-dominant combined flows in an offshore direction perpendicular to the shoreline, following coastal set-up and downwelling (Duke and others, 1991), and following the action of storm-enhanced rip currents. Hummocky cross stratification is linked to the growth of large, three-dimensional wave ripples. The bedforms were generated by aggradation during waning oscillatory-dominant combined flow and oscillatory flow, and through reworking by storm and swell waves (Duke and others, 1991; Cheel and Leckie, 1992).

Hummocky cross-stratified sandstone beds represent deposition under storm conditions, whereas mudstone interbeds are interpreted as the record of fairweather conditions, intervening between successive storms (Hamblin and Walker, 1979; Dott and Bourgeois, 1982). The amalgamation of storm beds points toward frequent recurrence of storms and/or higher energy storms, probably in a more proximal nearshore setting (Dott and Bourgeois, 1982; Aigner and Reineck, 1982). Variant HS_A is composed almost exclusively of completely amalgamated storm beds, whereas variant HS_B contains laterally traceable fairweather mudstone interbeds (Figure 5-3). Amalgamated hummocky cross-stratified sandstone beds, like the ones observed in the "upper" Tuscarora Sandstone, are interpreted to represent deposits of the lower shoreface (for example Harms and others, 1975; Swift and others, 1987).

A shallow-marine origin for facies HS is supported, furthermore, by the presence and type of trace fossils, and the presence of acritarchs in fairweather mudstone interbeds.

Escape burrows in sandstone beds are rarely observed in both polished slabs and outcrop. This can be related to the difficulty to observe these traces in outcrop and/or to a real paucity of these traces. The most dominant trace fossil is *Skolithos*, especially in variant HS_B. *Skolithos* traces are interpreted as the dwelling burrows of suspension-feeding organisms populating sands in the littoral/shallow sublittoral zone under relatively high-energy conditions (Frey, 1975). *Skolithos* traces can be observed reaching through sandstone beds, creating conspicuous small protusions at the tops and bases of sandstone beds. These burrows might indicate the presence of opportunistic organisms, which rapidly recolonized an area following a storm and its severe effects on the pre-storm organism population (Vossler and Pemberton, 1988; Frey, 1990). Variant HS_A (amalgamated hummocky cross-stratified sandstone) is therefore interpreted to represent deposits of the upper lower shoreface, whereas variant HS_B (hummocky cross-stratified sandstone and mudstone) is interpreted to represent deposits of the lower lower shoreface, seaward of deposits of variant HS_A.

Dark Clastic Facies

Description. Facies DC (dark clastic facies) consists predominantly of very fine-grained sandstone, siltstone, and rarely silty mudstone. Deposits of this facies commonly are dark gray (even black) to light gray in color (Figure 5-1F), and contain sparse marcasite concretions (up to 5 cm in diameter). Intervals of this facies generally are thin (Figure 5-3), ranging from 1 cm to 10 cm. Thicker intervals are rare, but reach up to 80 cm at the South Gap locality (Figure 5-1B). The thickness of these intervals is laterally variable and can be seen reduced to zero due to erosion by deposits of facies SX. Thin, planar or ripple cross-stratified beds of facies SX (1 to 10 cm thick) can be found within thicker intervals of facies DC (Figure 5-1F). These thin beds of white sandstone are commonly finer grained than beds of the same facies found above and beneath the interval of facies DC. Bases of facies DC are distinct, and tops are sharply defined and always scoured by superjacent deposits of facies SX.

Stratification appears to be planar or slightly wavy, when mm-thick laminae of white sand are visible within the dark-colored sediment. Laminae of dark sediment are also detectable within white sandstone of the adjacent facies SX. Soft-sediment deformation occurs in several intervals of facies DC. At South Gap, this includes an interval of folded strata including a recumbent fold with an apparent vergence toward the northwest. Bioturbation is prominent and is represented by *Arthropycus* burrows filled with white sand

and by *Chondrites* traces. The *Arthropycus* traces originate in superjacent deposits of facies SX, or emanate from thin beds of this facies interbedded within a thicker interval of facies DC (Figure 5-1F). The animal responsible for the *Arthropycus* burrow seemed to have mined the darker deposits for nutrients, bioturbating the host sediment to varying degrees (Figure 5-1F). The animal responsible for *Chondrites*, on the other hand, seems to have inhabited facies DC from the start and is not related to deposits of facies SX. Some examples of marine acritarchs were recovered from this facies (G. Wood, pers. comm.; Hayes, 1974).

Facies DC is intimately associated with deposits of facies SX (Figure 5-3), and in one instance occurs as an interbed in deposits of facies G (at the Draper Mountain locality). This facies does not occur in the most proximal outcrops at Catawba Mountain and Fagg, and occurs at the base of the "upper" Tuscarora Sandstone at the Draper Mountain locality (Figure 5-3).

Interpretation. Deposits of facies DC (dark clastic facies) are closely associated with deposits of variant SX_A (Figure 5-3). The occurrence of the trace fossils *Arthropycus* and *Chondrites*, together with acritarchs, can be interpreted to indicate a marine depositional setting. I consider facies DC as the finer grained fairweather deposits of the lower upper shoreface and middle shoreface. The sediment accumulated by suspension settling during longer and calmer interludes between brief and violent storm episodes, which are represented by the coarser grained deposits of variant SX_A.

The finer grained fairweather deposits settled from suspension and commonly were bioturbated to varying degrees. Finer grained fairweather deposits have been reported from upper and middle shoreface depositional settings (for example, Leithold and Bourgeois, 1984; Greenwood and Mittler, 1985), but they are rarely preserved. The finer grained material is commonly removed by oscillatory currents and transported farther offshore. The preservation of any finer grained fairweather deposits necessitates special paleogeographic and/or environmental circumstances (Leithold and Bourgeois, 1984). The absence of cross stratification within deposits of facies DC might indicate that the fairweather oscillatory currents due to shoaling waves did not reach the threshold to mold the fine-grained sediment into bedforms (Clifton, 1988), or that the depositional site of the finer grained sediment was sheltered from excessive current action, such as in troughs between bars (Leithold and Bourgeois, 1984; Greenwood and Mittler, 1985). The thin, coarser grained, white sandstone beds of variant SX_A, which can be found rarely within

thicker intervals of facies DC, might represent sediment reworked from bar tops during fairweather conditions, or sediment reworked during minor storms. Redistribution of this coarser sediment temporarily overwhelmed suspension settling of finer grained material.

The preserved fairweather deposits are just a fraction of the formerly present deposits, because of erosion by storm-enhanced rip currents. Erosion of facies DC provided fine-grained, dark-colored detritus, which might be responsible for the dark color of some of the sandstone beds of variant SX_A (Figure 5-2B), and for accentuation of stratification in other beds of this facies.

The gray to dark-gray color of the fairweather deposits points toward elevated amounts of organic matter in these deposits. The gray color in conjunction with abundant *Chondrites* burrows indicates dysaerobic environmental conditions, whereas the dark-gray coloration together with a decrease in (or absence of) bioturbation indicates more anaerobic environmental conditions (Savrda and Bottjer, 1991). Anoxia immediately beneath the sediment-water interface at a modern gravelly shoreface was reported by Hart and Flint (1989) from Chesil Beach, England.

The organic-rich fairweather deposits accumulated within the nearshore zone of the Taconic foredeep, which was a semi-enclosed, narrow, shallow-marine basin bound to the southeast by the terrestrial part of the foredeep and the externides of the Taconic orogen, and to the northwest by a peripheral bulge. The organic-rich deposits might have accumulated in response to high organic productivity in the surface water of the marine foredeep. Settling of organic matter through the water column and decay of this organic matter could have lead to oxygen deficiency in lower levels of the water column. Dysaerobic to anaerobic conditions, then, developed at or near the sea bottom, while most of the water column itself remained oxygenated.

High primary productivity can be linked to possible blooms in phytoplankton. Phytoplankton blooms are frequent in some modern shallow-marine settings and are related to anthropogenic eutrophication of marine waters (Oschmann, 1991). Volcanism may have been responsible for supply of abundant nutrients (Ulmishek and Klemme, 1990) for eutrophication of the surface waters within the Taconic foredeep. Active volcanism was probably common during the Early Silurian. It was connected to active terrane accretion and the closing of Iapetus just to the southeast and east (present coordinates) of the Taconic foredeep. Phytoplankton blooms reaching into the shallow-water nearshore zone might have been aided by the fact that the Taconic foredeep at this point in time was reestablished as a marine basin. The foredeep reverted back to a marine basin following subaerial

exposure during isostatic basin rebound (Dorsch and others, 1990). This paleogeographic situation included a regional transgression onto the subaerial exposure surface and the creation of a shallow and narrow marine foredeep.

The importance of high primary organic productivity for the origin of facies DC of the "upper" Tuscarora Sandstone is underscored by the grain size of this facies. Although oxygen deficiency is reported within sediment of silt- and fine-sand-size (Oschmann, 1991), it is not common and necessitates a higher contribution of organic matter (Tyson and Pearson, 1991). The grain size of the organic-rich deposits within the "upper" Tuscarora Sandstone, therefore, might indicate a high influx of organic matter most likely related to high rates of primary organic productivity.

Organic-rich deposits, interestingly, can be found in different paleotectonic settings during the Early Silurian (Thickpenney and Leggett, 1987). Organic-rich deposits associated with Laurentia include, for example, sediment deposited on Iapetan oceanic crust and later incorporated into the Southern Uplands accretionary prism (Leggett and others, 1982), deposits confined to narrow successor basins developed within the internides of the Taconic orogen (for example, Drake and others, 1989), and deposits within the Taconic foredeep. Iapetus, however, was not uniformly "poisoned" during overall eustatic sea-level rise in the Early Silurian. Lower Silurian, shallow-marine deposits in eastern Tennessee, for example, do not contain organic-rich sediment (Driese and others, 1991), despite the fact that the area of present-day eastern Tennessee was connected to the active Taconic foredeep to the northeast, and to Iapetus to the southwest (Bolton, 1992). The coeval occurrence of organic-rich deposits on part of the Laurentian continental margin facing Iapetus and their possible genetic link to tectonism poses an interesting problem, which needs further study.

Preservation of fairweather deposits is also related to recurring storm sedimentation. Storm deposits buried the fairweather deposits and eliminated the possibility of any reworking, such as winnowing by oscillatory currents, and offshore transport of the fine-grained sediment. The presence of any fairweather deposits between storm deposits and the lack of complete amalgamation of storm beds on the upper and middle shoreface, can be related to less severe storm events or, more likely, to the abundant creation of accommodation space (see below for a further discussion).

The prominently folded bed of facies DC at South Gap is interpreted to represent a slumped horizon. The mechanism inducing slumping might have been an earthquake. Gravity caused movement of the deposits along a slope provided by the shoreface. The apparent vergence of a recumbent fold toward the northwest indicates the direction of the

paleoslope. This conclusion supports the inferred northeast-southwest trend of the paleoshoreline, which is based on orientations of symmetrical-ripple crests predominantly from the overlying Rose Hill Formation.

'Transition Complex'

Description. The 'transition complex' is 2.07 m thick and can be found only at the Narrows locality, where it forms the top of the "upper" Tuscarora Sandstone (Figure 5-3). It overlies a completely bioturbated bed of facies HS, and is overlain sharply by shale of the Rose Hill Formation (Figure 5-3).

The complex is dominated by thin (1.5 to 10 cm) sandstone beds, which range from fine/medium to coarse/very coarse in grain size. Most of the sandstone beds are coated by a thin (≤ 1 cm) rim of iron mineralization. Interbedded with the sandstone beds is mudstone. In the lower part of the 'transition complex', the thin sandstone beds display load features, including complete disruption of beds and development of small ball-and-pillow structures. Bioturbation is abundant and includes horizontal traces (*Planolites*) and vertical burrows (*Skolithos*). Part of the complex shows iron-hydroxide-crusts. The coarser grained sandstone beds appear massive and contain some well rounded quartz granules, mudstone intraclasts (up to 3 cm in length), brachiopods (*Ancillotoechia* sp., P. Sheehan, pers. comm., 1993), and phosphate grains of granule size. Stratification in the finer grained sandstone beds is wave-ripple cross stratification and horizontal stratification, but is predominantly destroyed due to bioturbation.

The top of the 'transition complex' is formed by a prominent coarse-grained sandstone bed of maximum 30 cm in thickness (Figure 5-3). The sandstone bed is well sorted (very coarse sand occurs in minor amounts), and the quartz grains are well rounded. Broken brachiopod fragments and olive-green mudstone intraclasts occur rarely. The top of the sandstone bed displays one single bedform. It is approximately symmetrical in cross section with a strongly rounded and straight crest. Internally, the bed appears massive except for a few planar cross strata dipping in opposite directions.

Interpretation. The thin, fine-grained sandstone beds displaying wave-ripple cross stratification and planar stratification are interpreted as tempestites. The sandstone beds were rapidly emplaced within finer grained deposits causing loading. Together with the moderate amount of mudstone, the degree of bioturbation, and the position above deposits of the lower shoreface, the 'transition complex' can be considered as deposits of the offshore

transition zone. The coarser grained, thin sandstone beds probably also represent storm beds made up of coarser material eroded from the upper shoreface. The distinctive sandstone bed, which forms the top of the 'transition complex', appears analogous to coarse-grained, wave-formed ripples described by Leckie (1988). Ripples of this type can occur within the shoreface, the offshore transition zone, and along transgressive surfaces. Their genesis is related to oscillatory/oscillatory-dominant flow associated with storm-wave action (Leckie, 1988). I interpret the distinctive sandstone bed at the top of the 'transition complex' at Narrows as a winnowed lag associated with rapid transgression, which established the depositional conditions for the shale-dominated Rose Hill Formation (see further discussion below).

The iron coatings on sandstone beds are interpreted as secondary mineralization. The iron was most likely derived from hematitic sandstone beds within the overlying Rose Hill Formation. In fact, the first hematitic sandstone bed of the overlying Rose Hill Formation occurs just 50 cm above the top of the 'transition complex'. The iron-hydroxide crusts probably developed from weathering of iron rims associated with sandstone beds.

FACIES STACKING AND SEQUENCE STRATIGRAPHIC INTERPRETATION

The vertical stacking of facies within the "upper" Tuscarora Sandstone reveals a fining-upward trend (Figure 5-5). Together with this fining-upward trend, the beds become thinner and the degree of bioturbation increases up section. This observation can be best appreciated at the most distal outcrop localities at Narrows and South Gap, where the largest array of diverse facies of the "upper" Tuscarora Sandstone is developed (Figures 5-5, 5-6). A departure from this trend is found at the localities along Catawba Mountain, where a finer grained facies interval (variant SX_B) underlies a fining-upward facies succession (Figure 5-5). For each single outcrop, the vertical stacking of facies indicates an upward-deepening, marginal-marine depositional setting. The "upper" Tuscarora Sandstone, therefore, can be interpreted to represent a transgressive facies succession.

The "upper" Tuscarora Sandstone is thickest in the distal outcrop localities in the northwest and thins towards the proximal outcrop localities in the southeast (Figure 5-5). The fine-grained deposits of facies HS occur only in the distal outcrop belts. Deposits of facies DC occur in the distal and medial outcrop belts, but do not appear in the proximal outcrop belts (Figure 5-5).

Figure 5-5: Stratigraphic correlation diagram of the "upper" Tuscarora Sandstone in southwestern Virginia drawn on a palinspastic base. Abbreviations: trans. - transition complex at the top of the outcrop section, Narrows locality; sb - sequence boundary; ts - transgressive surface; wrs - wave-ravinement surface; trs - tidal-ravinement surface; mfs - (maximum) marine-flooding surface; the '+'-sign between abbreviations denotes amalgamation of the respective stratigraphic surfaces; wavy line - unconformity (Tu = "Tuscarora unconformity", W = Wallbridge Discontinuity); 'X' within measured sections denotes covered interval; outcrop localities: 1 - Narrows; 2 - South Gap; 3 - Cascades; 4 - Gap Mountain; 5 - Draper Mountain; 6 - Catawba Mountain I; 7 - Catawba Mountain II; 8 - Fagg II; 9 - Fagg I; refer to Figure 1-3 for location of outcrops.

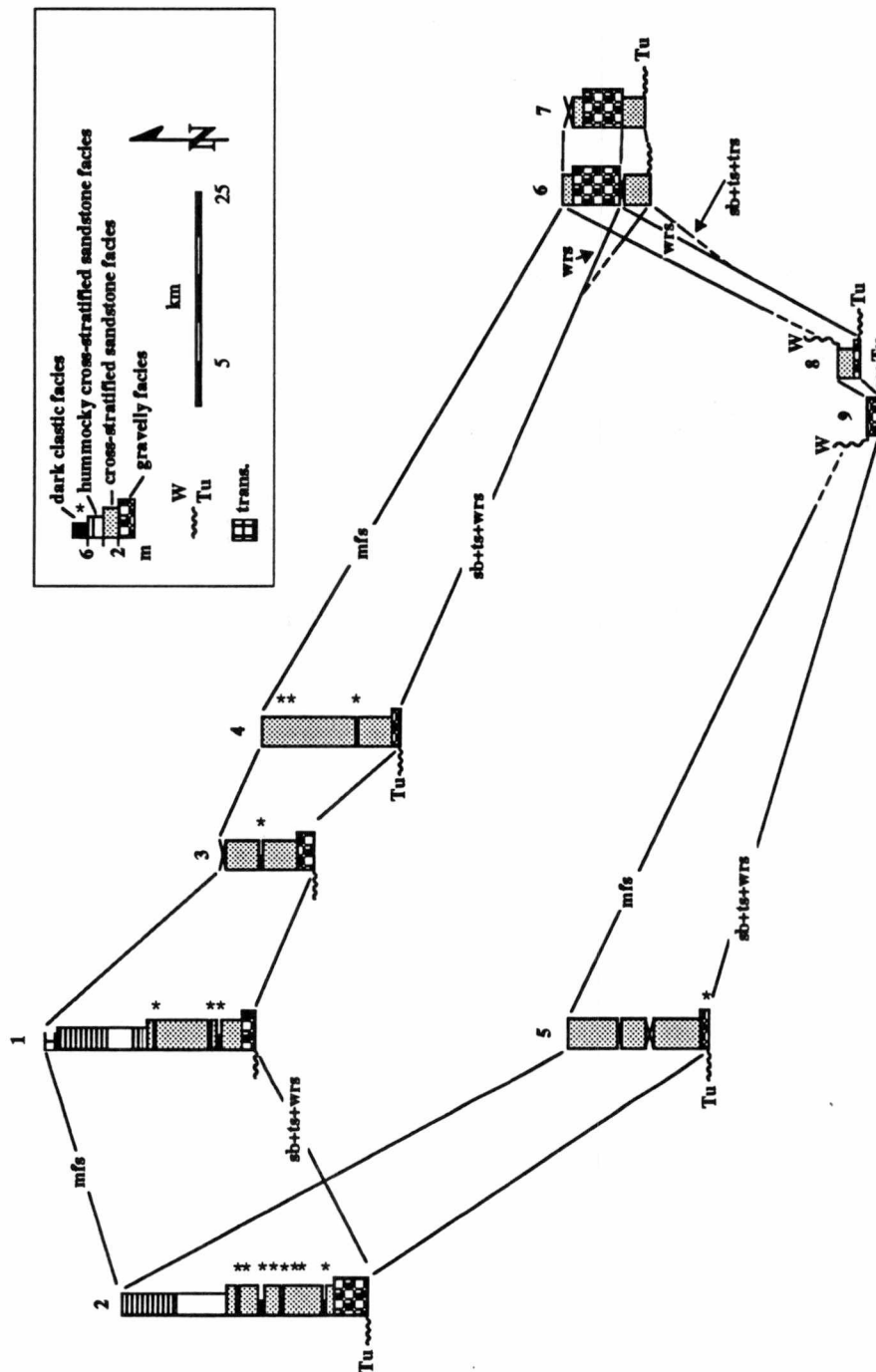
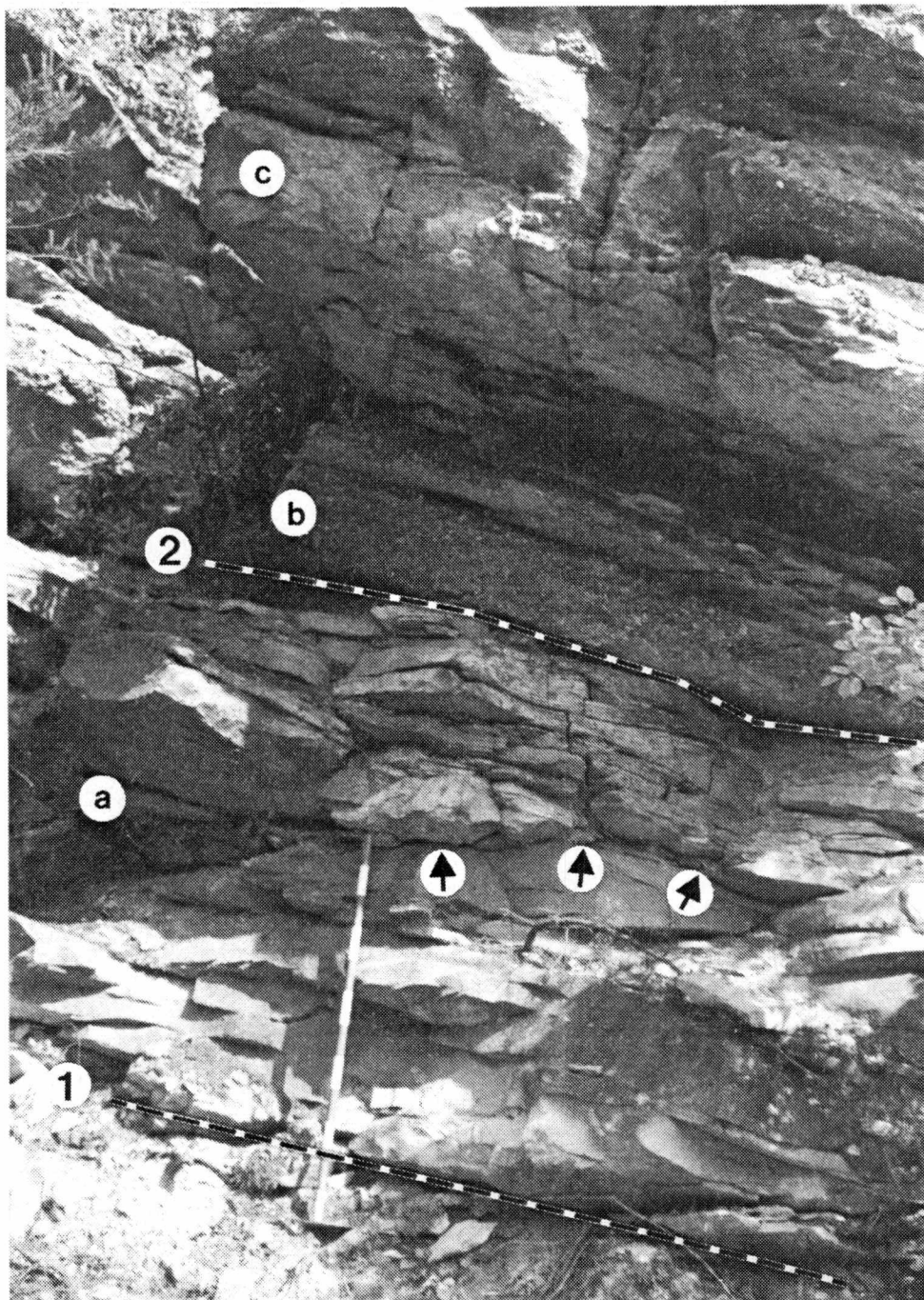


Figure 5-6: Outcrop Catawba Mountain II. Depicted is the contact between the Martinsburg Formation and the "upper" Tuscarora Sandstone along the "Tuscarora unconformity" (1). Facies of the "upper" Tuscarora Sandstone include variant SX_B (estuarine deposits: a) and variant G_A (lag conglomerate: b), which grades upward into variant G_B (c). Key stratigraphic surfaces in this outcrop include the sequence boundary, which is merged with the transgressive surface and the tidal-ravinement surface (1), and the wave-ravinement surface, which is developed as the sharp erosive surface separating variant SX_B from variant G_A (2). Arrows outline internal scour surface within estuarine deposits; staff is 1.20 m.



The transgressive facies succession of the "upper" Tuscarora Sandstone onlaps a subaerial exposure surface, proceeding from the northwest toward the southeast through time. The subaerial exposure surface covers successively (from the northwest toward the southeast) Juniata Formation (Gap Mills, WV locality, not shown), "lower" Tuscarora Sandstone, and Martinsburg Formation. The disconformity separating the "upper" Tuscarora Sandstone from the various subjacent stratigraphic units has been termed the "Tuscarora unconformity" (Dorsch and others, 1990). Its origin is thought to be related to a phase of quiescence in Taconic compressional tectonism, during which time isostatic rebound uplifted both the Taconic orogen and its adjacent foredeep, thereby creating the subaerial exposure surface (Dorsch and others, 1990). The "Tuscarora unconformity" forms the lower boundary of the "upper" Tuscarora Sandstone, and represents a sequence boundary not related to pure eustatic sea-level fall, but to tectonism.

The sequence boundary is overlain by marginal-marine deposits (facies G). Fluvial deposits, which are expected to have covered the erosional surface once, are lacking. The fluvial deposits were reworked during the transgression and provided the coarser grained detritus for facies G. Over the extent of the field area, therefore, the transgressive surface merges with the sequence boundary. This stratigraphic setting is similar to the one described for Silurian deposits in the northern part of the Taconic foredeep in New York (Brett and others, 1990).

The fluvial deposits were eroded and reworked during transgression by the process of erosional shoreface retreat associated with the action of storm currents (Stamp, 1921; Swift, 1968; Niedoroda and others, 1985; Thorne and Swift, 1991). The occurrences of laterally discontinuous thin beds of variant G_A immediately above the sequence boundary represent lag deposits, which formed during the earliest stages of transgressive erosion. Erosional shoreface retreat swept the sequence boundary clean of its fluvial deposits and may have eroded beneath the (original) sequence boundary. The removal of 10 m (or more) of deposits during erosional shoreface retreat is reported from near-recent settings (Swift, 1968; Niedoroda and others, 1985; Demarest and Kraft, 1987). The erosional surface developed during erosional shoreface retreat (wave-ravinement surface, *sensu* Allen and Posamentier, 1993) is merged, like the transgressive surface, with the sequence boundary (Figure 5-5).

The spatial distribution of key stratigraphic surfaces at Catawba Mountain deviates from the situation described from outcrop localities further to the northwest (Figure 5-6). At Catawba Mountain, estuarine sandstone is sandwiched between sequence boundary

("Tuscarora unconformity") and wave-ravinement surface (Figures 5-5, 5-6). The latter is marked by a discontinuous bed of lag conglomerate at the base of facies G (Figures 5-5, 5-6). The estuarine sandstone is interpreted as the fill of an incised "valley" (valley is put here in quotation marks, because of the small dimensions of the "valley" at Catawba Mountain in comparison to other modern and ancient examples of incised valleys and their fills; see for example, Van Wagoner and others, 1990; Allen and Posamentier, 1991; 1993).

Development of the wave-ravinement surface, which caps the incised-"valley"-fill deposits at Catawba Mountain, probably is responsible for decapitation of the incised-"valley"-fill deposits and for erosional removal of any finer grained estuarine deposits, which might have succeeded the estuarine sandstone. Decapitation occurred as the shoreline migrated landward over the valley fill.

The preserved fill of the incised "valley" is exclusively estuarine. Coarser grained remnant fluvial deposits, which often constitute the basal portion of incised-valley-fills (for example, Dalrymple and others, 1992; Allen and Posamentier, 1993), are absent at Catawba Mountain. The fluvial deposits within the incised "valley" probably were removed by deep estuarine erosion accompanying transgression within the estuary, as described from similar depositional settings by Swift (1973), Cant (1991), and Dalrymple and others (1992).

Erosion was concentrated at the estuary mouth and was probably accomplished by migrating tidal channels situated at the estuary mouth (compare to Swift, 1973; Cant, 1991; Dalrymple and others, 1992). The migration of tidal channels led to removal of subjacent estuarine and older fluvial deposits (Dalrymple and others, 1992). The sequence boundary at the base of the incised-"valley"-fill deposits, therefore, should be amalgamated with another erosive surface (tidal-ravinement surface, *sensu* Allen and Posamentier, 1993) related to removal of fluvial and older estuarine "valley"-fill, and deposition of younger estuarine sediment (Figure 5-6).

Placement of the transgressive surface at Catawba Mountain is controversial. Van Wagoner and others (1990) and Posamentier and Vail (1988) customarily place the transgressive surface on top of estuarine deposits of the incised valley. Thorne and Swift (1991) and Allen and Posamentier (1993) argue, however, that estuarine deposits above fluvial deposits indicate transgression and that, therefore, the transgressive surface should reside at the base of the estuarine deposits. We follow the reasoning of the latter authors: the sequence boundary at Catawba Mountain is merged with the transgressive surface and with a ravinement surface (tidal-ravinement surface) (Figures 5-5, 5-6).

The "upper" Tuscarora Sandstone is overlain by the Rose Hill Formation along a distinct contact (Figure 3-3C). The Rose Hill Formation commences with a thick section of shale, which contains thin (predominantly ≤ 10 cm) fine- to fine/medium-grained sandstone beds. The sandstone beds exhibit sharp-erosive bases, and symmetrical ripples, interference ripples, and small hummocks and swales on bed tops. Stratification types include wave-ripple cross stratification, hummocky cross stratification, and planar stratification. The sandstone beds typically show load features, including the complete fragmentation of beds into pseudonodules. Identifiable trace fossils consist of *Planolites* and *Skolithos*. The shale yielded marine acritarchs (G. Wood, pers. comm., 1992). The lower part of the Rose Hill Formation is interpreted as offshore shale interspersed with sandy tempestites of distal character. These deposits are sharply juxtaposed against different facies of the "upper" Tuscarora Sandstone, such as transition-zone deposits ('transition complex' at the Narrows locality), lower shoreface deposits (South Gap locality), and various upper shoreface deposits at outcrop localities further to the southeast (Figure 5-5).

The immediate top of the "upper" Tuscarora Sandstone is developed differently at different outcrop localities. At the Gap Mountain locality, a thin and discontinuous (0 to 3 cm), coarse- to very coarse-grained sandstone bed occurs. The bed is bioturbated and contains dispersed quartz granules and a few pebbles (up to 5 mm). At the McCoy locality, a coarser grained bed is lacking, but the top of the "upper" Tuscarora Sandstone is covered by large vertical and oblique burrows of uncertain affinity. At the South Gap locality, a completely bioturbated coarse- to very coarse-grained sandstone bed (12 cm thick) contains pebbles up to 1.5 cm in length and phosphatized grains (Figure 3-3C). At the Narrows locality, the top of the "upper" Tuscarora Sandstone is formed by the distinctive coarse-grained sandstone bed already described above (see description of the 'transition complex').

The distinctive contact between the different facies of the "upper" Tuscarora Sandstone and the heterolithic deposits of the Rose Hill Formation sharply separates deposits of shallower-water affinity from superjacent deposits of deeper-water affinity. This contact marks a rapid increase in water depth and is interpreted as a marine-flooding surface (Van Wagoner and others, 1988; 1990). The coarser grained deposits at the top of the "upper" Tuscarora Sandstone in some outcrop sections can be considered as discontinuous lag deposits resting directly on the flooding surface. The coarser material might represent eroded material from the upper shoreface transported to deeper water during marine flooding. Winnowing due to wave action concentrated the coarser grains and also caused incorporation of material from subjacent deposits, such as mudstone clasts and abraded

brachiopods. Winnowing due to wave action might also be responsible for the stratification in the coarse-grained sandstone at the top of the 'transition complex' at the Narrows locality. The phosphatized grains in some of the lag deposits and extensive bioturbation indicate low sedimentation rates during initial rapid flooding. This marine-flooding surface represents a distinct and easily recognizable marker for placement of the lithostratigraphic boundary between the Rose Hill Formation and the Tuscarora Sandstone.

The marine-flooding surface marking a distinct regional lithologic change (termination of white quartz-sand deposition) can also be viewed as a maximum-flooding surface. The maximum-flooding surface forms the lower stratigraphic bounding surface of the highstand systems tract (Posamentier and others, 1988), which is represented by the heterolithic deposits of the Rose Hill Formation. The "upper" Tuscarora Sandstone, bound at its base by a sequence boundary ("Tuscarora unconformity") and at its top by the maximum-flooding surface, constitutes the transgressive systems tract (Posamentier and others, 1988). A lowstand systems tract (Posamentier and others, 1988) is not preserved within the facies succession of the "upper" Tuscarora Sandstone. Deposits of the lowstand systems tract were removed by erosion, which led to the merging of the transgressive surface with the sequence boundary throughout the field area.

The transgressive systems tract, represented by the upward-deepening facies succession of the "upper" Tuscarora Sandstone, is interpreted to consist of a single, uninterrupted parasequence. Based on the facies distribution within this parasequence, the parasequence is retrogradational in character. The retrogradational parasequence cannot be subdivided into smaller parasequences (thus requiring that the transgressive systems tract of the "upper" Tuscarora Sandstone be composed of a parasequence set) by the insertion of marine-flooding surfaces in the outcrops of the study area. A possible exception is the most distal outcrop at Narrows. Here, a marine-flooding surface could be placed following the first hummocky cross-stratified sandstone bed, which is amalgamated to a subjacent trough cross-stratified sandstone bed (Figure 5-3, at 14.06 m). An interval of thinner bedded, hummocky cross-stratified sandstone beds with bioturbation overlies this probable flooding surface. Placement of a marine-flooding surface at this level would split the "upper" Tuscarora Sandstone at the Narrows locality into a lower uninterrupted (and still) retrogradational parasequence (from sequence boundary to probable marine-flooding surface; ca. 51% of the total outcrop section), and an upper parasequence displaying a progradational-then-retrogradational trend (probable marine-flooding surface to maximum

marine-flooding surface). There is no physical evidence for subdividing the upper parasequence further into a progradational and retrogradational part.

A similar probable marine-flooding surface cannot be placed at the same stratigraphic position (first hummocky cross-stratified sandstone bed amalgamated to trough cross-stratified sandstone bed; Figure 5-3, at 18.58 m) at the South Gap locality. The "upper" Tuscarora Sandstone at the South Gap locality, like that at the other outcrop localities farther to the southeast, cannot be subdivided into separate parasequences. It appears that the "upper" Tuscarora Sandstone is composed of a single, uninterrupted retrogradational parasequence in the proximal, medial, and distal outcrop belts. Only at the most distal outcrop locality is the "upper" Tuscarora Sandstone split into a lower retrogradational parasequence and an upper composite parasequence.

DISCUSSION

Based on the defined facies and their environmental interpretation, the "upper" Tuscarora Sandstone, as it is exposed within the Valley and Ridge of southwestern Virginia, represents shallow-marine deposits of a storm-dominated shoreline situated at the southeastern margin of the marine part of the Taconic foredeep. The shoreline most likely was barred (Hunter and others, 1979; Clifton, 1981; Leithold and Bourgeois, 1984; Greenwood and Mittler, 1985) and high-energy conditions were developed during storms. Low-energy periods, however, were also important, as is shown by the nature of the preserved fairweather deposits. Non-marine foredeep deposits are expected further toward the orogen in the southeast and northeast, but are not exposed within the Valley and Ridge of southwestern Virginia.

The proposed environmental interpretation is at variance with earlier interpretations put forward for this part of the Tuscarora Sandstone in southwestern Virginia (Hayes, 1974; Lampiris, 1975; Whisonant, 1977). Time-equivalent deposits in eastern Tennessee, however, were interpreted as storm-dominated shallow-marine deposits by Driese and others (1991). Cotter (1983b), furthermore, delineated a substantial amount of shallow-marine shelf deposits within the Tuscarora Sandstone of Pennsylvania.

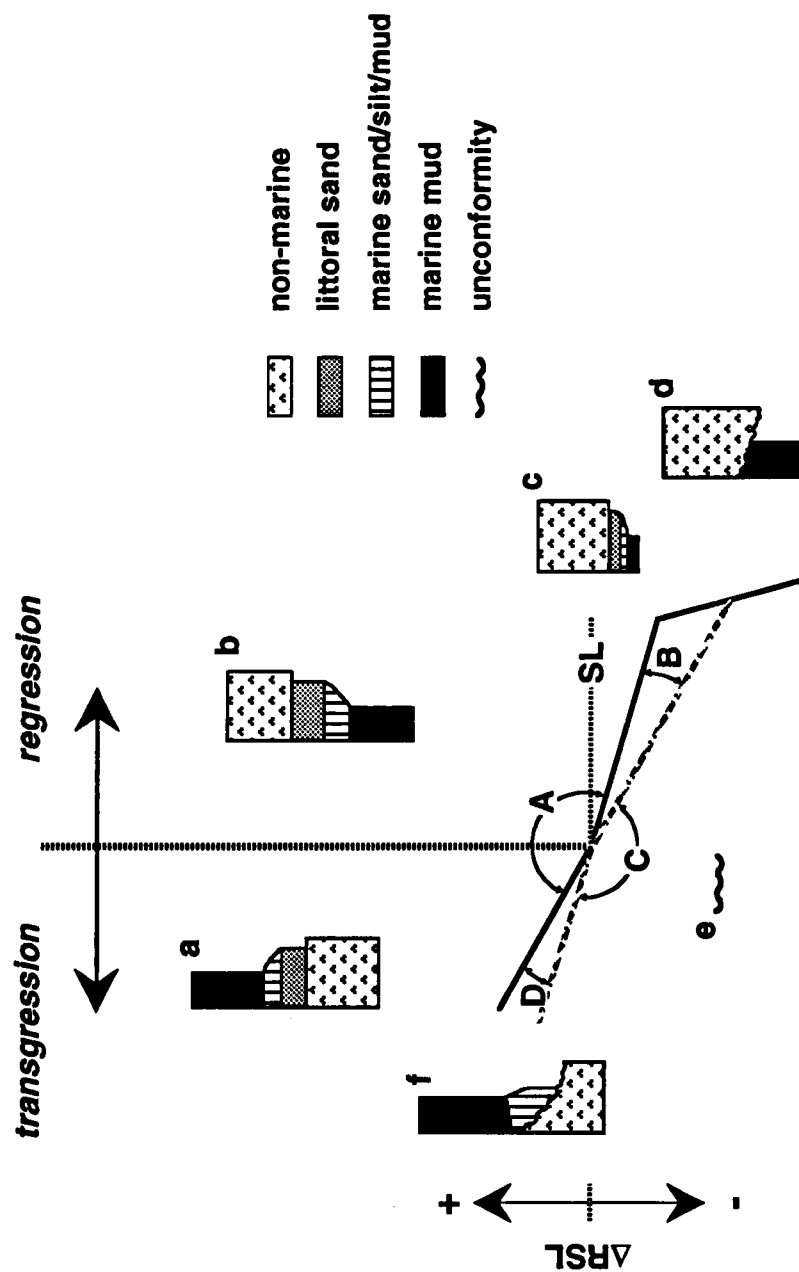
The coarser grained deposits within the "upper" Tuscarora Sandstone of southwestern Virginia are related predominantly to the action of storms and can be designated as storm deposits (tempestites). These storm deposits of the upper to lower

shoreface are amalgamated to a varying degree. The stratigraphic section is dominated by these storm deposits, which represent relatively short intervals of time (Dupre, 1984). Most of the time of deposition is contained within the preserved fairweather deposits and in the diastems created by storm erosion of fairweather deposits and older storm deposits (Dupre, 1984). The fact that fairweather deposits within the lower upper shoreface and middle shoreface are preserved at all requires special environmental conditions, such as high rates of sedimentation and pronounced basin subsidence (Leithold and Bourgeois, 1984).

The development and preservation of a transgressive facies succession, furthermore, demands special circumstances. Figure 5-7 displays different cases of shoreline migration and the resulting facies successions, based on a simple theoretical model developed by Cant (1991). Stratigraphic section 'a' most closely corresponds to the situation encountered in the "upper" Tuscarora Sandstone. The transgressive facies succession is created by migration of the shoreline into part of sector A (to the left of the transgression/regression divide), and represents a gradual fining-upward marine succession related to transgression (Cant, 1991). The transgressive facies succession is the result of a single, uninterrupted landward migration of the shoreline (Cant, 1991), a stratigraphic pattern rarely described in the literature (Elliott, 1986; Cant, 1991). Marine transgression commonly involves pronounced erosional shoreface retreat concomitant with development of a prominent ravinement surface that is overlain by a thin "condensed" and sandy stratigraphic unit, which represents an amalgam of different nearshore environments (see, for example, Swift, 1968; Demarest and Kraft, 1987; Thorne and Swift, 1991). This situation and the resulting facies succession is depicted in stratigraphic section 'f' in Figure 5-7 (Cant, 1991). As discussed in the earlier section on facies stacking and sequence stratigraphy, a component of erosional shoreface retreat is believed to have operated during relative sea-level rise and onlap of deposits of the "upper" Tuscarora Sandstone. It probably was responsible for reworking of older ?fluvial deposits and for the merging of sequence boundary, transgressive surface, and wave-ravinement surface. Succeeding this bundle of key stratigraphic surfaces, however, is the transgressive facies succession of the "upper" Tuscarora Sandstone, and not a thin transgressive sheet sandstone followed by offshore-marine mudstone.

The stratigraphic model depicted in section 'a' of Figure 5-7 necessitates the steady creation of accommodation space and the availability of sediment. The observed upward-fining trend, interpreted to reflect a gradual deepening of the depositional site with time, indicates that steady creation of accommodation space outpaced sediment supply. The few stratigraphic-sedimentologic studies describing transgressive facies successions (Hobday and

Figure 5-7: Summary diagram of shoreline migration and resulting facies successions. Shown are the sediment surface (bold black line) using simplified straight line segments for different environments (non-marine, shallow-marine), the different sectors (A - D), and the stratigraphic facies successions (a - f) resulting from shoreline migration into each of these sectors. The relative preserved thickness of the different facies depends on the angles of migration (modified from Cant, 1991). Abbreviations: SL - sea level, Δ RSL - change in relative sea-level ('+' = relative sea-level rise, '-' = relative sea-level fall). Shoreline is located where sea level touches sediment surface. The facies succession of the "upper" Tuscarora Sandstone corresponds to the situation depicted in section a, which formed by translation of the shoreline into the transgression part of sector A. For a detailed discussion of all the different situations depicted, refer to Cant (1991).



Tankard, 1978; Bourgeois, 1981; Hein, 1987) all stress the importance of continual tectonic subsidence and steady sediment supply for development and preservation of the transgressive succession.

I concur with this view and suggest tectonic subsidence as the main factor in development and preservation of the transgressive facies succession of the "upper" Tuscarora Sandstone. The "upper" Tuscarora Sandstone developed within the Taconic foredeep, which was dynamically coupled to the Taconic orogen. Tectonic activity (or lack thereof) within the orogen, therefore, is mirrored within the fill of the foredeep and the configuration of the foredeep.

The inception of the Taconic foredeep is tied to loading of Laurentian lithosphere by the growing Taconic orogen (Chapple, 1973; Jacobi, 1981; Quinlan and Beaumont, 1984). The sequential development of the Taconic foredeep is reflected by the evolution of its foredeep fill. It was argued earlier (Dorsch and others, 1990; see Chapter 2), that the "Tuscarora unconformity" originated during a phase of quiescence in compressional tectonism within the Taconic orogen. This lull in compressional tectonism succeeded a time interval of active compressional tectonism. Compressional tectonism was responsible for the development of the Taconic foredeep through flexural subsidence induced by lithospheric loading through the growing orogen, and for the evolution of the foredeep fill from deep-marine to shallow-marine/non-marine deposits. During the interlude of quiescence in compressional tectonism, erosional and tectonic thinning of the orogen lead to an isostatic response compensating for the erosional and tectonic unloading. The isostatic response consisted of epeirogenic uplift of both the orogen and its adjacent foredeep. This regional uplift resulted in the cutting of a west- to northwest-dipping erosional surface within the foredeep. Subsequent renewed sedimentation within the foredeep created the "Tuscarora unconformity", which is considered to represent a basin-rebound unconformity (*sensu* Cant and Stockmal, 1989).

The "upper" Tuscarora Sandstone was deposited during a crucial phase in the evolution of the Taconic foredeep. The foredeep experienced a second phase of active subsidence, probably due to another extended episode of lithospheric loading reflecting renewed compressional tectonism within the orogen (Dorsch and others, 1990; see Chapter 2). This phase of foredeep subsidence created the necessary space for accommodation of the upper part of the Martinsburg-Shawangunk clastic wedge. Transgression onto the erosion surface and onlap of deposits of the "upper" Tuscarora Sandstone were closely related to the commencement of this second phase of foredeep subsidence. Detritus for the

transgressive facies succession was provided by reworking of older ?fluvial deposits and by contributions from the now active orogen. Development and preservation of the transgressive stratigraphic pattern of the "upper" Tuscarora Sandstone most likely were governed by the interplay of steady tectonic subsidence and sediment supply.

The discussion above also illustrates the dominant influence of tectonism on relative sea-level changes and on the resulting sequence stratigraphic framework in southwestern Virginia during the Llandoveryan. The "upper" Tuscarora Sandstone constitutes the transgressive systems tract, which onlaps onto a regional sequence boundary during tectonically controlled relative sea-level rise. The sequence boundary itself was formed during relative sea-level fall caused by flexural isostatic rebound within part of the Taconic foredeep. The transgressive systems tract, furthermore, is made up of a single retrogradational parasequence (probably two at the Narrows locality). Parasequences in general display a progradational facies stacking whereas retrogradational parasequences, on the other hand, are rare (Van Wagoner and others, 1990). The retrogradational parasequence of the "upper" Tuscarora Sandstone reflects the unique conditions created by the dominance of tectonic subsidence in conjunction with sediment supply.

The discussion emphasizes that active tectonism was more important than eustasy in development and preservation of the transgressive facies succession/transgressive systems tract/retrogradational parasequence represented by the "upper" Tuscarora Sandstone. Eustatic effects probably came to prominence at the end of deposition of the "upper" Tuscarora Sandstone and at the onset of accumulation of the Rose Hill Formation. The regional (maximum) marine-flooding surface, which caps the "upper" Tuscarora Sandstone, can be placed into the Late Llandoveryan (Lampiris, 1975; R. Bambach, pers. comm., 1992). An eustatic sea-level rise is documented for the early Telychian (Late Llandoveryan) from different continents (Johnson and others, 1991), and the flooding event at the base of the Rose Hill Formation might be tentatively correlated with this eustatic sea-level rise. Other eustatic sea-level changes documented by Johnson and others (1991) for the Lower Silurian (older than Late Llandoveryan) are not detectable within deposits of the "upper" Tuscarora Sandstone. Their signal probably was overwhelmed by the dominant influence of tectonism and sediment supply. An exception might be the flooding surface, which can be placed within the middle part of the "upper" Tuscarora Sandstone at the most distal outcrop at Narrows. At this locality, eustasy might have overcome the dominant influence of tectonism and sediment supply. The probable eustatic signal, however, is not detectable at outcrop localities farther towards the orogen to the southeast. It might be expected to appear in

more distal parts of the Taconic foredeep to the northwest, which are now covered beneath the Appalachian Plateau.

Mutti and Sgavetti (1987) clearly pointed out the importance of regional stratigraphic analysis for differentiating between tectonic or eustatic dominance on the development of stratigraphic patterns and distribution of key stratigraphic surfaces. The area of southwestern Virginia in conjunction with the Valley and Ridge in eastern Tennessee constitutes a prime study area for investigating this problem. In eastern Tennessee, the effects of the end-Ordovician glacio-eustatic sea-level changes are well documented (Driese and others, 1991; Chapter 2). Glacio-eustatic sea-level fall created a subaerial exposure surface capped by paleosols. The succeeding glacio-eustatic sea-level rise is reflected by a widespread but thin sheet sandstone, thought to be caused by erosional shoreface retreat (Gogola, 1990; Driese and others, 1991). The glacio-eustatic sequence boundary encompasses only a small lacuna, and can be traced from southwesternmost Virginia into northern Alabama and Georgia, a distance of approximately 300 km along strike.

The situation in southwestern Virginia (and probably to the northeast), described above and in Chapter 2, is radically different. The area was situated within the active Taconic foredeep in front of the developing Taconic orogen in the central Appalachians. Tectonism, instead of glacio-eustasy, was the main determinant for the development of the regional stratigraphic pattern and of the key stratigraphic surfaces. The sequence boundary ("Tuscarora unconformity") encompasses a larger lacuna and has a tectonic cause (flexural isostatic rebound). It cut out evidence of the end-Ordovician glacio-eustatic sea-level changes within the area of the active foredeep (Chapter 2), and replaced the glacio-eustatic sequence boundary. Similarly, tectonism left its dominant imprint on the development of the stratigraphic succession above the sequence boundary and is ultimately responsible for suppression of the Lower Silurian eustatic signals till the onset of deposition of the Rose Hill Formation.

CONCLUSIONS

1. The "upper" Tuscarora Sandstone within southwestern Virginia is bound at its base by the "Tuscarora unconformity" and at its top by a (maximum) marine-flooding surface, which is in turn overlain by the Rose Hill Formation.

2. Based predominantly on stratification types and the trace-fossil suite, the "upper" Tuscarora Sandstone is interpreted to represent storm-dominated deposits of the surf zone through the offshore transition zone. This shallow-marine succession is characterized by amalgamated tempestites, with fairweather deposits mostly eroded away. Notable, however, is the presence of fairweather deposits rich in organic matter, which intervene between rip-current deposits of the lower upper to middle shoreface.

3. Throughout the field area, the stacking of facies and variants within the "upper" Tuscarora Sandstone exhibits a fining- and deepening-upward trend. The stratigraphic unit can be designated a single, complete, transgressive facies succession of shallow/marginal-marine deposits.

4. The "Tuscarora unconformity" represents a sequence boundary onto which the "upper" Tuscarora Sandstone onlapped, proceeding from the northwest toward the southeast. Throughout its extent, the sequence boundary is merged with the transgressive surface and a wave-ravinement surface. Only at Catawba Mountain is the wave-ravinement surface separated from the sequence boundary, and estuarine deposits of an incised "valley" are situated between these two key stratigraphic surfaces.

5. In sequence stratigraphic nomenclature, the "upper" Tuscarora Sandstone represents a transgressive systems tract composed of a single retrogradational parasequence. Only at the most distal outcrop locality at Narrows is the transgressive systems tract divisible into two separate parasequences.

6. The special circumstances leading to development and finally preservation of the complete transgressive facies succession encompass the steady creation of accommodation space and the availability of sediment. Creation of accommodation space can be linked to continual tectonic subsidence during a renewed phase of foredeep subsidence concomitant with compressional tectonism within the Taconic orogen. Ample sediment supply might also reflect rejuvenated compressional tectonism following a phase of basin rebound. Creation of accommodation space during deposition of the "upper" Tuscarora Sandstone was never overwhelmed by sediment supply.

7. Tectonism was the main determinant for the development of the regional stratigraphic pattern and of the key stratigraphic surfaces during the Llandoveryan in southwestern Virginia. Eustatic signals were suppressed until the onset of deposition of the Rose Hill Formation. In eastern Tennessee, on the other hand, uppermost Ordovician to Lower Silurian glacio-eustasy was the dominant influence on development of the regional stratigraphic pattern.

CHAPTER 6

CONCLUSIONS

1. The stratigraphic succession consisting of the Juniata Formation, Tuscarora Sandstone, and Rose Hill Formation (Upper Ordovician to Lower Silurian) forms part of the Martinsburg-Shawangunk clastic wedge, which constitutes the fill of the Taconic foredeep, a peripheral foreland basin associated with the Taconic orogeny in the central Appalachians. The stratigraphic units, as part of the foreland molasse, succeed the foreland flysch ("turbiditic" Martinsburg Formation) and its lateral/distal equivalents ("tempestitic" Martinsburg Formation and Reedsville Shale).

2. The most significant stratigraphic break, manifested in the "Tuscarora unconformity", is associated with the Tuscarora Sandstone. 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. 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 and the Cherokee Discontinuity.

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. 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 (see below) 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.

4. Development of the "Tuscarora unconformity" closely followed, and was 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.

5. 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.

6. *Subjacent to the "Tuscarora unconformity,"* the Juniata Formation and "lower" Tuscarora Sandstone (Upper Ordovician) conformably succeed the underlying Martinsburg Formation. They form an uninterrupted coarsening-upward succession, which is terminated abruptly by the "Tuscarora unconformity". The "lower" Tuscarora Sandstone is interpreted to represent a wedge-shaped sediment body, which constitutes the lithostratigraphic equivalent of the upper Juniata Formation within more proximal outcrop belts. The original areal distribution of the "lower" Tuscarora Sandstone is obscured by erosion associated with isostatic basin rebound.

7. The Juniata Formation and "lower" Tuscarora Sandstone of southwestern Virginia are interpreted to represent deposits of a shallow-marine foredeep. The facies and variants of the two formations correspond to different hydrodynamic zones within the shallow-marine foredeep, ranging from the middle shoreface to the offshore-marine zone. Most of the two formations represent deposits of the offshore-marine setting. The ambient storm system was the prime determinant for facies development, subdividing the clastic deposits into storm deposits (tempestites) and fairweather deposits. The interpretation of the red-bed succession of the Juniata Formation as shallow-marine in origin emphasizes that red coloration *per se* is not an infallible indicator for a terrestrial depositional environment.

8. Sediment was supplied to the shallow-marine setting through storm-induced downwelling currents enhanced by the interaction with wave-generated currents, and through storm-enhanced rip currents. The bedforms and larger-scale sediment-storage bodies on the sea-floor migrated predominantly in an offshore direction in response to a vigorous and persistent storm-generated combined-flow current system.

9. The persistence of a shallow-marine depositional setting throughout most of the Juniata Formation and "lower" Tuscarora Sandstone, and the development of a thick stratigraphic section of shallow-marine deposits together imply a delicate balance between creation of accommodation space (subsidence: predominantly through tectonic loading, augmented by sediment compaction and sediment loading) and sediment supply. The sandier-upward trend displayed by the two formations (and the upper part of the subjacent Martinsburg Formation) might be the combined effect of an increase in subaerial relief of the source area (orogen) and of a secular change in the caliber of the sedimentary rocks made available for erosion within the source area. A cyclic stratigraphic organization is not readily apparent within the Juniata Formation and "lower" Tuscarora Sandstone. This might be related to the continuous creation of accommodation space coupled with efficient distribution of the abundantly supplied sediment by the powerful storm-generated current system. In the most distal outcrop belt, fining-upward motifs within the upper part of the Juniata Formation might be linked to eustatic influence.

10. *Superjacent to the "Tuscarora unconformity,"* the "upper" Tuscarora Sandstone of southwestern Virginia consists of an array of recurring facies. These facies are interpreted as marginal-marine, storm-dominated deposits of a barred nearshore zone. The different facies mostly represent deposits of the upper to lower shoreface. In addition, deposits of the offshore transition zone are preserved at the most distal (with respect to the Taconic orogen) outcrop locality, whereas estuarine deposits are preserved at the most proximal outcrop locality.

11. The "upper" Tuscarora Sandstone is composed predominantly of storm deposits (tempestites). Fairweather deposits, which accumulated during interludes between major storms, are represented by finer grained sediment. Notable is the preservation of fairweather deposits of the middle and lower upper shoreface. These deposits are rich in organic matter, which might be related to nearshore phytoplankton blooms brought about during marine transgression by ample supply of probable volcanogenic nutrients.

12. The stacking pattern of facies requires that the "upper" Tuscarora Sandstone be interpreted as a continuous transgressive facies succession, which overlapped onto a subaerial

erosion surface during relative sea-level rise. This transgressive facies succession is framed by prominent stratigraphic surfaces: a sequence boundary ("Tuscarora unconformity") at the base, and a (maximum) marine-flooding surface at the top. The top stratigraphic surface forms an easily identifiable marker for placement of the lithostratigraphic boundary between the "upper" Tuscarora Sandstone and the overlying Rose Hill Formation in southwestern Virginia. Other identified key stratigraphic surfaces include the transgressive surface, a wave-ravinement surface, and a tidal-ravinement surface. The transgressive facies succession of the "upper" Tuscarora Sandstone constitutes a transgressive systems tract, which is composed of a single, continuous, retrogradational parasequence. At the most distal outcrop locality at Narrows, a flooding surface divides the "upper" Tuscarora Sandstone into a lower retrogradational parasequence and an upper progradational-then-retrogradational parasequence.

13. Development and preservation of the transgressive facies succession, transgressive systems tract, and retrogradational parasequence of the "upper" Tuscarora Sandstone are believed to be tied to tectonism. The "upper" Tuscarora Sandstone was deposited within the Taconic foredeep during the onset of a new episode of flexural subsidence, related to lithospheric loading by the growing Taconic orogen. The transgressive systems tract of the "upper" Tuscarora Sandstone overlapped the sequence boundary, which originated earlier during uplift associated with flexural isostatic basin rebound. Gradual and continued subsidence created accommodation space at a rate that outpaced the rate of ample sediment supply, and was ultimately responsible for development of the transgressive facies succession and the retrogradational parasequence.

14. Southwestern Virginia, because of its location within the active Taconic foredeep, provides an example of the dominant role that tectonism can play in the development of regional stratigraphic patterns and key stratigraphic surfaces. Eustatic sea-level changes were overwhelmed by the influence of tectonism and sediment supply, and their signal was suppressed. Eustasy as the dominant influence on development of stratigraphic patterns and key stratigraphic surfaces probably reappears with the development of the (maximum) marine-flooding surface capping the "upper" Tuscarora Sandstone during the ? early Telychian. The sequence boundary ("Tuscarora unconformity"), transgressive systems tract, and retrogradational parasequence as elements of sequence stratigraphy most likely originated through the influence exerted by tectonic activity and sediment supply within the orogen-foredeep couplet associated with the Taconic orogeny.

15. *On a regional scale* (central Virginia to northern Alabama/Georgia), the uppermost Ordovician to Lower Silurian stratigraphic units above the Upper Ordovician red-bed succession in the central and southern Appalachian Valley and Ridge can be subdivided into the distinctly different 'White Sandstone Lithosome' (Tuscarora Sandstone, Poor Valley Ridge Sandstone Member of the Clinch Sandstone, and some beds/bedsets within the Rockwood Formation) and 'Heterolithic Lithosome' (Rose Hill Formation, Rockwood Formation, and Hagan Shale Member of the Clinch Sandstone). In southwestern Virginia, the 'White Sandstone Lithosome' dominates, which is divided by the "Tuscarora unconformity" into the "lower" and "upper" Tuscarora Sandstone, and is succeeded by the 'Heterolithic Lithosome'. In extreme southwestern Virginia and eastern Tennessee, the 'Heterolithic Lithosome' dominates, which commences with the 'basal transgressive sandstone' and encapsulates the more exotic 'White Sandstone Lithosome'.

16. The lithostratigraphic term Tuscarora Sandstone should be used within the area covered by the "Tuscarora unconformity" and/or where the "lower" Tuscarora Sandstone interfingers with the Juniata Formation. Clinch Sandstone, on the other hand, should be used within the area marked by the absence of the "Tuscarora unconformity" and by the presence of the 'White Sandstone Lithosome' contained within the 'Heterolithic Lithosome'.

17. In contrast to the commonly held view, the 'White Sandstone Lithosome' does not form a simple, homogeneous, and uniform quartzarenite blanket throughout the central and southern Appalachians, but hides a more complex history. This lithosome is divisible into separate components, with each component having its distinct tie to a different developmental stage of the Taconic orogen in the central Appalachians and to eustatic sea-level changes.

18. The detritus for the "lower" Tuscarora Sandstone was shed from the growing Taconic orogen and was deposited within the foredeep during thrust-load induced foredeep subsidence. The glacio-eustatic sea-level events during the Hirnantian (latest Ordovician) are thought to be reflected in the Whirlpool Sandstone (subsurface of southern Ohio and parts of West Virginia), whose stratigraphic position and origin corresponds to that of the 'basal transgressive sandstone' (extreme southwestern Virginia to northern Alabama/Georgia). Detritus for the Whirlpool Sandstone was derived from erosion of "lower" Tuscarora Sandstone during glacio-eustatic sea-level drop.

19. The "Tuscarora unconformity" developed following a cessation in Taconic compressional tectonism. Flexural isostatic uplift/rebound converted part of the Taconic foredeep from an active depositional site to an active erosional site. In the area of uplift

(denudation area), evidence for the Hirnantian glacio-eustatic sea-level events was cut out, and the produced erosional detritus (derived predominantly from the "lower" Tuscarora Sandstone) was redistributed radially away from the denudation area into parts of the foredeep not affected by rebound, and into areas at the fringe of the foredeep and beyond (parking area and fill area). The 'White Sandstone Lithosome' in extreme southwestern Virginia and eastern Tennessee (Poor Valley Ridge Sandstone and bedsets within the Rockwood Formation) is interpreted to be part of this redistributed material, which interrupted the normal, mud-dominated sedimentation in that area. The "Clinton" sandstone in the subsurface of southern Ohio is regarded as a lithostratigraphic equivalent. The quartz-rich detritus was overprinted and distributed within the fill area by the ambient storm system. The isolated bedsets of the 'White Sandstone Lithosome' within the Rockwood Formation, demarcating the farthest spread of this lithosome, might represent forced regressions.

20. The "upper" Tuscarora Sandstone is interpreted to be related to a new phase of compressional tectonism and active foredeep subsidence, in concert with eustatic sea-level rise in the Llandoveryan (see above). The transgression reworked erosional detritus covering the denudation area, and thereby destroyed evidence of the distributive system. Most of the material for the "upper" Tuscarora Sandstone, however, is believed to have come from the Taconic orogen during this new phase of thrusting.

21. Taconic tectonism exerted a strong influence upon the origin of the 'White Sandstone Lithosome' within the central and southern Appalachians. Flexural isostatic uplift of part of the Taconic foredeep destroyed accommodation space and converted part of the foredeep from a sediment sink into a sediment exporter. Sediment export caused by tectonism (flexural isostatic uplift) complements sediment export through sediment bypassing, which is described from various shallow-marine and terrestrial foredeeps.

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APPENDICES

APPENDIX 1

Outcrop Measured Sections

All thickness measurements are in meters (m). Grain size of sand (Wentworth size scale) is abbreviated as follows: vf - very fine; f - fine; md - medium; cs - coarse; vcs - very coarse. Directional measurements are given in dip angle and dip direction (for example, 33°/217). The type of directional indicator is abbreviated: trough cross stratification (TX); planar cross stratification (PX), (current) ripple cross stratification (RX), tool mark (TM), flute cast (FC), prod mark (PM), parting lineation (PL), gutter cast (GC), symmetrical ripple crest (SRC), scour/channel axis (SC); see also Appendix 2. Acritarch samples taken within different measurement units are indicated, using abbreviations (for example, GPM-7 for outcrop locality and sample number); for more details on sample spots see Appendix 3.

outcrop locality: FAGG I

small outcrop along VA 603, north of the North Fork Roanoke River, near Fagg village; ca. 4 km SW of Ironto; Montgomery Co.

stratigraphy: "upper" Tuscarora Ss.; absent: Juniata Fm., "lower" Tuscarora Ss., Rose Hill Fm.;

unit thickness	cumulative thickness	
—	—	<u>Rocky Gap Ss. (?)</u> : acc. to Diecchio (1986) (not measured), Wallbridge Discontinuity at base;
1.55	1.55	<u>"upper" Tuscarora Ss.</u> : gravelly sandstone with dispersed conglomerate layers/lenses; sand: cs to vcs, also md; gravel: 1-1.5 cm, up to 2 cm; bedding: indistinct; base: sharp, scoured, reaching into subjacent Martinsburg Fm.; top: distinct-sharp, mineralization; intern: trough cross stratification (but hard to decipher);
—	—	<u>Martinsburg Fm.</u> : (not measured); FGG-1;

outcrop locality: FAGG II

small natural outcrop hidden in the woods along north bank of North Fork Roanoke River, SE of VA 603; ca. 2.9 km SW of Ironto; Montgomery Co.

stratigraphy: "upper" Tuscarora Ss.; absent: Juniata Fm., "lower" Tuscarora Ss., Rose Hill Fm.;

unit thickness	cumulative thickness
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—	—	Ridgeley Ss.(?): acc. to Diecchio (1986) (not measured), Wallbridge Discontinuity at base
		"upper" Tuscarora Ss.:
2.01	2.85	sandstone; sand: md/cs to vcs, some dispersed gravel (0.5 cm); intern: trough cross stratification
0.83	0.83	gravelly sandstone with dispersed conglomerate layers and lenses; sand: cs/vcs; gravel: up to 5.5 cm; intern: trough cross stratification (sets: 0.10 -0.14 m)
—	—	Martinsburg Fm.: (not measured); FGG-2

outcrop locality: CATAWBA MOUNTAIN I

natural outcrop along Appalachian Trail, ca. 310 m NE of VA 311, on ridge crest, ca. 2.15 km E of Catawba; Roanoke Co.;

stratigraphy: Rose Hill Fm., "upper" Tuscarora Sandstone; absent: "lower" Tuscarora Ss., Juniata Fm.;

unit thickness	cumulative thickness	
—	—	"Keefer Ss.": (not measured)
		Rose Hill Fm.:
10.80	33.17	(covered)
1.28	22.37	sandstone; maroon-red, hematitic; sand: f to f/md; some mudstone clasts; float: some current ripples (top), horizontal trace fossils (base)
9.55	21.09	(covered)
		"upper" Tuscarora Ss.:
1.32	11.54	sandstone; sand: md to md/f, some dispersed vcs sand and granules, rare pebbles; bedding: indistinct; intern: trough cross stratification; 080891-m37 (TX)
2.19	10.22	gravelly sandstone; sand: md/cs to cs/vcs, dispersed granules and some pebbles (max. 3 cm); intern: trough cross stratification; 080891-m36, -m35, -m34 (all TX)
0.35	8.03	gravelly sandstone; sand: md to cs, with dispersed granules; bedding: 0.10 m, 0.25 m; distinct tops and bases; intern: trough cross stratification, ripple cross stratification; 080891-m32 (TX)
3.52	7.68	gravelly sandstone; cs to cs/vcs, also some md, dispersed granules and pebbles (max. 3 cm), gravel sometimes in patches, or concentrated in troughs and on bed tops; bedding: indistinct; intern: trough cross stratification, mutually intersecting (sets: up to 0.25 m thick and 1.80 m wide), rare ripple cross stratification; 080891-m33, -m31, -m30, -m29, -m28, -m27, 042290-m1, -m2 (all TX)
0.70	4.16	(covered)
1.12	3.46	sandstone, hard, caramel-brown; sand: md/f; a few mudstone clasts; bedding: 0.85 m, 0.27 m, distinct tops and bases; intern: trough cross stratification, ripple cross stratification; 080891-m24, -m25, -m26, (all TX)
0.40	2.34	(covered)
1.94	1.94	sandstone, brownish white; md to md/f; with some mudstone clasts; bedding: 0.15 to 0.25 m, distinct to subtle bed tops and bases; intern: trough cross stratification (sets: 0.07 to 0.15 m thick, up to 1.3 m wide), planar cross stratification (sets: up to 0.50 m thick, but usually much thinner), some ripple cross stratification, ?reactivation surfaces; 042390-m5, -m1, 080891-m22 (all

TX), 042390--m4, -m3, -m2 (all PX); trace fossils: *Monocraterion*, *Rusophycus* (lowermost bed)

— — **Martinsburg Fm.:** (not measured)

outcrop locality: CATAWBA MOUNTAIN II

outcrop along forestry road, ca. 2 Km NE of VA 311, (forestry road enters VA 311 ca. 50 m N of Appalachian Trail/VA 311 intersection; forestry road is blocked off by a swing gate); Roanoke Co.;
stratigraphy: Rose Hill Fm., "upper" Tuscarora Ss.; absent: "lower" Tuscarora Ss., Juniata Fm.;

unit thickness	cumulative thickness	
		"upper" Tuscarora Ss.:
1.35	9.34	sandstone; sand: cs/md, some dispersed granules; bedding: indistinct; intern: trough cross stratification; top of the "upper" Tuscarora Ss. and the Rose Hill Fm. are not exposed
4.30	7.99	gravelly sandstone, grayish-white; sand: cs to cs/vcs, some md, dispersed granules and pebbles (max. 2.5 cm), in parts reaching up to 30% gravel; bedding: indistinct; intern: trough cross stratification (sets: 0.08 to 0.35 m thick); note: displaced block of this interval ca. 30 m to the left further along the forestry road (good for study of cross stratification and gravel dimensions); 042590-m3, -m1, -m4 (all TX)
0.75	3.69	gravelly sandstone to pebble conglomerate, white; sand: cs/vcs, dispersed granules and pebbles (max. 9 cm); in lower part laterally discontinuous clast-supported pebble conglomerate (0.15 to 0.40 m thick, well-rounded pebbles); pebble content decreases upward; bedding: indistinct, conglomerate base undulatory-erosive (scoured), top gradational into gravelly sandstone; intern: trough cross stratification, rare planar cross stratification, conglomerate appears massive to crudely planar cross-stratified; some olive-colored mudstone clasts within pebble conglomerate
2.94	2.94	sandstone, yellowish-white, weathering olive green; sand md, also md/f, well sorted; discontinuous olive mudstone/claystone seams (max. 0.01 m thick), abundant olive mudstone clasts; bedding: 0.25 to ca. 0.80 m, scours outlined by aligned mudstone clasts, bed tops and bases distinct, in parts erosive; intern: trough cross stratification (sets: 0.15 to 0.35 m thick, up to 1.50+ m wide, mutually intersecting sets), some planar-wedge cross stratification (set: 0 to 0.30 m thick), rare ripple cross stratification; 042490-m2, -m3 (all TX), 042490-m4, -m5 (all PX); trace fossils: <i>Rusophycus</i> , <i>Planolites</i> , <i>Arthropycus</i> , ?trilobite scratch marks

— — **Martinsburg Fm.:** (not measured)

outcrop locality: DRAPER MOUNTAIN

outcrop on both sides of VA 11, at small parking lot on crest of Draper Mtn. (Pulaski Wayside Picnic Area), ca. 3.2 km S of Pulaski Courthouse; Pulaski Co.;

stratigraphy: Rose Hill Fm., "upper" and "lower" Tuscarora Ss., Juniata Fm.; note: outcrop is overturned!

unit thickness	cumulative thickness
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— — **Rocky Gap Ss.:** (not measured)

Rose Hill Fm.:

2.00	41.49	(covered)
0.65	39.49	sandstone, iron coating; sand: md to md/f;
3.20	38.84	(covered)
1.20	35.64	siltstone/sandstone, maroon-red; sand: vf; completely bioturbated; DPM-5;
0.17	34.44	sandstone, maroon-red, hematitic; sand: f/vf
2.80	34.27	(covered)

"upper" Tuscarora Ss.:

2.40	31.37	sandstone, grayish-white, uppermost part stained maroon-red; sand: md/cs to cs; bedding: appears 0.25 to 0.60 m; intern: completely bioturbated ('pipe-rock'); trace fossils: <i>Skolithos</i>
2.91	29.07	sandstone, grayish-white, weathering orange-brown; sand: md/cs to cs; bedding: predominantly ≤ 0.20 m, max. 0.42 m, distinctive bed tops and bases; intern: completely bioturbated ('pipe-rock'), vertical burrows often outlined in orange-red; trace fossils: <i>Skolithos</i>
1.78	26.16	sandstone, brownish-white; sand: md to md/cs; bedding: 0.20 to 0.60 m, distinct bed tops and bases; intern: trough cross stratification, rare ripple cross stratification, some bioturbation (dense at bed tops); 080891-m21 (TX); trace fossils: <i>Skolithos</i>
0.43	24.38	(covered)
2.79	23.95	sandstone, brownish-white, hard, glassy; sand: md to md/cs, in parts cs/vcs laminae; bedding: 0.15 to 0.30 m, max. 0.60 m, distinct bed tops and bases; intern: trough cross stratification, rare bioturbation; 032890-m3, 080891-m20 (all TX); trace fossils: <i>Skolithos</i>
0.43	21.16	sandstone; sand: md to md/cs; intern: completely bioturbated ('pipe-rock'); trace fossil: <i>Skolithos</i>
1.03	20.73	(covered)
1.48	19.70	sandstone, in parts heavily weathered; sand: md to cs, some vcs grains; bedding: indistinct; intern: bioturbation (in parts 'Pipe-rock'); trace fossil: <i>Skolithos</i>
0.90	18.22	sandstone; sand: cs to cs/vcs; bedding: 0.45 m, distinct bed tops and bases; intern: trough cross stratification
2.37	17.32	sandstone, brownish-white; sand: md to md/cs, some cs laminae, rare dispersed granules; bedding: 0.25 to 0.40 m, distinct bed tops and bases; intern: trough cross stratification (sets: 0.08 to 0.40 m thick), some ripple cross stratification; 032890-m2, 080891-m19, -m18, -m17, 032790-m3 (all TX)
1.47	14.95	sandstone, whitish-gray; sand: cs/vcs; bedding: 0.10 m (in upper part) to 0.65 m (in lower part), distinct bed tops and bases; intern: trough cross stratification, planar cross stratification (set: 0.50 m thick), some ripple cross stratification, bioturbation (middle part of unit is completely bioturbated); 080891-m11, -m14 (all TX), 080891-m12, -m13 (all PX), 080891-m15 (RX); trace fossil: <i>Arthropycus</i>
0.35	13.48	gravelly sandstone; sand: cs to vcs, dispersed granules and pebbles; intern: trough cross stratification (sets: ≤ 0.10 m thick), or completely bioturbated; trace fossil: <i>Arthropycus</i> ; interbedded thin (≤ 3 cm) layers of dark gray siltstone, with marcasite; DPM-3, DPM-4
0.35	13.13	gravelly sandstone to pebble conglomerate; sand: md/cs, gravel: up to 2 cm; intern: trough cross stratification, massive (conglomerate), bioturbation; trace fossils: <i>Rusophycus</i> , ? <i>Phycodes</i> , <i>Arthropycus</i>

"lower" Tuscarora Ss.:

0.43	12.78	(covered; muddy siltstone after excavation; DPM-2)
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1.05	12.35	sandstone, brownish-white; Sand: md/cs to cs, few pebbles at base of lowermost bed; one mudstone seam; bedding: 0.09 to 0.28 m, distinct bed tops and bases; intern: trough cross stratification, some ripple cross stratification, some bioturbation; trace fossils: <i>Monocraterion</i>
1.00	11.30	sandstone, whitish-brown; sand: cs/md and vcs/cs, few dispersed granules and pebbles (max. 1.5 cm); some mudstone clast holes (3 to 5 cm long); bedding: 0.42 m, sandstone beds capped by ≤ 0.10 m thick mudstone beds; intern: trough cross stratification, rare bioturbation; 080891-m10, 032690-m4 (all TX); trace fossils: <i>Skolithos</i>
2.07	10.30	sandstone, whitish-brown, hard; some mudstone; sand: md/cs to cs/vcs, some dispersed pebbles and granules; bedding: 0.60 m for thick sandstone beds, 0.04 to 0.07 m for thinner sandstone beds interbedded with mudstone (some mudstone beds display cleavage), fining-upward motif; intern: trough cross stratification (sets: up to 0.15 m thick), planar cross stratification, ripple cross stratification, rare bioturbation; 080891-m8, -m7 (all TX), 032690-m3 (PX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
2.07	8.23	sandstone, white, hard; sand: md/cs to cs, some dispersed pebbles, in parts concentration of gravel (especially some bed tops and bases); bedding: 0.12 to 0.45 m, distinct bed tops and bases (outlined by gravel accumulations), unit is capped by 0.25 m of mudstone; intern: trough cross stratification (sets: 0.05 to 0.20+ m thick), planar cross stratification (sets: 0.07 m), rare bioturbation; 080891-m6 (PX), -m5 (TX); trace fossils: <i>Arthropycus</i>
1.82	6.16	sandstone, brownish-white, hard; sand: md/cs to cs/vcs, dispersed pebbles and granules, often at bed tops and bases; bedding: 0.40 and 1.00+ m, topped by 0.08 m thick mudstone bed, some mudstone clast holes at bed bases; intern: trough cross stratification, planar cross stratification (set: 0.30 m thick), ripple cross stratification; 080891-m4 (PX), -m3, -m2 (all TX)
1.91	4.34	(gravelly) sandstone and mudstone; sand: md/cs to cs/vcs, abundant dispersed granules and pebbles, often at bed tops (winnowed lags) and bed bases, in parts thin conglomeratic layers, mudstone clasts and mudstone clast holes (max. 5 cm in longest axis); bedding: 0.14 to 0.55 m (sandstone), 0.05 to 0.17 m (mudstone), distinct bed tops and bases, lithologies arranged in sandstone-mudstone fining-upward motifs (couplets); intern: trough cross stratification, some ripple cross stratification
0.60	2.43	(covered)
1.83	1.83	sandstone, pinkish-white, hard; sand: md/cs, with dispersed vcs grains, granules and pebbles (max. 1.7 cm), some mudstone clast holes; bedding: 0.18 to 0.51 m, a few thin mudstone interbeds; intern: trough cross stratification, planar cross stratification; 040590-m4 (TX), -m2 (PX)

(rest of "lower" Tuscarora Ss. and underlying Juniata Fm. covered or inaccessible for measurement)

outcrop locality: GAP MOUNTAIN

outcrop along VA 460, wind gap on crest of Gap Mtn., ca. 2 km SE of Newport, at Giles/Montgomery Co.-line;

stratigraphy: Rose Hill Fm., "upper" and "lower" Tuscarora Ss., Juniata Fm.;

unit thickness	cumulative thickness	
—	—	"Keefer Ss.": (not measured)

Rose Hill Fm.

- | | | |
|------|--------|--|
| 1.33 | 145.14 | sandstone, whitish-gray; abundant interbedded mudstone, light gray; sand: md, mudstone clasts; bedding: 0.01 to 0.04 m, distinct bed tops (interference ripple and symmetrical ripple formsets) and bed bases (load casts); intern: ripple cross stratification, wavy stratification, bioturbation; trace fossils: unspecified tracks & trails, <i>Planolites</i> , <i>Skolithos</i> , <i>Cruziana</i> (exact contact to "Keefer Ss. indistinct and uncertain) |
| 0.92 | 143.81 | sandstone, bluish light gray, hard; sand: f; soft sediment deformation (ball-and-pillow), bed base with large load casts reaching into subjacent mudstone) |
| 0.32 | 142.89 | shale, gray; GPM-20 |
| 1.38 | 142.57 | sandstone, maroon, hematitic, hard; sand: f to f/md, some cs/vcs, few dispersed granules, mudstone clasts; some marcasite; bedding: 0.10 to 0.20 m, distinct bed tops (some interference ripple formsets) and bed bases (some load casts), unit top 0.02 to 0.05 m beds with interbedded thin mudstone; intern: trough cross stratification, ripple cross stratification |
| 3.20 | 141.19 | (predominantly covered)
top 0.50 m interbedded f, hematitic sandstone beds (0.01 to 0.05 m, with load casts, bioturbated) and olive shale, (rest of the unit probably made up of the same material) |
| 2.41 | 137.99 | sandstone, maroon, hematitic, hard; sand:md/f to cs, few dispersed granules, mudstone clasts, scattered shell hash; bedding: 0.25 to 0.72, distinct bed tops (some winnowed cs lags) and bed bases; intern: high-angle cross stratification (most likely: trough-type) |
| 2.57 | 135.58 | sandstone, maroon, hematitic, hard; interbedded gray mudstone in the top 0.85 m; sand: f to f/md, mudstone clast layers, some shell hash; bedding: 0.20 to 0.50 (lower part) and 0.01 to 0.07 m (upper part of unit), distinct bed tops (some interference-ripple formsets) and bed bases (some load casts), unit is fining and thinning upward; intern: ripple cross stratification, trough cross stratification, bioturbation; 080991-m45 (TX); trace fossils: <i>Planolites</i> , <i>Skolithos</i> |
| 8.30 | 133.01 | sandstone, maroon, hematitic, hard; mudstone interbedded to varying degree (upper half of unit); sand: f to f/md, lowermost part with dispersed cs/vcs and granules, dispersed mudstone clasts and in layers (max. 5 cm long, up to 1 cm thick), shell hash; bedding: 0.05 to 0.20 m (lower part of unit), 0.02 to 0.12 m (upper part of unit), some lateral change in thickness, distinct bed tops (some interference ripple and symmetrical ripple formsets, ? hummocks) and bed bases (some gutter casts, load casts)lower 2/3 of unit displays clear fining and thinning upward trend, upper 1/3 displays a crude similar trend; intern: trough cross stratification (sets: up to 0.15 m thick, lower part of unit), abundant ripple cross stratification, micro-hummocky cross stratification (in upper part of unit), bioturbation; 060990-m3 (SRC), -m2 (GC), 080991-m43, -m44 (all TX); trace fossils: unspecified tracks & trails, ? <i>Skolithos</i> , <i>Planolites</i> |
| 2.45 | 124.71 | sandstone, maroon to steel-gray, hematitic, hard; interbedded olive shale/mudstone; sand: f to md, some dispersed cs and granules, some shell hash, mudstone chips; bedding: ≤ 0.02 m to 0.15 m, distinct bed tops (some undulosity: ? hummocks) and bed bases; intern: ripple cross stratification, trough cross stratification, ?wave-ripple cross stratification, bioturbation (up to 100%); trace fossils: unspecified tracks & trails, <i>Skolithos</i> , <i>Planolites</i> |
| 0.80 | 122.26 | shale, olive-gray; interspersed maroon, hematitic sandstone beds (md, with dispersed cs and granules, <i>Skolithos</i> , <i>Planolites</i>); GPM-17, GPM-16 |
| 2.33 | 121.46 | sandstone, maroon, hematitic, hard; sand: cs/md to f/md; bedding: hard to decipher, parts completely bioturbated; intern: bioturbation, relict ripple cross |

		stratification, trough cross stratification; trace fossils: <i>Skolithos</i> , <i>Planolites</i> ; this unit combined with succeeding upper unit displays a fining upward trend
8.72	119.13	sandstone, maroon with green reduction spots to greenish gray with maroon burrows, hematitic in the upper 2.50 m; sand: f to md; some interbedded siltstone and mudstone; bedding: dominated by bioturbation (up to 100%, relict: ≤ 0.08 to 0.25; intern: massive (homogenized by bioturbation), rare relict trough cross stratification and ripple cross stratification; trace fossils: <i>Skolithos</i> , <i>Planolites</i>
3.90	110.41	shale/mudstone, olive-gray; with interspersed light-gray sandstone beds; sand: f to f/md; bedding: 0.01 to 0.14 m, distinct bed tops and bases, some ball-and-pillow; intern: wave-ripple cross stratification, some planar stratification, bioturbation; GPM-15; trace fossils: <i>Planolites</i>
		"upper" Tuscarora Ss.:
0.72	106.51	sandstone, brown; sand: md/f; top is formed by a thin discontinuous granule conglomerate (ca. 0.06 m thick); intern: relict trough cross stratification, mostly bioturbated ('pipe-rock'); trace fossils: <i>Skolithos</i>
2.15	105.79	sandstone, dark gray, hard; sand: md/f to cs, some vcs grains; bedding: 0.15 to 0.25 m, max. 0.60 m, distinct bed tops and bases; intern: trough cross stratification, rare ripple cross stratification, abundant bioturbation; 080991-m42, -m41 (all TX); trace fossils: <i>Skolithos</i>
1.58	103.64	sandstone, dark gray, blackish; sand: md/f to md/cs; bedding: 0.10 to 0.25 m, bed tops and bases with abundant burrow protrusions; intern: completely bioturbated ('pipe-rock'); trace fossils: <i>Skolithos</i>
1.19	102.06	sandstone, dark gray to black, with white vertical streaks (related to burrows), hard; sand: md to cs; bedding: 0.06 to 0.14, bed tops and bases with abundant burrow protrusions, rare thin mudstone interbeds (≤ 0.01 m); intern: trough cross stratification, some ripple cross stratification, abundant bioturbation; 060790-m1 (TX); trace fossils: <i>Skolithos</i>
0.27	100.87	sandstone, dark gray with white vertical streaks; sand: f/md; intern: planar stratification, bioturbation; trace fossils: <i>Skolithos</i>
2.04	100.60	sandstone, light gray to grayish-white, hard, some tobacco-brown weathering; sand: md/f to md; bedding: 0.16 to 0.40 m, distinct bed tops and bases, with burrow protrusions; intern: relict trough cross stratification, abundant bioturbation; 080991-m40 (TX); trace fossils: <i>Skolithos</i>
0.71	98.56	sandstone, brownish-gray; sand: md/cs to cs; bedding: 0.24 and 0.47 m, distinct bed tops and bases; intern: trough cross stratification; 080991-m38, -m39 (all TX)
1.93	97.85	sandstone, grayish-white, hard; sand: md/f to md, rarely cs; bedding: 0.40 m, bed tops and bases not well defined; intern: trough cross stratification (sets: up to 0.15 m thick), rare bioturbation; trace fossils: <i>Skolithos</i>
0.29	95.92	sandstone, bluish-gray, hard; sand: f/md, silty in lower part; intern: planar stratification, a few dark/black laminae
0.81	95.63	sandstone, gray, glassy, hard; sand: md to md/f; bedding: 0.53 and 0.28 m; intern: trough cross stratification, rare bioturbation; 080991-m37 (TX); trace fossils: <i>Skolithos</i>
0.79	94.82	sandstone, gray, hard; sand: vcs/cs, some dispersed granules, md/f near top; intern: trough cross stratification; 080991-m36 (TX)
0.40	94.03	muddy siltstone to sandstone, gray to dark gray; sand: f to f/md; intern: planar stratification, splitting paper thin
4.50	93.63	sandstone, grayish-white, glassy, hard; sand: md to cs, a few dispersed granules; bedding: hard to decipher, some 0.30 to 0.40 m, but also thicker; intern: trough cross stratification, rare planar cross stratification, rare planar

- stratification, very rare bioturbation; 080991-m33, -m34, -m35, 060590-m3 (all TX), 061190-m1 (PX); trace fossils: ?*Skolithos*
- 1.03 89.13 gravelly sandstone, bluish-gray, some red coloration; sand: cs to vcs, some md, dispersed granules and pebbles (max. 2 cm); intern: trough cross stratification (sets: ≤ 0.15 m thick); 080991-m33, 060691-mx, 060590-m2 (all TX)
- 0.20 88.10 granule conglomerate, clast-supported to matrix-supported, with dispersed; grades upward into gravelly sandstone by addition of sandy matrix pebbles;

(the overlying was measured directly along VA 460, southbound lane; correlation to outcrop trace along ridge crest above VA 460 was accomplished using the base of the gravelly sandstone/base of "upper" Tuscarora Ss.)

"lower" Tuscarora Ss.:

- 1.40 87.90 sandstone, whitish-gray, some siltstone; sand: md to md/cs; abundant bioturbation, some relict stratification (trough cross stratification, ripple cross stratification); top of unit is weathered (unconformity acted as modern-day flow conduit); cut from above by "Tuscarora unconformity"; trace fossils: *Skolithos*
- 2.94 86.50 sandstone, brownish-white; interbedded olive gray mudstone (max. 0.24 m thick, usually ≤ 0.05 m); sand: md to md/cs, some dispersed coarser grains (incl. one pebble), mudstone clasts (max. 3 cm long, 1 cm thick); bedding: 0.05 to 0.30 m, distinct bed tops and bed bases; intern: trough cross stratification (sets: up to 0.15 m thick), ripple cross stratification, bioturbation; GPM-12, GPM-11; 052790-m1 (TX); trace fossils: unspecified tracks & trails, *Skolithos*, *Planolites*, *Cruziana*, *Rusophycus*
- 6.88 83.56 sandstone, orange-brownish white, hard; some/rare thin interbedded olive gray mudstone; sand: cs to md, mudstone clasts (max. 5 cm long, 1 cm thick, a few are maroon); bedding: 0.12 to 0.30 m (max. 0.70 m), rare discontinuous mudstone seams within sandstone beds, distinct bed tops and bases; intern: trough cross stratification (sets: up to 0.20 m thick), rare planar stratification, some ripple cross stratification, rare planar cross stratification (set: 0.13 m thick), some bioturbation; 052790-m2, 052690-m3, 052490-m3 (all TX), 052690-m1 (PX); trace fossils: *Skolithos*
- 3.71 76.68 sandstone, grayish-white, some pinkish orange brown; interbedded olive gray mudstone (≤ 0.05 m thick); sand: md/cs, some f and cs, mudstone clasts (gray or maroon, max. 2 cm long, 0.3 cm thick); bedding: distinct bed tops and bed bases, some thin discontinuous mudstone seams within sandstone beds (amalgamation); intern: trough cross stratification (sets: up to 0.20 m thick), some bioturbation; GPM-10; 052490-m2 (TX); trace fossils: some unspecified tracks & trails, *Rusophycus*, *Skolithos*, *Monocraterion*
- 0.15 72.97 claystone/mudstone, light gray; GPM-9
- 4.68 72.82 sandstone, pinkish grayish-white, rarely light maroon, hard, some interbedded olive gray to maroon mudstone; sand: md/f to md/cs, maroon mudstone clasts; bedding: 0.12 to 0.30 m, max. 0.55 m, mudstone interbeds ≤ 0.10 m, max. 0.21 m, distinct bed tops (rare symmetrical-ripple formsets) and bed bases (scouring); intern: trough cross stratification (sets: up to 0.17 m thick), rare planar cross stratification (set: 0.10 m thick), bioturbation (up to 100%); 052190-m3, 052390-m2 (all TX), -m1 (PX), 052190-m2 (SRC); trace fossils: unspecified tracks & trails, *Monocraterion*, *Skolithos*, *Rusophycus*,

Juniata Fm.:

- 1.91 68.14 sandstone, pinkish-brownish-gray, hard; some mudstone (top of unit); sand: md, maroon mudstone clasts, some dispersed cs quartz grains; bedding: 0.03 to 0.20 m (max. ca. 0.40 m), amalgamation, distinct bed tops and bases; intern:

		trough cross stratification, bioturbation; GPM-8; 092691-m9 (TX); trace fossils: <i>Rusophycus/Cruziana</i> , <i>Planolites</i>
2.56	66.23	mudstone, silty, maroon to siltstone; interbedded with sandstone, caramel white to greenish-gray; sand: f to md/f, maroon mudstone clasts; bedding: 0.03 to 0.13 m (max. 0.28 m), distinct bed tops (some interference-ripple formsets) and bases (some erosive); intern: ripple cross stratification, some trough cross stratification (sets: up to 0.06 m thick), some planar stratification, abundant bioturbation (up to 100%); GPM-7; 051990-m1 (PL), 092691-m8 (TX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i>
2.23	63.67	sandstone, pinkish-caramel to whitish-brown, hard; interbedded maroon silty mudstone; sand: f/md to md, maroon mudstone clasts; bedding: 0.13 to 0.45 m, distinct bed tops and bases (sharp-erosive, some scouring); intern: trough cross stratification (set: up to 0.10 m), rare planar cross stratification (set: 0.10 m), bioturbation; 051890-m2 (PX), 051890-m3 (SC-axis), 092691-m7 (TX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Skolithos</i>
22.23	61.44	mudstone to muddy siltstone, maroon; interbedded with sandstone, maroon, partly bleached greenish-gray, hard; sand: f to md/f, mudstone clasts; bedding: many 0.05 to 0.15 m (max. 0.42 m), distinct bed tops and bed bases; intern: trough cross stratification, ripple cross stratification, some planar cross stratification (sets: up to 0.20 m thick), rare planar stratification, abundant bioturbation (up to 100%); GPM-6, GPM-5, GPM-4; 092691-m6, 051690-m1 (all TX), 051590-m2 (PX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Skolithos</i> , <i>Planolites</i>
4.13	39.21	sandstone, maroon, hard; rare thin (0.05 to 0.13 m) maroon mudstone interbeds; sand: f/md to md/f, mudstone chips; bedding: hard to discern (0.30 to 0.50 m ?); intern: trough cross stratification (sets: up to 0.40 m thick), some ripple cross stratification, some bioturbation; 052690-m6 (TX); trace fossils: <i>Monocraterion</i> ; note: some cleavage
1.22	35.08	sandstone, maroon, hard; interbedded with maroon mudstone; sand: f to f/md, maroon mudstone clasts; bedding: 0.10 to 0.23 m (sandstone), 0.05 to 0.10 m (mudstone), distinct bed tops and bases; intern: trough cross stratification, ripple cross stratification, some bioturbation; trace fossils: <i>Monocraterion</i>
3.15	33.86	silty mudstone, maroon; interbedded with maroon sandstone; sand: f; bedding: 0.08 to 0.30 m, distinct bed tops and bases; intern: hummocky cross stratification; 092691-m5 (PL)
3.21	30.71	sandstone, maroon, some bleaching to greenish-gray; some silty mudstone, maroon (one 0.88 m interval 0.38 m from unit base); sand: f/md to md/f, abundant mudstone clasts; bedding: 0.30 to 0.52 m, distinct bed tops and bases; intern: trough cross stratification (sets: up to 0.30 m thick), some ripple cross stratification; GPM-3; 092691-m3, 051190-m2, -m3 (all TX)
3.32	27.50	sandstone, maroon, some bleaching, hard; some interbedded mudstone to silty mudstone, maroon; sand: f, maroon mudstone clasts, rare cs quartz grains; bedding: 0.08 to 0.30, amalgamation (discontinuous claystone seams within thicker bedsets), distinct bed tops (micro-hummocks) and bases (sharp-erosive, tool marks, some gutter casts); intern: hummocky cross stratification, wave-ripple cross stratification, bioturbation; GPM-2; trace fossils: unspecified tracks & trails, <i>Rusophycus</i> , <i>Cruziana</i>
1.74	24.18	sandstone, maroon, hard; sand: f to f/md, some mudstone clasts; bedding: difficult to discern, thinner beds 0.10 to 0.20 m, amalgamation; intern: hummocky cross stratification; 052690-m5
3.57	22.44	sandstone, maroon, in parts bleached greenish-gray, hard; maroon muddy siltstone (upper part of unit), sand: f/md, abundant mudstone clasts (up to 4 cm long), some dispersed cs quartz grains; bedding: $\leq$ 0.15 m (max. 0.90 m), distinct bed tops and bases; intern: trough cross stratification, ripple cross

		stratification, bioturbation (upper part of unit); GPM-1; 092691-m2, 052690-m5 (all TX)
1.50	18.87	(covered)
1.63	17.37	sandstone, maroon; sand: f, some mudstone clasts; bedding: hard to discern, amalgamation; intern: hummocky cross stratification
2.03	15.74	(covered)
1.02	13.71	sandstone, maroon, some maroon siltstone; sand: f to f/md, mudstone clasts, shell hash, few dispersed cs grains; bedding: 0.08 to 0.19 m, distinct bed tops and bases; intern: wave-ripple cross stratification, hummocky cross stratification, bioturbation
2.01	12.69	(covered)
1.68	10.68	sandstone, maroon; some claystone to silty mudstone, maroon; sand: f to f/md, abundant shell hash, some mudstone clasts; bedding: 0.08 to 0.12 m, distinct bed tops and bed bases; intern: wave-ripple cross stratification, micro-hummocky cross stratification, some current-ripple cross stratification (? combined flow), bioturbation; 092691-m1 (RX); body fossils: <i>Lingula</i>
9.00	9.00	(covered)

(overlying was measured along ridge crest above VA 460, southbound lane)

outcrop locality: COVE MOUNTAIN

outcrop along VA 603 and Interstate I-77 (northbound) at gap through Cove Mtn., ca. 5 km N of Wytheville; Wythe Co.;

stratigraphy: "lower" Tuscarora Ss., Juniata Fm.; absent: Rose Hill Fm., "upper" Tuscarora Ss.;

unit thickness	cumulative thickness	
—	—	<u>Oriskany Ss./Rocky Gap Ss.:</u> acc. to Hayes (1974) (not measured)
		<u>"lower" Tuscarora Ss.:</u>
		(note: CVE-11, CVE-12, CVE-13 sampled along VA 603 outcrop; locations were correlated down to I-77 outcrop)
3.74	96.56	sandstone, whitish/bluish-gray to dark gray (darker color just beneath unconformity at top of unit), some siltstone and mudstone; some rusty specks; sand: md to cs, some f/md, some granules, mudstone clasts; bedding: 0.04 to 0.08 m, and up to ca. 0.30 m, amalgamation to thicker bedsets (discontinuous/scoured-out mudstone seams), distinct bed tops and bed bases (erosional); intern: trough cross stratification (sets: ≤ 0.15 m thick), some planar cross stratification, ripple cross stratification, bioturbation (up to 100%); CVE-12, CVE-13; 020391-m1, 092691-m26, -m27, -m28 (all TX), -m29 (PX), -m30 (RX); trace fossils: unspecified tracks & trails, <i>Skolithos</i> , <i>Monocraterion</i>
0.17	92.82	siltstone, muddy
9.22	92.65	sandstone, grayish-white, hard; some interbedded thin mudstone, siltstone; some rusty specks; sand: md to cs/md, mudstone clasts, molds up to 9 cm long; bedding: 0.10 to 0.40, some thin discontinuous mudstone seams, beds amalgamated to thicker bedsets, distinct bed tops (some "large" ripple formsets) and bed bases (erosional, some scouring: relief max. 0.20 m); intern: trough cross stratification (sets: up to 0.17 m thick, mutually cross-cutting), ripple cross stratification, some planar cross stratification (sets: ≤ 0.15 m thick),

		some planar stratification, bioturbation (in some cases up to 100%), massive; CVE-11; 020191-m8, 020291-m3, -m13, 092991-m13, -m14, -m16, -m19, -m20, -m21, -m22, -m23, -m24 (all TX), -m15, -m17, -18 (PX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Skolithos</i> , <i>Rusophycus</i> , <i>Cruziana</i>
0.30	83.43	sandstone, greenish-brown, f/md, some cs grains, bioturbated
3.97	83.13	sandstone, light-gray, greenish, some mudstone interbeds; rusty specks; sand: md to cs, dispersed vcs grains, some mudstone clasts; bedding: 0.08 to 0.25, amalgamation, distinct bed tops (hummocks) and bed bases (sharp-erosional, scouring: relief up to 0.15 m); intern: trough cross stratification (sets: $\leq$ 0.17 m thick), some planar cross stratification (sets: $\leq$ 0.07 m thick), ripple cross stratification, some planar stratification, bioturbation (up to 80%); 01191-m3 (SC-axis), 092991-m8, -m10, -m11, -m12, 020191m3 (all TX), -m15 (PX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Skolithos</i> , <i>Rusophycus</i>
2.44	79.16	sandstone md/f, some cs), grayish-green, crumbly, bioturbated; some distinct beds (0.03 to 0.15 m, ripple cross stratification, trough cross stratification, 011991-m2 (TX)), some granuly winnowed top lag; <i>Monocraterion</i> , <i>Skolithos</i> , recess (very easy to correlate from I-77 to VA 603)
5.18	76.72	sandstone, bluish-gray to greenish-gray, hard, some interbedded thin discontinuous mudstone seams; rusty specks; sand: md/cs to vcs/cs, dispersed granules, some pebbles, abundant mudstone clasts; bedding: 0.7 to 0.30 m, amalgamation, distinct bed tops (some cs winnowed lags) and bed bases (sharp-erosive); intern: trough cross stratification (sets: $\leq$ 0.15 m thick), some planar cross stratification (sets: up to 0.10 m thick), ripple cross stratification, bioturbation; 032091-m3, -m4, 092991-m7 (all TX), -m2, -m1, (all PX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
0.15	71.54	mudstone, gray, bioturbation
3.13	71.39	sandstone, bluish-gray, hard, some thin discontinuous mudstone seams; rusty specks; sand: md to cs/vcs, granules, mudstone clasts; bedding: 0.10 to 0.30 m, amalgamation, distinct bed tops (with cs winnowed lags, some ripple formsets) and bed bases (sharp-erosive, scouring); intern: trough cross stratification (sets: $\leq$ 0.15 m thick), some ripple cross stratification, bioturbation; 032791-m3, -m7, -m4, -5, -m6 (all TX); trace fossils: <i>Monocraterion</i>
1.05	68.26	sandstone, greenish-gray, hard, some thin discontinuous mudstone seams; rusty specks; sand: md to cs/vcs (near base), mudstone clasts; bedding: wedge-shaped, inclined, thinning to left, basal scouring; intern: trough cross stratification, some ripple cross stratification, bioturbation; 032790-m1, -m2 (all TX); trace fossils: <i>Monocraterion</i>
3.17	67.21	sandstone, greenish-gray to bluish-gray, some thin discontinuous mudstone seams; rusty specks; sand: md to cs, some granules, mudstone clasts (up to 3 cm long); bedding: 0.11 to 0.32 m (max. 0.62 m), amalgamation, distinct bed tops (broad undulosity: larger bedform troughs, some cs winnowed lags) and bed bases (sharp-erosive, scouring); intern: trough cross stratification (sets: $\leq$ 0.15 m thick), ripple cross stratification, bioturbation; 092991-m4 (TX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i> , <i>Arthropycus</i> , <i>Rusophycus</i>
0.14	65.97	sandstone, grayish-green, md, mostly bioturbated, some relict ripple cross stratification, <i>Skolithos</i> , recess in outcrop
9.11	63.90	sandstone, greenish-gray to bluish-gray; rare interbedded gray mudstone (important for deciphering internal architecture); rusty specks; sand: md to md/cs, some f, mudstone clasts; bedding: hard to decipher, 0.18 to ca. 0.80 m, discontinuous mudstone seams, amalgamation of beds, distinct bed tops (some current-ripple formsets) and bed bases (sharp-erosive, scouring: relief up to 0.12 m), wide undulosity topping some thicker bedset reflect not broad mudstone-filled scours but abandoned larger bedforms with preserved troughs;

		intern: trough cross stratification (sets: ≤ 0.18 m thick), ripple cross stratification, some planar stratification, bioturbation, some massive (bioturbated to 100%); 032891-m1, -m10 (all RX), -m2, -m3, -m4, 092991-m2, -m3 (all TX); trace fossils: <i>Arthropycus</i> , <i>Monocraterion</i> , <i>Skolithos</i>
0.17	54.79	silty mudstone, greenish-gray, bioturbation
2.62	54.62	sandstone, whitish-gray to grayish-green, discontinuous thin greenish-gray silty mudstone interbeds; rusty specks; sand: md to cs/md, mudstone clasts; bedding: 0.12 to 0.35 m, amalgamation, mostly distinct bed tops and bed bases sharp, some scouring); intern: trough cross stratification (sets: ≤ 0.15 m thick), some ripple cross stratification, bioturbation; 040691-m1, -m2, -m3, -m4 (TX); trace fossils: unspecified tracks & trails, <i>Skolithos</i>
1.52	52.00	sandstone, whitish-gray; interbedded with greenish-gray mudstone and siltstone (some maroon patches); abundant rusty specks; sand: f/md to md, green mudstone clasts; bedding: prominent shallow scour with inclined heterolithic fill, 0.03 to 0.25 m, pronounced lateral change in thickness, distinct bed tops (some ripple formsets) and bed bases (sharp-erosive, scouring: relief ≤ 0.04 m); intern: trough cross stratification, ripple cross stratification, hummocky cross stratification (one bed: highest occurrence of HCS within this outcrop section), bioturbation; 041191-m1, -m2 (all RX), 040691-m6 (TX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
0.55	50.48	sandstone, light-gray; f/md to md; abundant rusty specks; trough cross stratification (sets: ≤ 0.10 m thick), ripple cross stratification; upper bed with distinctive scoured base (relief: ca. 0.20 m); 092991 (SC-axis), 041191-m4 (TX); bioturbation

Juniata Fm.:

(the overlying was measured along I-77 northbound, last maroon silty mudstone interbed and some other key beds in units below were used for correlation from VA 603 to I-77)

(placement of Juniata/"lower" Tuscarora lithostratigraphic boundary at the last laterally continuous maroon silty mudstone bed; you should feel free to choose your own boundary !)

6.91	49.93	sandstone, greenish-gray to brownish, some relict maroon patches; some interbedded maroon or green mudstone; abundant rusty specks; sand: f to md; bedding: large interval completely bioturbated, 0.02 to 0.20 m (some up to 0.40 m in upper part of unit), some distinct bed tops (some current-ripple formsets) and bed bases (sharp-erosive); intern: trough cross stratification, ripple cross stratification, abundant bioturbation, massive; CVE-7, CVE-8; 040591-m3, -m4, 122190-m1 (all TX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
1.93	43.02	sandstone, maroon, partly bleached greenish-gray; interbedded silty mudstone; sand: md/f; bedding: prominent wide scour (relief: ca. 1.50 m) filled with heterolithic sediment, 0.04 to 0.15 m; intern: ripple cross stratification, trough cross stratification, planar stratification, abundant bioturbation, massive (top of unit, bioturbated to 100%); 040591-m1 (RX), -m2, 092891-m12 (all TX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Skolithos</i>
7.17	41.09	sandstone, maroon, some bleaching to greenish-gray; interbedded muddy siltstone and mudstone; sand: f/vf to md/f, few maroon mudstone clasts; bedding: mostly indistinct due to bioturbation (large intervals completely bioturbated), relict ≤ 0.10 m beds (some lateral thinning), some ripple formsets, abundant (non-pedogenic) slickensides in upper part of unit; intern: massive, bioturbation, relict ripple cross stratification, some relict trough

		cross stratification, rare planar stratification; CVE-6; trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
4.70	33.92	sandstone, greenish-gray, some maroon, hard; interbedded with some maroon mudstone to muddy siltstone; rusty specks; sand: md, some f, rare cs/vcs/granule grains, abundant mudstone clasts (dispersed or as layers); bedding: ≤ 0.50 m, discontinuous mudstone seams, amalgamation of beds, distinct bed tops (hummocks) and bed bases (sharp-erosional, scouring: relief ≤ 0.20 m, some load casts); intern: trough cross stratification (sets: ≤ 0.17 m thick), planar cross stratification (sets: ≤ 0.40 m thick), ripple cross stratification, bioturbation; CVE-5; 092891-m9, -m10, 121890-m4 (all TX), 121890-m5, 121990-m1, -m2, -m3, -m4 (all PX); trace fossils: <i>Monocraterion</i> , <i>Arenicolites</i> , <i>Skolithos</i>
4.23	29.22	sandstone, maroon, bleached to grayish-green; interbedded with maroon muddy siltstone to silty mudstone; some rusty specks; sand: f to md/f, mudstone clasts; bedding: 0.04 to 0.15 m (max. 0.25 m), mostly distinct bed tops (some current-ripple formsets) and bed bases (sharp-erosional, scouring), top of unit with scour (relief: ca. 0.70 m); intern: trough cross stratification (sets up to 0.07 m thick, up to 0.20 m in scour), ripple cross stratification, abundant bioturbation (up to 100%), massive; 092891-m7 (SC-axis), -m8, 121890-m2 (all TX), 121890-m3 (RX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Skolithos</i>
7.56	24.99	sandstone, maroon to grayish-yellow, hard; interbedded with maroon muddy siltstone to silty mudstone; some rusty specks; sand: f to md, some coarse, abundant maroon or greenish-gray mudstone clasts (up to 4 cm long), some granules, few pebbles, rare fossils (granule/pebble/brachiopod conglomerate); bedding: ≤ 0.50 m, intervals with ≤ 0.10 m beds, rare thin discontinuous conglomerate layer (0 to 0.03 m), amalgamation of beds to thicker bedsets, distinct bed tops (some ripple formsets, some "large" ripples) and bed bases (sharp-erosive, prominent scouring: relief: 0.10 to 0.60 m); intern: trough cross stratification (sets: predom. ≤ 0.15 m thick, but up to 0.50 m, mutually intersecting), ripple cross stratification, some planar stratification, bioturbation (up to 100%), massive; CVE-3, CVE-4; 121490-m1, -m2, -m5, 092891-m2, -m3, -m5 (all TX), 121690-m2, 092791-m4, 092891-m1 (RX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Skolithos</i> ; body fossils: <i>Lingula</i> , other (ribbed) brachiopods
6.80	17.43	sandstone, maroon, interbedded with maroon siltstone; sand: f/vf to f/md, abundant maroon mudstone clasts (dispersed or as conglomerate layers); bedding: predom. difficult to discern, up to 0.40 m, bioturbated (up to 100%) intervals, bed bases (some erosional) and tops not well defined; intern: normal grading, ripple cross stratification, massive, some hummocky cross stratification, some planar stratification, some trough cross stratification; trace fossils: unspecified tracks & trails, <i>Skolithos</i>
1.57	10.63	sandstone, maroon; interbedded with maroon muddy siltstone; sand: f to f/md, maroon mudstone clasts; bedding: 0.02 to 0.20 m, max. 0.40 m; intern: hummocky cross stratification, micro-hummocky cross stratification, ripple cross stratification, some soft-sediment deformation (ball-and-pillow), bioturbation; 100290-m1 (RX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
1.18	9.06	sandstone, maroon, f to f/md, scouring (relief ca. 0.30 m), wave-ripple cross stratification, micro-hummocky cross stratification, current-ripple cross stratification, rare trough cross stratification (in scour, sets: ≤ 0.08 m thick), abundant bioturbation (unspecified tracks & trails, <i>Monocraterion</i>); 093090-m2 (PL), -m1 (RX)
7.88	7.88	sandstone, maroon, partly bleached to greenish-gray; interbedded with maroon muddy siltstone to mudstone; sand: vf/f to f/md, abundant maroon mudstone clasts; bedding: predom. ≤ 0.12 m, max. 0.37 m pronounced lateral changes in

thickness, distinct bed tops (some micro-hummocks, some interference-ripple and symmetrical-ripple formsets) and bed bases (sharp-erosive, some gutter casts, some load casts); intern: normal grading, hummocky cross stratification, micro-hummocky cross stratification, wave-ripple cross stratification, bioturbation, massive (complete bioturbation); CVE-1, CVE-2; 092791-m1 (GC), 092990-m2 (SRC); trace fossils: unspecified tracks & trails, *Skolithos*, *Monocraterion*

(overlying was measured along VA 603)

— — **Martinsburg Fm.:** (not measured)

outcrop locality: McCoy

outcrop along N&W railway tracks, on east bank of New River and to the E of VA 625, ca. 2.9 km NNW of McCoy; Montgomery Co,

stratigraphy: Rose Hill Fm., "upper" and "lower" Tuscarora Ss., Juniata Fm.;

unit thickness	cumulative thickness	
—	—	"Keefer Ss.": (not measured, covered)
		Rose Hill Fm.:
4.25	37.89	(covered; contact to "Keefer Ss. uncertain)
1.84	33.64	sandstone, hematitic, hard; sand: f to md/cs; mudstone clasts very abundant, forming mudstone-clast conglomerate layers; rare mudstone interbeds; bedding: 0.05 to 0.13 m, distinct bed tops and bases, rare interference-ripple formsets (bed tops), rare gutter casts and load casts (bed bases); intern: ripple cross stratification, trough cross stratification, bioturbation; 050391-m2, 080991-m30, -m31, -m32 (all TX), 050391-m1 (GC); 080991-m29 (RX)
3.66	31.80	sandstone, grayish-maroon, hematitic; sand: cs/md, some dispersed vcs, few granules, one bed f/vf; abundant mudstone clasts (max. 2 cm long, 0.5 cm thick), often in layers, some mudstone seams; bedding: ≤ 0.10 m, in lower part 0.15 to 0.35 m, bed tops and bases hard to see; some load casts and some interference-ripple formsets (associated with mudstone seams), rare wrinkle marks; intern: ripple cross stratification, trough cross stratification, planar stratification (f/vf-grained bed), bioturbation; 080991-m28 (TX)
1.84	28.14	sandstone, greenish gray to maroon, hematitic, hard; olive green mudstone dominates in the upper part of the unit; sand: md/cs to cs, some f, rare granules, mudstone clasts; bedding: ≤ 0.10 m beds encased in mudstone (upper part of the unit), ≤ 0.20 m (lower part of the unit, with discontinuous mudstone seams); distinct bed tops (some interference-ripple and symmetrical-ripple formsets, some micro-hummocks) and bed bases (some tool marks); unit fines upward from sand-dominated to mudstone-dominated; intern: trough cross stratification (lower part of unit), micro-hummocky cross stratification and planar stratification (dominating in the upper 2/3 of unit, bioturbation, escape burrows; 080991-m27 (TM), 052991-m2 (SRC); trace fossils: unspecified tracks & trails (incl. ?gastropod tracks), <i>Monocraterion</i> , <i>Rusophycus</i>
2.94	26.30	sandstone, hematitic, hard; olive mudstone interbeds (upper part of unit); sand: f to f/md, some dispersed coarser grains, abundant mudstone clasts (often in layers), some fossil hash; bedding: 0.30 m to 0.02 m (thinning upwards trend), distinct bed tops (some interference-ripple formsets) and bed bases (some load

		casts, rare ball-and-pillow); units fines upward (more mud); intern: ripple cross stratification, trough cross stratification, planar stratification, micro-hummocky cross stratification, bioturbation; trace fossils: unspecified tracks & trails, <i>Rusophycus</i> , <i>Skolithos</i> , <i>Monocraterion</i> , <i>Planolites</i>
1.68	23.36	(covered)
2.40	21.68	mudstone, brownish-olive; interbedded sandstone, maroon, hard; sand: f to md, some dispersed cs grains, mudstone clasts; bedding: ≤ 0.04 m, one bed 0.15 m, distinct bed tops (broadly undulatory: micro-hummocks) and bed bases (sharp-erosive, some load casts); intern: ripple cross stratification, planar stratification, micro-hummocky cross stratification, rare trough cross stratification, bioturbation
1.50	19.28	(covered)
10.31	17.18	sandstone, maroon, hematitic, hard; sand: f/md to cs, some dispersed cs/vcs grains; rare mudstone interbeds; bedding: large parts completely homogenized by bioturbation, 0.05 to 0.25 m; intern: relict ripple cross stratification, trough cross stratification (sets: up to 0.07 m thick), abundant bioturbation; 080991-m26 (TX); trace fossils: <i>Skolithos</i>
0.82	7.47	sandstone, gray, hard; abundant mudstone; sand: f, rare md/cs; bedding: 0.02 to 0.16 m, distinct bed tops (some interference-ripple formsets, micro-hummocks) and bed bases (some gutter casts, load casts, tool marks), lateral change in thickness; intern: micro-hummocky cross stratification, wave-ripple cross stratification, planar stratification, bioturbation; 040491-m4 (PM), -m3 (SRC), -m1 (TM), 080991-m22, -m23, -m24 (all TM), -m25 (PL); trace fossils: unspecified tracks & trails, <i>Skolithos</i>
1.77	6.65	mudstone, olive, bioturbated to varying degree; few sandstone interbeds, sand: f, rare cs with few granules, gray; bedding: distinct, ≤ 0.02 m, interference-ripple formsets and micro-hummocks; intern: ripple cross stratification, bioturbation
0.95	4.88	sandstone, greenish-gray; olive mudstone interbeds; sand: f; bedding: wavy appearance, 0.02 to 0.10 m, distinct bed tops (some interference-ripple formsets, some winnowed lags) and bases (some load casts); intern: wave-ripple cross stratification, micro-hummocky cross stratification, bioturbation; 080991-m20, -m21 (TM); trace fossils: unspecified tracks & trails (incl. ?gastropod tracks), <i>Planolites</i> , <i>Skolithos</i>
0.32	3.93	sandstone, gray; sand: f; intern: soft-sediment deformation (convolute lamination)
3.61	3.61	sandstone, brownish-gray; interbedded with mudstone, olive; sand: f, some md, rare cs/vcs, mudstone clasts, rare phosphatized pebbles (max. 1.5 cm); bedding: many ≤ 0.02 m, 0.05 to 0.12 m, lateral thickness changes, mudstone beds up to 0.55 m; distinct bed tops (micro-hummocks, interference-ripple formsets) and bed bases (some load casts), some distinctive ball-and-pillow; intern: micro-hummocky cross stratification, planar stratification, massive (coarser beds), bioturbation; MCY-2; 080991-m15, -m16, -m17, -m18, -m19 (all TM), 032391-m12 (GC); trace fossils: unspecified tracks & trails, <i>Skolithos</i> , <i>Monocraterion</i> , <i>Planolites</i>

"upper" Tuscarora Ss.:

ca. 14.00 unit is covered with black soot from railroad trains; sandy conglomerate at base; in parts strongly bioturbated; trace fossils: *Skolithos*, 'strange' vertical and oblique burrows at top of unit (in contact with Rose Hill Fm.)

"lower" Tuscarora Ss.: (not measured in detail, partly covered)

—	—	sandstone; bedding: 0.20-0.40 m, near top 0.50-0.70 m; some mudstone; intern: trough cross stratification, bioturbation; MCY-1; 032391-m5, -m6, -m7, -m8, -m9, -m10, -m11 (all TX); trace fossils: <i>Rusophycus</i>
—	—	Juniata Fm.: (not measured, covered)
—	—	some maroon-red sandstone; high-angle cross stratification; 032391-m4, -m3, -m2 (all TX), -m1 (PX)

outcrop locality: CASCADES

natural outcrop along Cascades Trail, at Hanging Rock, ca. 2.4 km NE of Cascades Recreation Area Parking Lot, ca. 6 km NE of Pembroke; Giles Co.;

stratigraphy: Rose Hill Fm. "upper" and "lower" Tuscarora Ss., Juniata Fm. ?;

unit thickness	cumulative thickness	
—	—	Rose Hill Fm.: (not measured, covered)
		"upper" Tuscarora Ss.:
		(top covered, covered interval unknown)
3.86	13.80	sandstone, brownish-light gray, hard; sand: f to f/md, some vf; bedding: 0.08 to 0.20 m, max. 0.40 m, distinct bed bases and tops; intern: trough cross stratification (sets: up to 0.10 m), some ripple cross stratification, rare planar-wavy stratification, some bioturbation; 080991-m14 (TX); trace fossils: <i>Arthropycus</i> , <i>Skolithos</i> , some unspecified horizontal tracks & trails
0.35	9.94	sandstone, brownish-gray; sand: f/md; soft-sediment deformation (convolute lamination involving the whole bed, no downward protrusions)
0.50	9.59	sandstone, brownish-gray to grayish-black, some black siltstone; sand: md/f; bedding: 0.03 to 0.10 m; intern: ripple cross stratification (sand), abundant bioturbation; trace fossils: <i>Arthropycus</i>
1.59	9.09	sandstone, grayish-white, glassy, hard, some orange streaks (?Fe-staining); sand: f to f/vf, some md; bedding: hard to decipher, some beds 0.17 to 0.30 m; intern: trough cross stratification, some ripple cross stratification, rare vertical burrows; few weathered-out mudstone clasts (now holes of 2 cm diameter)
2.52	7.50	sandstone, white, glassy, hard; sand: cs/vcs to f/md and f, some dispersed granules; one thin (0.05 m) granule-pebble layer; bedding: hard to decipher, some beds 0.12 to 0.43 m; intern: trough cross stratification
0.78	4.98	gravelly sandstone; sand: cs to vcs, with dispersed granules and some pebbles; bedding: 0.20 to 0.30 m; intern: trough cross stratification; 080991-m13 (TX)
0.22	4.20	sandstone, grayish-white; sand: vf/f; intern: planar stratification, bioturbation; trace fossil: <i>Arthropycus</i>
1.35	3.98	gravelly sandstone, white, hard; sand: vcs to cs, dispersed granules and pebbles (max. 1 cm), in parts conglomeratic pockets; some greenish mudstone clasts; bedding: 0.11 to 0.35 m; intern trough cross stratification (sets: 0.10 to 0.18 m thick), some ripple cross stratification, bioturbation; 080991-m12, -m11, -m10, -m9, -m8 (all TX); trace fossil: <i>Arthropycus</i>
0.13	2.63	pebble conglomerate, clast-supported; sand: cs/vcs, gravel: max. 6 cm observed longest axis; conglomerate bed fines upward into gravelly sandstone; some holes originating from weathered-out mudstone clasts; base: undulatory-erosive; intern: trough cross stratification (in upper sandy portion), bioturbation; 080991-m7 (TX); trace fossil: <i>Arthropycus</i> ; this bed forms the base of the prominent overhang within the outcrop

		"lower" Tuscarora Ss.:
0.58	2.50	sandstone, gray, with reddish stain, glassy, hard; sand: f; bedding: 0.07 to 0.33 m, distinct bed tops and bases; intern: trough cross stratification (sets: 0.05 to 0.11 m, max. 0.20 m thick), planar cross stratification (set: 0.10 m thick), ripple cross stratification, bioturbation; 080991-m6 (PX), -m5 (TX); trace fossils: <i>Rusophycus</i> , <i>Arthropycus</i> , unspecified thin horizontal tracks & trails (? <i>Planolites</i>)
1.26	1.92	sandstone, grayish, reddish stain, hard; sand: f/md to f; some siltstone; bedding: 0.03 to 0.15 m, distinct bed tops and bases, preserved ripple formsets (spacing: 0.15 m); intern: trough cross stratification (sets: $\leq$ 0.07 m), ripple cross stratification, rare planar stratification, bioturbation; 080991-m4 (TX); trace fossils: <i>Rusophycus</i> , <i>Cruziana</i> , unspecified vertical burrows (? <i>Skolithos</i>) and horizontal tracks & trails
0.66	0.66	sandstone; sand: md/cs, some mudstone-clast holes; bedding: 0.18 to 0.30 m, distinct bed tops and bases; preserved 3D-dune formsets (height: ca. 0.07 m, spacing: ca. 0.60 m); intern: trough cross stratification (sets: 0.12 m thick); 053191-m1, 0.80991-m1 (all TX), -m2, -m3 (all RX) (rest of "lower" Tuscarora Ss. and all of Juniata Fm. not exposed)

outcrop locality: SOUTH GAP

outcrops along Interstate I-77 (northbound) and VA 52, at gap through Wolf Creek Mtn./Rich Mtn. (Rocky Gap), ca. 1.5 km S of Rocky Gap (village); Bland Co.;

stratigraphy: Rose Hill Fm., "upper" and "lower" Tuscarora Ss., Juniata Fm.;

unit thickness	cumulative thickness	
—	—	"Keefer Ss.": (not measured)
		Rose Hill Fm.
1.05	194.80	claystone, greenish-brown; interbedded sandstone, brown, mineralization; sand: cs/md, some conglomeratic; massive, crinoid ossicles, brachiopod fragments; Fe-oxide weathering crusts; unconformably overlain by "Keefer Ss."
2.10	193.75	shale, olive gray; interbedded with sandstone, gray, hard; sand: f to md, some md/cs, some mudstone clasts; bedding: $\leq$ 0.4 m (max. 0.14 m), lateral changes in thickness, overall wavy appearance, distinct bed tops (some interference-ripple formsets, micro-hummocks) and bed bases (load casts), top bed with coarser winnowed lag (incl. phosphate granules); intern: wave-ripple cross stratification, some current-ripple cross stratification, planar/wavy stratification, bioturbation; SGP-14; 060191-m1 (RX); trace fossils: unspecified tracks & trails, <i>Planolites</i> , ? <i>Rusophycus</i> , <i>Skolithos</i>
1.00	191.65	sandstone, maroon, hematitic, tobacco-brown (upper 1/5 of unit), hard; sand: md to cs (lower 4/5 of unit), f (upper 1/5), fossil hash, mudstone clasts; some interference-ripple formsets; intern: trough cross stratification (sets: up to 0.12 m thick, hematitic lower 4/5), hummocky cross stratification (non-hematitic upper 1/5, changes thickness laterally), bioturbation; 060191-m2, -m3 (all TX); trace fossils: unspecified tracks & trails, <i>Skolithos</i>
3.85	190.65	sandstone, greenish-gray, hard, middle part maroon, hematitic; interbedded olive gray mudstone/shale (max. 0.09 m); sand: f/md, dispersed cs/vcs, granules, shell hash, abundant mudstone clasts; bedding: overall wavy appearance, $\leq$ 0.10 m, lateral amalgamation to thicker bedsets, distinct bed tops (?interference-ripple formsets, wrinkle marks) and bed bases (some load casts, some scouring: relief ca. 0.25 m); intern: wave-ripple cross stratification,

- trough cross stratification, some current-ripple cross stratification, bioturbation; SGP-13; 060191-m18, -m19 (all RX); trace fossils: unspecified tracks & trails, *Skolithos*, *Planolites*, ?*Rusophycus*; body fossils: brachiopods
- 4.42** 186.80 sandstone, maroon, hematitic, hard; rare interbedded olive mudstone; sand: md/f to md,cs, dispersed vcs, granules, abundant mudstone clasts; bedding: 0.08 to 0.20 m (max. 0.30 m), distinct bed tops (some coarse winnowed lags, rare current-ripple and symmetrical-ripple formset) and bases; intern: trough cross stratification (sets up to 0.17 m thick), some ripple cross stratification; 060191-m16, 121090-m3 (all RX), -m2, 060191-m14, -m15 (all TX), 060191-m17 (SRC); trace fossils: unspecified tracks & trails, *Monocraterion*, *Skolithos*, *Planolites*
- 2.63** 182.38 sandstone, maroon, hematitic; sand: cs, some md and vcs; distinct unit base and top (ripple formsets); intern: planar cross stratification (sets: up to 0.80 m thick, foreset laminae up to 0.01 m thick), some ripple cross stratification; 060191-m10, -m10
- 1.25** 179.75 sandstone, maroon, hematitic, hard; thin (≤ 0.03 m) mudstone interbeds; sand: md to cs, dispersed vcs, granules, abundant mudstone clasts, some fossil hash; bedding: overall wavy appearance, 0.05 to 0.15 m, lateral amalgamation, distinct bed tops (some winnowed lags, some symmetrical-ripple formsets) and bed bases (some tool marks); intern: trough cross stratification, ripple cross stratification; 081191-m50, -m51, -m49 (all TX), 121090-m1 (SRC)
- (the overlying was measured on ledge above VA 52; correlation up/down the outcrop using contact between unit described above and below)
- 0.50** 178.50 sandstone, gray, hard; sand: f to f/md, fossil hash in lower parts of beds, mudstone clasts, some dispersed cs; bedding: 0.18 and 0.25 m, thin gray mudstone interbeds (max. 0.10 m), lateral amalgamation, distinct bed tops (interference-ripple formsets, some wrinkle marks) and bed bases (scouring, relief ca. 0.10 m); intern: hummocky cross stratification
- 18.97** 178.00 shale/mudstone, olive gray; interbedded with sandstone, brownish-gray, rarely hematitic and maroon; sand: vf to f/vf, some coarser material (phosphate granules and rare pebbles, shell hash, mudstone clasts, cs/vcs quartz grains), normal grading; bedding: typically 0.01 to 0.17 m, some up to 0.40 m, partial amalgamation, lateral changes in thickness, abrupt termination of beds, distinct bed tops (hummocks, micro-hummocks, symmetrical-ripple and interference-ripple formsets; rare wrinkle marks) and bed bases (scouring, gutter casts, load casts, rare ball-and-pillow; tool marks, pod casts); intern: hummocky cross stratification, wave-ripple cross stratification, planar stratification, bioturbation; SGP-12, SGP-11, SGP-10, SGP-9, SGP-8, SGP-7, SGP-6; 081191-m43, -m44, -m45, -46, -m47, -m48, -m29x, -m30, -m33, -m36, -m37, -m38, -m39, -m40, -m41, 080990-m1 (all TM), 081290-m1, 080990-m10, -m7, -m6, -m5, -m3, (all SRC), 081090-m3, 080990-m9, -m4, 081191-m42, -m34, -m35, -m32, -m31 (all GC), 080990-m11 (PL), 080990-m8, -m2 (RX); trace fossils: unspecified tracks & trails, *Planolites*, *Skolithos*
- 3.22** 159.03 sandstone, greenish-gray, f/md; completely bioturbated; top 0.05 m: winnowed lag (phosphate granules and pebbles, cs quartz grains)
- 4.12** 155.81 sandstone, reddish-gray, hard; some thin gray olive mudstone interbeds; sand: f to f/md, some vf and md/cs, some dispersed phosphate granules and rare pebbles, mudstone clasts; bedding: mostly ≤ 0.07 m, amalgamation to 0.20 m bedsets, distinct bed tops (some winnowed lags, symmetrical-ripple and interference-ripple formsets, micro-hummocks) and bed bases (load casts, common ball-and-pillow); intern: micro-hummocky cross stratification, wave-ripple cross stratification, combined-flow ripple cross stratification, planar stratification, trough cross stratification (in lower part of unit), bioturbation;

		081191-m29, 080390-m2 (all RX), 080390-m1, -m3 (SRC); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
3.67	151.69	sandstone, gray; interbedded shale/mudstone; sand: f to f/md, abundant phosphate granules and pebbles, dispersed vcs quartz grains: forming thin conglomeratic beds; bedding: 0.01 to 0.11 m, some lateral amalgamation to thicker bedsets (max. 0.20 m), distinct bed tops (symmetrical-ripple formsets) and bed bases (load casts, ball-and-pillow), coarser grained beds more indistinct; intern: combined-flow ripple cross stratification, planar/wavy stratification, micro-hummocky cross stratification, some trough cross stratification, massive (coarser grained beds), bioturbation; SGP-5; 060391-m6x, -m7x, 081190-m28, 080190-mx2, -mx3, -mx4 (all RX), 081190-m28x, 080190-mx1 (all SRC); trace fossils: unspecified tracks & trails, <i>Rusophycus</i> , <i>Planolites</i> , <i>Skolithos</i>
3.48	148.02	sandstone, gray, hard, rarely hematitic; interbedded gray shale/mudstone; sand: f to f/md, dispersed vcs quartz grains and phosphate granules /pebbles; bedding: 0.05 to 0.20 m, up to 0.35 m, some lateral change in thickness, distinct bed bases (load casts, ball-and-pillow, tool marks, gutter casts) and bed tops (some winnowed coarse lags, some micro-hummocks), homogenized beds always overlain by phosphate-grain-bearing winnowed lag; intern: ripple cross stratification, some planar stratification, hummocky cross stratification (0.35 m bed), bioturbation (up to 100%); 080190-m2 (GC), 080190-m1 (TM), 060391-m2 (RX); trace fossils: <i>Skolithos</i> , <i>Planolites</i> , some brachiopod molds
4.70	144.54	sandstone, gray; abundant interbedded gray shale/mudstone; sand: f/vf to f/md, bedding: 0.01 to 0.10, up to 0.25 m, distinct bed tops (some winnowed lags) and bed bases (some tool marks), indistinct in bioturbated parts; intern: micro-hummocky cross stratification, planar stratification, bioturbation (up to 100%); SGP-4, SGP-3; trace fossils: <i>Planolites</i> , <i>Skolithos</i> , brachiopod molds
		<u>"upper" Tuscarora Ss.:</u>
0.26	139.84	sandstone, gray; sand: f to f/md, silty in lower part, gravelly in upper part; upper part with phosphatized granules and pebbles (max. 1.5 cm) and vcs grains; intern: completely bioturbated
0.52	139.58	sandstone, grayish-white, hard; sand: f to f/md; bedding: amalgamated 0.10 m beds, different thickness laterally, some discontinuous mudstone seams, distinct bed tops and bases; intern: (micro) hummocky cross stratification, bioturbation (up to 100%); trace fossils: <i>Planolites</i> , <i>Skolithos</i>
0.97	139.06	sandstone, grayish-white, hard; sand: f to f/md; bedding: amalgamated beds (0.08 to 0.25 m, top bed 0.45 m); intern: hummocky cross stratification, bioturbation (including escape burrows), one shale clast (0.50 m long, 0.04 m thick)
5.66	138.09	sandstone, grayish-white; sand: f to f/md, some vf; bedding: distinct beds amalgamated to varying degrees, thin (0.01 to 0.08 m) discontinuous gray shale interbeds, beds from 0.10 to 0.22 m (max. 0.30, min. 0.04 m), pronounced lateral change in thickness; distinct bed tops and bases, some hummock formsets on bed tops (spacing 0.80 to 1.6 m), bed bases erosive and reaching into underlying bed; some tool marks; shale clasts; intern: hummocky cross stratification, rare wave-ripple cross stratification, abundant bioturbation; 081191-m11 (TM); SGP-2; trace fossils: <i>Skolithos</i> , <i>Planolites</i>
1.49	132.43	sandstone, grayish-white; sand: f; bedding: amalgamated beds, 0.05 to 0.30 m, lateral change in thickness; very thin (mm) laterally discontinuous shale seams (one shale bed 0.05 m); distinct bed tops (with some hummock formsets: spacing up to 2.0 m) and erosive bases, with burrow protrusions; shale clasts; intern: hummocky cross stratification, abundant bioturbation; trace fossils: <i>Skolithos</i>
0.13	130.94	shale, dark gray, silty; pinches out farther up in outcrop; SGP-1

- 4.30 130.81 sandstone, grayish-white, hard, some dark brown rusty spots; sand: f to f/md; bedding: amalgamated beds, discontinuous shale seams (predominantly ≤ 0.01 m), some bed tops with preserved hummock formsets (spacing up to 1.1 m) and rare symmetrical-ripple formsets, bed bases erosive; burrow protrusions on bed tops/bases; shale clasts; intern: hummocky cross stratification, some planar stratification, combined flow ripple cross stratification, abundant bioturbation; 072790-m1 (SRC), m2 (RX); trace fossils: *Planolites*, *Skolithos*
- (the overlying was measured along VA 52, whereas the underlying was measured on the ledge above VA 52; a distinctive, continuous, thin symmetrical ripple bed was used for correlation)
- 0.74 126.51 top part: sandstone; sand: md; intern: trough cross stratification, some ripple cross stratification, bioturbation; scoured into underlying middle part, pinches out over a short distance to the right, increases in thickness to 0.30 m to left (lateral distance ca. 6 m); exposed right margin of a shallow channel ?; trace fossils: *Skolithos*
middle part: sandstone (0.20 to 0.60 m thick), md/f, shale clasts; capped by a olive green siltstone (ca 0.10 m); scoured into underlying lower part (max. scour relief 0.28 m); intern: hummocky cross stratification, bioturbation; trace fossils: *Skolithos*
lower part: sandstone, sand: md; 0.40 to 0.15 m thick; intern: trough cross stratification, bioturbation; trace fossils: *Skolithos*
- 0.92 125.77 sandstone, grayish-white, hard; sand: cs (basal) to md; bedding: 0.06 to ca. 0.30 m, bed tops and bases indistinct, unit base erosional (scouring into underlying); intern: trough cross stratification, rare planar cross stratification, rare ripple cross stratification some planar stratification, abundant bioturbation; 072690-m1 (PX); trace fossils: *Skolithos*, *Arthropycus*
- 0.53 124.85 siltstone, sandy, dark gray to black; marcasite; some thin white sandstone beds (md/cs, planar stratified); predominantly bioturbated; scoured from above; some galena, manganite
- 2.54 124.32 sandstone (grayish-white) and siltstone (muddy to vf sandstone, dark gray to black); sand: md to md/cs, rare cs/vcs; bedding: 0.11 to 0.44 m, distinct bed tops, bed bases erosive (scouring into underlying darker lithologies); mudstone clasts; intern: trough cross stratification, some ripple cross stratification; abundant bioturbation; 072690-m3, -m2 (TX), -m1x (RX); trace fossils: *Monocraterion*, *Arenicolites*, *Skolithos*, unspecified horizontal tracks & trails; dark lithologies: bedding: 0.01 to 0.19 m, scoured from above by sandstone (including complete erosion), bioturbated to varying degree
- 0.83 121.78 siltstone, black to dark gray, in part sandy or muddy; some mm-thick white sand laminae, marcasite; abundant bioturbation (note: on road level, overlying white sandstone bed scours into this unit, with a scour relief of 0.25 m)
- 0.67 120.95 sandstone, brownish white, hard; sand: md/cs to cs; distinct unit top, unit base erosive; intern: trough cross stratification (sets: 0.07 to 0.21 m), planar cross stratification (set: 0.30 m thick), black mudstone clasts near bed top, bioturbation; 073190-m1 (PX); trace fossils: *Arthropycus*
- 1.44 120.28 sandstone, white, hard; sand: md/cs to cs/vcs, some dispersed granules; bedding: 0.05 to 0.15 m, distinct bed tops, erosive bed bases; intern: trough cross stratification, ripple cross stratification, rare planar cross stratification, abundant bioturbation; 073190-m2; trace fossils: *Arthropycus*, *Skolithos*; interbedded: thin (mm to 0.03 m) dark gray to black mudstone beds (one dark gray siltstone bed reaches 0.17 m), beds laterally discontinuous
- 5.18 118.84 sandstone, grayish-white, hard; sand: cs/md to cs/vcs, some dispersed granules, black mudstone chips; bedding: predominantly 0.15 to 0.30, max. 0.62 m, distinct bed tops and bed bases; mm-thick black mudstone/siltstone seams

- between some sandstone beds; intern: trough cross stratification (sets: 0.08 to 0.28 m thick), some ripple cross stratification, bioturbation, rare marcasite nodules (2 cm diameter); trace fossils: *Arthropycus*, *Monocraterion*, siltstone, black to dark gray; interspersed with thin white sandstone beds; soft-sediment deformation (slump); abundant *Arthropycus* associated with the interbedded sandstone
- 0.41 113.66 sandstone, grayish-white; sand: cs/vcs, dispersed granules; bedding: ca. 0.46 and 0.68 m, distinct bed bases and tops; intern: trough cross stratification (gravelly) sandstone, grayish-white, hard; sand: md/cs to vcs/cs, abundant dispersed granules, some pebbles, mudstone-clast holes (max. 8 cm long); bedding: 0.20 to ca. 0.60 m, bed tops and bases predominantly distinct; intern trough cross stratification (sets: 0.11 to 0.35 m thick), mutually intersecting sets, planar cross stratification (sets: up to 0.12 m thick); 072490-m2 (PX)
- 3.05 112.11 sandstone, sand: md/cs to cs, mudstone-clast holes; bedding: ≤ 0.25 m; intern: planar cross stratification (sets: 0.24 m thick), trough cross stratification (sets: ≤ 0.10 m); 072490-m1 (PX)
- 0.63 109.06

(the overlying was measured along Va 52 starting at the road and climbing upward to the ledge above VA 52, whereas the underlying was measured along I-77 (northbound) on the other side of the interstate; the distinctive, continuous, dark and slumped siltstone bed above the thick sandstone interval was used for correlation)

- 0.75 108.43 gravelly sandstone, white, hard; sand: cs to vcs, abundant dispersed granules and pebbles (max. 1.5 cm), mudstone clasts (9 cm long, 2 cm thick, some clast holes are even larger); bed base is distinctly erosive and scours into the underlying (relief up to 0.50 m); intern: trough cross stratification (sampled on this side of the interstate: SGP-33, SGP-34)

(measured on this side of the interstate: 041591-m9, -m10, -m11, -12, -m3, -m4, -m5, -m6, -m7, -m8 (all TX))

"lower" Tuscarora Ss.:

- 3.41 107.68 sandstone, gray to grayish-white, hard; sand: cs, dispersed vcs and granules, some md, abundant mudstone clasts (max. 8 cm long, 2 cm thick); very rare discontinuous gray mudstone interbeds or seams; bedding: 0.12 to 0.40 m, distinct bed tops and bases (with mudstone holes); intern: trough cross stratification (sets: up to 0.20 m thick); SGP-32; 041591-m2x, -m1, 081890-m2 (all TX); unit is cut from above by the "Tuscarora unconformity"
- 10.68 104.27 sandstone, brownish/grayish-white, abundant rusty specks, hard; interbedded gray mudstone; sand: md to cs, some md/f and vcs, rare laterally discontinuous conglomerate beds (max. 0.12 m thick), abundant mudstone clasts (max. 5 cm long, 2 cm thick); bedding: unit is broken into packages (1.75 to 2.87 m thick) displaying fining-upward trends (decrease in sand content/increase in mud content, upper reaches are always heterolithic), decrease in bed thickness, decrease in scale of cross stratification, bases always erosional/scoured: relief up to 0.25 m, 0.15 to 0.45 m (in lower parts of packages), ≤ 0.15 m (in upper parts of packages), some amalgamation of beds (discontinuous mudstone seams), distinct bed tops (some undulation) and bed bases (load casts, rare ball-and-pillow, scouring); intern: trough cross stratification (sets: up to 0.20 m thick), ripple cross stratification, rare planar cross stratification, bioturbation; SGP-31, SGP-30, SGP-29, SGP-28, SGP-27, SGP-26; 081890-m1, 081790-m5, -m4, -m3, 081690-m3, 081191-m26, -m25, -m24, -m23, -m22, -m21, -

m20 (all TX); 081790-m2 (RX); trace fossils: unspecified tracks & trails, *Rusophycus*, *Cruziana*, *Monocraterion*, *Planolites*

Juniata Fm.:

- | | | |
|-------|-------|--|
| 2.30 | 93.59 | sandstone, greenish-gray to maroon; interbedded with mudstone, gray to maroon; sand: md to md/f, one conglomerate layer (0.04 m, silicified gray mudstone pebbles), some mudstone clasts; bedding: predom. 0.04 to 0.12 m, lateral changes in thickness, distinct bed tops and bases (erosive, some load casts); intern: trough cross stratification (sets: 0.06 m thick), ripple cross stratification, bioturbation; SGP-25; 081690-m1 (RX), -m2 (TX); trace fossils: <i>Monocraterion</i> , abundant <i>Rusophycus</i> |
| 2.27 | 91.29 | sandstone, maroon; interbedded with silty mudstone to mudstone, maroon; sand: f/md, some mudstone clasts; bedding: 0.09 to 0.50 m, bed tops and bases partly distinct; intern: trough cross stratification (sets rarely up to 0.10 m thick), ripple cross stratification, abundant bioturbation (up to 100%); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i> |
| 1.02 | 89.02 | sandstone, yellowish-brown, relict maroon streaks; sand: md to cs/md, maroon mudstone clasts (max. 3 cm long, ≤ 1 cm thick); rare mudstone, as discontinuous thin interbeds; bedding: 0.12 to 0.55 m, beds amalgamated to thicker bedsets, distinct bed tops and bases (sharp-erosive); intern: trough cross stratification (sets: up to 0.14 m thick), some ripple cross stratification; 081590-m3 (TX) |
| 4.55 | 88.00 | mudstone, silty, maroon, bioturbated; interbedded with some sandstone, maroon; sand: f to md, abundant maroon mudstone clasts; bedding: 0.01 to 0.20 m, lateral changes in thickness, distinct bed tops and bed bases (erosive), one scour; intern: trough cross stratification, ripple cross stratification, abundant bioturbation (up to 100%), note: one bed (0.04 to 0.17 m thick) with hummocky cross stratification (= highest occurrence of HCS in Juniata Fm. at this outcrop); 081191-m18 (TX); trace fossils: unspecified tracks & trails, <i>Skolithos</i> , <i>Rusophycus</i> |
| 1.43 | 83.45 | sandstone, maroon; sand: f/md, some coarser material, abundant maroon mudstone clasts in parts; rare discontinuous maroon mudstone (≤ 0.02 m); bedding: up to 0.25 m, lateral changes in thickness, amalgamation to thicker bedsets, distinct bed tops (unit top with undulosity) and bed bases (erosive); intern: trough cross stratification (sets: up to 0.18 m thick, mutually cross-cutting), some planar cross stratification (sets: up to 0.08 m thick), some ripple cross stratification, some bioturbation; 081191-m17 (RX), 081490-m3 (RX), -m4 (PX); trace fossils: unspecified tracks & trails |
| 1.75 | 82.02 | mudstone, silty, maroon; interbedded with abundant sandstone, maroon, partly bleached; sand: md/f to md/cs, some vf/f, some dispersed cs and few pebbles, abundant maroon mudstone clasts (arranged in part in thin "conglomeratic" layers); bedding: 0.03 to 0.07 m (max. 0.20 m), distinct bed tops and bed bases; intern: ripple cross stratification, some trough cross stratification, abundant bioturbation; 081190-m15 (TX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i> |
| 2.91 | 80.27 | sandstone, maroon to bleached; sand: md to cs/md, top f, some dispersed granules, maroon mudstone clasts; bedding: 0.15 to 0.50 m, rare discontinuous maroon mudstone interbeds, amalgamation to thick bedset, distinct bed tops and bed bases (erosive, some load casts); intern: trough cross stratification (sets: up to 0.25 m thick, mutually cross-cutting), some bioturbation; 081190-m12, -m13, -m14, -m16, 081590-m1 (all TX); trace fossils: <i>Monocraterion</i> , <i>Arenicolites</i> , <i>Rusophycus</i> |
| 18.78 | 77.36 | mudstone, silty, maroon; interbedded with abundant sandstone, maroon, partly bleached; sand: f/md to cs/md, some dispersed coarser material (incl. rare |

		pebbles), abundant maroon mudstone clasts, some thin (0 to 0.05 m) conglomeratic layers; bedding: predom. 0.05 to 0.20 m, also thinner and rarely thicker beds, some lateral changes in thickness (down to 0), some amalgamation (discontinuous mudstone beds), distinct bed tops (some washed-out ripple formsets) and bed bases (sharp erosive, prominent scouring, some load casts); intern: trough cross stratification (sets: ≤ 0.15 m), ripple cross stratification, planar cross stratification, rare planar stratification, abundant bioturbation (up to 100%); SGP-20, SGP-21, SGP-22, SGP-23; 081290-m2, -m4, -m5, -m6, -m7, 081191-m8, -m9, -m10, 081390-m1, 081390-m3 (TX), 081290-m3, 081191-m11 (RX), 081190-m5, 081290-m8 (PX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Rusophycus</i> , <i>Planolites</i> , <i>Skolithos</i> , <i>Cruziana</i> , rare <i>Arenicolites</i> ,
2.07	58.58	sandstone, maroon, bleached; rare interbedded maroon silty mudstone, some siltstone; sand: f to md/cs, some maroon mudstone clasts; bedding: 0.20 to 0.60 m, amalgamation to thicker bedsets, distinct bed tops and bases (sharp); intern: trough cross stratification (sets: ≤ 0.10 m, max. 0.20 m), planar cross stratification (sets: 0.06 m thick), some ripple cross stratification, some bioturbation; 081191-m7, -m6 (TX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
1.21	56.51	mudstone, silty, maroon; interbedded thin (≤ 0.05 m) f/vf sandstone, maroon; micro-hummocky cross stratification (intern); micro-hummocks, combined-flow ripples (bed tops); bioturbation (incl. escape burrows); 081090-m3
7.19	55.30	mudstone, silty, maroon; interbedded sandstone, maroon, partly bleached; sand: f to md/f, abundant maroon mudstone clasts, few dispersed granules; bedding: predom. 0.04 to 0.15 m (max. 0.49 m), lateral changes in thickness, some beds as shallow scour fills (terminate along the outcrop exposure), some amalgamation of beds, distinct bed tops and bed bases (sharp-erosive, prominent scouring); intern: trough cross stratification (sets: ≤ 0.10 m thick), ripple cross stratification, rare planar stratification, bioturbation (up to 100%); 081191-m3 (RX), -m2, -m4, 081190-m2 (all TX); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Rusophycus</i> , <i>Skolithos</i>
2.34	48.11	sandstone, maroon, bleached to greenish-yellow; rare interbedded finer material (siltstone to silty mudstone); sand: f to md, abundant maroon mudstone clasts; bedding: up to 0.25 m, distinct bed tops and bases, large scour-and-fill structure(s) ?; intern: trough cross stratification (sets: up to 0.17 m thick, mutually cross-cutting), some ripple cross stratification, some bioturbation; 080890-m2, 081191-m1 (all TX); trace fossils: <i>Monocraterion</i>
10.49	45.77	sandstone, maroon, partly decolored (greenish); interbedded with abundant fines (silty mudstone to muddy siltstone), maroon; sand: f to md, some coarser material (up to rare granules/pebbles), mudstone clasts, rare shell hash; bedding: predom. 0.02 to 0.15 m, some up to 0.35 m, some amalgamation, some lateral changes in thickness, distinct bed tops and bed bases (sharp-erosive, scouring); intern: trough cross stratification (sets: rarely up to 0.15 m thick), ripple cross stratification, bioturbation (up to 100%); SGP-19; 080890-m1 (TX); trace fossils: unspecified tracks & trails, <i>Rusophycus</i> , <i>Skolithos</i> , <i>Cruziana</i> , some <i>Planolites</i>
14.19	35.28	sandstone, maroon, partly decolored (greenish); interbedded with abundant fines (muddy siltstone to silty mudstone), maroon; sand: vf to f, some shell hash, mudstone clasts, very rare dispersed granules, two coarser grained sandstone beds (0 to 0.04 m thick); bedding: predom. ≤ 0.10 m (max. 0.39 m), distinct (if not too much overprinted by burrows) bed tops (micro-hummocks, rare symmetrical-ripple formsets) and bed bases (tool marks); intern: micro-hummocky cross stratification, soft-sediment deformation (convolute lamination, ball-and-pillow), some wave-ripple cross stratification, planar stratification, abundant bioturbation (large intervals bioturbated to 100%);

		SGP-18; 080790-m2 (TM), 080790-m1 (SRC); trace fossils: unspecified tracks & trails, <i>Skolithos</i> , <i>Planolites</i> (note: fault in lower part of the unit)
1.90	21.09	siltstone, sandy, maroon, some vf sandstone interbeds (up to 0.04 m thick, micro-hummocky cross stratification); wave-ripple cross stratification, soft-sediment deformation (ball-and-pillow); all contained within scour outline and constitute heterolithic scour fill; in parts complete bioturbation
2.15	19.19	siltstone to sandy mudstone, maroon; interbedded maroon sandstone; sand: vf to vf/f; bedding: 0.03 to 0.11 m, lateral changes in thickness, distinct bed tops (micro-hummocks, symmetrical-ripple formsets) and bases (some ball-and-pillow); intern: micro-hummocky cross stratification, wave-ripple cross stratification, planar stratification; 010391-m1 (SRC); trace fossils: unspecified tracks & trails, <i>Skolithos</i> , <i>Rusophycus</i>
1.12	17.04	sandstone, maroon, hard; sand: f/vf; unit base with pronounced scour (relief ca. 0.70 m); intern: hummocky cross stratification, amalgamated (discontinuous thin maroon mudstone seams), wave-ripple cross stratification (near top of unit), some escape burrows
15.92	15.92	mudstone, silty, maroon to muddy siltstone; interbedded with maroon sandstone; sand: vf to f/vf, some mudstone clasts, some shell hash, fining-upward; bedding: predom. ≤ 0.15 m, also up to 0.30 m, lateral changes in thickness, some amalgamation, distinct bed tops (symmetrical-ripple and combined-flow ripple and interference-ripple formsets, micro-hummocks, hummocks) and bed bases (erosive, some load casts); intern: micro-hummocky cross stratification, hummocky cross stratification, wave-ripple cross stratification, planar stratification, soft sediment deformation (ball-and-pillow), abundant bioturbation (up to 100%); SGP-16, SGP-17; 080190-m3 (PL), -m5 (RX), -m4, 080290-m1 (all SRC); trace fossils: unspecified tracks & trails, <i>Rusophycus</i> , <i>Cruziana</i> , <i>Planolites</i> , <i>Skolithos</i> ; body fossil: <i>Lingula</i>
		(the overlying was measured along I-77, northbound lane)
—	—	Martinsburg Fm.: (not measured, covered)

outcrop locality: NARROWS

outcrops along VA 460 (both north- and southbound), east bank of New River, gap through Peters Mtn./East River Mtn., ca. 1.5 km N of Narrows High School; Giles Co.;

stratigraphy: Rose Hill Fm., "upper" and "lower" Tuscarora Ss., Juniata Fm.;

unit thickness	cumulative thickness	
—	—	"Keefer Ss.": (not measured);
		Rose Hill Fm.:
4.15	188.08	sandstone, light brown, hard; interbedded with olive shale/mudstone; sand: f, some md; bedding: ≤ 0.01 to 0.08 m (amalgamated), 0.20 m (lowermost bed), lateral change in thickness, distinct bed tops (micro-hummocks) and bed bases; upper 1.20 m of unit with Fe-oxide weathering crusts (just beneath unconformable contact to "Keefer Ss."), lower 0.15 m of unit is hematitic; intern: planar stratification, massive, some ripple cross stratification (lowermost bed), rare bioturbation; NRW-19, NRW-18
4.59	183.93	sandstone, maroon, hematitic, hard; some olive mudstone interbeds (up to 0.04 m thick); sand: f/vf to md, some dispersed cs grains, abundant mudstone clasts

		(isolated or arranged in layers), some fossil hash; bedding: predom. 0.02 to 0.08 m, amalgamated to 0.20 to 0.40 m bedsets, lateral change in thickness, beds in upper part of unit up to 0.35 m, distinct bed tops (some symmetrical-ripple formsets, some winnowed cs lags) and bed bases (some load casts, tool marks); intern: trough cross stratification, ripple cross stratification, bioturbation (up to 100%); 041291-m4, -m3 (all RX); trace fossils: unspecified tracks & trails, <i>Planolites</i> , <i>Rusophycus</i> , <i>Skolithos</i> , <i>Monocraterion</i>
5.25	179.34	sandstone, maroon, hematitic, hard; interbedded with abundant olive shale/mudstone (up to 0.11 m thick, 0.38 m of shale at base of unit); sand: f/vf to md/cs, fossil hash, mudstone clasts; bedding: ≤ 0.09 m, lateral change in thickness (including pinch-out), amalgamation of beds to thicker bedsets, distinct bed tops (some symmetrical-ripple and interference-ripple formsets) and bed bases (some load casts, tool marks, scouring); intern: ripple cross stratification, planar stratification, trough cross stratification, bioturbation; NRW-17; 041290-m2 (TX), 102589-mx (SRC); trace fossils: unspecified tracks & trails, <i>Planolites</i> , <i>Skolithos</i>
0.70	174.09	sandstone, maroon, hematitic; sand: cs/vcs to f/vf (top of unit), mudstone clasts (max. 4 cm long, 1 cm thick); bedding: unit top distinct (current-ripple formset), unit base convex upward (scouring into subjacent unit, relief up to 0.40 m); intern: trough cross stratification, ripple cross stratification; 103190-m1 (RX)
0.72	173.39	sandstone, maroon, hematitic; interbedded with abundant maroon shale/mudstone; sand: f, pebbly at base of unit, mudstone clasts (often as layers); bedding: 0.01 to 0.05 m, amalgamated to thicker bedsets (≤ 0.14 m), lateral change in thickness, distinct bed tops and bases (load casts, tool marks, some scouring); intern: ripple cross stratification, bioturbation; trace fossils: unspecified tracks & trails, <i>Skolithos</i>
20.09	172.67	shale/mudstone, light olive to grayish; interbedded with sandstone, olive-brown; sand: vf/f to f, abundant shell hash (as discontinuous basal lags or coquina beds), mudstone clasts, rare dispersed phosphate granules; bedding: 0.01 to 0.15 m, lateral change in thickness (pronounced 'pinch-and-swell') up to 0, amalgamated to thicker bedsets (up to 0.45 m), distinct bed tops (micro-hummocks and hummocks, some symmetrical-ripple and interference-ripple formsets) and bed bases (scouring, tool marks, gutter casts, pod casts, load casts); intern: hummocky cross stratification, micro-hummocky cross stratification, planar stratification, bioturbation; NRW-16, NRW-15, NRW-14, NRW-13, NRW-12, NRW-11, NRW-10, NRW-9, NRW-8, NRW-7; 081091-m25, -m28, -m20, -m12, -m16, -m11, 053191-m1, 102489-m1 (all GC), 081089-m26, -m27, -m29, -m18, -m19, -m21, -m22, -23, -m24, -m14, -m15, -m9, -m10 (all TM), 081089-m17 (FC), 102489-m3, 102589-m1, 102489-m4, -m5, -m3 (all SRC); trace fossils: unspecified tracks & trails, <i>Chondrites</i> , <i>Monocraterion</i> , <i>Planolites</i> , <i>Skolithos</i> ; body fossils: abundant brachiopods (<i>Eocoelia intermedia</i> , <i>E. curtisi</i> , <i>Eocoelia</i> sp., <i>Ancillotoechia</i> sp., <i>Protochonetes</i> sp.), abundant trilobites, abundant ostracodes, graptolites (<i>Monograptus</i> sp.), crinoid ossicles
1.63	152.58	sandstone, bluish-gray; some interbedded olive mudstone (≤ 0.06 m); sand: f/vf, some f/md, basal beds with phosphate pebbles (conglomerate) at base, some mudstone clasts; bedding: 0.09 to 0.40 m, ≤ 0.03 m associated with mudstone interbeds, lateral changes in thickness, amalgamation, distinct bed tops (some hummocks, some symmetrical-ripple formsets) and bed bases (scouring, gutter casts); intern: hummocky cross stratification, fossil molds; 102389-m1 (GC)
2.85	150.95	sandstone, interbedded olive shale in the upper 1/3 of unit; sand: f/md to md, some phosphatized coarser grains, some fossil hash; bedding: bioturbated to varying degree (up to 100%), 0.01 to 0.07 m (in top 1/3 of unit), distinct bed

		tops (rare symmetrical-ripple formsets) and bed bases (rare gutter casts, load casts); some Fe-coating; intern: bioturbation, ripple cross stratification, planar/low-angle stratification; NRW-6; 102289-m5 (GC), 081091-m8, 011690-m8 (all RX); trace fossils: <i>Monocraterion</i> , <i>Skolithos</i>
3.12	148.10	sandstone, gray, some Fe-coating; interbedded with olive shale; sand: f to f/md, some mudstone clasts; bedding: typically ≤ 0.07 m, some amalgamation discontinuous mudstone seams), overall wavy appearance, distinct bed tops (rare symmetrical-ripple formsets) and bed bases (some load casts); intern: bioturbation, micro-hummocky cross stratification, some ripple cross stratification; NRW-5; trace fossils: <i>Monocraterion</i> , <i>Planolites</i>
3.38	144.98	sandstone, maroon, hematitic (lower 2/3 of unit), hard; some olive or maroon shale/mudstone interbeds (esp. in lower 2/3 of unit); sand: f/md, some shell hash, some dispersed cs grains and phosphate granules, mudstone clasts; bedding: ≤ 0.10 m, amalgamated to thicker bedsets (upper 1/3 of unit) or dispersed within shale/mudstone (lower 2/3 of unit), distinct bed tops (symmetrical-ripple and interference-ripple formsets, micro-hummocks) and bed bases (some load casts, tool marks, some scouring); intern: some current-ripple and abundant wave-ripple cross stratification, some trough cross stratification, micro-hummocky cross stratification, planar stratification, bioturbation; NRW-4; 081091-m5, -m6, -m7, 060391-m1 (all RX), 102289-m3 (SRC); trace fossils: unspecified tracks & trails, <i>Monocraterion</i> , <i>Planolites</i> , <i>Skolithos</i>
4.04	141.60	shale/mudstone, olive; interbedded with sandstone, greenish maroon, hard; sand: f to md, abundant mudstone clasts (often in layers); bedding: 0.01 to 0.07 m, thicker at the top of unit (0.15 m), top bed is 0.55 m, lateral change in thickness, distinct bed tops (symmetrical-ripple formsets, micro-hummocks) and bed bases; intern: abundant wave-ripple cross stratification, some current-ripple cross stratification and trough cross stratification, bioturbation; NRW-3; trace fossils: <i>Planolites</i>
0.34	137.56	sandstone, maroon, hematitic, hard; sand: vf/f; intern: hummocky cross stratification, sharp bed base and distinct broadly undulatory bed top
0.41	137.22	shale, olive
0.79	136.81	sandstone, greenish, Fe-coating, hard; sand: f, some mudstone clasts; intern: hummocky cross stratification, some wave-ripple cross stratification (in upper part), some bioturbation; sharp bed base and distinct bed top (symmetrical-ripple formsets)
1.65	136.02	shale, olive; rare interbedded sandstone, caramel; sand: f/md; bedding: ≤ 0.01 m, laterally discontinuous, one bed 0.07 m, sharp bed bases (tool marks) and distinct bed tops (micro-hummocks); intern: micro-hummocky cross stratification, some wave-ripple cross stratification, bioturbation; NRW-2; 081090-m4 (TM); trace fossils: <i>Skolithos</i> , <i>Planolites</i>
1.65	134.37	sandstone, reddish-gray to maroon, hematitic, hard; some interbedded olive shale/mudstone; sand: vf/f to md/f, mudstone clasts; bedding: ≤ 0.10 m, some amalgamation to thicker bedsets, 0.50 m (lowermost bed), lateral changes in thickness, distinct bed tops (micro-hummocks, some symmetrical-ripple formsets) and bed bases (some load casts), rare ball-and-pillow; intern: abundant wave-ripple cross stratification, hummocky cross stratification, some current-ripple cross stratification, bioturbation; 081091-m3, -m2 (all RX); trace fossils: unspecified tracks & trails, <i>Skolithos</i>
0.41	132.72	shale, olive; with sandstone ball-and-pillows/pseudonodules; NRW-1 (note small normal fault)

"upper" Tuscarora Ss.:

'transition complex':

- 0.30 132.31 sandstone, greenish-gray; sand: well-rounded and well-sorted, cs, also md and vcs, with olive mudstone clasts and abraded brachiopods; some Fe-coating; bedding: bed thickness appears to change laterally, large symmetrical ripples on bed top; intern: massive to ?planar cross stratification (foresets dip into opposite directions)
- 1.77 132.01 mudstone, olive brown; interbedded with sandstone, gray, green to reddish-brown; sand: f to cs; some granules, mudstone clasts, phosphate grains, Fe-coating to varying degree; abundant Fe-oxide weathering crusts; bedding: predom. ≤ 0.10 m, load casts, ball-and-pillow structures, pseudonodules; intern: (coarser grained beds) massive, with brachiopods (*Ancillotoechia* sp.), (finer grained beds) wave-ripple cross stratification, planar stratification, abundant bioturbation; trace fossils: *Planolites*, *Skolithos*
- 6.81 130.24 sandstone, white, hard; sand: f to f/md; some mudstone interbeds; mudstone clasts and clast holes; bedding: predom. 0.08 to 0.25 m, amalgamated to varying degree (then up to 0.50 m thick composite beds), pronounced lateral changes in thickness; discontinuous olive mudstone interbeds (a few cm to max. 0.10 m) and seams; distinct bed tops and erosive bed bases, some preserved hummocks and rare symmetrical-ripple formsets (bed tops) and some tool marks (bases); dense burrow protrusions on bed tops and bases; intern: hummocky cross stratification, planar stratification, abundant bioturbation (some beds completely bioturbated); NRW-22A; 101589-m2 (SRC); trace fossils: *Skolithos*, *Planolites*
- 3.19 123.43 sandstone, white, hard; sand: f to f/md; bedding: amalgamated beds, 0.10 to 0.40 m, rare discontinuous mudstone seams (≤ 2 cm), few hummocky bed tops discernible; intern: hummocky cross stratification, planar stratification, bioturbation; trace fossils: *Skolithos*
- 1.42 120.24 sandstone interbedded with mudstone; sand: f to f/md; bedding: 0.04 to 0.08 m, lateral changes in thickness, distinct bed tops and bases; intern: abundant bioturbation, planar stratification, hummocky cross stratification; NRW-21; trace fossils: *Skolithos*
- 0.50 118.82 sandstone, white, hard; sand f/md, abundant mudstone clasts in lower part; distinct flat bed top and erosive scoured bed base, amalgamated to subjacent bed; intern: hummocky cross stratification
- 7.49 118.32 sandstone, white, hard; sand: cs to md, some vcs, very rare mudstone interbeds (≤ 2 cm); bedding: mostly hard to see, 0.10 to 0.25 m, max. 0.45 m, some distinct bed tops and bases, rare current-ripple formset; intern: trough cross stratification (sets: up to 0.30 m thick, 1.2 m wide), some ripple cross stratification, bioturbation; 011690-m4, -m3, 041491-m6, -m7, -m8, -m9, -m11 (all TX), 101289-m1 (RX); trace fossils: *Skolithos*, *Arthropycus*, *Planolites*
- 0.38 110.83 sandstone interbedded with siltstone; siltstone, dark gray to black, beds ≤ 0.03 m; sand: cs/vcs to md; bedding: 0.06 to 0.12 m, partly amalgamated, distinct bed tops and bases, one symmetrical-ripple formset; intern: ripple cross stratification; trough cross stratification, bioturbation; 101189-m6 (TX), 101189-m5 (SRC); trace fossils: *Arthropycus*
- 0.69 110.45 sandstone, grayish-white, hard; sand: cs/vcs, some md, rare dispersed pebbles; distinct bed top and base; intern: trough cross stratification, rare bioturbation; 041391-m1 (TX)
- 0.60 109.76 sandstone, whitish-gray, hard; interbedded with siltstone, dark gray to black; sand: md/f to cs/vcs; bedding: 0.05 to 0.10 m, distinct bed tops and bases, lower coarser grained beds with erosive scoured base and mudstone clasts; intern: ripple cross stratification, abundant bioturbation; NRW-20; trace fossils: *Arthropycus*

- 2.74 109.16 sandstone, grayish-white, hard; sand: md to cs, with some vcs, rare dispersed pebbles; bedding: hard to see, base of unit scoured into subjacent unit; intern: trough cross stratification, some ripple cross stratification, some bioturbation; 101189-m2x (TX); trace fossils: *Skolithos*, *Monocraterion*
- 1.65 106.42 gravelly sandstone, hard; sand: md to cs/vcs, dispersed granules and pebbles (up to 4 cm); mudstone-clast holes; bedding: top of unit scoured from above, base of unit erosional into subjacent unit; intern: trough cross stratification, planar cross stratification (set: up to 0.50 m thick); 011690-m2 (PX)

(the overlying was measured along road level, starting at the base of the "conglomerate" marking the onset of the "upper" Tuscarora Ss.)

"lower" Tuscarora Ss.:

(measured on slope above VA 460)

- 1.29 104.77 sandstone, grayish-white; sand: md, gray mudstone clasts; intern: trough cross-stratification, some bioturbation; 101690-m1, 011690-m11 (all TX), 100989-m2 (SRC); cut from above by "Tuscarora unconformity"; trace fossils: unspecified tracks & trails, *Rusophycus*, *Skolithos*

Juniata Fm.:

- 4.62 103.48 sandstone, maroon; sand: f to md, abundant maroon mudstone clasts; bedding: ≤ 0.20 m, amalgamation of beds, long stretches of this unit completely bioturbated, distinct bed tops and bed bases; intern: trough cross stratification (sets: ≤ 0.10 m thick), ripple cross stratification, some planar stratification, bioturbation (incl. some escape burrows), massive (due to complete bioturbation); NRW-22B (taken at road level); trace fossils: *Skolithos*, some *Rusophycus*
- 2.21 98.86 sandstone, maroon, hard; rare interbedded maroon mudstone; sand: f to f/md and md/cs, abundant maroon mudstone clasts; bedding: ≤ 0.20 m, distinct bed tops (some symmetrical-ripple and interference-ripple formsets) and bed bases (some tool marks), note: series of two broad scours/channels incised into this unit, relief ca. ≤ 0.80 m; intern: ripple cross stratification, trough cross stratification (large sets in scours: up to 0.20 m), some bioturbation; 100989-m6, -m4 (all SRC), -m5 (TX), 100389-m3 (SC-plane); trace fossils: some unspecified tracks & trails, *Rusophycus*, *Skolithos*
- 6.01 96.65 sandstone, maroon, partly bleached greenish-gray, hard; amalgamation of beds to thicker bedsets (discontinuous thin mudstone seams), some interbedded maroon siltstone and mudstone; sand: f to md, some cs, rare dispersed granules, maroon mudstone clasts; bedding: ≤ 0.20 m (max. 0.95 m for planar/low-angle-stratified bed), some lateral change in thickness, mostly distinct bed tops (some symmetrical-ripple and ?interference-ripple formsets, some winnowed cs lags) and bed bases (sharp-erosive, some tool marks); intern: trough cross stratification (sets: ≤ 0.11 m thick), ripple cross stratification, planar/low-angle stratification, abundant bioturbation, massive (completely bioturbated intervals; NRW-23; 011590-m3, 120789-m21 (all TX), 100989-m8 (SRC); trace fossils: unspecified tracks & trails, *Monocraterion*, *Skolithos*, *Rusophycus*, *Cruziana*

(the overlying was measured from road level up the slope to the base of the "conglomerate"; there are several faults further to the right/south along road level)

- 6.50 90.64 sandstone, maroon, partly bleached yellowish/greenish-gray; interbedded with maroon mudstone, some siltstone; sand: f to cs, maroon mudstone clasts;

- bedding: ≤ 0.12 m, max. 0.34 m, distinct bed tops (some winnowed cs lag) and bed bases (sharp-erosive, some tool marks, rare gutter casts); intern: trough cross stratification (sets: ≤ 0.15 m thick), ripple cross stratification, bioturbation; NRW-25, NRW-24; 120789-m22, 081091-m50, 100289-m6, -m1, -m5 (all TX), -m51 (RX); trace fossils: *Monocraterion*, *Rusophycus*, *Skolithos*,
- 3.37 84.14 sandstone, maroon, partly bleached greenish-yellow; interbedded thin maroon mudstone; sand: f/vf to md, abundant maroon mudstone clasts; bedding: ≤ 0.20 m, discontinuous thin mudstone seams, amalgamation of beds to thicker bedsets, distinct bed tops and bed bases (sharp-erosive, some gutter casts, tool marks, some load casts); intern: trough cross stratification, ripple cross stratification (sets: ≤ 0.12 m, max. 0.17 m thick), some planar cross stratification, bioturbation; 120789-m15 (GC), 081091-m47 (SC-axis), 120789-m19, 081091-m48 (all PX), -m49 (RX), 120789-m16 (TX); trace fossils: *Skolithos*, *Rusophycus*, *Monocraterion*
- 2.69 80.77 muddy siltstone to sandstone (f), maroon; predom. bioturbated (up to 100%), some trough cross stratification, ripple cross stratification; some tool marks; NRW-26; trace fossils: *Skolithos*
- 1.22 78.08 sandstone (f to md), maroon, hard; maroon mudstone clasts; trough cross stratification (mutually cross-cutting), some discontinuous mudstone seams; some bioturbation (*Skolithos*); 120789-m12, -m13 (all TX)
- 3.44 76.86 mudstone, maroon; interbedded with sandstone, maroon, some bleaching to greenish-yellow, hard; sand: f to md, some maroon mudstone clasts; bedding: ≤ 0.07 m, but up to 0.38 m, some lateral change in thickness, distinct bed tops and bed bases (sharp-erosive, scoured, tool marks), one mudstone-filled scour; intern: trough cross stratification, ripple cross stratification, some planar stratification, bioturbation; NRW-27; 081091-m46 (TX), 120789-m11 (SC); trace fossils: unspecified tracks & trails, *Cruziana*, *Rusophycus*, *Monocraterion*, *Skolithos*
- 2.01 73.42 sandstone, maroon, some bleaching, hard; some interbedded maroon mudstone; sand: f to md/f, some md/cs, maroon mudstone clasts; bedding: ≤ 0.25 m, discontinuous mudstone seams, amalgamation to thicker bedsets, distinct bed bases (sharp-erosive, gutter casts, tool marks) and bed tops (rare symmetrical-ripple formsets), note: prominent Liesegang banding; intern: trough cross stratification, ripple cross stratification, rare planar stratification, rare planar cross stratification, some bioturbation; 120789-m9 (TX), 081091-m45, 120789-m7 (all RX), 120789-m4, -mx (all GC); trace fossils: unspecified tracks & trails, *Rusophycus*, *Skolithos*
- 4.16 71.41 mudstone, maroon; interbedded with sandstone, maroon; sand: f to md/cs, mudstone clasts, rare phosphate granules; bedding: ≤ 0.15 m, max. 0.25 m, some amalgamation, distinct bed tops (rare symmetrical-ripple formsets) and bed bases (sharp-erosive, scouring, tool marks, pod casts, gutter casts, load casts); intern: trough cross stratification, ripple cross stratification, some planar cross stratification, bioturbation; NRW-28; 092290-m1, 120789-m1, 081091-m42, -m43, -m44, 100289-m23 (all TX), 100289-m22, -m21 (all RX), 120789-m2 (PX); trace fossils: *Rusophycus*, *Monocraterion*, *Arenicolites*, *Cruziana*, *Skolithos*
- 1.22 67.25 sandstone, maroon, partly bleached greenish-gray; some interbedded discontinuous maroon mudstone; sand: f to md/cs, abundant maroon mudstone clasts; bedding: amalgamation of beds to thicker bedsets, distinct bed tops (some symmetrical-ripple formsets) and bed bases (sharp-erosive, scouring); intern: trough cross stratification (sets: ≤ 0.10 m thick), planar cross stratification (set: 0.18 m thick), ripple cross stratification, some planar stratification, some bioturbation; 120289-m16, -m17, -m18, -m19 (all TX); trace fossils: *Monocraterion*, *Skolithos*

7.16	66.03	mudstone, maroon; interbedded with maroon sandstone, some bleaching to greenish-gray; sand: f to md. some cs, maroon mudstone clasts; bedding: predom. ≤ 0.15 m, max. 0.50 m, some lateral change in thickness, distinct bed tops and bed bases (sharp-erosive, scouring), some bioturbated intervals (up to 100%); intern: ripple cross stratification, trough cross stratification (sets: ≤ 0.10 m, max. 0.30 m thick), bioturbation (incl. escape burrows), some massive; NRW-29; 120289-m9, -m10, -m12, -m13, -m14, 081091-m36, -m38, -39, -m41 (all TX), -m37, -m40 (RX), trace fossils: unspecified tracks & trails, <i>Cruziana</i> , <i>Rusophycus</i> , <i>Skolithos</i> , <i>Monocraterion</i>
0.45	58.87	sandstone, maroon, hard; f, distinct top and base, hummocky cross stratification (note: highest occurrence of HCS within Juniata Fm. in this outcrop), some <i>Skolithos</i>
0.32	58.42	sandstone, maroon, interbedded with maroon mudstone; sand: f/md to md, mudstone clasts; bedding: 0.10 and 0.12 m, distinct bed tops and bed bases (sharp-erosive, tool marks, gutter casts, load casts); intern: trough cross stratification, planar cross stratification, bioturbation; NRW-30; 120289-m6 (GC), -m7 (PX); trace fossils: <i>Skolithos</i> , <i>Rusophycus</i>
1.28	58.10	sandstone, maroon, hard, some maroon mudstone; sand: f to f/md, maroon mudstone clasts; bedding: 0.30 to 0.60 m, distinct bed bases and tops; intern: planar cross stratification (sets: up to 0.40 m thick), trough cross stratification, some ripple cross stratification, some bioturbation; 072290-mx, 081091-m34 (all PX), -m35 (TX); trace fossils: <i>Rusophycus</i> , <i>Cruziana</i>
2.32	56.82	sandstone, maroon to silty mudstone; sand: f, some maroon mudstone clasts; bedding: predominantly bioturbated, some ≤ 0.10 m beds, distinct bed tops (some symmetrical-ripple formsets) and bed bases; intern: wave-ripple cross stratification, massive, abundant bioturbation; 081091-m33 (RX); trace fossils: <i>Skolithos</i> , <i>Rusophycus</i>
0.66	54.50	sandstone, maroon, hard; sand: f, some maroon mudstone clasts, some shell hash; bedding: low-angle inclined (looks like lateral accretion bedding, but beds internally are not cross-stratified), unit base sharp-erosive (tool marks), unit top flat to hummocky; intern: ?planar stratification in inclined beds, very thin discontinuous mudstone seams (amalgamation), some bioturbation
5.97	53.84	sandstone, maroon; some interbedded maroon mudstone; sand: f to f/vf, some shell hash, some maroon mudstone clasts; bedding: predominantly bioturbated (100%), individual beds ≤ 0.10 m, one bed 0.10 to 0.50 m (pronounced lateral change in thickness), some distinct bed tops (micro-hummocks, some symmetrical-ripple and interference-ripple formsets) and bed bases (sharp-erosive, tool marks); intern: micro-hummocky cross stratification, wave-ripple cross stratification, massive, abundant bioturbation (incl. escape burrows); NRW-31; 081091-m32 (TM); trace fossils: unspecified tracks & trails, <i>Skolithos</i>
0.64	47.87	sandstone, maroon, hard; sand: f, maroon mudstone clasts; bedding: pronounced lateral change in thickness, unit base sharp-erosional, tool marks, unit top undulatory (wide hummocks & swales - spacing 3.0 m- with superimposed ?symmetrical-ripple formsets); intern: low-angle cross stratification (in parts sigmoidal), discontinuous mudstone seam (amalgamation), some bioturbation; 090989-m1 (SRC); trace fossils: <i>Cruziana</i> , <i>Rusophycus</i>
10.36	47.23	muddy siltstone to silty mudstone, rare claystone, maroon; interbedded with sandstone, maroon; sand: f, v/f, mudstone clasts; bedding: 0.10 to 0.30 m, some lateral change in thickness, commonly in discrete beds, but also some amalgamation to thicker bedsets, distinct bed bases (sharp-erosive, tool marks, some gutter casts, some load casts) and bed tops (hummocks, some symmetrical-ripple formsets); intern: hummocky cross stratification, micro-hummocky cross stratification, some wave-ripple cross stratification, normal grading, abundant bioturbation (up to 100%, esp. in background fines);

		120289-m5 (TM); trace fossils: unspecified tracks & trails, <i>Skolithos</i> , <i>Arenicolites</i>
1.23	36.87	shallow scour, with heterolithic scour fill: thin sandstone beds (f, maroon, 0.01 to 0.15 m, micro-hummocky cross stratification, tool marks), set in silty mudstone; abundant bioturbation; scour host-sediment made up of the same heterolithic material, some symmetrical-ripple formsets, some gutter casts; 090689 (SRC), -m1 (GC)
11.12	35.64	silty mudstone to muddy siltstone, rare claystone, maroon; interbedded with sandstone, maroon, sand: f, vf/f, mudstone clasts, some shell hash; bedding: 0.07 to 0.30 m (max. 0.52 m), lateral changes in thickness, mostly isolated beds, but some amalgamation, distinct bed bases (sharp-erosive, some load casts, some tool marks, rare pod casts) and bed tops (hummocks, micro-hummocks, some symmetrical-ripple formsets); intern: micro-hummocky cross stratification, hummocky cross stratification, some wave ripple cross stratification, some planar stratification, normal grading, abundant bioturbation (up to 100%); 120289-m1 (PL); trace fossils: unspecified tracks & trails, <i>Skolithos</i>
4.68	24.52	sandstone, maroon, bleached greenish-gray, hard; one interbed of maroon siltstone/vf sandstone (0.48 m, ca. 2 m above base of unit); sand: f; bedding: commonly difficult to discern, some 0.08 to 0.20 m, some combined-flow ripple formsets; intern: amalgamated hummocky cross stratification, some wave-ripple cross stratification, abundant soft sediment deformation (ball-and-pillow), rare bioturbation; 120289-m1 (PL), 090289-m2 (RX); trace fossils: <i>Rusophycus</i> , <i>Cruziana</i>
0.75	19.84	sandstone, maroon, f, to siltstone, bioturbated; note: a deep channel cuts through this unit into the underlying unit, the channel is inaccessible; it appears to be filled with sandstone beds, some appearing crumbly (bioturbated to 100% ?), dip of channel margins estimated as 20-25°; top of channel fill cut by succeeding sandstone unit
6.94	19.09	sandstone, maroon, bleached greenish-gray, hard, rare maroon siltstone; sand: f, shell hash material, some mudstone clasts; bedding: hard to identify discrete beds, amalgamated beds, unit base and internally scour outlines (relief: ca. 0.25 m); intern: hummocky cross stratification (many swales and some hummocks), some wave-ripple cross stratification, one bed of planar cross stratification (coarser grained bed: shell hash), rare bioturbation
5.21	12.15	sandstone, maroon; interbedded with muddy siltstone/silty mudstone, maroon; sand: vf to f, bedding: 0.05 to 0.25 m, lateral changes in thickness, some amalgamation, abundant soft sediment deformation (ball-and-pillow), distinct bed tops (micro-hummocks, symmetrical-ripple and combined-flow ripple formsets) and bed bases (sharp-erosive, load casts, tool marks); intern: micro-hummocky cross stratification, wave-ripple cross stratification, some planar stratification, abundant bioturbation (up to 100%); NRW-32; 072090-m2 (RX); trace fossils: unspecified tracks & trails, <i>Rusophycus</i> , <i>Skolithos</i>
0.50	6.94	sandstone, maroon gray, hard; sand: f, with abundant shell hash, mudstone clasts; unit base erosional, unit top distinct and arched; intern: ?hummocky cross stratification, capped by planar cross stratified coarser shell hash material; 072090-m1 (RX)
6.44	6.44	muddy siltstone to silty mudstone, some claystone, maroon; interbedded sandstone, maroon; sand: vf/f, some shell hash; bedding: 0.05 to 0.15 m, lateral changes in thickness, distinct bed tops (micro-hummocks) and bed bases (sharp-erosive); intern: micro-hummocky cross stratification, abundant bioturbation (up to 100%); NRW-33; trace fossils: unspecified tracks & trails, <i>Skolithos</i> , <i>Planolites</i>

(overlying units measured along VA 460 northbound)

— — Martinsburg Em.: (not measured);

APPENDIX 2

Directional Measurements

The following lists the paleocurrent and other directional measurements obtained from the different outcrop sections. Measurements were obtained with a Clar-Compass (Freiberger Model). Measurements were taken on different beds for the same sedimentary structure (i.e., trough axes were recorded only once for each bed); measurements were recorded from the same bed for different sedimentary structures, if the opportunity was there (i.e., gutter casts and tool marks were recorded from the base of the same bed, but never two gutter casts, etc. were recorded from the base of the same bed). The original measurements were corrected for structural tilt using the stereonet. A second correction was applied for some outcrops, following the final configuration of the palinspastic map. This second correction involves a rotation (either clockwise or anti-clockwise) around a vertical axis.

Measurements were obtained from the following sedimentary structures (abbreviation in parentheses): **trough cross stratification** (TX, unidirectional, predominantly measurement of trough axes on suitable 3D-exposures); **planar cross stratification** (PX, unidirectional, measurement of foreset plane); **(current) ripple cross stratification** (RX, unidirectional; measurement of foreset plane, trough axis, or lee-side of bedform); **tool mark** (TM, bidirectional, measurement of groove axis); **scour and channel** (SC, bidirectional, measurement of either channel/scour axis, or channel/scour-margin plane with reconstruction of channel/scour axis); **gutter cast** (GC, bidirectional, measurement of gutter axis); **symmetrical ripple crest** (SRC, bidirectional; measurement of crestline); **parting lineation** (PL, bidirectional, measurement of ridge or furrow); **flute cast** (FC, unidirectional); **prod mark** (PM, unidirectional, axis);

The following list will include the outcrop locality, the original measurement code (as it appears in the field notebook), the original measurement (with type of sedimentary structure abbreviated and in parentheses), measurement of structural dip and dip direction in the outcrop (for the first correction - stereonet), and the final reading (final result after both the first and second correction were applied). Measurements are given with dip angle (°) and dip direction. Note: some of the measurement codes comprise multiple measurements (although each single measurement was still obtained from a different bed).

Data for the second correction: Narrows (7° clockwise); Gap Mountain (11° clockwise); Catawba Mountain I (13° anti-clockwise); Catawba Mountain II (13° anti-clockwise).

Outcrop locality: **NARROWS**

Code	original measurment	first correction	final result
Rose Hill Formation:			
081091-m30	05°/285 (TX)	30°/155	22°/285
081091-m25	08°/261 (GC)	"	(14°)/262-082
	05°/265 (GC)	"	(14°)/265-085
	10°/275 (GC)	"	(22°)/274-094
	10°/265 (GC)	"	(17°)/263-083
	09°/118 (GC)	"	(15°)/303-123
	06°/115 (GC)	"	(17°)/299-119
	10°/252 (GC)	"	(10°)/251-071
081091-m29	02°/264 (TM)	"	(09°)/268-088
081091-m28	04°/255 (GC)	"	(09°)/258-078
081091-m27	07°/216 (TM)	"	(07°)/102-282
081091-m26	01°/264 (TM)	"	(09°)/268-088
081091-m24	02°/271 (TM)	21°/141	(15°)/275-095
081091-m23	05°/191 (TM)	"	(08°)/197-017
081091-m22	02°/049 (TM)	"	(03°)/237-057
081091-m21	12°/085 (TM)	"	00°/274-094
081091-m20	05°/115 (GC)	"	(14°)/301-121
081091-m19	01°/269 (TM)	"	(12°)/274-094
081091-m18	10°/092 (TM)	"	(02°)/280-100
081091-m17	05°/253 (FC)	"	12°/257
081091-m16	10°/145 (GC)	30°/155	(19°)/332-152
081091-m15	02°/283 (TM)	"	(20°)/285-105
081091-m14	09°/115 (TM)	"	(14°)/300-120
081091-m12	10°/253 (GC)	"	(03°)/260-080
081091-m11	10°/083 (GC)	"	(01°)/273-093
081091-m10	05°/227 (TM)	"	(04°)/232-053
081091-m9	17°/115 (TM)	"	(07°)/303-123
081091-m8	11°/262 (RX)	"	19°/261
081091-m7	15°/285 (RX)	"	32°/280
081091-m6	10°/319 (RX)	"	38°/321
081091-m5	23°/254 (RX)	"	23°/247
081091-m4	02°/250 (TM)	"	03°/257-077
081091-m3	12°/285 (RX)	"	29°/282
081091-m2	02°/089 (TX)	"	08°/276
081091-m1	05°/255 (TX)	"	14°/258
041291-m4	11°/291 (RX)	25°/159	27°/291
041291-m3	07°/255 (RX)	"	09°/258
041291-m2	21°/295 (TX)	"	38°/291
122689-m1	20°/113 (SRC)	"	(01°)/304-124
	19°/101 (SRC)	"	(04°)/292-112
	12°/096 (SRC)	"	00°/286-106
041291-m1	10°/335 (TX)	"	35°/341
102589-mx	01°/207 (SRC)	"	(15°)/217-037
	01°/253-073 (SRC)	"	(01°)/259-079

103190-mx	27°/323 (TX)	"	50°/323
103190-m1	09°/323 (RX)	"	34°/335
102589-m2	24°/175 (GC)	"	00°/354-174
102589-m1	07°/236 (SRC)	"	00°/241-061
102589-m3	19°/136 (GC)	"	(05°)/325-145
102489-m5	12°/213 (SRC)	"	(03°)/218-038
102489-m4	00°/245-65 (SRC)	"	(01°)/253-073
102489-m3	03°/033 (SRC)	21°/141	(10°)/223-043
102489-m1	05°/043 (GC)	"	(08°)/233-053
	10°/125 (GC)	"	(11°)/312-132
	17°/121 (GC)	"	(03°)/309-129
053191-m1	12°/128 (GC)	30°/155	(12°)/317-137
011690-m9	21°/109 (TM)	"	00°/300-120
102389-m3	00°/228-048 (SRC)	"	(08°)/237-057
102389-m1	15°/115 (GC)	"	(10°)/304-124
102289-m5	21°/090 (GC)	"	(06°)/284-104
011690-m8	10°/235 (RX)	"	03°/239
102289-m3	11°/213 (SRC)	"	(04°)/218-138
060391-m1	08°/119 (RX)	"	25°/354

"upper" Tuscarora Sandstone:

101589-m2	11°/235 (SRC)	30°/165	00°/238-058
041491-m1	10°/100 (TX)	"	02°/288
041491-m2	04°/089 (TX)	25°/157	04°/279
041491-m3	05°/090 (TX)	"	04°/277
041491-m4	27°/345 (TX)	"	50°/355
041491-m5	03°/335 (TX)	"	28°/339
011690-m4	15°/280 (TX)	30°/165	25°/276
011690-m3	15°/305 (TX)	"	35°/301
041491-m6	20°/295 (TX)	"	37°/288
041491-m7	15°/315 (TX)	"	40°/313
101289-m1	07°/310 (RX)	27°/163	28°/313
041491-m8	10°/281 (TX)	30°/165	21°/279
041491-m9	00°/295-115 (TX)	"	18°/298
041491-m11	25°/285 (TX)	"	36°/275
101189-m6	10°/145 (TX)	30°/167	10°/326
101189-m5	00°/265-85 (SRC)	"	(04°)/264-084
041391-m1	15°/295 (TX)	30°/165	32°/284
101189-m2x	27°/291 (TX)	"	40°/272
011690-m2	09°/183 (PX)	30°/167	22°/340

"lower" Tuscarora Sandstone:

100989-m2	10°/183 (SRC)	25°/154	(04°)/289-109
101690-m1	25°/130 (TX)	25°/170	09°/317
011690-m11	15°/305 (TX)	"	32°/302
	10°/320 (TX)	"	31°/322

Juniata Formation:

100989-m5	12°/297 (TX)	32°/167	30°/292
100389-m3	20°/163 (SC-plane)	"	273-093 (flow)
100989-m4	13°/101 (SRC)	"	00°/292-112
100989-m6	21°/106 (SRC)	"	(04°)/299-119
100989-m8	10°/238-58 (SRC)	"	(06°)/243-63
100789-m1	10°/175 (PX)	27°/169	17°/353

	25°/164 (PX)	"	04°/047
011590-m3	17°/315 (TX)	"	38°/314
120789-m21	20°/265 (TX)	"	19°/262
120789-m22	17°/265 (TX)	"	17°/263
100289-m6	20°/281 (TX)	26°/171	27°/278
100289-m1	17°/093 (TX)	"	10°/099
100289-m5	10°/123 (TX)	"	06°/315
011190-m2	05°/305 (TX)	"	23°/307
129789-m16	15°/294 (TX)	30°/160	34°/290
120789-m17	03°/004 (PX)	"	33°/345
120789-m19	19°/103 (PX)	"	26°/027
120789-m15	20°/305 (GC)	25°/157	00°/314-134
	05°/235 (GC)	"	00°/241-61
120789-m13	10°/273 (TX)	"	20°/274
120789-m12	10°/125 (TX)	"	12°/312
120789-m11	37°/169 (SC-plane)	25°/156	296-116 (flow)
120789-m10	02°/107 (RX)	"	13°/292
081091-m46	11°/291 (TX)	"	24°/290
081091-m45	13°/285 (RX)	"	24°/283
081091-m44	20°/348 (TX)	"	45°/352
081091-m43	11°/307 (TX)	"	26°/307
081091-m42	12°/277 (TX)	"	19°/277
081091-m51	12°/286 (RX)	25°/157	27°/285
081091-m50	11°/277 (TX)	"	24°/276
081091-m49	10°/133 (RX)	"	13°/320
081091-m48	08°/109 (PX)	"	20°/005
081091-m47	17°/205 (SC-axis)	"	00°/211-31
	10°/253 (SC-axis)	"	(07°)/255-75
	01°/267 (SC-axis)	"	(05°)/272-92
081091-m41	02°/352 (TX)	23°/159	24°/002
081091-m40	13°/277 (RX)	"	23°/277
081091-m39	20°/281 (TX)	"	30°/278
081091-m38	11°/280 (TX)	"	21°/279
081091-m37	05°/260 (RX)	"	09°/264
081091-m36	10°/269 (TX)	"	17°/272
081091-m35	18°/287 (TX)	"	30°/283
081091-m34	20°/335 (PX)	"	35°/344
081091-m33	16°/315 (RX)	"	36°/316
081091-m32	08°/305 (TM)	23°/160	(27°)/307-127
	05°/283 (TM)	"	(17°)/286-106
081091-m31	05°/085 (TX)	"	02°/274
120789-mx	20°/097 (GC)	25°/156	00°/287-107
120789-m4	15°/105 (GC)	"	00°/295-115
120789-m7	05°/330 (RX)	"	30°/343
120789-m9	10°/283 (TX)	"	24°/284
091889-m1	09°/091 (GC)	"	(01°)/280-100
100289-m23	10°/287 (TX)	25°/165	22°/287
	22°/314 (TX)	"	42°/313
100289-m22	15°/245 (RX)	"	10°/247
100289-m21	10°/317 (RX)	"	32°/319
120789-m2	19°/267 (PX)	"	34°/317
120789-m1	20°/289 (TX)	"	32°/285
092290-m2	17°/183 (TM)	"	(07°)/189-009
092290-m1	17°/289 (TX)	"	29°/286
120289-m19	10°/299 (TX)	"	26°/300

	10°/315 (TX)	"	31°/317
120289-m17	09°/297 (TX)	"	25°/298
120289-m18	20°/303 (TX)	"	36°/300
	10°/280 (TX)	"	21°/279
	10°/325 (TX)	"	33°/328
120289-m16	12°/291 (TX)	"	36°/290
120289-m14	10°/281 (TX)	"	20°/282
	10°/315 (TX)	"	31°/317
120289-m13	27°/282 (TX)	23°/159	37°/276
120289-m12	26°/291 (TX)	"	40°/286
120289-m10	11°/248 (TX)	"	10°/250
120289-m9	15°/273 (TX)	"	24°/272
120289-m6	08°/067 (GC)	"	(08°)/358-178
120289-m7	11°/075 (PX)	"	24°/013
072290-mx	07°/062 (PX)	25°/165	28°/007
	07°/042 (PX)	"	29°/002
091089-m1	01°/265 (SRC)	23°/160	00°/272-92
090989-m1	13°/245 (SRC)	"	(08°)/246-66
120289-m5	15°/082 (TM)	"	00°/269-89
090689-m2	00°/255-75 (SRC)	23°/163	00°/262-82
090689-m1	01°/255 (GC)	"	00°/262-82
090689-m5	15/135 (SC-plane)	25°/165	293-113 (flow)
120289-m2	06°/341 (RX)	28°/167	32°/353
090289-m2	15°/335 (RX)	"	43°/347
120289-m1	28/129 (PL)	33°/161	00°/318-138
072090-m1	07°/325 (RX)	"	40°/345
072090-m2	12°/047 (RX)	"	44°/004

outcrop locality: SOUTH GAP

Code	original measurement	first correction	final result
<u>Rose Hill Formation:</u>			
060191-m1	11°/315 (RX)	28°/175	31°/308
060191-m3	25°/265 (TX)	"	21°/254
060191-m2	27°/265 (TX)	"	23°/252
060191-m18	14°/230 (RX)	28°/170	24°/321
060191-m19	20°/333 (RX)	"	48°/342
121090-m4	15°/092 (TX)	"	05°/102
121090-m3	20°/230 (RX)	"	25°/298
060191-m14	09°/135 (TX)	"	14°/314
060191-m16	11°/285 (RX)	"	34°/332
060191-m17	04°/256 (SRC)	"	(02°)/255-075
060191-m15	10°/021 (TX)	"	27°/026
060191-m9	26°/047 (PX)	"	47°/020
060191-m10	38°/171 (PX)	"	09°/173
081191-m51	18°/275 (TX)	"	22°/265
081191-m50	05°/283 (TX)	"	15°/280
081191-m49	02°/295 (TX)	"	17°/291
081191-m48	20°/115 (TM)	29°/168	(07°)/296-116
081191-m47	10°/068 (TM)	"	(12°)/254-74
081191-m46	15°/102 (TM)	"	(01°)/286-106

081191-m45	03°/085 (TM)	"	(01°)/266-086
081191-m44	05°/080 (TM)	"	(01°)/261-081
081191-m43	05°/265 (TM)	"	(08°)/262-082
081191-m42	35°/137 (GC)	"	(08°)/322-142
081191-m41	21°/115 (GC)	"	(02°)/300-120
081191-m40	07°/083 (GC)	"	(03°)/265-085
081191-m39	02°/076 (GC)	"	(02°)/258-078
081191-m38	06°/105 (GC)	"	(08°)/286-106
081191-m37	05°/247 (GC)	"	(01°)/245-065
081191-m36	14°/108 (GC)	"	(01°)/292-112
081191-m35	20°/103 (GC)	"	(05°)/290-110
081191-m34	10°/080 (GC)	"	(07°)/265-085
081191-m33	03°/259 (GC)	"	(03°)/257-077
081191-m32	01°/067 (GC)	"	(05°)/249-069
081191-m31	11°/125 (GC)	"	(10°)/306-126
081191-m30	04°/076 (TM)	"	(03°)/259-079
081191-m29	20°/278 (RX)	29°/167	40°/318
081191-m29x	02°/258 (TM)	"	00°/257-077
081191-m28	07°/297 (RX)	"	40°/338
081191-m28x	02°/241 (SRC)	"	(06°) 242-062
060191-m7	15°/265 (RX)	28°/170	34°/324
060191-m8	10°/265 (RX)	"	31°/330
060191-m11	49°/143 (PX)	"	25°/121
060191-m12	45°/166 (PX)	"	16°/160
060191-m13	60°/185 (PX)	"	33°/195
060291-m4	18°/239 (TX)	"	05°/233
060291-m1	32°/225 (PX)	"	27°/278
120190-m1	10°/245 (SRC)	"	(01°)/242-062
060191-m6	35°/265 (RX)	"	47°/298
060191-m9	16°/255 (TX)	"	11°/249
081290-m1	05°/253 (SRC)	29°/168	(01°)/250-70
081090-m3	26°/165 (GC)	"	(03°)/342-162
	24°/125 (GC)	"	(01°)/310-130
	30°/165 (GC)	"	(01°)/345-165
	27°/161 (GC)	"	(02°)/341-161
080990-m9	09°/213 (GC)	"	(11°)/213-033
	25°/135 (GC)	"	00°/318-138
	05°/205 (GC)	"	(17°)/207-027
	20°/153 (GC)	"	(09°)/338-158
	12°/061 (GC)	"	(19°)/250-070
	28°/161 (GC)	"	(01°)/341-161
	14°/117 (GC)	"	(04°)/299-119
080990-m10	07°/229 (SRC)	"	(06°)/228-048
080990-m11	00°/265-085 (PL)	"	(02°)/265-085
080990-m7	08°/260 (SRC)	"	(08°)/256-076
	00°/253-073 (SRC)	"	(02°)/254-074
080990-m8	21°/253 (RX)	"	34°/308
080990-m5	20°/125 (GC)	"	(02°)/309-129
080990-m6	00°/245-065 (SRC)	"	(06°)/246-066
080990-m1	02°/265 (TM)	"	(06°)/263-083
080990-m3	04°/241 (SRC)	"	(03°)/241-061
080990-m2	14°/225 (RX)	"	25°/318
080990-m4	26°/197 (GC)	"	00°/194-014
	27°/121 (GC)	"	(05°)/307-127
080390-m3	09°/066 (SRC)	29°/167	(12°)/252-072

080390-m2	14°/175 (RX)	"	15°/342
080390-m1	02°/227 (SRC)	"	00°/226-046
060391-m8	10°/225 (RX)	27°/171	23°/328
060391-m7x	04°/285 (RX)	"	31°/344
060391-m6x	22°/233 (RX)	"	26°/300
080190-mx4	40°/167 (RX)	"	13°/159
080190-mx3	20°/198 (RX)	"	13°/306
080190-mx2	03°/139 (RX)	"	24°/353
080190-mx1	14°/243 (SRC)	"	(04°)/239-059
080190-m1	00°/265-085 (TM)	"	(01°)/265-085
080190-m2	00°/255-075 (GC)	"	(02°)/256-076
060391-m2	06°/041 (RX)	"	34°/004
073090-m1	26°/190 (TM)	"	00°/188-008

"upper" Tuscarora Sandstone:

072790-m1	22°/205 (SRC)	28°/169	00°/206-026
072790-m2	19°/135 (RX)	"	07°/325
072690-m1	05°/322 (PX)	"	33°/344
072690-m1x	02°/355 (RX)	"	30°/348
072690-m3	10°/355 (TX)	"	37°/351
072690-m3x	12°/035 (TX)	"	34°/034
072690-m2	10°/035 (TX)	"	34°/049
073190-m1	20°/269 (PX)	"	36°/315
073190-m2	20°/279 (PX)	"	39°/318
041591-m11	29°/345 (TX)	24°/174	52°/340
041591-m12	16°/330 (TX)	"	38°/324
041591-m10	20°/355 (TX)	"	44°/355
041591-m9	17°/334 (TX)	"	39°/329
041591-m8	15°/325 (TX)	"	36°/319
041591-m7	10°/295 (TX)	"	21°/289
041591-m6	24°/335 (TX)	"	46°/329
041591-m5	29°/330 (TX)	"	50°/320
072490-m2	05°/015 (PX)	28°/169	34°/352
041591-m4	25°/323 (TX)	24°/174	44°/312
072490-m1	18°/230 (PX)	28°/169	24°/309
041591-m3	26°/333 (TX)	24°/174	47°/322
081191-m27	12°/246 (TM)	28°/169	(04°)/242-062

"lower" Tuscarora Sandstone:

041591-m2x	20°/315 (TX)	24°/174	37°/307
041591-m1	14°/313 (TX)	"	32°/305
081890-m2	11°/322 (TX)	"	31°/317
081890-m1	06°/331 (TX)	"	31°/328
081790-m5	12°/293 (TX)	"	23°/285
081790-m4	02°/318 (TX)	"	21°/315
081790-m3	04°/132 (TX)	"	14°/311
081790-m2	05°/162 (RX)	"	18°/357
081690-m3	10°/142 (TX)	"	11°/320
081191-m26	03°/092 (TX)	"	02°/273
081191-m25	14°/251 (TX)	"	07°/246
081191-m24	10°/315 (TX)	"	28°/310
081191-m23	09°/315 (TX)	"	26°/310
081191-m22	12°/287 (TX)	"	21°/281
081191-m21	12°/301 (TX)	"	26°/294

081191-m20	15°/311 (TX)	"	32°/303
<u>Juniata Formation:</u>			
081690-m2	07°/325 (RX)	24°/174	27°/321
081690-m1	19°/135 (RX)	"	01°/318
081690-m3	06°/105 (TX)	"	02°/286
081590-m1	08°/311 (TX)	"	25°/306
081390-m3	07°/297 (TX)	"	19°/293
081390-m1	18°/329 (TX)	"	39°/323
081490-m3	01°/288 (RX)	"	12°/285
081490-m2	24°/070 (PX)	"	40°/032
081190-m3	18°/075 (PX)	27°/172	34°/026
081191-m1	07°/307 (TX)	"	26°/301
081191-m2	14°/287 (TX)	"	24°/278
081191-m3	15°/289 (RX)	"	25°/279
081191-m4	01°/116 (TX)	"	13°/294
081191-m5	19°/115 (PX)	"	21°/028
081191-m6	05°/300 (TX)	"	22°/295
081191-m7	15°/335 (TX)	"	40°/330
081191-m8	07°/321 (TX)	"	30°/316
081191-m9	10°/323 (TX)	"	33°/318
081191-m10	03°/322 (TX)	"	26°/319
081191-m11	03°/285 (RX)	27°/174	12°/281
081191-m12	10°/303 (TX)	"	26°/296
081191-m13	15°/305 (TX)	"	31°/295
081191-m14	07°/259 (TX)	"	04°/257
081191-m15	01°/288 (TX)	"	12°/284
081191-m16	02°/287 (TX)	"	12°/283
081191-m17	01°/125 (TX)	"	16°/304
081191-m18	14°/340 (TX)	"	40°/336
081290-m8	36°/215 (PX)	27°/172	24°/260
081290-m7	15°/303 (TX)	"	31°/293
081290-m6	06°/333 (TX)	"	31°/330
081290-m5	06°/331 (TX)	"	30°/328
081290-m4	04°/335 (TX)	"	30°/332
081290-m3	10°/311 (RX)	"	30°/304
081290-m2	10°/275 (TX)	"	15°/270
081190-m4	20°/320 (PX)	"	45°/338
	14°/314 (TX)	"	34°/306
081090-m3	30°/204 (RX)	"	18°/272
081190-m2	25°/286 (TX)	"	31°/270
081190-m1	00°/277-097 (SC-axis)	"	07°/275
080890-m2	40°/295 (TX)	"	49°/270
080890-m1	20°/204 (wing of TX)	30°/166	20°/306
	33°/183 (wing of TX)	"	10°/246
			(trough axis: 10°/254)
080790-m2	16°/109 (TM)	28°/159	(02°)/292-112
080790-m1	17°/238 (SRC)	34°/172	00°/233-053
010391-m1	20°/205 (SRC)	27°/172	00°/215-035
080290-m1	06°/249 (SRC)	"	00°/248-068
080190-m5	14°/263 (RX)	"	26°/251
080190-m4	00°/241-061 (SRC)	"	(00°)/240-060
080190-m3	26°/101 (PL)	34°/148	(01°)/287-107

outcrop locality: GAP MOUNTAIN

Code	original measurement	first correction	final result
<u>Rose Hill Formation:</u>			
060990-m2	09°/243 (GC)	61°/145	(02°)/237-57
060990-m3	10°/225 (SRC)	"	(20°)/233-53
080991-m43	35°/175 (TX)	"	12°/354
080991-m44	30°/178 (TX)	"	27°/358
080991-m45	30°/140 (TX)	"	31°/331
<u>"upper" Tuscarora Sandstone:</u>			
060790-m1	44°/205 (TX)	60°/155	03°/019
060590-m3	40°/157 (TX)	50°/155	10°/347
061190-m1	37°/165 (PX)	"	15°/321
060590-m2	45°/165 (TX)	"	05°/353
060691-mx	37°/194 (TX)	"	05°/017
080991-m33	38°/170 (TX)	"	20°/358
080991-m34	33°/180 (TX)	"	12°/007
080991-m35	39°/155 (TX)	"	12°/346
080991-m36	27°/167 (TX)	"	22°/357
080991-m37	07°/177 (TX)	"	38°/013
080991-m38	16°/170 (TX)	60°/155	42°/005
080991-m39	12°/181 (TX)	"	40°/020
080991-m40	27°/170 (TX)	"	30°/002
080991-m41	30°/164 (TX)	"	30°/354
080991-m42	35°/190 (TX)	"	18°/015
<u>"lower" Tuscarora Sandstone:</u>			
052790-m1	45°/193 (TX)	60°/145	04°/007
052790-m2	55°/169 (TX)	59°/146	02°/350
052690-m3	35°/190 (TX)	"	12°/013
052690-m1	32°/189 (PX)	"	40°/304
052490-m3	39°/173 (TX)	58°/151	17°/359
052490-m2	31°/187 (TX)	"	19°/014
052390-m2	50°/185 (TX)	55°/153	01°/004
052390-m1	40°/173 (PX)	"	20°/304
052190-m3	27°/175 (TX)	"	22°/005
052190-m2	46°/160 (SRC)	55°/145	(08°)/346-166
<u>Juniata Formation:</u>			
092691-M8	10°/156 (TX)	34°/159	24°/347
092691-M5	04°/019 (PL)	37°/115	(08°)/217-037
092691-M3	06°/173 (TX)	"	36°/009
	02°/343 (TX)	"	22°/012
092691-m2	02°/325 (TX)	50°/135	48°/341
092691-m1	29°/132 (RX)	50°/143	20°/321
092691-m9	25°/135 (TX)	55°/145	30°/325
051990-m1	36°/213 (PL)	54°/133	(12°)/199-019
051890-m3	30°/092 (SC-axis)	54°/135	12°/289
092691-m7	22°/172 (TX)	"	22°/002
051890-m2	40°/137 (PX)	"	14°/321
051690-m1	25°/175 (TX)	57°/150	27°/006

051590-m2	40°/143 (PX)	60°/145	20°/339
092691-m6	02°/179 (RX)	56°/153	46°/021
052690-m6	50°/170 (TX)	60°/163	10°/359
051190-m3	26°/175 (TX)	55°/135	21°/353
051190-m2	25°/185 (TX)	"	14°/011
092691-m4	16°/186 (TX)	"	20°/019
	24°/178 (TX)	"	18°/007
052690-m4	02°/060 (PL)	"	(09°)/248-068
052690-m5	34°/175 (TX)	50°/145	16°/357

outcrop locality: McCOY

Code	original measurement	first correction	final result
<u>Rose Hill Formation:</u>			
050391-m2	41°/115 (TX)	65°/155	14°/305
050391-m1	20°/115 (GC)	"	(31°)/291-111
052991-m2	05°/245 (SRC)	"	(01°)/241-61
040491-m4	20°/075 (PM)	67°/145	01°/268
040491-m3	50°/135 (SRC)	"	(12°)/321-141
040491-m1	42°/123 (TM)	"	(16°)/311-131
032391-m12	53°/107 (GC)	"	(01°)/308-128
080991-m32	36°/127 (TX)	65°/155	23°/311
080991-m31	30°/167 (TX)	"	34°/348
080991-m30	43°/147 (TX)	"	22°/329
080991-m29	22°/140 (RX)	"	42°/317
080991-m28	39°/113 (TX)	"	15°/304
080991-m27	75°/161 (TM)	"	10°/338-158
080991-m26	02°/265 (TX)	67°/145	26°/248
080991-m25	04°/249 (PL)	"	(12°)/236-056
080991-m24	06°/077 (TM)	"	(18°)/251-071
080991-m23	26°/085 (TM)	"	(12°)/272-092
080991-m22	12°/081 (TM)	"	(17°)/259-079
080991-m21	45°/238 (TM)	"	(17°)/193-013
080991-m20	05°/263 (TM)	"	(37°)/242-062
080991-m19	55°/135 (TM)	"	(12°)/319-139
080991-m18	62°/126 (TM)	"	(04°)/316-136
080991-m17	65°/151 (TM)	"	(02°)/328-148
080991-m16	64°/147 (TM)	"	(03°)/326-146
080991-m15	55°/110 (TM)	"	(06°)/308-128
<u>"upper" Tuscarora Sandstone:</u>			
covered - no measurements			
<u>"lower" Tuscarora Sandstone:</u>			
032391-m11	46°/103 (TX)	"	11°/297
032391-m10	37°/114 (TX)	"	18°/292
032391-m9	50°/135 (TX)	"	17°/318
032391-m8	39°/107 (TX)	"	19°/296
032391-m7	39°/105 (TX)	"	17°/294
032391-m6	46°/126 (TX)	"	18°/313
032391-m5	45°/195 (TX)	"	08°/358

Juniata Formation:

032391-m4	36°/125 (TX)	62°/158	19°/310
032391-m3	62°/125 (TX)	"	07°/317
032391-m2	51°/117 (TX)	"	02°/313
032391-m1	60°/175 (PX)	"	15°/260

outcrop locality: **DRAPER MOUNTAIN**

Code	original measurement	first correction	final result
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Rose Hill Formation:

covered - no measurements

"upper" Tuscarora Sandstone:

032890-m3	46°/195 (TX)	60°/159	07°/314
032890-m2	60°/185 (TX)	68°/160	08°/334
032790-m3	10°/245 (TX)	63°/164	04°/268
080891-m15	18°/211 (RX)	"	26°/293
080891-m14	04°/235 (TX)	"	14°/267
080891-m13	42°/155 (PX)	"	22°/328
080891-m12	35°/191 (PX)	"	35°/010
080891-m11	12°/245 (TX)	"	03°/277
080891-m17	21°/221 (TX)	"	16°/289
080891-m18	13°/238 (TX)	"	08°/274
080891-m19	25°/230 (TX)	68°/160	08°/282
080891-m20	45°/117 (TX)	60°/159	06°/009
080891-m21	50°/275 (TX)	"	16°/305

"lower" Tuscarora Sandstone:

040590-m2	30°/193 (PX)	59°/162	36°/008
040590-m3	33°/205 (TX)	"	14°/305
032690-m4	35°/215 (TX)	63°/164	11°/304
032690-m3	90°/305-125 (PX)	"	48°/225
080891-m10	40°/200 (TX)	"	16°/317
080891-m9	45°/145 (PX)	"	24°/307
080891-m8	23°/237 (TX)	"	03°/283
080891-m7	38°/215 (TX)	"	10°/308
080891-m6	30°/220 (PX)	"	50°/016
080891-m5	25°/235 (TX)	"	04°/285
080891-m4	45°/182 (PX)	"	24°/018
080891-m3	50°/208 (TX)	"	04°/318
080891-m2	45°/190 (TX)	"	05°/325

Juniata Formation:

covered - no measurements

outcrop locality: CATAWBA MOUNTAIN I

Code	original measurement	first correction	final result
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Rose Hill Formation:

covered - no measurements

"upper" Tuscarora Sandstone:

080891-m37	52°/181 (TX-plane)	45°/155	313-133 (flow)
080891-m36	17°/157 (TX)	"	28°/324
080891-m35	33°/159 (TX)	"	12°/325
080891-m34	25°/141 (TX)	"	18°/309
080891-m33	43°/132 (TX-plane)	"	307-127 (flow)
080891-m32	38°/138 (TX)	"	06°/309
080891-m31	45°/135 (TX-plane)	"	317-137 (flow)
080891-m30	20°/148 (TX)	"	22°/314
080891-m29	31°/149 (TX)	"	12°/317
080891-m28	30°/155 (TX)	"	15°/322
080891-m27	23°/158 (TX)	"	22°/325
042290-m2	19°/143 (TX)	46°/157	27°/310
042290-m1	10°/133 (TX)	"	33°/296
042390-m5	28°/167 (TX)	45°/155	16°/333
042390-m4	51°/173 (PX)	"	14°/215
042390-m3	50°/180 (PX)	"	19°/225
042390-m2	30°/197 (PX)	46°/156	29°/283
042390-m1	25°/158 (TX)	45°/155	20°/325
080891-m22	29°/177 (TX)	"	13°/342
080891-m24	29°/152 (TX)	"	16°/336
080891-m25	30°/160 (TX)	"	15°/327
080891-m26	27°/154 (TX)	"	18°/324

outcrop locality: CATAWBA MOUNTAIN II

Code	original measurement	first correction	final result
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Rose Hill Formation:

covered - no measurements

"upper" Tuscarora Sandstone:

042590-m3	20°/150 (TX)	35°/165	14°/317
042590-m1	20°/145 (TX)	"	13°/313
042590-m4	30°/165 (TX)	"	05°/333
042490-m2	27°/157 (TX)	"	08°/325
042490-m3	31°/174 (TX)	"	04°/340
042490-m4	21°/265 (PX)	19°/155	34°/287
042490-m5	21°/197 (PX)	49°/162	40°/307

outcrop locality: CASCADES

Code	original measurement	first correction	final result
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Rose Hill Formation:

covered - no measurements

"upper" Tuscarora Sandstone:

080991-m14	04°/335 (TX)	18°/121	19°/338
080991-m13	09°/134 (TX)	"	09°/315
080991-m12	07°/320 (TX)	"	24°/322
080991-m11	04°/345 (TX)	"	17°/348
	11°/015 (TX)	"	15°/020
080991-m10	02°/183 (TX)	"	05°/002
080991-m9	05°/009 (TX)	"	11°/012
080991-m8	01°/005 (TX)	"	08°/006
080991-m7	04°/325 (TX)	"	21°/326

"lower" Tuscarora Sandstone:

080991-m6	15°/318 (PX)	"	32°/309
080991-m5	15°/291 (TX)	"	33°/290
080991-m4	20°/215 (TX)	"	20°/208
053191-m1	01°/215 (TX)	"	02°/215
080991-m3	04°/125 (RX)	"	14°/305
080991-m2	04°/149 (RX)	"	11°/329
080991-m1	05°/315 (TX)	"	23°/316

Juniata Formation:

covered - no measurements

outcrop locality: COVE MOUNTAIN

Code	original measurement	first correction	final result
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"lower" Tuscarora Sandstone:

020391-m1	10°/175 (TX)	34°/169	24°/356
020291-m13	10°/205 (TX)	"	23°/334
020291-m12	12°/005 (TX)	"	46°/007
020291-m3	05°/181 (TX)	"	24°/001
020191-m8	05°/125 (TX)	44°/167	26°/299
020291-m2	04°/337 (TX)	"	48°/332
020191-m5	00°/265-085 (ripple-axis)	"	(05°)/262-082
020191-m3	10°/153 (TX)	"	33°/331
011991-m3	45°/137 (SC-axis)	"	(03°)/328-148
011991-m2	11°/297 (TX)	"	34°/281
032091-m4	10°/151 (TX)	"	32°/329
032091-m3	07°/323 (TX)	"	46°/312
032091-m2	20°/105 (PX)	"	38°/016
032091-m1	20°/165 (PX)	"	24°/349
032791-m6	02°/287 (TX)	"	22°/278
032791-m5	14°/301 (TX)	"	40°/280

032791-m4	12°/270 (TX)	"	16°/259
032791-m7	19°/323 (TX)	"	56°/305
092991-m30	19°/149 (RX)	34°/169	17°/012
092991-m29	29°/192 (PX)	"	14°/293
092991-m28	17°/166 (TX)	"	17°/354
092991-m27	11°/115 (TX)	"	08°/296
092991-m26	06°/315 (TX)	"	33°/307
092991-m24	01°/203 (TX)	"	27°/027
092991-m23	01°/157 (TX)	"	32°/335
092991-m22	01°/287 (TX)	"	16°/282
092991-m21	10°/189 (TX)	"	23°/010
092991-m20	05°/202 (TX)	"	23°/025
092991-m19	09°/351 (TX)	"	42°/352
032790-m3	05°/312 (TX)	44°/167	39°/301
032790-m2	15°/335 (TX)	"	58°/325
032790-m1	05°/335 (TX)	"	48°/326
032091-m5	14°/323 (TX)	44°/166	52°/309
032891-m9	04°/155 (TX)	"	39°/333
032891-m8	02°/330 (TX)	"	43°/324
032891-m7	10°/155 (TX)	"	33°/334
032891-m6	05°/127 (TX)	"	38°/308
032891-m10	29°/143 (RX)	"	20°/020
032891-m5	04°/157 (TX)	"	39°/335
032891-m4	01°/327 (TX)	"	41°/321
032891-m3	25°/159 (TX)	"	19°/339
032891-m2	11°/307 (TX)	"	40°/287
032891-m1	01°/330 (RX)	"	40°/325
040691-m4	05°/287 (TX)	"	24°/275
040691-m3	06°/307 (TX)	"	38°/294
040691-m2	20°/271 (TX)	"	24°/253
040691-m1	36°/295 (TX)	"	51°/252
040691-m6	25°/148 (TX)	"	19°/329
041191-m3	02°/101 (TX)	"	17°/279
041191-m2	40°/285 (RX)	"	46°/241
041191-m1	10°/279 (RX)	"	23°/266
041191-m4	14°/295 (TX)	"	37°/276
040591-m5	02°/329 (TX)	44°/170	42°/321
040591-m7	31°/333 (TX)	"	50°/322
040591-m6	00°/325-145 (TX)	"	39°/317
092991-m18	20°/186 (PX)	44°/167	26°/332
092991-m17	15°/125 (PX)	"	34°/006
092991-m16	01°/140 (TX)	"	36°/321
092991-m15	25°/122 (PX)	"	30°/023
092991-m14	02°/090 (TX)	"	06°/269
092991-m13	03°/315 (TX)	"	38°/304
092991-m12	12°/229 (TX)	"	40°/330
092991-m11	10°/134 (TX)	"	26°/310
092991-m10	04°/165 (TX)	"	40°/345
092991-m9	30°/115 (PX)	"	39°/033
092991-m8	06°/255 (TX)	"	30°/251
092991-m7	01°/163 (TX)	"	43°/341
092991-m6	04°/001 (TX)	"	47°/008
092991-m4	20°/295 (TX)	"	39°/271
092991-m3	12°/273 (TX)	44°/166	20°/259
092991-m2	10°/275 (TX)	"	20°/262

092991-m1	29°/120 (SC-axis)	"	(04°)/308-108
<u>Juniata Formation:</u>			
040591-m4	18°/165 (TX)	44°/173	25°/345
040590-m3	25°/145 (TX)	"	15°/327
122190-m1	12°/117 (TX)	"	14°/297
040591-m2	20°/105 (TX)	"	08°/299
040591-m1	00°/275-95 (RX)	45°/171	10°/270
121990-m4	28°/173 (PX)	"	17°/348
121990-m2	17°/166 (PX)	"	28°/352
121890-m4	04°/281 (TX)	"	20°/271
121890-m3	04°/284 (RX)	44°/167	21°/273
121690-m6	40°/135 (PX)	44°/171	24°/058
121490-m2	16°/335 (TX)	"	64°/328
121490-m1	03°/338 (TX)	48°/160	51°/337
100290-m1	25°/143 (RX)	45°/167	22°/011
093090-m2	19°/095 (PL)	"	00°/283-103
093090-m1	21°/155 (RX)	"	20°/355
092990-m2	19°/113 (SRC)	"	(09°)/296-119
121990-m1	31°/210 (PX)	45°/171	28°/307
121990-m3	24°/187 (PX)	"	23°/333
121890-m5	11°/181 (PX)	44°/167	34°/340
121490-m5	07°/284 (TX)	44°/171	20°/275
121690-m2	06°/285 (RX)	"	21°/274
092891-m12	09°/106 (TX)	45°/171	11°/286
092891-m11	29°/194 (PX)	"	22°/321
092891-m10	03°/307 (TX)	44°/167	35°/297
092891-m9	11°/286 (TX)	"	28°/271
092891-m7	40°/115 (SC-axis)	"	(11°)/302-122
092891-m8	07°/305 (TX)	"	37°/291
092891-m6	06°/285 (RX)	46°/165	26°/272
092891-m5	06°/283 (TX)	"	24°/271
092891-m3	02°/289 (TX)	"	24°/280
092891-m2	05°/113 (TX)	"	15°/267
	15°/096 (TX)	"	03°/282
	01°/275 (TX)	"	22°/288
092891-m1	05°/285 (RX)	"	25°/273
092791-m4	06°/279 (RX)	45°/167	20°/269
092791-m1	14°/253 (GC)	"	(06°)/244-064

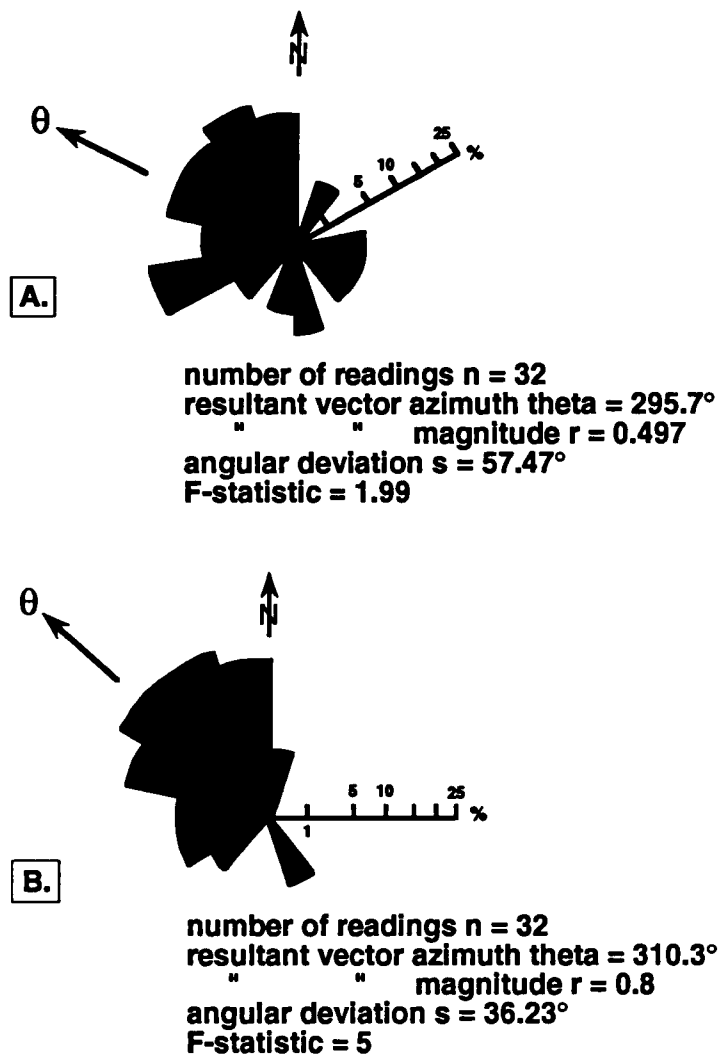


Figure A-1. Unidirectional measurements from the Rose Hill Formation of southwestern Virginia. A - high-angle cross stratification; B - current-ripple cross stratification.

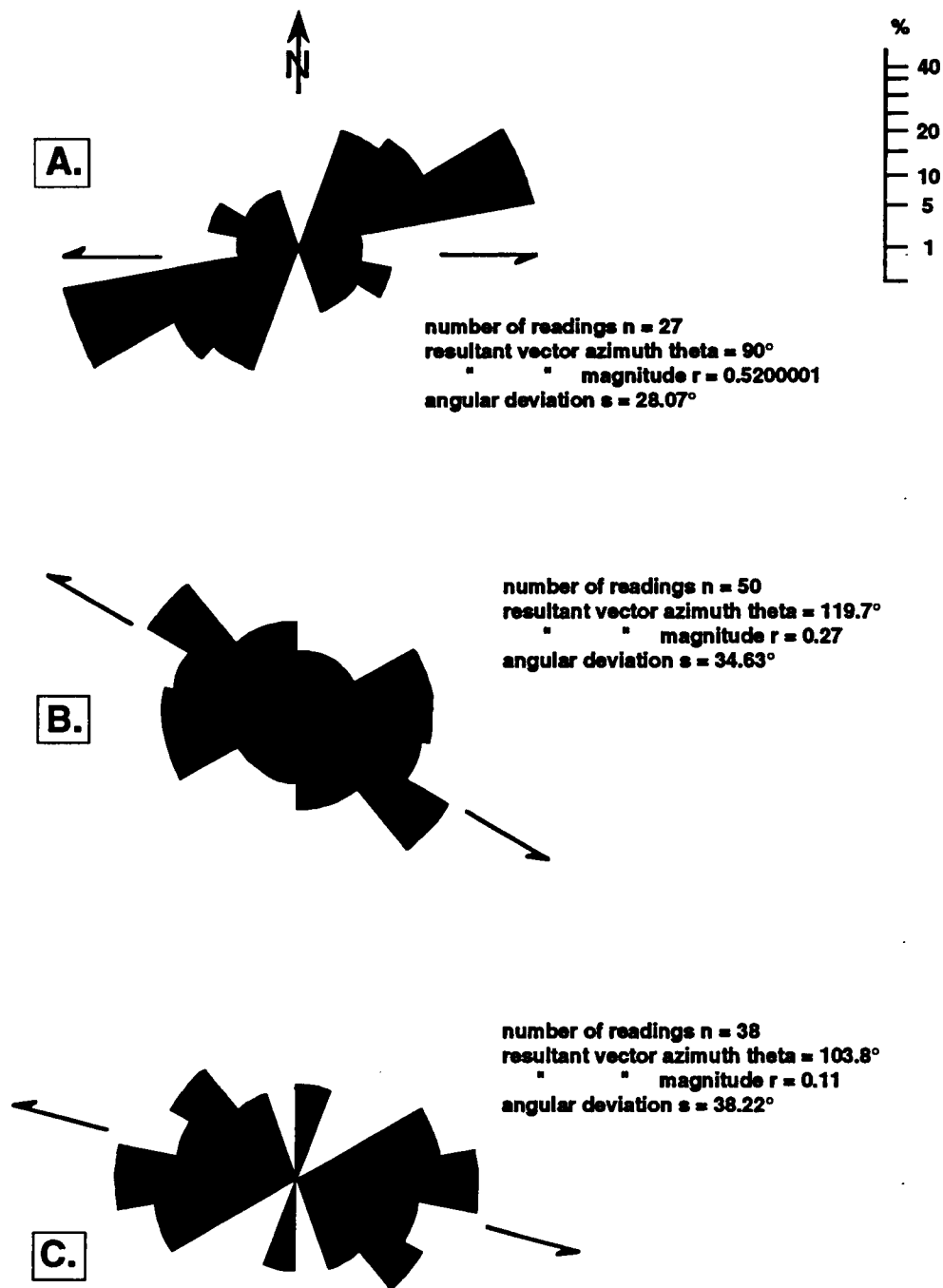


Figure A-2. Bi-directional measurements from the Rose Hill Formation of southwestern Virginia. A - symmetrical-ripple crests; B - gutter casts; C - tool marks.

APPENDIX 3

Sampling Locations for Acritarchs

Mudstone, shale, and siltstone samples were retrieved from the Juniata Formation, Tuscarora Sandstone, and Rose Hill Formation. The aim was to process the samples for organic-walled microphytoplankton (acritarchs). The samples were taken from vertical intervals, commonly between 7 and 15 cm thick, and were put in marked sample bags. The distance to an easily recognizable marker horizon within the outcrop (usually above or below the "Tuscarora unconformity") was measured. The sample bags were left in the outcrop at the sampling spots, and photos were taken at the end of each work day, documenting by photo the exact sampling spots. The samples were shipped to Amoco Production Company in Houston for processing by Dr. Gordon Wood. Due to overseas assignments and constraints dictated by Amoco priorities, the micropaleontological investigations on the samples from the field area are still only rudimentary. Only some samples were processed and these were only screened for occurrences of microfossils. No age assignments are available as of this date.

The sample spots for each outcrop locality are listed in the following pages, because further data and refinement of already available data can be expected from Dr. Wood. The samples are listed with their acronyms for each outcrop locality, the distance to an identified marker horizon is indicated, as is the vertical sampling interval (note: the distance to the marker horizon is measured from the mid-point of the sampling interval).

The results are given as follows: ◇ - sample was not processed; bb - sample was processed, but did not yield fossils (barren of palynomorphs); aa - sample was processed and did yield microfossils (acritarchs).

Sample location: Cove Mountain;

Sample abbreviation: CVE;

Map: Wytheville Quadr. (7.5), VA;

Location: outcrop along VA 306, above (and east of) the northbound lane of I-77; samples CVE-1 to -13 were taken from the outcrop along VA 306 and measured with respect to the Devonian Wallbridge Discontinuity (s. below); note: frequent rock falls!

Sedimentologic log for the upper 2/3 of the Tuscarora Ss. was taken directly along the northbound lane of I-77, with key horizons correlated to VA 306 (ca. 20 m distance);

Stratigraphy: Juniata Fm., Tuscarora Ss.; the Devonian Wallbridge Discontinuity cuts into the Tuscarora Ss., hence there is no Rose Hill Fm. preserved; the contact between the Juniata Fm. and the Tuscarora Ss. is gradational;

Marker Datum: (used here) Devonian Wallbridge Discontinuity situated at the top of the Silurian section; measurements are downward from this datum;

SAMPLE	cm below marker datum	vertical sampling interval (cm)	results
Tuscarora Ss.:			
CVE-9	3460	10	<>
CVE-10	2150	10	<>
CVE-11	0660	10	<>
CVE-12	0240	07	<>
CVE-13	0130	09	<>
Juniata Fm.:			
CVE-1	9604	14	<>
CVE-2	9241	11	<>
CVE-3	7787	07	<>
CVE-4	7659	08	<>
CVE-5	6376	12	<>
CVE-6	5614	11	<>
CVE-7	4853	05	<>
CVE-8	4774	10	<>

Sample location: Fagg;

Sample abbreviation: FGG;

Map: Ironto Quadr. (7.5), VA;

Location: two outcrop localities: 1) Fagg I (along VA 603), 2) Fagg II (along north bank of North Fork Roanoke River, south of west end of railroad tunnel, in woods);

Stratigraphy: Martinsburg Fm./Reedsville Sh., "upper" Tuscarora Ss. Uppermost Martinsburg/Reedsville, Juniata Fm., and "lower" Tuscarora cut out by the "Tuscarora unconformity"; the Devonian Wallbridge Discontinuity cuts from above into the "upper" Tuscarora (i.e. Rose Hill Fm, and most of "upper" Tuscarora are missing, too).

Marker Datum: base of conglomeratic sandstone/sandy conglomerate (= base of "upper" Tuscarora Ss.);

SAMPLE	cm above/below marker datum	vertical sampling interval (cm)	results
locality FAGG I (Martinsburg Fm./Reedsville Sh.):			
FGG-1	45 (below)	10	<>
locality FAGG II (Martinsburg Fm./Reedsville Sh.):			
FGG-2	75 (")	10	<>

Sample locality: Narrows;

Sample abbreviation: NRW;

Map: Narrows Quadr. (7.5), WVA/VA;

Location: outcrop along northbound lane of US 460; note: very dangerous, because of narrow road and busy traffic;

Stratigraphy: Juniata Fm., "lower" Tuscarora Ss., "upper" Tuscarora Ss., Rose Hill Fm.;

Marker Datum: base of sandy conglomerate (= base of "upper" Tuscarora);

SAMPLE	cm above/below marker datum	vertical	sampling interval (cm)	results
Rose Hill Fm.:				
NRW-1	2774 (")		08	aa
NRW-2	3051 (")		10	aa
NRW-3	3329 (")		07	aa
NRW-4	3713 (")		06	aa
NRW-5	4161 (")		08	aa
NRW-6	4609 (")		07	aa
NRW-7	4866 (")		08	<>
NRW-8	5104 (")		07	<>
NRW-9	5234 (")		09	<>
NRW-10	5325 (")		08	<>
NRW-11	5512 (")		07	<>
NRW-12	5615 (")		10	<>
NRW-13	5844 (")		08	<>
NRW-14	6093 (")		08	<>
NRW-15	6303 (")		07	<>
NRW-16	6740 (")		09	<>
NRW-17	6942 (")		09	aa
NRW-18	7961 (")		08	aa
NRW-19	8201 (")		09	aa
"upper" Tuscarora Ss.:				
NRW-20	0449 (above)		10	aa
NRW-21	1435 (")		08	bb
NRW-22A	2248 (")		10	<>
"lower" Tuscarora Ss.:				
Juniata Fm.:				
NRW-33	9804 (below)		04	<>
NRW-32	9435 (")		07	<>
NRW-31	5683 (")		07	<>
NRW-30	4670 (")		10	<>
NRW-29	3932 (")		10	<>
NRW-28	3450 (")		07	<>
NRW-27	3057 (")		08	<>
NRW-26	2461 (")		12	<>
NRW-25	1570 (")		06	<>
NRW-24	1475 (")		10	bb
NRW-23	1155 (")		07	bb
NRW-22B	0095 (")		07	bb

Sample locality: South Gap;

Sample abbreviation: SGP;

Map: Rocky Gap Quadr. (7.5), VA;

Location: outcrop along Interstate I-77, through Rich Mtn./Wolf Creek Mtn.; Juniata Fm., "lower" Tuscarora Ss., and parts of the "upper" Tuscarora Ss. measured along the northbound lane of I-77 (samples SGP-16 through SGP-34); "upper" Tuscarora Ss. and Rose Hill Fm. measured along VA 52 (above the southbound lane of I-77) (samples SGP-1 through SGP-12; uppermost Rose Hill Fm. measured along ledge above VA 52 (samples SGP-13 through SGP-15);

Stratigraphy: Juniata Fm., "lower" Tuscarora Ss., "upper" Tuscarora Ss., Rose Hill Fm.;

Marker Datum: base of conglomeratic sandstone/sandy conglomerate (= base of "upper" Tuscarora Ss.);

SAMPLE	cm above/below marker datum	vertical sampling interval (cm)	results
Rose Hill Fm.			
SGP-3	03235 (")	08	aa
SGP-4	03673 (")	07	aa
SGP-5	04309 (")	07	aa
SGP-6	05162 (")	10	aa
SGP-7	05650 (")	07	aa
SGP-8	06035 (")	08	aa
SGP-9	06221 (")	06	aa
SGP-10	06614 (")	07	aa
SGP-11	06836 (")	08	aa
SGP-12	07038 (")	06	bb
SGP-13	07981 (")	08	aa
SGP-14	08464 (")	09	aa
SGP-15	08704 (")	10	<>
"upper" Tuscarora Ss.:			
SGP-33	01007 (above)	07	<>
SGP-34	01267 (")	07	<>
SGP-1	02336 (")	12	aa
SGP-2	03053 (")	09	aa
"lower" Tuscarora Ss.:			
SGP-26	01233 (")	07	bb
SGP-27	00978 (")	12	<>
SGP-28	00701 (")	09	bb
SGP-29	00551 (")	08	<>
SGP-30	00440 (")	07	bb
SGP-31	00415 (")	07	bb
SGP-32	00003 (")	04	<>
Juniata Fm.:			
SGP-16	10730 (below)	08	<>
SGP-17	09878 (")	06	<>
SGP-18	08366 (")	07	<>
SGP-19	06197 (")	08	<>
SGP-20	04902 (")	09	<>
SGP-21	03885 (")	10	<>
SGP-22	03563 (")	10	<>
SGP-23	03133 (")	09	<>
SGP-24	02586 (")	08	<>
SGP-25	01510 (")	06	bb

Sample locality: Draper Mountain;

Sample abbreviation: DPM;

Map: Pulaski Quadr. (7.5), VA;

Location: top of Draper Mountain, at Pulaski Wayside picnic area; outcrops north and south of US 11;

Stratigraphy: Juniata Fm., "lower" Tuscarora Ss., "upper" Tuscarora Ss., Rose Hill Fm.; the latter is cut from above by the Devonian Wallbridge Discontinuity; note: outcrop is overturned!

Marker Datum: base of conglomeratic sandstone (= base of "upper" Tuscarora Ss.);

SAMPLE	cm above/below marker datum	vertical sampling interval (cm)	results
Rose Hill Fm.:			
DPM-5	2144 (")	20	<>
"upper" Tuscarora Ss.:			
DPM-3	0049 (above)	06	<>
DPM-4	0049 (")	06	<>
"lower" Tuscarora Ss.:			
DPM-1	0267 (below)	09	<>
DPM-2	0005 (")	17	<>

Sample locality: McCoy;

Sample abbreviation: MCY;

Map: Radford North Quadr. (7.5), VA;

Location: outcrop on east-side of New River Water Gap, along Norfolk and Western railroad tracks;

Stratigraphy: Juniata Fm., "lower" Tuscarora Ss., "upper" Tuscarora Ss., Rose Hill Fm.; outcrop is in the same strike belt as Gap Mountain outcrop locality;

Marker Datum: base of conglomeratic sandstone (= base of "upper" Tuscarora Ss.);

SAMPLE	cm above/below marker datum	vertical sampling interval (cm)	results
Rose Hill Fm.:			
MCY-2	1485 (above)	15	<>
"upper" Tuscarora Ss.:			
"lower" Tuscarora Ss.:			
MCY-1	0410 (below)	20	<>

Sample locality: Gap Mountain;

Sample abbreviation: GPM;

Map: Newport Quadr. (7.5), VA;

Location: wind gap on crest of Gap Mountain, along southeast-bound lane of US 460, at the Giles/Montgomery county line;

Stratigraphy: Juniata Fm., "lower" Tuscarora Ss., "upper" Tuscarora Ss., Rose Hill Fm.; base of Juniata Fm. is not exposed; Juniata Fm. and "lower" Tuscarora Ss. are covered along road level and were measured along crest of Gap Mountain (samples GPM-1 through GPM-12); "upper" Tuscarora Ss. and Rose Hill Fm. were measured along road level (samples GPM-13 through GPM-20);

Marker Datum: base of conglomeratic sandstone (= base of "upper" Tuscarora Ss.);

SAMPLE	cm above/below marker datum	vertical sampling interval (cm)	results
Rose Hill Fm.:			
GPM-14	1892 (above)	17	<>
GPM-15	2222 (")	20	aa
GPM-16	3377 (")	18	aa
GPM-17	3422 (")	15	aa
GPM-18	4194 (")	23	aa
GPM-19	5065 (")	21	<>

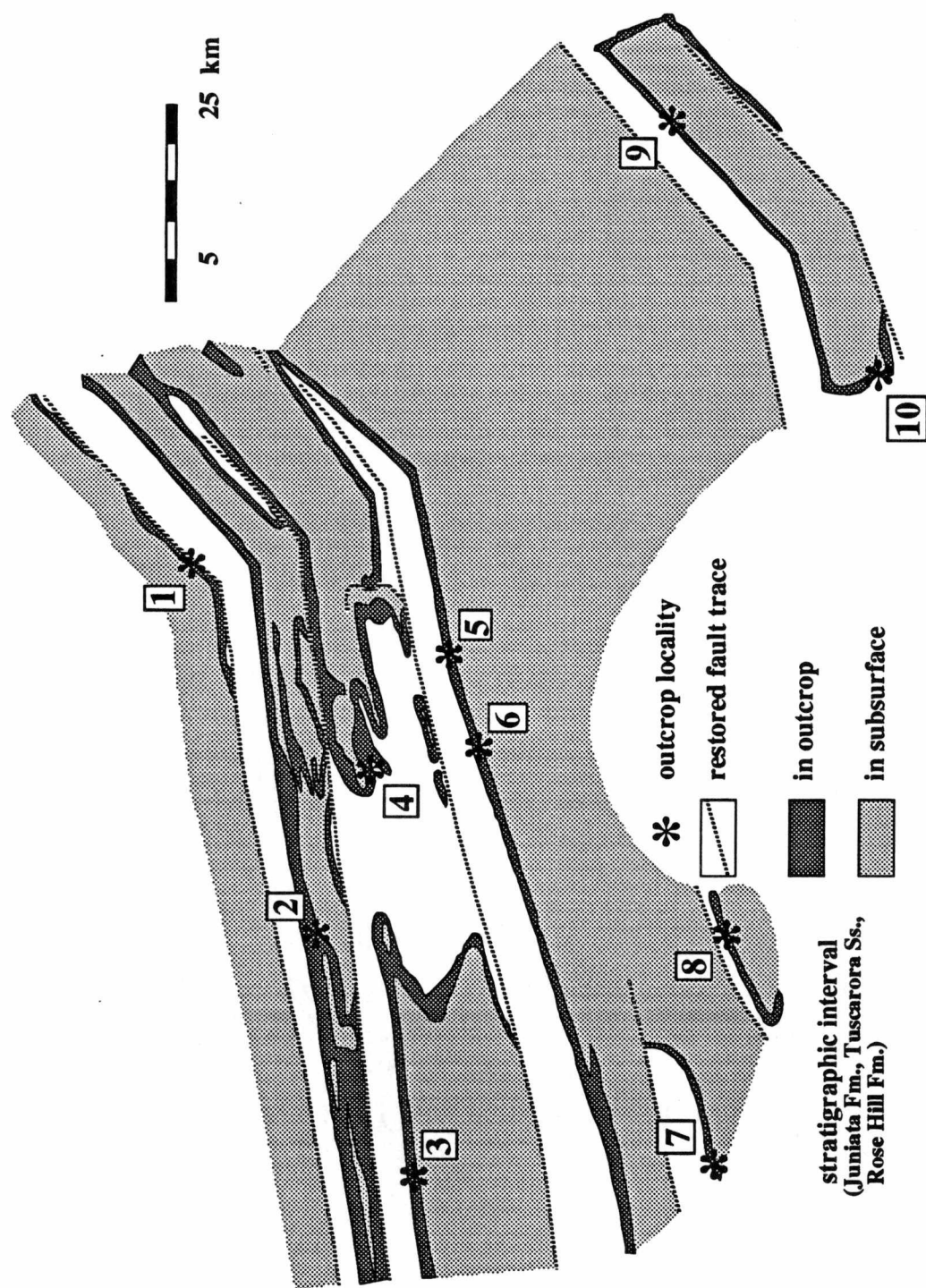
GPM-20	5483 (")	12	aa
"upper" Tuscarora Ss.:			
"lower" Tuscarora Ss.:			
GPM-9	1500 (")	15	<>
GPM-10	1165 (")	17	bb
GPM-11	0414 (")	20	<>
GPM-12	0295 (")	10	<>
GPM-13	0005 (")	10	<>
Juniata Fm.:			
GPM-1	6658 (below)	12	<>
GPM-2	6143 (")	15	<>
GPM-3	5922 (")	14	<>
GPM-4	4374 (")	17	<>
GPM-5	3317 (")	15	<>
GPM-6	2666 (")	17	<>
GPM-7	2329 (")	15	<>
GPM-8	1986 (")	13	<>

APPENDIX 4

Palinspastic Base Map for Southwestern Virginia

The palinspastic base map (Figure A-3) is based on four unpublished balanced cross sections through southwestern Virginia constructed by B. Couzens and Dr. W. Dunne (University of Tennessee-Knoxville). These cross sections constitute an improvement over the cross sections by Woodward and Gray (1985) and Roeder and others (1978) through the same area. The different thrust sheets were restored to their pre-Alleghanian position based on the balanced cross sections. Because of preserved cut-offs, this did not provide any difficulties. An exception, however, is restoration of the original location of the Catawba Syncline, because displacement on the Pulaski thrust is not easily ascertained. Bartholomew (1987) estimated a displacement on the Pulaski thrust of ca. 100 to 110 km. This value seems to be highly unlikely (too large), because of the employment of an overly shallow ramp. Woodward and Gray (1985) estimated a displacement of ca. 30 km, whereas Hatcher (pers. comm., see also Hatcher and others, 1989) gave a value of 62 km. A value of 47 km for displacement on the Pulaski thrust was selected for construction of the palinspastic map.

Figure A-3: Palinspastic base map for southwestern Virginia. Outcrop localities are as follows: 1 - Gap Mills; 2 - Narrows; 3 - South Gap; 4 - Cascades; 5 - Gap Mountain; 6 - McCoy; 7 - Cove Mountain; 8 - Draper Mountain; 9 - Catawba Mountain I, II; 10 - Fagg I, II. Map is based on unpublished balanced cross sections by B. Couzens and W. Dunne.



VITA

Joachim Oskar Dorsch was born in Gerolzhofen, Bavaria (West Germany) on February 4, 1959. He grew up in the tiny village of Sulzheim, Bavaria. The 'Volksschule' (primary school) was attended in Sulzheim and Wülflingen, Bavaria. From 1970 to 1979, he attended the humanistic branch of the 'Regiomontanus-Gymnasium Haßfurt' (secondary school) in Haßfurt, Bavaria, and graduated with the 'Abitur', which includes the Latinum and Graecum. The obligatory military service was spent in Bayreuth and Weiden, Bavaria. From November 1980 to July 1987, he studied geology and paleontology at the 'Julius-Maximilians-Universität Würzburg', Bavaria, and completed his 'Vordiplom' in March 1983 and his 'Diplom' in July 1987. The studies in Germany were interrupted by one year of graduate studies in geology at the State University of New York at Buffalo, New York (August 1983 to May 1984). He entered the Ph.D. program in geology at the University of Tennessee at Knoxville in August 1987 and was supported as both a Teaching and as a Research Assistant.