

**STRATIGRAPHIC ARCHITECTURE AND PALEOGEOGRAPHY OF THE  
JUNIATA FORMATION, CENTRAL APPALACHIANS**

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## ABSTRACT

Late Ordovician (Cincinnatian) strata of the central Appalachians provide an opportunity to study the effects of both tectonics and eustasy within a foreland-basin setting. The Juniata Formation consists of red sandstones, siltstones, and shales that were deposited as part of an extensive siliciclastic basin-fill that resulted from the Taconic Orogeny. This study attempts to resolve some of the questions regarding tectonic and eustatic influences on sedimentation by (1) reconstructing the paleogeographic environment of the Juniata Formation and (2) examining the stratigraphic architecture of the Juniata Formation. A combination of both outcrop and subsurface data was analyzed.

Seven facies were identified in this study, including: (1) “proto-vertisols”, (2) red shale/mudstone, (3) siltstone/silty mudstone with interbedded sandstones, (4) quartz arenite and sublithic arenite, (5) argillaceous sandstone, (6) hummocky-bedded sandstones and siltstones, and (7) lithic sandstones and conglomerates. These facies are grouped into four facies associations (A–D), which are interpreted to be deposited from the inner shelf to the upper shoreface. Isopach and paleocurrent data suggest the shoreline was oriented NE–SW and detrital sediment was dispersed west and southwest across the basin.

Tectonics controlled the 2<sup>nd</sup>-Order basin-fill pattern, and these patterns vary along the strike of the basin. Eustatic changes are expressed in two 3<sup>rd</sup>-Order sequences that were identified in the formation, and possibly in the 4<sup>th</sup>-Order (?) cycles of Facies Association A. The Ordovician–Silurian boundary is expressed as an unconformity throughout the study area, and along-strike variations in the structural setting of the basin were important in its development.

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## 1. INTRODUCTION

Uppermost Ordovician (Cincinnatian) strata in the eastern United States were deposited during a critical time in Earth's history. Not only had eastern Laurentia recently experienced a change from passive-margin to foreland-basin sedimentation associated with the Taconic Orogeny, but the world was also in transition from a greenhouse climate to an icehouse climate which climaxed with a short, intense cooling period known as the Hirnantian glaciation (Villas et al., 2002; Brenchley et al., 2003; Saltzman & Young, 2005). Cincinnatian strata of the central Appalachians, which include the siliciclastic Juniata Formation to the northeast and the carbonate Sequatchie Formation to the southwest, provide an opportunity to study the effects of both tectonics and eustasy within a foreland-basin setting. Few studies have sought to recognize the effects of the Late Ordovician glacial build-up in Gondwana in the stratigraphic record of Cincinnatian strata of the Central Appalachians. This study attempts to resolve some of the questions regarding tectonic and eustatic influences on Cincinnatian strata, by attempting to better understand the stratigraphic trends within the Juniata Formation along the structural strike of the Central Appalachian Basin.

Past researchers have focused mainly on either the northern portions of the Juniata Formation (Yeakel, 1962; Dennison, 1976; Ettensohn, 1994; Castle, 2001), the southern extent of the Juniata Formation (McBride, 1962; Kreisa, 1980; Bambach, 1987; Dorsch, 1993), or the equivalent Sequatchie Formation (Thompson, 1970c; Milici & Wedow, 1977). Therefore, generalizations about the depositional environment of the Juniata Formation tend to favor one region versus the other, and overlook major regional trends along structural strike of the basin. The only detailed study which attempted to address

this issue was conducted by Diecchio (1985), but he did not examine the southernmost exposures of the formation. In addition, there has been much disagreement whether tectonics (Dorsch, 1993; Castle, 2001), eustasy (Dennison, 1976; Diecchio, 1985), or both (Diecchio & Broderson, 1994) was the controlling factor on the formation of depositional sequences within the Juniata Formation, and on the unconformity present at the Ordovician-Silurian boundary (Bambach, 1987; Dorsch, 1993; Ettensohn, 1994).

### 1.1. *Study Objectives*

This study focuses on detailed sequence analysis based on stratigraphic and sedimentological analyses of the Juniata Formation with a goal of: (1) reconstructing the paleogeographic environment of the Juniata Formation, and (2) understanding the role of tectonics versus eustasy in the development of the stratigraphic architecture of the Juniata Formation. These questions are addressed by collecting and analyzing high-resolution outcrop and subsurface data. Lastly, this study attempts to clarify the nature of the Ordovician-Silurian boundary in the study area using these same methods. The majority of data used in this study, including gamma ray scintillometer measurements, were collected from a series of outcrops in the Valley and Ridge Province. Subsurface data were also used when available, but such data is quite sparse and often unreliable.

A secondary objective of this study is to test the applicability of gamma-ray scintillometer curves to the cyclic, siliciclastic character of the Juniata Formation. It has been suggested that handheld gamma-ray scintillometer outcrop logging provides accurate and consistent responses to changes in mineralogical content of various lithologies (Adams & Weaver, 1958; Aigner et al., 1995; Davies & Elliot, 1996). Curves produced from gamma-ray scintillometer data are a useful tool for regional outcrop

correlation, as well as correlations into the subsurface. The goal is to show that this form of data collection is useful and practical in the study of cyclical siliciclastic units.

### *1.2. Location of Study Area*

The area of interest for this study is situated in the central part of the Appalachians, extending from the highlands of West Virginia down through the Valley and Ridge of Virginia, and westward into the subsurface of West Virginia and Kentucky (Fig. 1). This area was chosen for its position within the Appalachian Basin: transitional between the classic, northern Juniata redbed locations and the carbonate Sequatchie Formation to the south. Outcrops are limited to the Valley and Ridge Province, which is bounded to the east by the metasedimentary, metavolcanic, and intrusive Precambrian and Paleozoic rocks of the Blue Ridge Province, and to the west by the flat-lying, Late Paleozoic sedimentary rocks of the Appalachian Plateau Province (Fig. 2). The Valley and Ridge Province consists of a series of southeast-dipping imbricate thrust sheets and secondary folds that formed during the Alleghanian Orogeny (Colton, 1970; Miller & Englund, 1975; Lemiszki & Kohl, 2006). Exposed rocks in this belt are early to late Paleozoic in age, and they pass into the subsurface of the Plateau Province to the west. Displacements on the thrusts are estimated to be up to tens of kilometers, and deformation becomes more extensive to the south (Dennison & Woodward, 1963; Lemiszki & Kohl, 2006). Within this study area, outcrops are located between the St. Clair Thrust to the west, and the Pulaski Thrust to the east (Fig. 3).

Subsurface data were collected from the West Virginia, Virginia, and Kentucky geological surveys. The data consists of wireline logs from early oil and gas wells located mainly in the Plateau Province. Here the Juniata Formation is present 6,000 to 8,000 feet

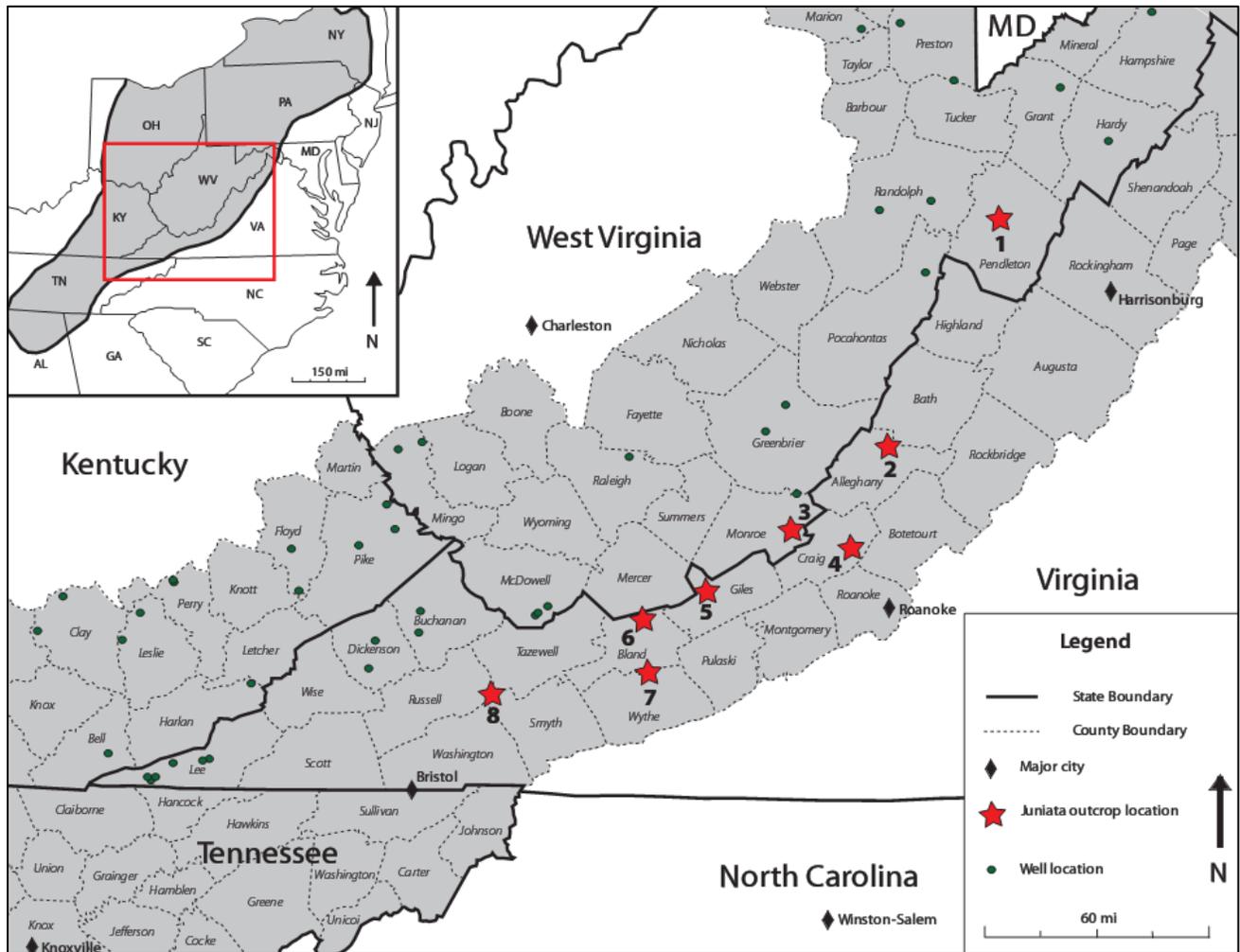


Figure 1: Location of the study area within the Appalachian Basin. Extent of the Appalachian Basin is shown in gray and the study area is outlined in red (inset). Outcrop locations in this study are represented by red stars, and the numbers correspond as follows: (1) North Fork Mountain, (2) Falling Springs, (3) Gap Mills, (4) New Castle, (5) Narrows, (6) South Gap, (7) Cove Mountain, (8) Red Rock Mountain.

below the surface, on average. The Junjata Formation can be found as shallow as 600 feet below the surface in portions of the Valley and Ridge of Virginia and as deep as 10,000 feet in western portions of West Virginia.

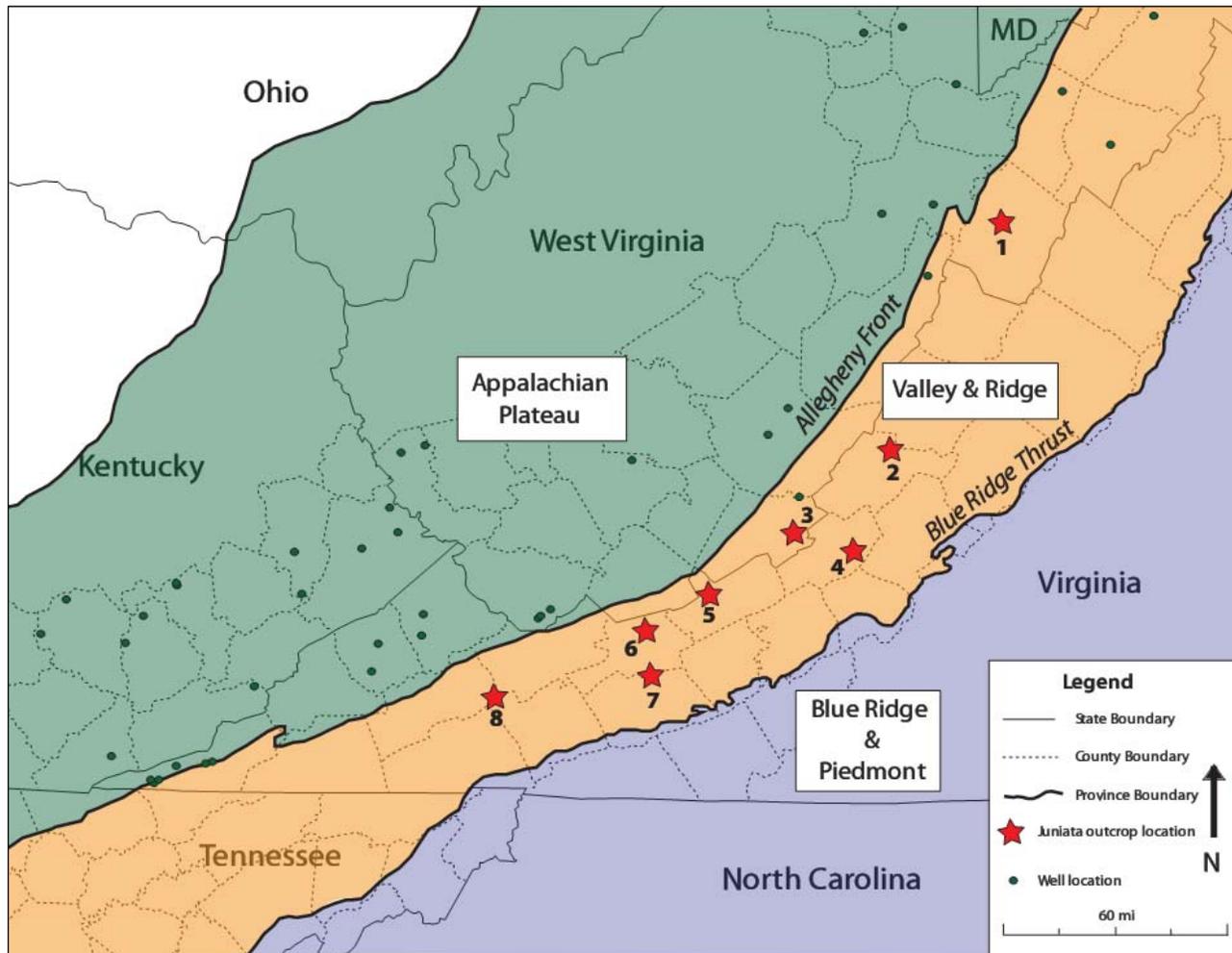


Figure 2: The physiographic provinces of the Central Appalachians. Outcrops are located in the Valley and Ridge Province, which is bounded by the Blue Ridge Thrust on the east and the Allegheny Front on the west. The Allegheny Front is an escarpment that separates the folded and faulted Paleozoic rocks of the Valley and Ridge from the flat-lying late Paleozoic rocks of the Appalachian Plateau.

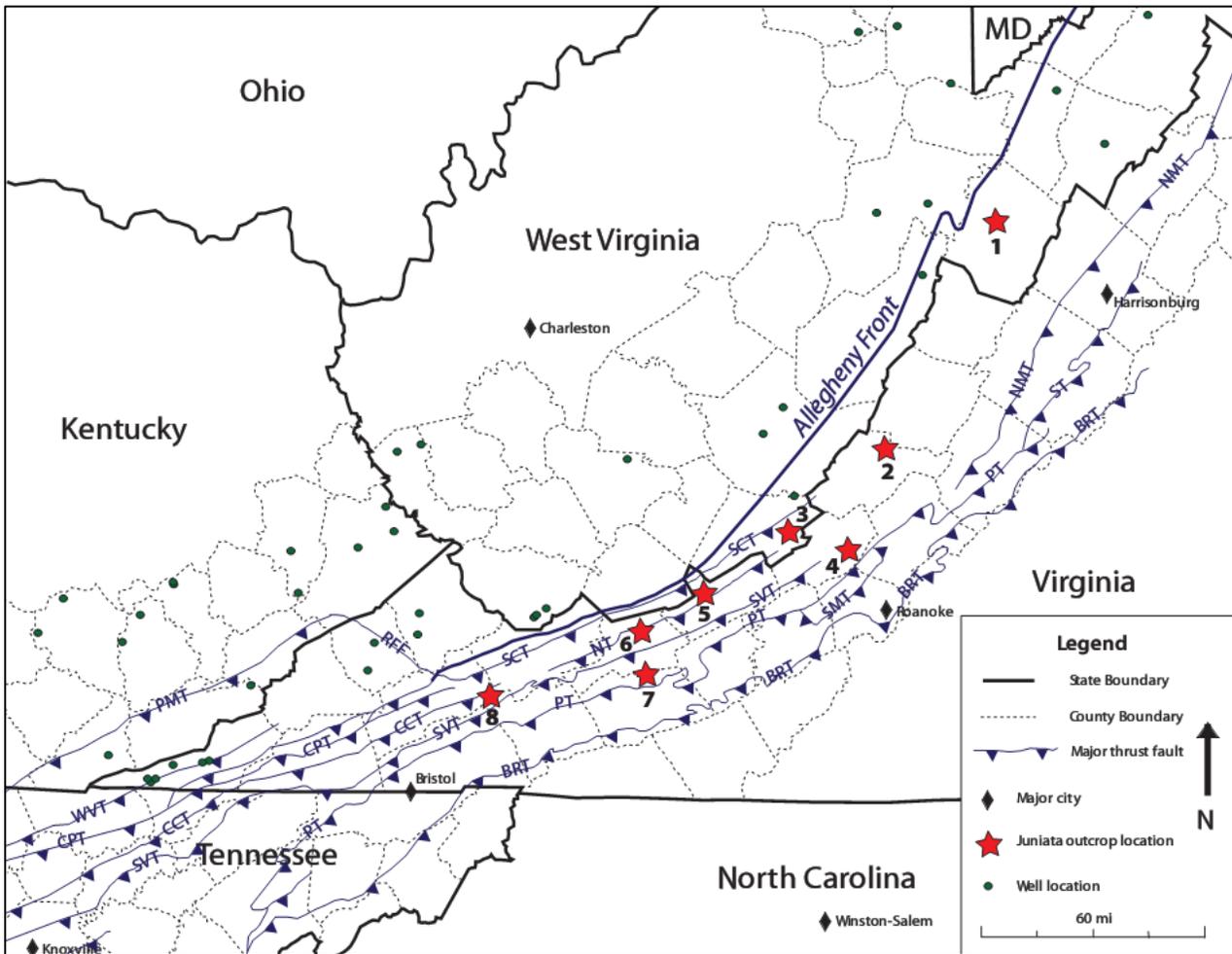


Figure 3: Map of the Valley and Ridge thrust sheets with the study area. Teeth are located on the overthrust sheet. Fault abbreviations are as follows: BRT- Blue Ridge Thrust; CCT- Copper Creek Thrust; CPT- Clinchport Thrust; NT- Narrows Thrust; NMT- North Mountain Thrust; PT- Pulaski Thrust; PMT- Pine Mountain Thrust; RFF- Russell Fork Fault; ST- Staunton Thrust; SCT- Saint Clair Thrust; SMT- Salem Thrust; SVT- Saltville Thrust; WVT- Wallen Valley Thrust.

## **2. GEOLOGIC HISTORY**

### *2.1. Regional Tectonics*

The Appalachian Basin is an elongate sedimentary basin that extends from the Canadian Shield southwestward into central Alabama, roughly parallel to the Atlantic coastline. The basin covers an area of about 206,900 sq. miles, or even more if the peripheral portions in Canada are included (Colton, 1970). It is no longer a physical “basin,” since most of it now consists of uplifted mountains and plateaus, but it actively accumulated sediment throughout the Paleozoic Era, totaling an estimated 510,000 cubic miles of basin fill (Colton, 1970). In this study, the period of the basin’s history that is of particular interest is during the onset and progression of the Taconic Orogeny. This event is considered to record the transition from a passive margin to a foreland basin, which is the depositional setting that persisted throughout the rest of the basin’s history (Rodgers, 1971; Mussman & Read, 1986; Ettensohn, 1994; Washington & Chisick, 1994).

The Taconic Orogeny has long been a major focus of Appalachian Basin studies. It is hypothesized, and generally accepted, that the orogeny was caused by either an island arc or a microplate collision with the Laurentian continent (Shanmugam & Lash, 1982). There has been much disagreement, however, on the exact timing of the Taconic Orogeny throughout the Appalachian Basin. Most workers have suggested that the timing of deformation is diachronous along the strike of the basin, corresponding to different phases within the orogeny (Rodgers, 1971; Shanmugam & Lash, 1982; Diecchio, 1991; Ettensohn, 1994). In the study area the earliest phase—the Blountian Phase of Rodgers (1971)—took place during the Middle Ordovician in the southern Appalachian Basin and is represented by the Knox Unconformity within Middle Ordovician carbonates

(Mussman & Read, 1986). Further west, the onset of the earliest phase of the Taconic Orogeny is recognized in the Nashville Dome by the introduction of siliciclastics, initiation of phosphate deposition, and a switch from tropical to temperate carbonates (Holland & Patzkowsky, 1997). A later tectonic event, the Taconic Tectophase (Ettensohn, 1994), occurred in the early Late Ordovician and is responsible for the extensive siliciclastic basin fill starting in the Trentonian Stage, and the angular unconformity between Late Ordovician and Early Silurian rocks of eastern Pennsylvania and northwest New Jersey (Colton, 1970; Rodgers 1971). Other workers, such as Washington & Chisick (1994), have suggested an initial phase of subsidence that was simultaneous throughout the majority of the basin in the Early Ordovician, but a varied arrival of the orogenic wedge from the Middle to the Late Ordovician.

Regardless of the exact timing of the orogeny itself, it is generally agreed upon that the extensive siliciclastic basin-fill of the Late Ordovician represents the shedding of sediments from the Taconic Highlands into the Appalachian Basin. Overall, the basin-fill pattern of the Taconic orogeny progresses from fine-grained, deep-water siliciclastic facies of the Martinsburg Formation, to shallow- water siliciclastic facies of the Reedsville Formation, and finally to near-shore and fluvial siliciclastic facies of the Juniata and Tuscarora Formation. The commencement of fine-grained sedimentation followed by coarser fluvial deposits, which is seen in the Late Ordovician sequence of the Appalachians, was suggested by Blair & Bilodeau (1988) to be an indicator of renewed tectonic activity. Lash (1989), however, described the Late Ordovician Martinsburg Formation as the last stage, or the basin-fill stage, of his five phases of early Paleozoic foredeep evolution. Ettensohn (1994) developed a model to explain the tectonic control

of major unconformities and stratigraphic sequences within the Appalachians as well. His model consists of a bulge movement and unconformity stage (the Knox Unconformity), a foreland basin and black shale deposition stage (the Utica Shale), a loading-type relaxation and deep basin infill stage (the Martinsburg Formation), and an unloading-type relaxation and basin “overflow” stage (the Juniata and Tuscarora Formations). This is similar to the recognized facies tracts and corresponding tectophases of Castle (2001). He places the Martinsburg Formation and the Reedsville Shale (deep water and shallow water facies tracts, respectively), within the early orogenic collision and subsidence tectophase, and considers the Juniata and Tuscarora Formations (shoreline sandstone and channelized fluvial sandstone facies, respectively) as part of the middle-to-late orogenic uplift and subsidence phase.

## *2.2. Regional Stratigraphy*

A generalized correlation chart for Middle Ordovician–Lower Silurian strata within the study area is illustrated in Figure 4. Unconformities are represented by wavy lines, and facies changes are denoted by diagonal lines. A brief description of these units can be found in the sections that follow.

### 2.2.1. Middle Ordovician

Middle Ordovician rocks of the Central Appalachian Basin are generally grouped within the North American Champlainian Series. This is equivalent to the Llanvirnian–Middle Caradoc of the European Series. Middle Ordovician rocks overlie Lower Ordovician rocks of the Canadian Stage, which are generally referred to as “Cambro-Ordovician” carbonates, or the Knox Group, or part of the Sauk Sequence (Neuman, 1976). These lower Ordovician carbonates are dominantly limestone and dolomite, and

System	European Series	N. American Series	N. American Stage	Eastern Tennessee	Southwest Virginia	Central Virginia/ West Virginia	Northern Virginia	
SILURIAN	Llandovery	Niagaran	Ontarian	Rose Hill Formation	Rose Hill Formation	Rose Hill Formation	Rose Hill Formation	
			Lewistonian	Clinch Sandstone	Clinch Sandstone "Upper" Tuscarora Sandstone	"Upper" Tuscarora Sandstone	Tuscarora Sandstone	
ORDOVICIAN	Ashgill	Cincinnatian	Richmondian	Sequatchie Formation	Sequatchie Formation "Lower" Tuscarora Sandstone Juniata Formation	Juniata Formation	Juniata Formation Oswego Sandstone	
			Maysvillian	Reedsville Shale	Reedsville Formation	Reedsville Formation Martinsburg Formation	Reedsville Shale Martinsburg Formation	
			Edenian			Trenton Limestone	Trenton Limestone	
								Dolly Ridge Formation
								Nealmont Formation
	Caradoc	Mohawkian	Trentonian	Trenton Limestone	Trenton Limestone	Moccasin Eggleston Bays Fincastle	Moccasin Eggleston	
			Blackriverian	Wardoll Ottosee Sevier	Wardoll Chatham Hill Liberty Hall Knobs	"Black River" Limestone		Edinburg/ Liberty Hall Formation

Figure 4: Correlation chart for Ordovician strata within the study area. Modified from Diecchio, 1985; Dorsh, 1993; Holland & Patzkowsky, 1996.

they represent a fairly uniform succession of subtidal, intertidal, and supratidal environments along the continental shelf of a passive margin (Neuman, 1976; Mussman & Read, 1986). Middle Ordovician strata, in contrast, consist of a complex series of interbedded calcareous and detrital rocks that represent a time of tectonic activity, which corresponds to the Taconic Orogeny. The onset of the Taconic Orogeny is represented by

the Knox Unconformity in the southern portion of the study area (Mussman & Read, 1986; Read, 1989), and all overlying rocks are considered to be Middle Ordovician in age. These rocks were deposited on the northwest margin of a foreland basin, whose depocenters appear to have been inherited from the previous Cambrian-Ordovician shelf (Read, 1980). Lithologies generally consist of peritidal, subtidal, and deep water carbonates and shale in the early Middle Ordovician, which pass upward into mixed calcareous and siliciclastic deposits during the late Middle Ordovician (Read, 1980). Early Middle Ordovician formations within the study area include the Lenoir, New Market, Blackford, and Lincolnshire; late Middle Ordovician formations include the Liberty Hall, Black River, Bays, Moccasin, Eggleston, and Trenton.

#### 2.2.2. Upper Ordovician

Upper Ordovician rocks of the Central Appalachians are grouped within the North American Cincinnati Series. This is equivalent to the Late Caradoc through Ashgill European Series. In the Central Appalachians, Upper Ordovician strata consists of a series of coarsening-upward and cleaning-upward, siliciclastic units that represent the shedding of sediments from the Taconic highlands and the subsequent filling of the Appalachian foreland basin. Together, these rock units comprise the southern portion of the Queenston “delta complex” (Dennison, 1976; Neuman, 1976; Diecchio, 1985). Typical lithologies are interbedded sandstones, siltstones, and shales that are generally dominated by coarser grain sizes in the east and finer grain sizes in the west. Further into the basin, these siliciclastic units interfinger with argillaceous carbonates of the western half of the Appalachian Basin (Keith, 1989; Holland & Patzkowsky, 1998). The Upper

Ordovician Formations in the study area consist of the Martinsburg, Reedsville, Oswego, Juniata, Sequatchie, and possibly the “Lower Tuscarora Sandstone” (Dorsch, 1993).

The beginning of Upper Ordovician sedimentation in the study area is marked by the Martinsburg and Reedsville Formations. The Martinsburg and Reedsville Formations have been studied extensively in the northern and southern portions of the Central Appalachians by McBride (1962) and Kreisa (1980, 1981), respectively. McBride (1962) described the Martinsburg Formation in southern Pennsylvania as a thick succession of shale, siltstone, and graywackes of turbidite origin. Kreisa (1981) interpreted the Martinsburg Formation of southwest Virginia as a storm-generated open marine platform deposit. To reconcile this difference, Diecchio (1985) pointed out that the Martinsburg Formation of Kreisa (1981) is equivalent to as the Reedsville Formation in more western areas of the Appalachian Basin, and that these two units grade laterally into one another. The Reedsville Formation also contains the characteristic *Orthorhynchula* zone in its uppermost part, which was also noted in the Martinsburg of Kreisa (1981). Therefore, what Kreisa (1981) called the Martinsburg Formation is referred to as the Reedsville Formation in this study. The uppermost part of the Martinsburg or Reedsville Formation has been interpreted to represent a eustatic lowering of sea level, as evidenced by the appearance of *Orthorhynchula* brachiopods, and the start of Ashgill sedimentation (Diecchio, 1985).

Overlying the Martinsburg and Reedsville Formation are the latest Ordovician (Richmondian) strata, which are the central focus of this study. In the Central Appalachians, Richmondian strata include the Oswego, Juniata, and Sequatchie Formations, and potentially the “Lower Tuscarora” Sandstone (Dorsch, 1993). The

Oswego, Juniata, and “Lower Tuscarora” represent the progradation of the Taconic clastic wedge into the basin, and the dominance of shallow marine to alluvial environments. These clastic units interfinger with the carbonate Sequatchie Formation and the Shellmound Formation in the southern-most part of the Appalachian Basin. The Oswego Formation (also known as the Bald Eagle Formation to the north) is a greenish-gray lithic arenite to lithic wacke that occurs only in the eastern-most outcrop belts (Diecchio, 1985). The Oswego underlies the distinctively red Juniata Formation, and it is typically distinguished from the Juniata Formation on the basis of color. However, Thompson (1970b) revealed that drab versus red color boundary in these two rock units is non-systematic and a result of diagenesis. Therefore, the drab and immature sandstones of the Oswego Formation are a facies equivalent to the red and more quartz-rich sandstones of the Juniata Formation.

The Juniata Formation was named by Darton (1896) for exposures along the Juniata River in Pennsylvania. Generally, the Juniata Formation consists of interbedded sandstones, siltstones, and shales that display a distinctive dusty red color. Together with the other Richmondian strata, the Juniata Formation makes up the most extensive redbed succession of the seven total redbed intervals of the Appalachian Basin (Dennison, 1976). A geographical display of the formations within the Appalachian Basin that are age-equivalents to the Juniata Formation can be found in Figure 5. Within the study area, the Juniata Formation is dominantly a shallow- marine deposit, with an abundance of *Skolithos* and *Cruziana* ichnofacies. Unfortunately, the Juniata Formation is generally devoid of body fossils and cannot be precisely biostratigraphically dated. The gradational

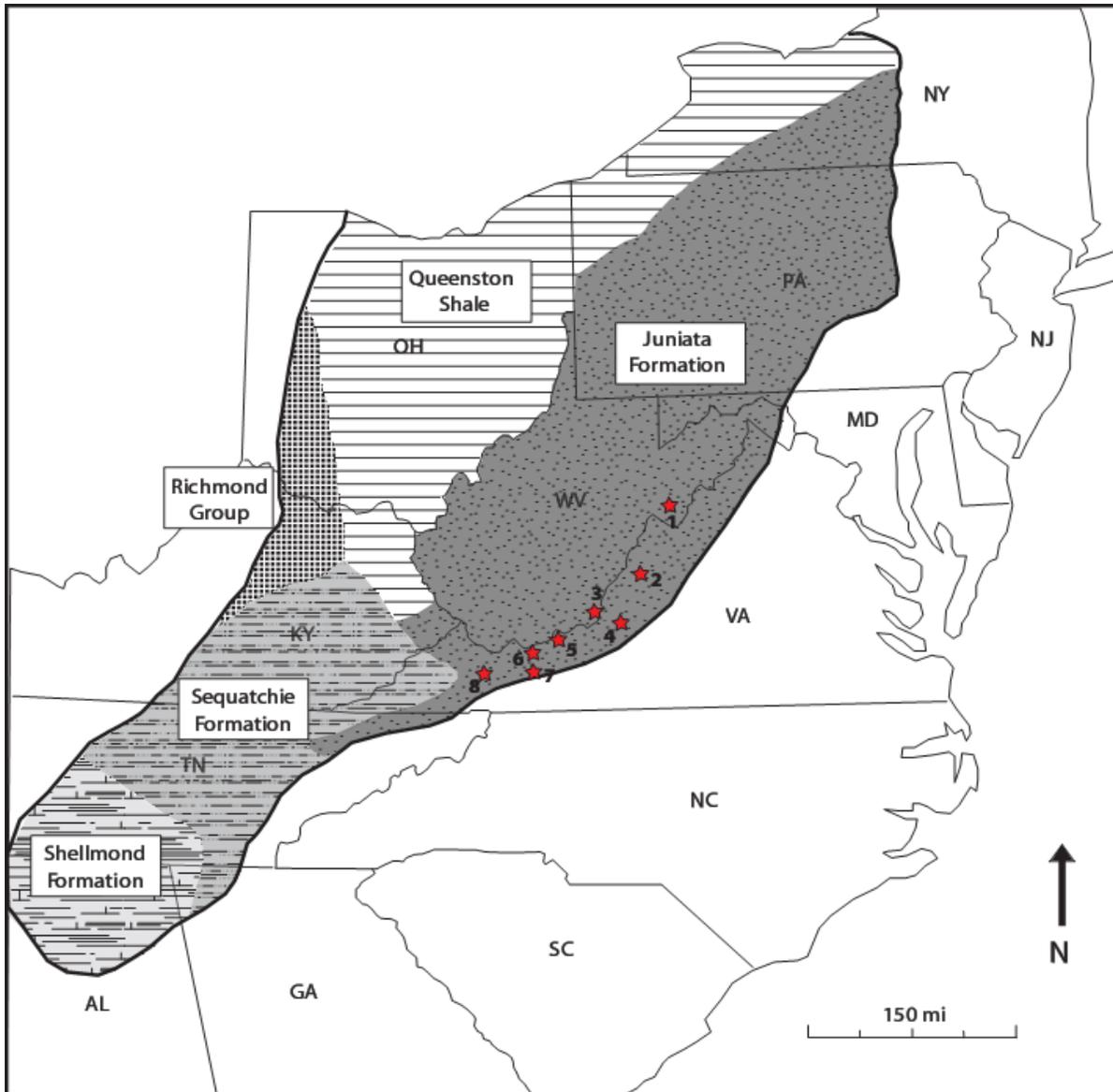


Figure 5: Distribution of Latest Ordovician formations in the Appalachian Basin. Red stars denote Juniata outcrop locations in this study. Modified from Dennison, 1976; Milici & Wedow, 1977.

to sharp contact with the overlying white quartz arenite of the Tuscarora Sandstone has been the traditional placement of the Ordovician-Silurian boundary.

### 2.2.3. Lower Silurian

The Lower Silurian units of this study are grouped with the North American lower Niagaran Series, or the European Llandovery Series. Specifically, they comprise the entire Lewistonian stage. From northeast to southwest, these units consist of the

Tuscarora Sandstone and the Clinch Sandstone, respectively. Although there are some slight lithological differences, these two units are generally distinguished by their position north or south of the New River (Dennison, 1970). The Tuscarora and Clinch sandstones are everywhere overlain by the Rose Hill Formation. Both the Tuscarora and Clinch sandstones are dominantly fine- to medium-grained, white quartz arenites with some thin interbedded shale (Hayes, 1974; Dorsch, 1993). These sandstone units exhibit a gross blanket geometry across the majority of the study area (Dennison, 1970).

Depositional environments for the Tuscarora/Clinch Sandstone range from marine, to estuarine, and to fluvial based upon stratigraphic and geographic position (Dennison, 1970; Hayes, 1974; Dorsch, 1993; Castle, 1998). Within the study area, shallow-marine and estuarine deposits are dominant (Dorsch, 1993). Like the Juniata Formation, the Tuscarora/Clinch Sandstone does not contain any body fossils, but does display a suite of trace fossils including *Skolithos* and *Arthropycus* (Diecchio, 1985).

### *2.3 Previous Paleoenvironmental Interpretations*

#### *2.3.1. Summary of paleoenvironments*

Numerous workers have conducted detailed studies on the Juniata Formation (and its facies equivalents) throughout the Appalachian Basin. A large majority of these studies were centered around Pennsylvania, which is the location of the depocenter. Both Yeakel (1962) and Meckel (1970) suggested an alluvial origin for the Juniata Formation in Pennsylvania and northern Virginia, citing high sand/shale ratios, current dispersal patterns, and maximum pebble size as evidence. Meckel (1970) further divided the Juniata Formation into two genetically-related facies: channel and non-channel (including flood plain and tidal flat environments). Dennison (1976) also recognized the Juniata

Formation as having a fluvio-deltaic character, but only in the eastern portions of Pennsylvania. Further west into the basin, he described the Juniata Formation, and its equivalent facies, as a shallow-marine deposit that was subaerial exposed at the end of the Ordovician. Ettensohn (1994) and Castle (2001) placed the Juniata Formation within the last phase of their tectonic sequence models (maximum loading and subsidence followed by “basin overflow”), based on its coarsening upward grain size trend. Ettensohn (1994) considered the Juniata to be a marginal marine deposit, whereas Castle (2001) placed the Juniata Formation within his progradational shoreline sandstone facies (coastal and alluvial sands).

Another group of workers have focused on the more southern portions of the Juniata Formation, especially around southwest Virginia. Kreisa (1980) was one of the first to conduct a detailed study of the facies within the Juniata Formation around southwest Virginia. He described the Juniata Formation as a basal sandstone body and tidal channel complex overlain by delta-plain mudflat deposits. Diecchio (1985) and Bambach (1987) also suggested a proximal marine setting for the Juniata Formation. The red coloration of the Juniata Formation was suggested by Diecchio (1985) to be the result of land-derived sediment that was deposited in a nearshore environment, such as a broad coastal lowland or delta plain that was intermittently submerged. A vastly different depositional environment was suggested by Dorsch (1993). He contended that delta plain, tidal, and fluvial interpretations were not compatible with his observations. Based on the presence of hummocky, wave-rippled, and high-angle cross-stratification, along with pervasive bioturbation, Dorsch (1993) interpreted the Juniata Formation as storm-

dominated deposits of a shallow marine epicontinental sea from the middle shoreface to offshore zones.

There has been significantly less work done on the Sequatchie Formation, which is the carbonate equivalent of the Juniata Formation in extreme southwest Virginia and eastern Tennessee. This likely is due to the fact that outcrops of the Sequatchie Formation are far less common than outcrops of the Juniata Formation, and its response in wireline logs can be somewhat ambiguous. The most detailed studies were conducted by Thompson (1970c) and Milici and Wedow (1977). Thompson (1970c) referred to the Sequatchie Formation as a biomicrite and a biomicrudite that represents the offshore-to-subtidal deposition on a shallow, open marine shelf. Strata which Thompson (1970c) referred to as Juniata (based primarily on color) was labeled as Sequatchie by Milici and Wedow (1977). Milici and Wedow (1977) considered the red beds to be a facies within the Sequatchie Formation which represent high tidal flat deposits. Thompson (1970c) also noted the presence of dolomite in his supratidal facies, which he attributed to precipitation from evaporating pore waters after periodic floodings on the tidal flats.

### 2.3.2. Summary of previous paleocurrent analyses

Numerous workers have reported paleocurrent directions within the Juniata Formation throughout the region. Therefore, additional paleocurrent measurements were not needed from the majority of field locations since they merely validated the previous measurements. A compilation of paleo-flow directions within the Juniata Formation that were reported by various researchers is found in Figure 6. Paleocurrent analyses for the Juniata Formation were conducted by Yeakel (1962), Kreisa (1980), Diecchio (1985), and Dorsch (1993) based on a variety of cross-beds, tool marks, and flute casts. In

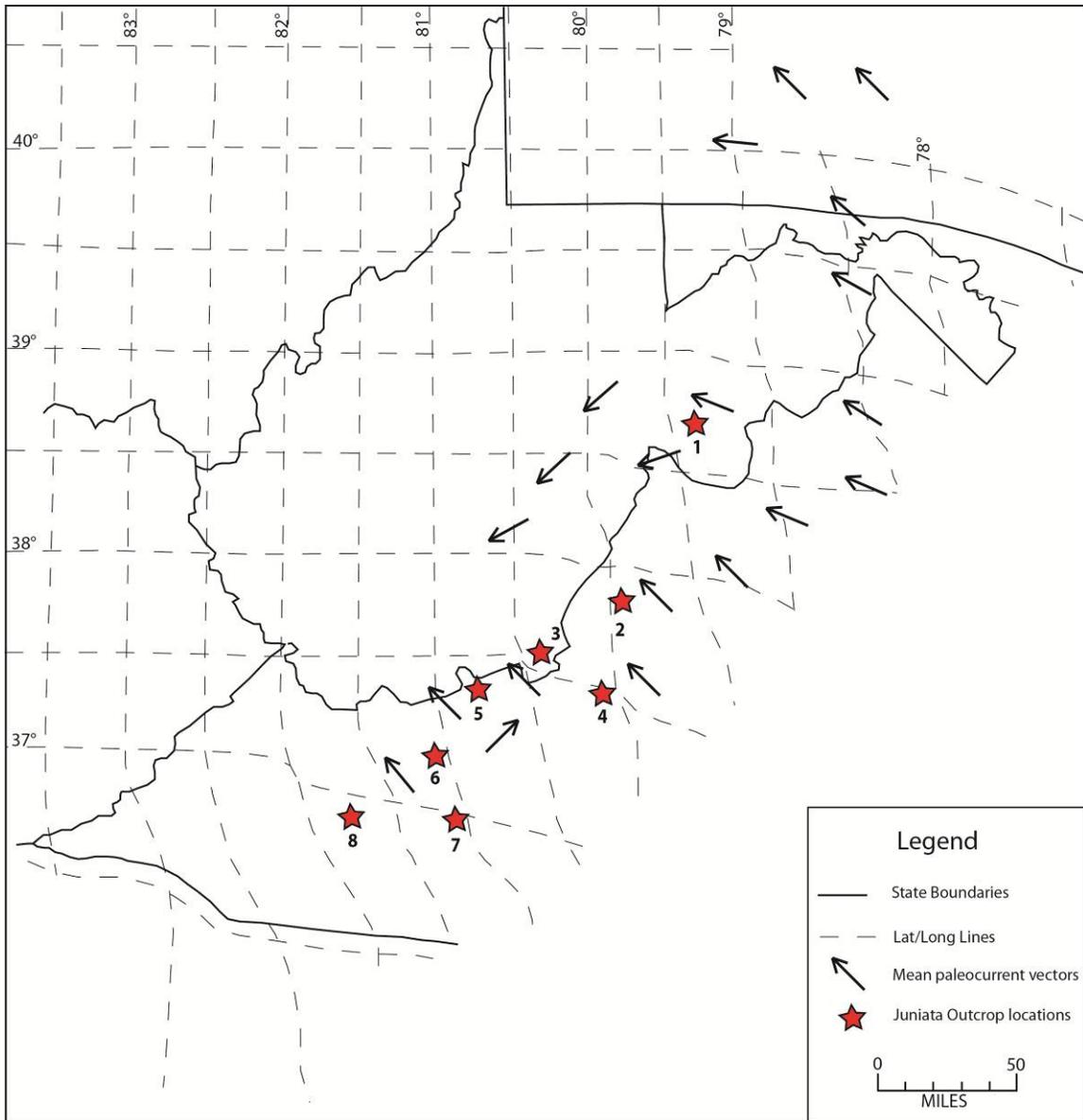


Figure 6: Compilation of paleo-flow directions within the Juniata Formation. Paleocurrent data is plotted on the palinspastic base of Dennison and Woodward, 1963. Based upon data from Yeakel, 1962; Kreisa, 1980; Diecchio, 1985; and Dorsch, 1993.

general, the Juniata shows two major sediment dispersal directions: northwest (with a minor northeast component) and southwest. In the area of south and central Pennsylvania, Yeakel (1962) reported a strong northwestern flow direction, representing offshore (fluvial?) flow from the tectonic highland roughly perpendicular to the strike of the basin. Further south into Virginia, Kreisa (1980), Diecchio (1985), and Dorsch (1993) also

reported dominant northwesterly flow directions. However, Kreisa (1980) and Dorsch (1993) documented a minor northeastern flow component that may represent longshore transport of sediment. In addition, Diecchio (1985) reported a dominance of southwestern flow directions in the eastern to central portion of West Virginia. These flow directions were interpreted to represent longshore transport within the basin (Diecchio, 1985).

Based upon these dominant flow directions, two source areas for the Juniata formation have been suggested by Diecchio (1985). The most extensive source area was the Taconic highlands to the east, which was responsible for the northwesterly-oriented offshore current directions from southwestern Virginia to Pennsylvania. A second, smaller source area also existed to the north in western Pennsylvania (Diecchio, 1985). This was likely the result of the prograding Queenston delta complex in Pennsylvania. As a result, these two source areas formed an embayment in the northeastern portion of West Virginia and the northern-most part of Virginia (Diecchio, 1985), which resulted in a more estuarine environment for the Juniata Formation in that location.

#### *2.4. The Ordovician-Silurian Boundary*

The location and the expression of the Ordovician-Silurian boundary in the rock units of the Central Appalachians have long been debated among researchers. The world Silurian type sections are located in Europe, and correlations in North America are based upon paleontology (Boucot, 1970). The classic Silurian exposures in New York are the standard reference section in the Appalachians (Fisher, 1960). Within the study area, however, there are no body fossils that can provide dating of the Ordovician-Silurian boundary. Therefore, the Ordovician-Silurian boundary has traditionally been placed at the contact between the Juniata Formation and Tuscarora/Clinch Sandstone based upon

the ages of the bounding formations (Martinsburg/Reedsville Formation of Late Ordovician age and the Rose Hill of Early Silurian Age) and the distinct lithology change throughout the basin (Dennison, 1970; Diecchio, 1985; Bambach, 1987). This practice has been brought into question by Dorsch and Driese (1995) due to the presence of what they refer to as the “Lower Tuscarora” Sandstone in southwestern Virginia. Dorsch and Driese (1995) consider the “Lower Tuscarora” Sandstone to be latest Ordovician in age and to represent a facies change from the Juniata Formation. They place the Ordovician-Silurian boundary at the unconformity between the “Lower Tuscarora” Sandstone and the traditional “Upper Tuscarora” sandstone of supposed Silurian age. The main difference between these two sandstone units is that the “Lower Tuscarora” sandstone is more lithic in character and contains more interbedded fine-grained deposits. Throughout the rest of the basin, the “Lower Tuscarora” Sandstone is generally absent and the boundary is placed at the unconformity between the Juniata Formation (or the Oswego Sandstone or Martinsburg Formation if the Juniata is absent) and the Tuscarora sandstone.

This unconformity has been given many names throughout the Appalachian Basin. Originally, the unconformity was known as the Taconic discontinuity by Wheeler (1963). Dennison and Head (1975) renamed the unconformity as the Cherokee Discontinuity in order to avoid confusion in relating it to the Taconic Orogeny. More recently, Dorsch et al. (1994) have suggested the term “Tuscarora Unconformity” to account for its expression in southwest Virginia. Regardless of the name, the unconformity spans much more time to the north and to the east of the basin, where the Juniata is completely absent in some locations. It has been suggested by Diecchio (1985) that the contact between the Juniata Formation and the Tuscarora Sandstone is

conformable in central portions of the Valley and Ridge, and therefore, no hiatus is present. Due to the extensive nature and the timing of the unconformity, there is still much debate as to whether it was caused by the eustatic lowering of sea level at the end of the Ordovician related to the Hirnantian Glaciation, or a renewed phase of tectonism within the basin. Most researchers generally favor a eustatic origin for the unconformity (Dennison, 1976; Diecchio, 1985; Ettensohn, 1994), but others that suggest a tectonic overprint in some areas (Bambach, 1987) or relate the unconformity to a large isostatic rebound event (Dorsch et al., 1994).

### 3. METHODOLOGY

#### 3.1. *Outcrop Data Collection*

A total of seven outcrop locations were logged in this study. A road cut section outside Narrows, Va, was not logged because it was too dangerous to access. Therefore, data from Kreisa (1980) were plotted in the same manner as the other outcrop logs and incorporated into the cross-sections. All field sites in this study are road cuts, except for the Red Rock Mountain site, which is a natural outcrop in the Clinch Mountain Wildlife Management Area of Virginia. All sections were measured using a Jacob's staff, except at the Red Rock Mountain location, because the horizontal orientation of the beds along the cliff prohibited its use. At this location, the section was measured using a 150 meter tape measure and corrected for dip using a Brunton compass. At every outcrop site, beds were described according to color, general mineralogy, grain size/shape/sorting, sedimentary structures, biogenic structures, and bedding contacts. Multiple samples of sedimentary structures and trace fossils were collected from various locations for further analysis, but no petrographic work was performed. The base of the Juniata Formation was picked based upon the first prominent red coloring and its position above the *Orthorhyncula* zone in the Reedsville/Martinsburg Formation. Similarly, the top of the Juniata Formation was also picked at the last red bed below the white and tan sandstones of the Tuscarora Formation.

Detailed photographs were taken at each location to document important characteristics and the representative facies of the Juniata Formation at that site. Many of these photographs are included as figures in this volume. Where possible, a photo mosaic of the field site was constructed in order to observe large-scale lateral characteristics.

Photo mosaics were compiled and constructed based upon the methods of Arnot et al. (1997). Full, outcrop-scale photo mosaics of the New Castle, Cove Mountain, and South Gap, locations are included in Appendix A.

### *3.2. Spectral Gamma-Ray Scintillometer Measurements*

The use of handheld gamma-ray scintillometer outcrop logging has been shown to provide accurate and consistent responses to changes in mineralogical content of various lithologies (Adams & Weaver, 1958; Aigner et al., 1995; Davies & Elliot, 1996). By utilizing commercial handheld scintillometers, trends in the total gamma-ray count and variation in the thorium/uranium ratio of five outcrops of the Juniata Formation were determined. Field gamma-ray measurements were obtained with a combination of two hand-held spectral gamma-ray scintillometers. At the Cove Mountain and North Fork Mountain sites, an Exploranium GR-320 spectral gamma ray scintillometer was used to collect data. Unfortunately, this scintillometer was no longer operational when it came time to sample other outcrops. Therefore, the GF Instruments GRS-2000 gamma-ray spectrometer was used at the New Castle, Gap Mills, and South Gap locations. No scintillometer data were collected at the Falling Spring, Narrows, or Red Rock Mountain sites because of accessibility issues and safety concerns. Because both scintillometers were similarly calibrated and collected data in the same manner, it is possible to directly compare data from both scintillometers.

Both the GRS-2000 spectrometer and the GR-320 scintillometer captures the continuous emitted gamma-ray radiation from a sample over an energy range of 0.4 to 3 MeV (million electron volts) on its detector for comparison to an internal cesium source (GF Instruments, 2000). The full spectrum of radiation is then delineated into “Regions

Of Interest” (ROI) by grouping channels corresponding to the peak gamma-ray outputs of known radionuclides. In rock, natural radioactivity is usually the result of the decay of potassium-40 ( $^{40}\text{K}$ ), uranium-238 ( $^{238}\text{U}$ ), and thorium-232 ( $^{232}\text{Th}$ ). In the case of  $^{40}\text{K}$ , gamma radiation is emitted with an energy of 1.764 MeV, and can be detected directly by the spectrometer. Uranium-238 and thorium-232, however, release energy outside of the spectrometer’s detection range ( $\sim 7$  MeV for  $^{238}\text{U}$ ). Consequently, the spectrometer uses daughter products of their decay series as a proxy for the measurement of the amount of each radionuclide present in the sampling area. Bismuth-214 ( $^{214}\text{Bi}$ ), with a characteristic gamma-ray energy of 1.764 MeV, is used to determine equivalent uranium (eU) present in parts per million (ppm). Thallium-232 ( $^{232}\text{Tl}$ ), with an energy of 2.615 MeV is used as a proxy for equivalent thorium (eTh) in ppm.

Gamma-ray intensity measurements for  $^{40}\text{K}$ , eTh, and eU were taken at two foot intervals along the outcrops and lined up with the log of the formation. Logging of the formation bed-by-bed was performed concurrently with the gamma-ray measurement. The total gamma-ray counts per second (Cps) were recorded, along with %K, ppm U, and ppm Th. This data was then input into a Microsoft Excel file to generate the curves used for comparison in the cross sections.

### *3.3. Subsurface Data Collection*

Subsurface data were collected from the West Virginia, Virginia, and Kentucky geological surveys. The data consists of wireline logs from early oil and gas wells located mainly in the Plateau Province. Gamma-ray logs were the primary type of wireline log examined in this study, and they were used to estimate sandy versus shaly lithologies (low gamma-ray values representing sandy units and high gamma-ray values representing

shaly units). A total of 32 well logs were obtained. Nearby outcrop gamma-ray logs were compared to subsurface logs for correlation and for examination of basinward trends in lithology. The well log data from the various state surveys were input into Landmark's GeoGraphix software for analysis and to generate subsurface cross-sections.

#### *3.4. Construction of Cross-Sections and Isopach Map*

Cross-sections were constructed based on the logs from the outcrop localities and its corresponding total gamma-ray curve, where available. Cross sections were initially hung on the contact with upper Tuscarora formation, because it was the only through-going surface that was easily identifiable in all locations. Trends in grain size and facies associations were tracked across the cross-sections, in combination with the patterns from the gamma-ray curves, in order to develop basic correlations. Detailed cross-sections can be found in Appendix B. The isopach map was constructed using thickness data collected from this study as well as from the study by Diecchio (1985). Control points from Diecchio (1985) were used to constrain contours in areas east and west of the outcrop and subsurface data locations in the study area. Isopach lines are only for the Juniata Formation, and they do not include the Oswego Formation or the "lower" Tuscarora Sandstone. Isopach lines were plotted on a palinspastic base, in order to return the data locations to their estimated pre-Alleghenian deformational positions. The base map was constructed using the Ordovician palinspastic base of Dennison and Woodward (1963).

#### 4. FACIES DESCRIPTIONS

The following facies descriptions are based entirely on logged outcrop data. The general characteristics of each facies are described in detail, including the dominant geometries of sediment bodies. See Appendix A for full outcrop-scale photo-mosaics and Appendix B for the detailed distribution of facies at specific outcrop sites.

##### 4.1. “*Proto-vertisols*”

Paleosols within the Juniata Formation consist of red mudstone to silty mudstone, commonly containing green reduction spots. This facies is crumbly, breaks into ped-like structures, and contains many randomly oriented, millimeter-scale slickensided surfaces. Since the paleosols pre-date the appearance of vascular land plants—the earliest terrestrial plant yet discovered is an ancient liverwort from eastern Gondwana that is Middle Ordovician in age (Rubinstein et al., 2010)—they contain no evidence of plant traces or rooting. Paleosols always exhibit sharp contacts with overlying facies, and scouring into the paleosol is common. The lower contacts are always gradational from a non-pedogenic silty mudstone. Rare *Skolithos* burrows from overlying units penetrate to the tops of the paleosols. Paleosols are a maximum of 16 cm thick, but are typically only about 5 cm in thickness. This facies has only been found in southwest Virginia, at the New Castle outcrop, so it is quite rare. The paucity of this facies may be due to either the actual lack of preservation, or a difficulty in recognizing it since its features are poorly preserved and hard to distinguish from non-pedogenic mudstone.

Retallack (1992) recognized two types of paleosols in the Juniata Formation in central Pennsylvania—entisols near the base of the Formation and inceptisols in the upper part of the formation. Driese & Foreman (1992) documented vertic paleosols in the

Juniata Formation of extreme southwest Virginia and eastern Tennessee, with thicker and better-developed paleosols located in Tennessee. The “proto-vertisol” facies of this study closely resembles the vertisols of Driese and Foreman (1992), but are much thinner and more poorly-developed.

#### 4.2. *Red Shale/Mudstone*

Red shales and mudstones are abundant throughout the Juniata Formation and commonly contain green reduction zones. Red shales are rarely silty, whereas mudstones commonly contain a significant portion of silt-sized grains. Overall, mudstone is much more common than shale, with mudstone making up approximately 80% of this facies. Although typically massive, mudstone rarely contains mm-scale laminations. Mudstones and shales exhibit a variety of geometries in outcrop, from thick, laterally continuous bodies to thin, scour-based lenses. The basal contacts of this facies are commonly gradational, normally fining-upward from a siltstone, but the upper contacts are almost always sharp and heavily scoured. Red shales appear to be devoid of bioturbation, but mudstones are commonly bioturbated (no specific traces identifiable), which gives them their massive appearance. Where the basal bedding plane of an overlying sandstone is visible, *Cruziana* traces rarely are present. This facies ranges in thickness from 1 inch to up to 7 feet, with the thickest sections located in the western parts of the region, where the facies is the most dominant. Thick covered intervals in stratigraphic sections most likely contain a large proportion of this facies due to its weakness and susceptibility to weathering. An example of the red shale and mudstone facies can be seen in Figure 7A.

#### 4.3. Siltstone/Silty Mudstone with Interbedded Sandstones

This facies is red to reddish gray and rarely contains green reduction zones. Siltstones and silty mudstones are commonly massive, but they are locally finely laminated in thin beds. In addition, siltstones and silty mudstones are usually very crumbly and heavily weathered. Thin, discontinuous sandstone beds are present within the siltstones and silty mudstones (Fig. 7B). Sandstones are reddish gray to tan and are fine- to very fine-grained, and are rarely argillaceous. Cross-stratification is rarely seen

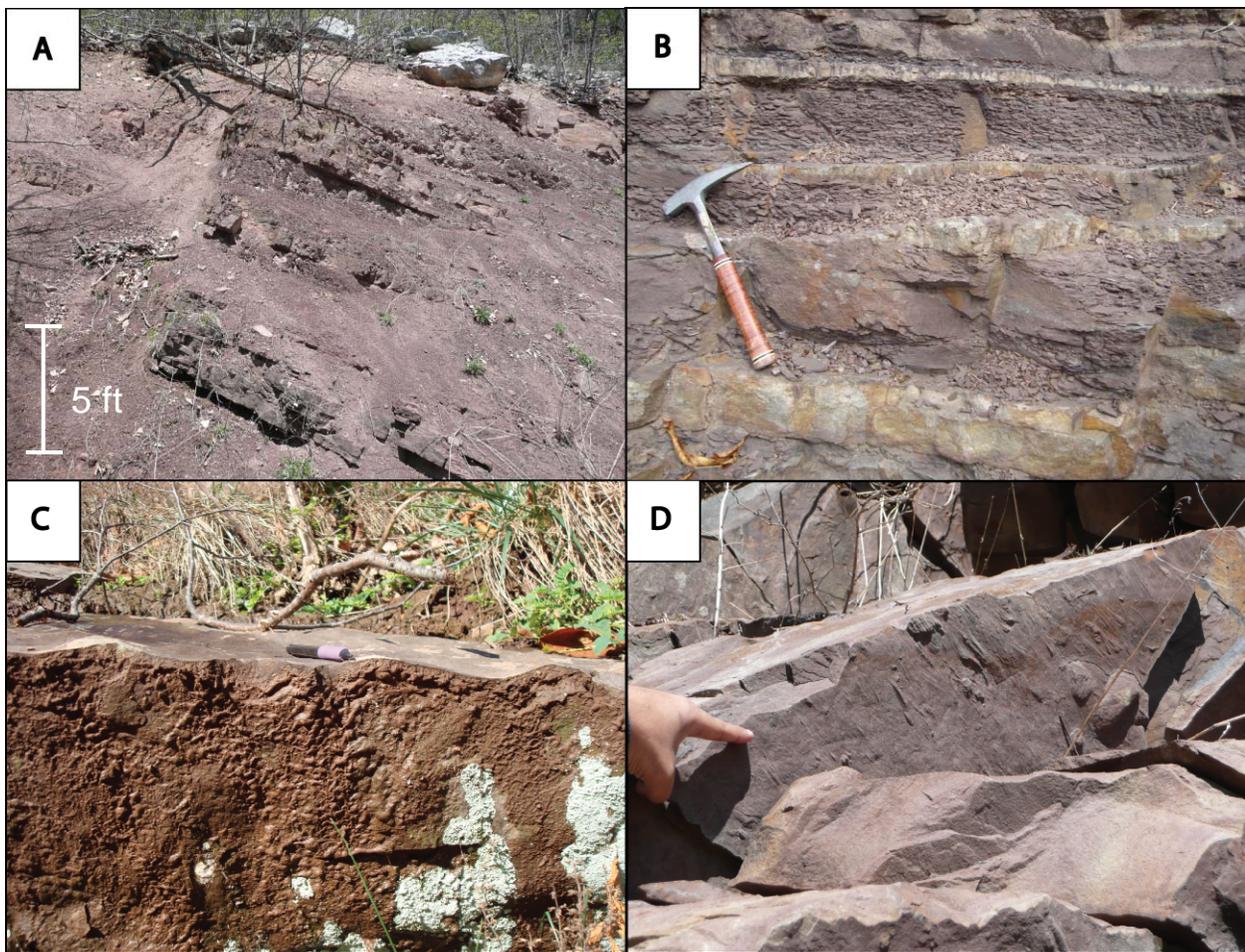


Figure 7: Representative facies and sedimentary structures of the Juniata Formation. A) Red mudstone from North Fork Mountain, WV. B) Siltstone with interbedded sandstones from New Castle, VA. Top sandstone bed is intensely burrowed (*Skolithos* tubes); rock hammer is 13 inches long. C) Symmetrical ripples along the top of a quartz arenite bed at New Castle, VA; pencil is approximately 6 inches long. D) Tool marks in a sublithic arenite at Falling Springs, VA.

within sandstone beds, which commonly contain small (< 3mm) siltstone and mudstone clasts. The contacts between the sandstones and siltstones within this facies are always sharp, with the base of the sandstone beds commonly showing scour features. As a whole, this facies most commonly has gradational lower and upper contacts with other facies, but sharp contacts with underlying or overlying facies are frequently exhibited as well. The majority of siltstones are bioturbated (except in the laminated beds) and small *Skolithos* burrows are seen. In common with the siltstones, sandstones are usually heavily bioturbated and dominated by *Skolithos* and rarely by *Monocriterion* burrows (Fig 8A, B). Siltstones at the base of the formation commonly contain *Planolites* traces (Fig. 8C), and a few samples of possible *Arenicolites* traces have also been observed in the middle of the formation. Stratigraphically, this facies is well-developed throughout the formation, but the thickest occurrences are in the middle to upper portion. Overall, the thickness of this facies ranges from 2 to 8 feet throughout the region.

#### 4.4. *Quartz Arenite and Sublithic Arenite*

Massive and cross-bedded quartz and sublithic arenites are common within the Juniata Formation. These facies range from red to tan in color, with some beds containing randomly scattered green reduction zones. *Liesegang* bands are also commonly seen in these rocks and tend to cross-cut primary bedding. These sandstones contain minor proportions (10% or less) of lithic grains and heavy minerals. These grains typically consist of mica, sedimentary rock fragments—usually siltstone and mudstone clasts—and the heavy minerals consist of hematite or possibly magnetite. Beds range from very fine- to medium-grained, with rare beds bordering on coarse-grained. These sandstones are either massive or cross-bedded, with tabular cross-bedding being the most prominent

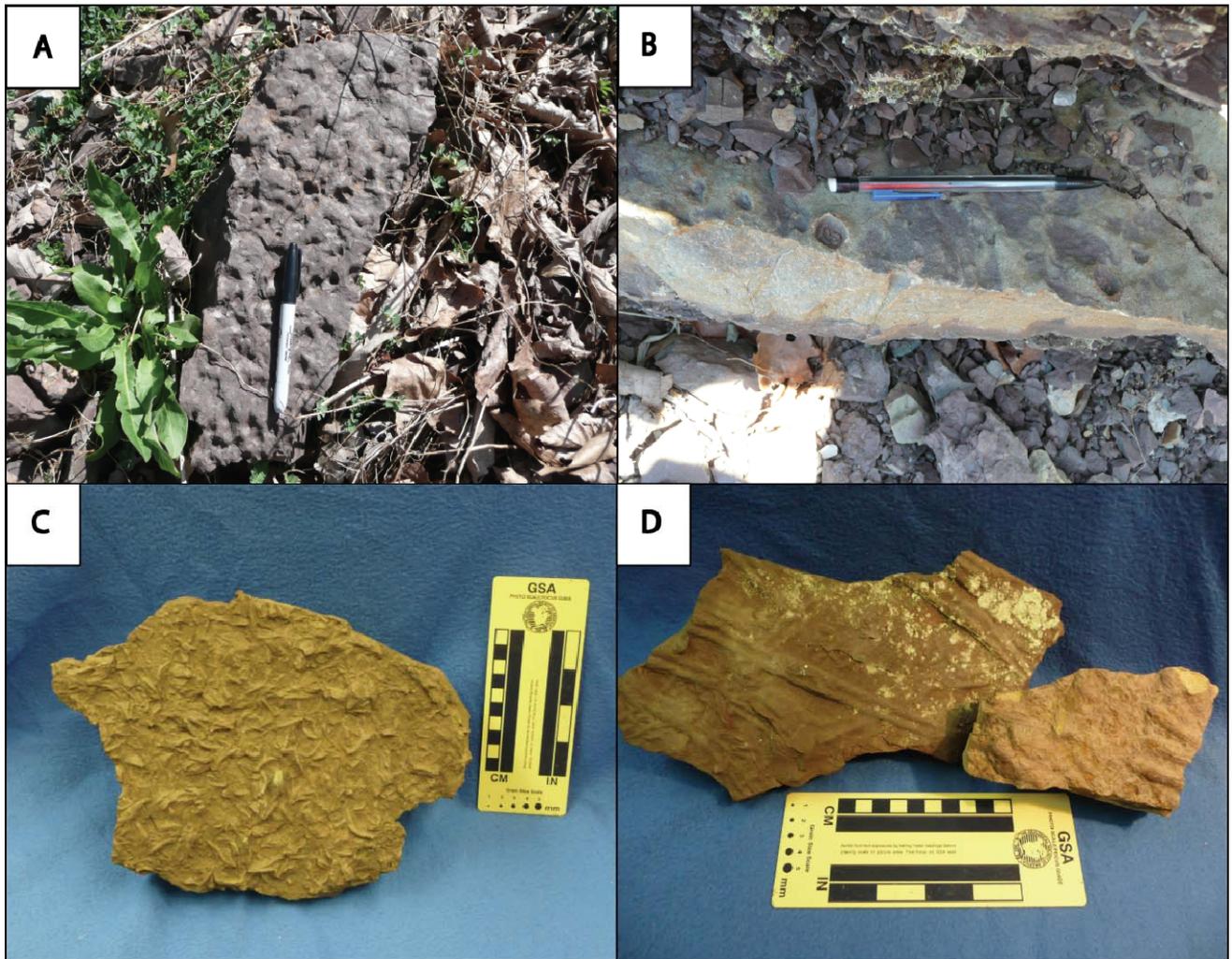


Figure 8: Common trace fossils in the Juniata Formation. A) *Skolithos* burrows in an argillaceous sandstone from South Gap, VA.; marker is approximately 5.5 inches long. B) *Monocriterion* burrows in a quartz arenite at South Gap, VA.; pencil is approximately 6 inches long. C) *Planolites* traces in an argillaceous sandstone from South Gap, VA. D) Two types of *Cruziana* traces in sublithic arenites; left sample is from South Gap, VA and the right sample is from New Castle, VA.

sedimentary structure. However, trough cross-bedding is common in the middle and upper portion of the formation as well. Symmetrical ripples are commonly present along the tops of beds (Fig. 7C), and megaripples are rarely exhibited as well. In addition to symmetrical ripples, interference ripples can also be found along the tops of sandstone beds.

This facies exhibits a greater variety of geometries than the other facies in the formation. Geometries include laterally continuous, thick sandstone beds (Fig. 9A), discontinuous, channeled beds (Fig. 9B), beds displaying pinching and swelling (Fig. 9B), and wedge-shaped beds (Fig. 9C). Bases of beds frequently contain scours, in the form of flute or gutter casts, above beds of silty mudstone or shale. Tool marks are also common on the base of sandstone beds (Fig. 7D). In general, the lower contacts of this facies are sharp or scoured and the upper contacts are either sharp or gradational. The majority of units within this facies lack evidence of bioturbation, but some thin beds, include rare *Skolithos* burrows. Where this facies overlies a shale/mudstone or siltstone, *Cruziana* traces are locally present at the bases of the beds (Fig. 8D). One potential example of *Roselia* has also been identified from a thin quartz arenite bed at South Gap, VA. This facies is abundant throughout the stratigraphic extent of the formation, but quartz arenites are more common toward the top of the formation and sublithic arenites are more common toward the base of the formation. Lithic and quartz arenite intervals vary greatly in thickness, from 2 inches to 15 feet.

#### 4.5. *Argillaceous Sandstone*

This facies is reddish gray to tan in color, and some units contain random green reduction zones. These sandstones range from quartz to sublithic arenites that contain minor to significant amounts of mud. Sandstone ranges in grain size from very fine- to medium-grained, but finer-grained lithologies are the most common. Mud in these rocks is rarely found in the form of mudstone drapes that define flaser or wavy bedding (Fig. 10A). The majority of argillaceous sandstones are thinly bedded and consistently alternate with beds of siltstone or silty shale. Some thin beds contain mm-sized mud and

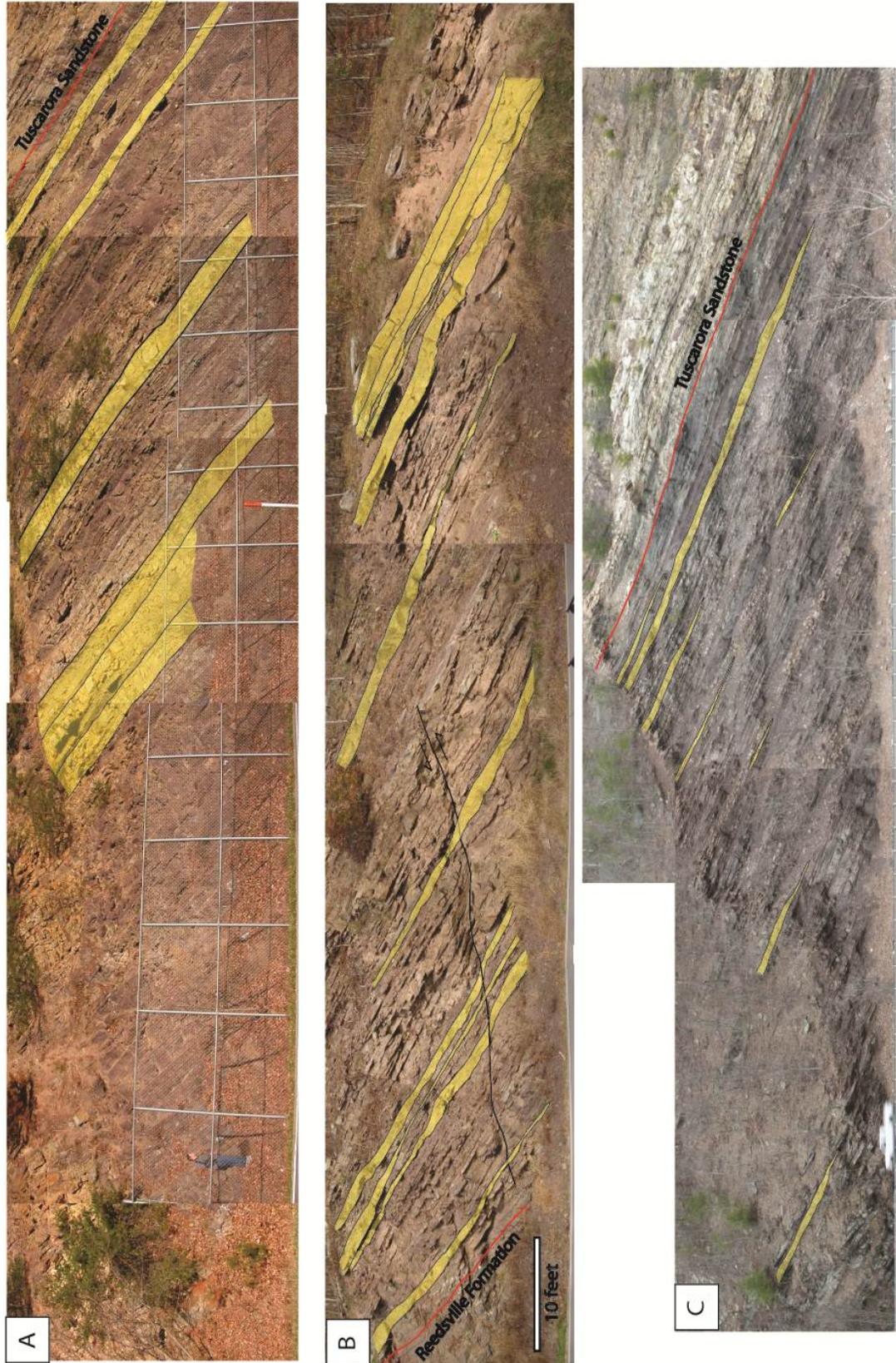


Figure 9: Geometries exhibited in the quartz and sublithic arenite facies. A) Thick, laterally continuous beds at Cove Mountain, Va. Quartz and sublithic arenites are the most abundant facies at this location. Person in foreground is approximately 6 feet tall. B) Channeling and pinching and swelling of beds at New Castle, Va. Few sandstone beds are laterally consistent in thickness at this location. C) Wedge-shaped sandstone bodies at South Gap, Va. Quartz and sublithic arenite intervals are much thinner at this location.

siltstone rip-up clasts that are concentrated at the bases of the beds. This facies is commonly laterally discontinuous, and scoured upper and lower contacts are common. Interference ripples are occasionally present at the top of beds, and these surfaces are rarely spotted with *Skolithos* and *Monocriterion* burrows. Argillaceous sandstone beds commonly are massive due to heavy bioturbation. This facies is not as abundant as the other sandstone facies, but it is developed throughout the formation, especially near the base. The thicknesses of argillaceous sandstone intervals range from 3 inches to 5 feet on average.

#### 4.6. *Hummocky-bedded Sandstones and Siltstones*

Sandstones in this facies are red to tan, and the siltstones are almost always red with sporadic green reduction spots. Sandstones range from very fine- to medium-grained and are usually interbedded with siltstones. Hummocky sandstone beds (Fig. 10B) tend to border on argillaceous, and they locally contain rip-up clasts of mudstone or siltstone. Other structures, such as convolute bedding and ball-and-pillow structures (Fig. 10C), are also present in this facies. Bedding contacts are generally sharp, and scouring is very common. Trace fossils are generally less common than in other facies, but *Skolithos* and *Cruziana* are rarely present. Overall, the size of the trace fossils within this facies is much smaller, and the distribution is less abundant, compared to those within other facies of the formation. This facies is restricted to the bottom 100 feet or less of the formation. The average thicknesses of hummocky-bedded sandstone and siltstone intervals range from 1 to 7 feet.



Figure 10: Sedimentary structures within the Juniata Formation. A) Mud drapes along low-angle cross-bed foresets, forming flaser bedding in a sandstone bed at New Castle, VA. B) Amalgamated hummocky sandstone beds at New Castle, VA. C) Ball and pillow structures in the hummocky bedded sandstone and siltstone facies at South Gap, VA; marker is approximately 5.5 inches long. D) Thin conglomerate bed with mudstone and siltstone rip-up clasts at South Gap, VA; pen top is approximately 1.5 inches long.

#### 4.7. *Lithic Sandstones and Conglomerates*

The lithic sandstone and conglomerate facies is one of the rarer facies within the Juniata Formation. It is usually dark red, with some color variety coming from various sedimentary rock clasts. Lithic grains in these sandstones and conglomerates consist almost entirely of sedimentary rock fragments (mudstone and siltstone clasts), with a minor amount of hematite grains and small quartz pebbles (Fig. 10D). Beds range from moderately to poorly sorted, and are usually medium- to very coarse-grained. Lithic

sandstones and conglomerates and are commonly laterally discontinuous, and almost always contain scoured lower contacts and sharp upper contacts. Trace fossils and bioturbation are completely absent within this facies. Lithic sandstone and conglomerate beds that are concentrated at the base of thicker sandstone successions locally appear to be lag deposits. This facies is scattered throughout the formation, and beds range from 1 to 6 inches thick.

## 5. REGIONAL THICKNESS TRENDS AND FACIES ASSOCIATIONS

### 5.1. *Regional Isopach Trends*

An isopach map for the Juniata Formation (Fig. 11) shows thickness data for the entire Formation, defined as all units above the Martinsburg/Reedsville Formation (or Oswego Sandstone where present) and below the Tuscarora Sandstone. The isopach map was compiled using a combination of outcrop and subsurface data from this study, as well as data published by Diecchio (1985). Although it has been noted that color boundaries are not a good indicator of formational or facies boundaries due to their probable diagenetic origin (Thompson, 1970a; Diecchio, 1985), the Juniata Formation is traditionally defined by its red color boundary and it is the only way to be consistent when examining the formation at a regional scale. The isopach map reveals an overall thickening of the formation to the northwest, with depocenters located in central Pennsylvania and western Maryland. In addition, the Juniata Formation thins dramatically to the east, and more gradually to the south and west. In easternmost outcrop belts, the Juniata Formation is completely absent due to removal beneath the Tuscarora Unconformity (Rodgers, 1971; Diecchio, 1985; Dorsch, 1994). The distribution of paleocurrents (Fig. 5) in combination with the thickness data from the isopach map, show two possible shoreline locations: one to the north in central Pennsylvania, which is likely the result of the prograding Queenston delta complex in Pennsylvania (Dennison, 1976), and one to the east parallel to the eastern basin margin.

The majority of the outcrop locations in this study are between 200 and 450 feet thick, with North Fork Mountain containing the thickest deposits (750 feet) and Cove Mountain containing the thinnest deposits (150 feet). This is due to North Fork Mountain

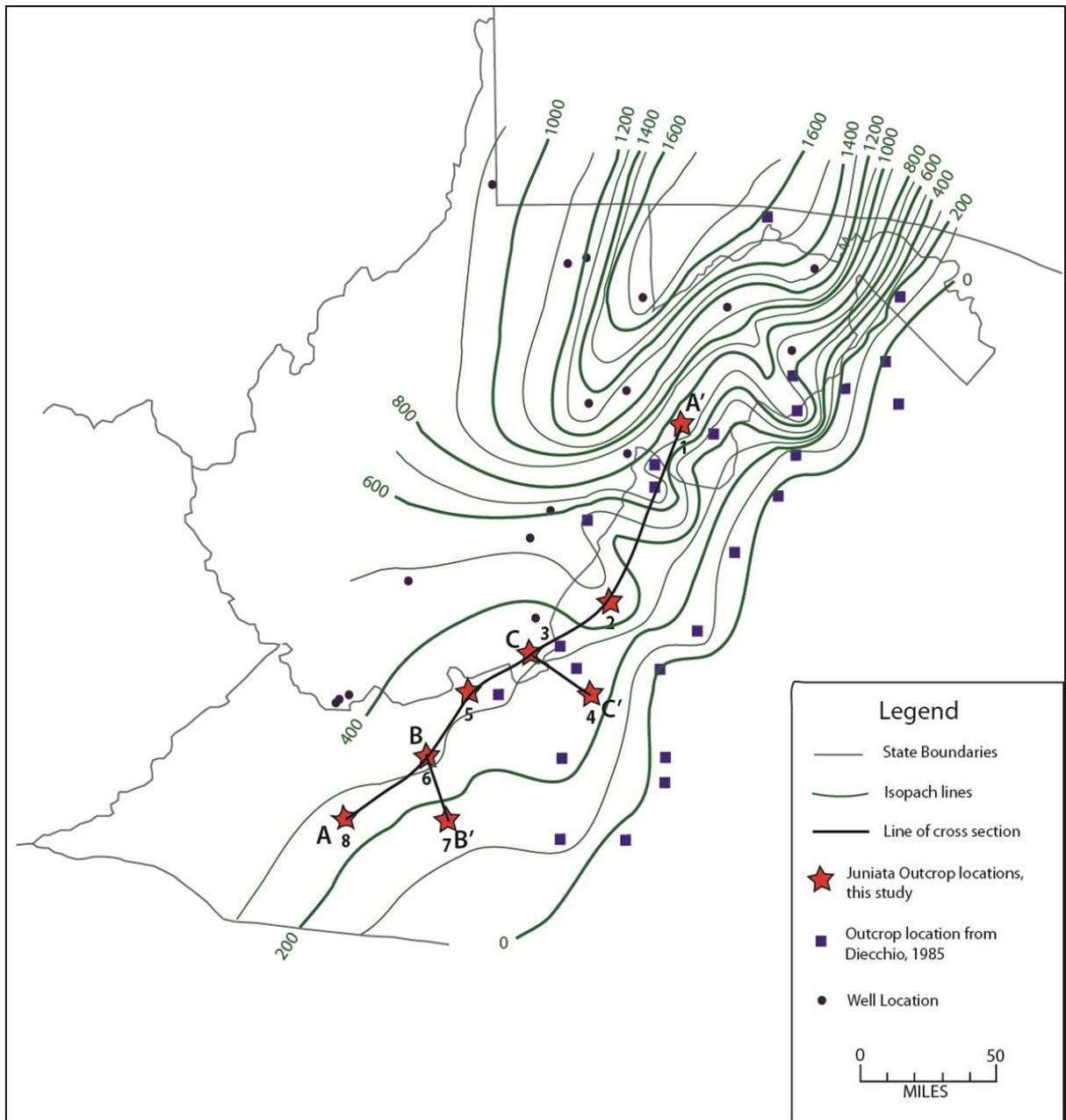


Figure 11: Regional isopach map of the Juniata Formation and lines of cross section. Data is plotted on the palinspastic base of Dennison and Woodward, 1963. Outcrop locations correspond as follows: (1) North Fork Mtn., WV; (2) Falling Springs, VA; (3) Gap Mills, WV; (4) New Castle, VA; (5) Narrows, VA; (6) South Gap, VA; (7) Cove Mtn., VA; (8) Red Rock Mtn., VA. Cross-section A–A' is along depositional strike, and B–B' and C–C' are along depositional dip.

being located much closer to the depocenter than the other outcrops, and Cove Mountain being the furthest southeast. The overall thickness of the formation does not change significantly throughout southwestern Virginia, but there is a variation in the distribution

of facies. Overall, the amount of sandstone increases to the north and to the east, whereas the amount of mudstone or shale increases to the south and west. Bioturbation also becomes more abundant to the southwest, with the Red Rock Mountain location exhibiting approximately 75% bioturbated facies. Based upon the regional facies data, the Juniata Formation can be broken into four regionally-distinct facies associations, which vary in extent geographically as well as temporally. These facies associations were correlated across the region and are presented in a series of cross sections (Fig. 11). A summary of the interpreted depositional environments for facies associations is given in Table 1.

## 5.2. *Facies Association A: Sandstone-to-Mudstone Fining-Upward Cycles*

### 5.2.1. Description

Facies Association A is best developed in the middle to upper part of the Juniata Formation (Fig. 12). The only location where Facies Association A is present at the base of the formation was at North Fork Mountain (Figs. 12 and 13), and this is likely because other facies associations that normally occur in lower parts of the formation in southwest Virginia are developed in the Oswego Sandstone at this location. The North Fork Mountain outcrop is also the location closest to the depocenter in this study. Geographically, this facies association is thickest to the north and to the west, with North Fork Mountain and Gap Mills containing the thickest expressions of Facies Association A (Fig. 12). This facies association becomes increasingly rare toward the south and east, with neither Cove Mountain nor South Gap containing any trace of Facies Association A (Fig. 14a and 15). Facies Association A is most typically underlain by Facies Association

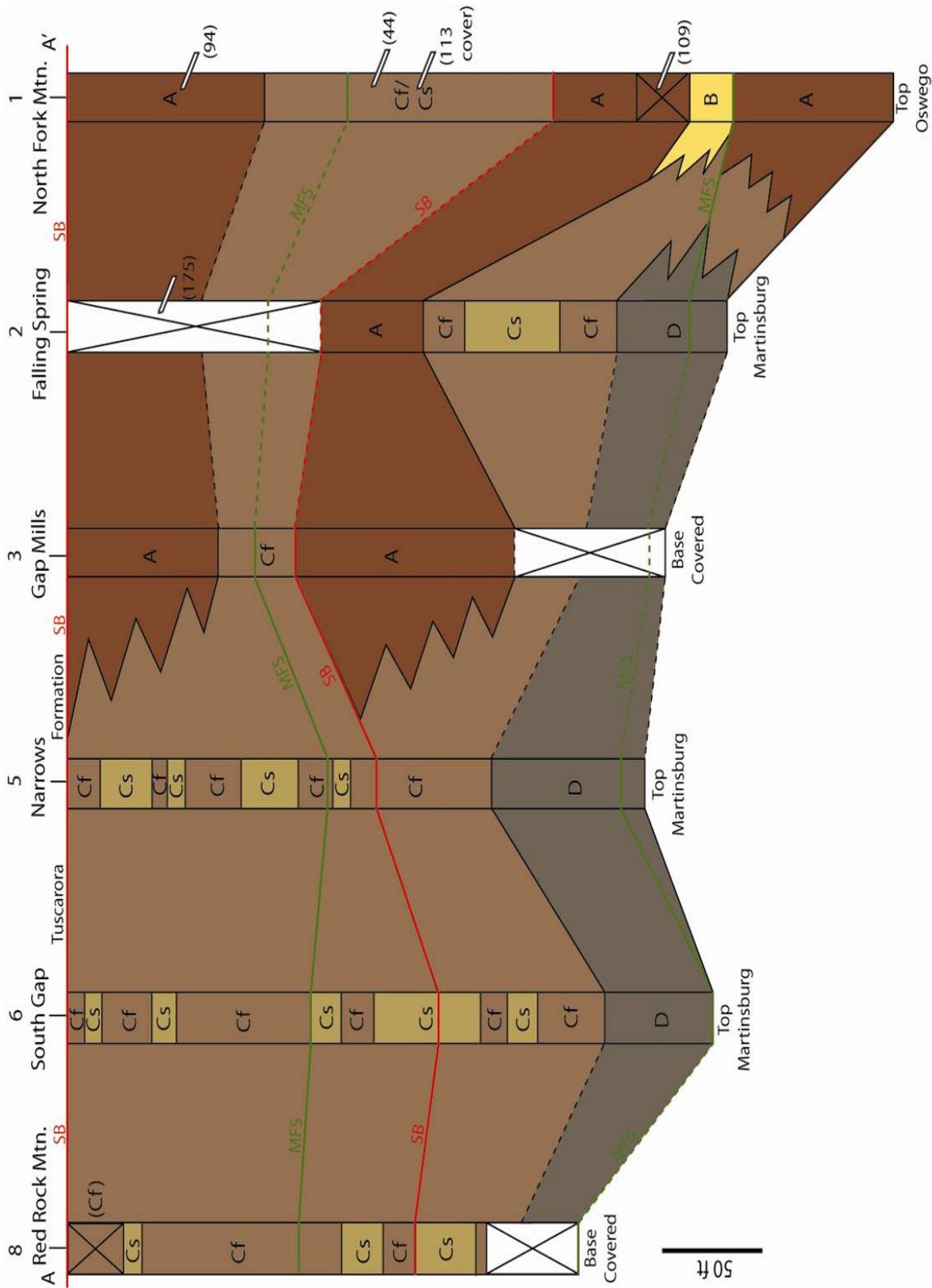


Figure 12: Cross section A–A'. Along-strike variations in facies association distribution. Cross-sections are hung on the contact with the Tuscarora Formation. Footage of excluded section is indicated underneath break marks. Crossed boxes indicate covered intervals. SB = Sequence Boundary; MFS = Maximum Flooding Surface

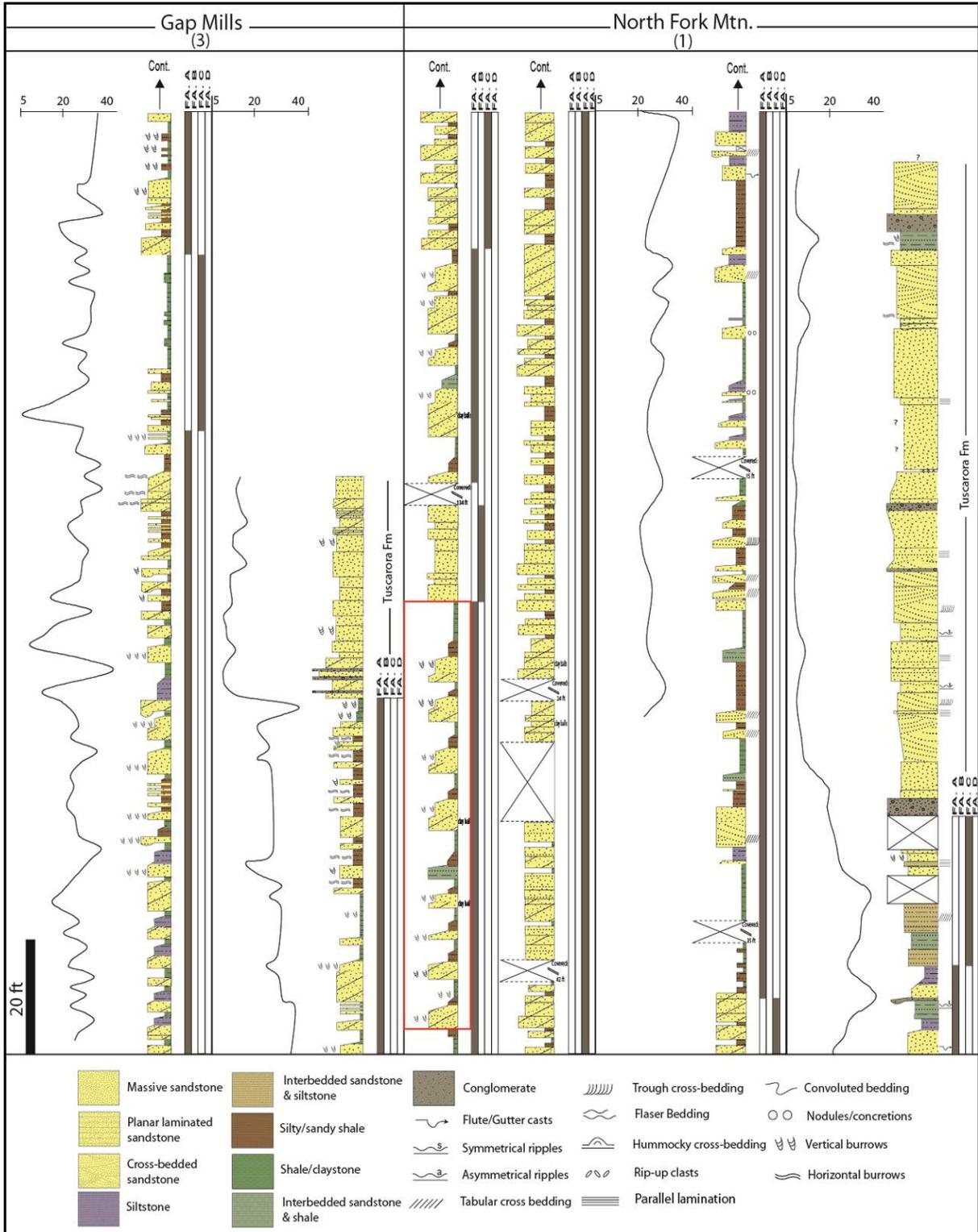


Figure 13: Distribution of Facies Associations: North Fork Mtn, WV and Gap Mills, WV. Gamma ray curve is located to the left of the strat columns and facies associations are shaded to the right. Red box denotes location of section in Figure 16.

C and, where Facies Association A is present at the top of the Juniata Formation, it is overlain by the Tuscarora Unconformity (Fig. 12).

Facies Association A is the most distinctive in the Juniata Formation. It consists of repetitive, stacked cycles of sharp-based quartz/sublithic arenite that grade into siltstone/silty mudstone with interbedded sandstones and capped by red mudstone. Rarely, the red mudstone facies grades into a “proto-vertisol” at the top of the cycle. This succession of facies, termed a fining-upward cycle, is repeated inconsistently, and the cycles are typically not complete—the red mudstone facies is commonly not present at the top of a cycle. Cycle thickness is variable, and the thicknesses of individual facies within a cycle are variable as well. Complete cycles range from 3 to 10 feet thick. The siltstone/silty mudstone with interbedded sandstones facies is commonly the thickest part of the cycle, ranging from 1 to 5 feet thick on average.

In general, quartz arenites are much more common than sublithic arenites in this facies association, and they are thicker as well. Davies et al. (2010) documented similar cycles in the Juniata Formation of central Pennsylvania, showing that this facies association persists around the depocenter. The quartz and sublithic arenites within this facies association range from massive to cross-bedded, with both tabular-planar and trough cross-bedding exhibited. Bases of these cycles are always sharp, with scouring common. Flute or gutter casts commonly are present at the base of sublithic/quartz arenite beds. In addition, intraformational mudstone clasts rarely are concentrated at the bases of arenite beds. Reactivation surfaces rarely are developed within the cross-stratified beds.

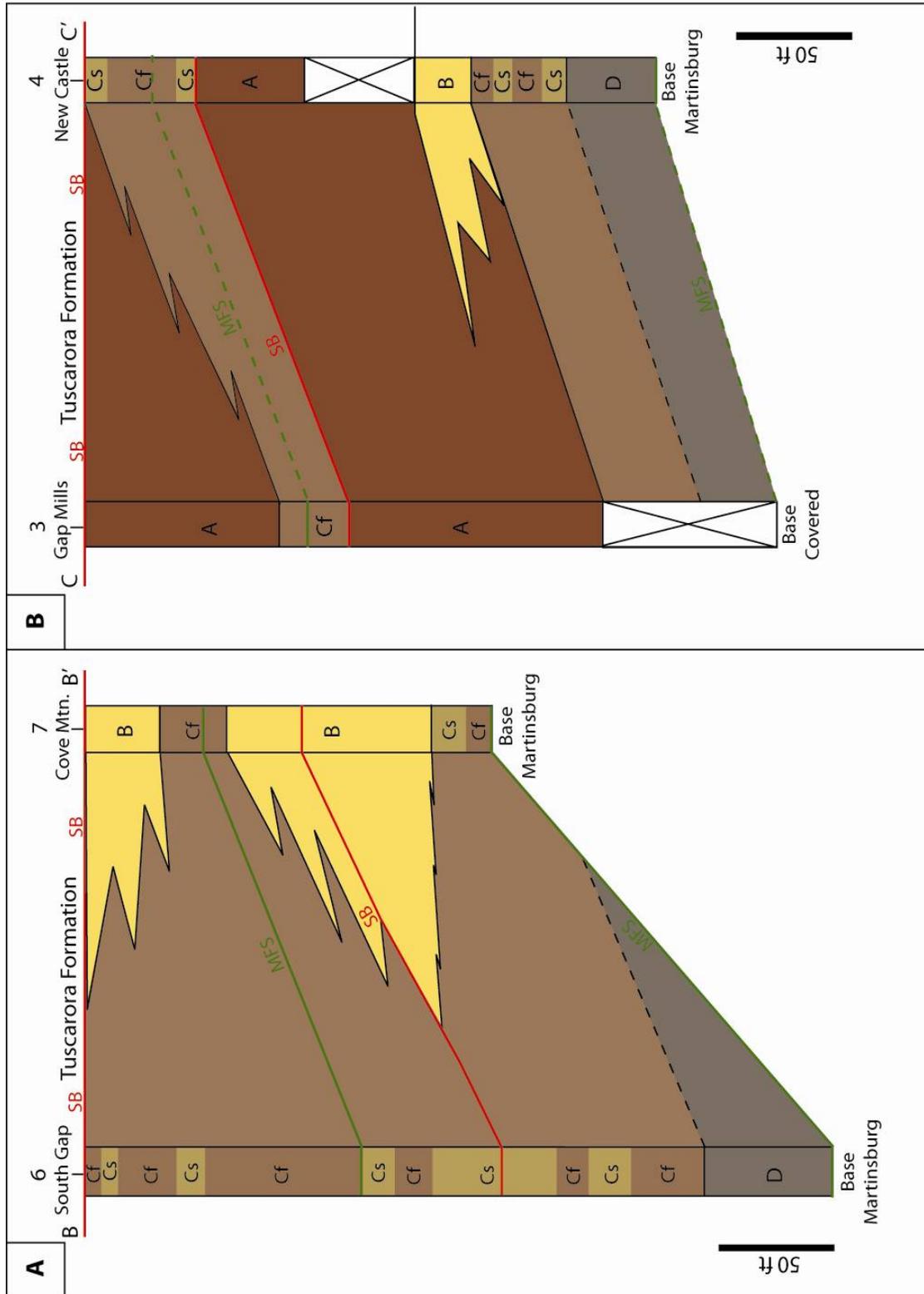


Figure 14: A) Cross section B-B'. B) Cross section C-C'. Trends in facies associations along depositional dip. Cross-sections are hung on the contact with the Tuscarora Formation. Crossed boxes indicate covered intervals. SB = Sequence Boundary; MFS = Maximum Flooding Surface.

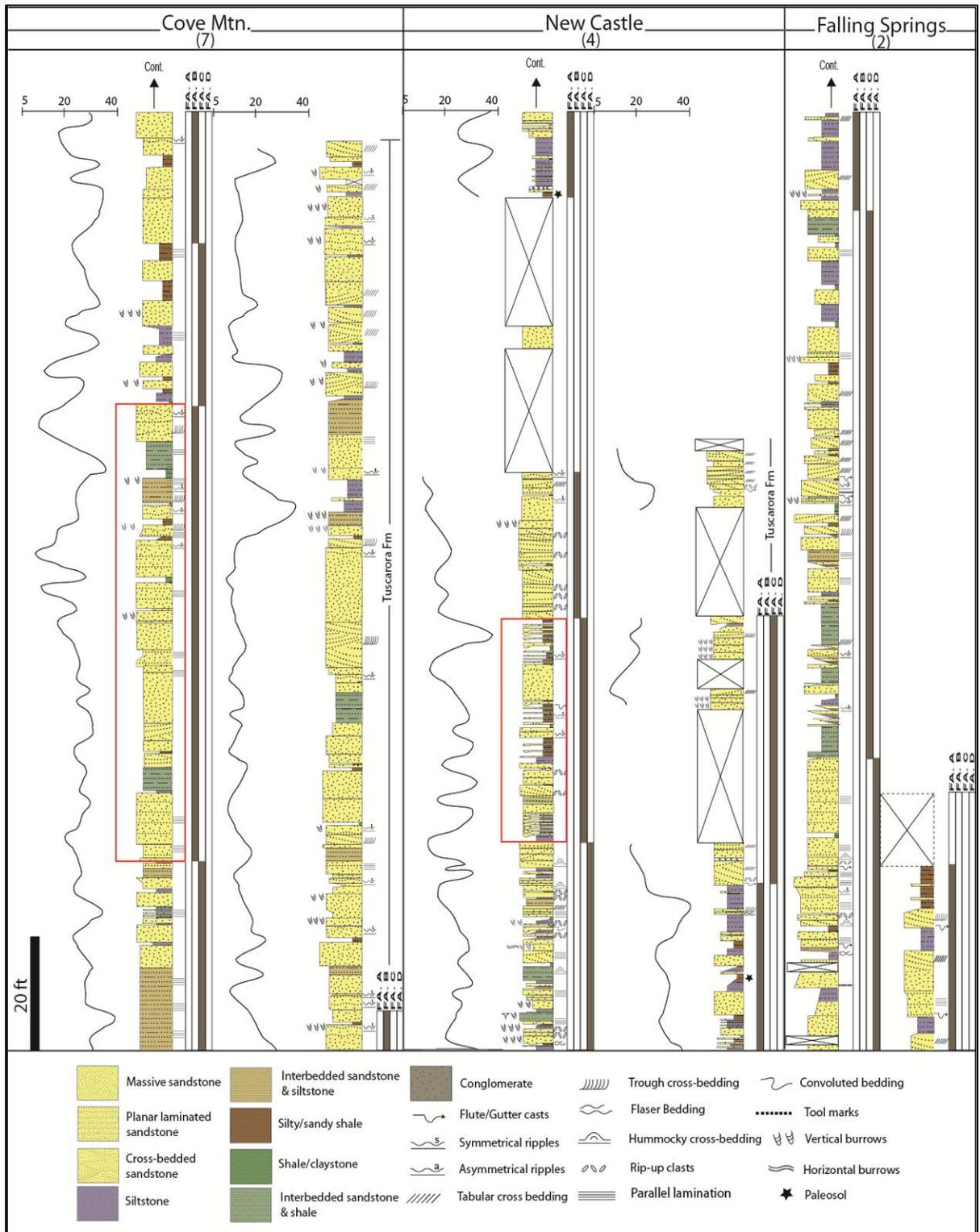


Figure 15: Distribution of Facies Associations: Cove Mtn., VA; New Castle, VA; Falling Springs, VA. Gamma ray curve is to the left of the strat columns and facies associations are shaded to the right. Red boxes denote location of section in Figures 18 and 21.

According to paleocurrent data collected in various parts of the study area from other researchers (Kreisa, 1980; Diecchio, 1985; Dorsch, 1993), sediment transport directions are highly variable within the Juniata Formation. Throughout the majority of the study area the dominant transport direction is to the northwest, but the further north and west an outcrop is located the more southwesterly the transport direction becomes (Fig. 6). Examination of rose diagrams from individual locations reveals a large scatter in paleocurrent direction, with many ranging from northeast to south.

The siltstones/silty mudstones with interbedded sandstones are always heavily bioturbated and dominated by *Skolithos*. As a result, the sandstones and mudstones of this facies tend to appear massive when located in the middle of a fining-upward cycle. Rarely, flaser or wavy bedding is exhibited in thin sandstone beds within this facies. Where the red mudstone facies is present at the top of the cycle, it has a gradational basal contact and is also commonly bioturbated. Identifiable burrows rarely are present in mudstone at the top of fining-upward cycles. Less commonly, mudstones at the top of cycles exhibit fine parallel lamination. The “proto-vertisols” facies always overlies a bioturbated mudstone, where present, and this facies only occurs within Facies Association A. A complete, representative stratigraphic succession for Facies Association A is shown in Figure 16.

In addition to its conspicuous nature in outcrop, Facies Association A also exhibits a characteristic gamma-ray signature in well logs and outcrop gamma-ray scintillometer curves (Figs. 14 and 16). The repetitive succession of sandstone grading to mudstone is expressed as a gradual increase in total gamma-ray counts that then drops abruptly at the overlying basal sandstone bed. This signature is much easier to identify

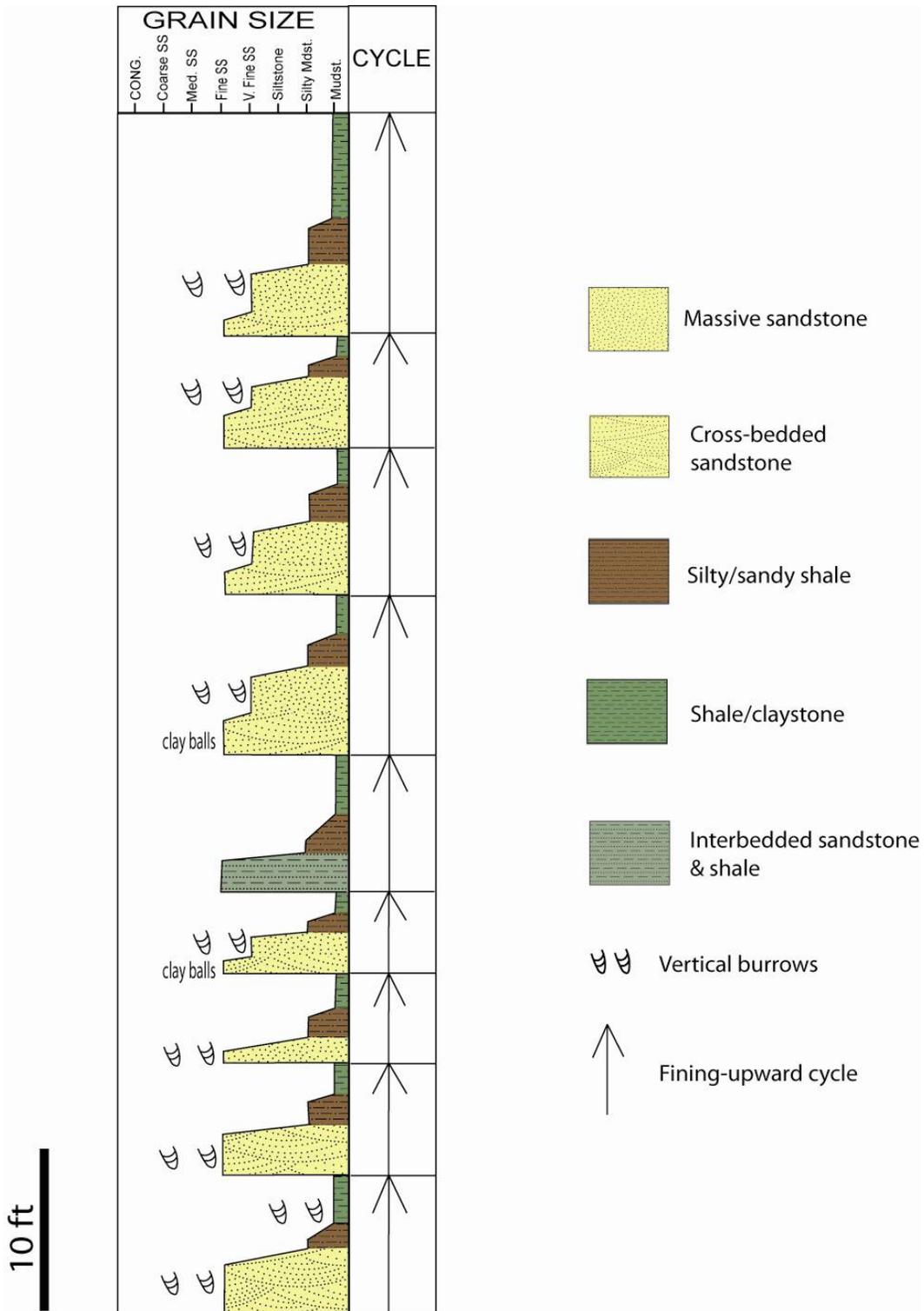


Figure 16: Representative stacking patterns of Facies Association A. Section is from North Fork Mtn, WV (location shown in red box on Fig. 13).

where the cycles are thicker, but thinner cycles also show high-frequency fluctuations in total gamma-ray count that are not as common in other parts of the formation.

Interpretation of cycles from gamma-ray curves must be approached with caution, however, because increased proportions of clay within sandstones can sometimes cause the sandstones to plot anomalously high on the curve. Conversely, high quartz silt content in mudstones can cause this facies to plot anomalously low on the gamma-ray curve.

#### 5.2.2. Interpretation

The facies and sedimentary structures present in Facies Association A were likely the result of deposition along a coastal plain, possibly on an intertidal flat, which was intermittently subaerially exposed. The repetitive successions of sharp-based quartz/sublithic arenite that grade into siltstone/silty mudstone with interbedded sandstones which is then capped by red mudstone (or rarely a “proto-vertisol”) possess a striking resemblance to the Ordovician tidal-flat cycles, or parasequences, described by Tankard and Hobday (1977). These authors recognized three facies within their semi-cyclic fining-upward cycles: a lower quartz arenite facies with a variety of tidal structures, a heterolithic facies with common flaser and lenticular bedding, and a maroon to reddish-brown mudstone facies. The cycles and structures exhibited in Facies Association A also integrate well into the tidal-flat coastline model of Klein (1971), which proposes a fining-upward sequence as the result of progradation of a suspension-dominated upper tidal flat over a mid tidal flat, characterized by alternating bedload and suspension, over a bedload-dominated lower tidal flat, which occurs in a subtidal setting.

Within the Juniata Formation tidal-flat cycles consist of a lower unit of sandstone, which is usually dominated by trough or planar cross-bedding but may also be massive.

This unit represents deposition on the lower tidal flat which is dominated by bedload transport of fine- to medium-grained sand. Reactivation surfaces, as well as variable cross-bed orientations reported by other researchers (Kreisa, 1980; Diecchio, 1985; Dorsch, 1993) could indicate deposition within the tidal zone that was affected by other processes, such as fair-weather and storm wave action and longshore drift (Klein, 1971; Klein & Ryer, 1978; Clifton, H. E., 2006; Davies et al., 2010). The tidal circulation model by Klein (1977) states that highly mature quartz arenites, much like the sandstones within Facies Association A, also suggests continuous reworking by tidal processes. The intraformational mudstone clasts, as well as the flute or gutter casts present at the base of these lower sandstone units, are likely the result of scour within the lower tidal zone (Kreisa, 1980; Davies et al., 2010). Therefore, a subtidal to low- tide terrace environment is suggested for the lower sandstone unit in this facies association.

Overlying the lower, subtidal sandstone unit is interbedded mudstone and sandstone, which reflects alternating suspension and bedload deposition, or a zone of transitional transport (Klein, 1971; Tankard & Hobday, 1977; Clifton, 2006). The presence of flaser and wavy bedding within the middle unit also is indicative of alternating bedload and suspension deposition. The middle unit is usually heavily bioturbated as well, with *Skolithos* burrows being the most prominent. The repeated alternation of suspension and bedload deposition, along with the prevalence of vertical burrows, is interpreted to be the result of deposition in the midflat region Klein (1971) and Tankard & Hobday (1977) interpreted interbedded mudstone and sandstone units with similar structures and bioturbation patterns as middle tidal flat deposits. The upper flat portion of Facies Association A is characteristically composed completely of mud,

and it is commonly bioturbated but also rarely laminated. The dominance of silt and clay particles within this unit points to a suspension-dominated depositional process. Although the “proto-vertisol” facies was not documented in every location of Facies Association A, other researchers have documented paleosols further south in extreme southwest Virginia (Driese & Foreman, 1992) and north in Central Pennsylvania (Retallack & Feakes, 1987) within similar facies associations. The rarity of paleosols in this study indicates either non-preservation or they were not documented due to the difficulty in distinguishing them from the mudstone facies. Regardless, the presences of paleosols at the top of these fining-upward cycles suggest a shallowing-upward trend and subaerial exposure. This places the upper mudflat in an upper intertidal to supratidal environment.

Considering the similarity of facies stacking patterns and sedimentary structures to documented tidal-flat cycles (Fig. 16), Facies Association A is interpreted to have formed on a coastal tidal flat. The meter-scale fining-upward cycles of Tankard and Hobday (1977) were estimated to have been produced in a mesotidal environment, with a tidal range of 2–3 meters. The fining-upward cycles of Facies Association A average 3–10 feet, which also places the environment within the mesotidal range. Work by Klein and Ryer (1978) showed that ancient shallow seas were dominated by tides and tidal circulation patterns, so the presence of such features within the Juniata Formation is not unusual on a global scale. The repetition of shallowing-upward cycles shows that these were prograding tidal flats, suggesting an overall regressive shoreline trend punctuated by rapid transgressions. The incomplete cycles that are commonly exhibited most likely reflect reworking of cycle tops during transgression.

Fining-upward cycles of Facies Association A were documented by Diecchio (1985), who attempted to correlate these cycles using well logs from West Virginia, and concluded that the regional scale of the cycles likely pointed to relative sea-level fluctuations that occurred while the entire basin was subsiding (due to tectonics and high sedimentation rates). Fining-upward cycles similar to those in the Juniata Formation have also been attributed to meandering fluvial systems (Retallack & Feakes, 1987). This interpretation, however, has recently been called into question by Davies et al. (2010) who argue for a shallow-marine origin. These authors cite abundant burrowing, cross-strata with variable and reversing directions, and heterolithic scour-fill as evidence for shallow-marine deposition, which was likely influenced by tides. Since the majority of these structures have also been documented within the study area, it is interpreted that the fining-upward cycles in Facies Association A are a result of shallow marine deposition and not fluvial processes.

Direct correlation of individual cycles in outcrop was not possible. This is due to the large distance between many of the outcrop sites, and the variation in the amounts of missing section due to the overlying Tuscarora Unconformity. However, the regional presence of these cycles at similar stratigraphic locations throughout the majority of the study area (Fig. 12) points to a likely allocyclic driver for these fining-upward cycles. Regional events could either be due to eustatic sea-level changes or increased subsidence as a result of tectonic and sediment loading throughout the basin (Dennison, 1976; Diecchio & Brodersen, 1994; Ettensohn, 1994; Castle, 2001). Of the two hypotheses, eustatic sea-level change is favored due to the scale and widespread geographic extent of the cycles, along with the contemporaneous occurrence of the Late Ordovician glacial

buildup and the Hirnantian Glaciation (Dennison, 1976; Villas et al., 2002; Brenchley et al., 2003; Saltzman & Young, 2005). Further basinward into Kentucky, meter-scale scales cycles of time-equivalent carbonate rocks have been attributed to high frequency sea-level fluctuations that resulted from the initiation of Gondwana glaciation (Pope & Read, 1997; Pope & Read, 1998).

### 5.3. *Facies Association B: Sandstone-Dominated Facies*

#### 5.3.1. Description

Facies Association B is the least common facies association in the study area and its thickness varies geographically. The facies association is thicker to the southeast, especially at the Cove Mountain locality where it makes up about 75 percent of the Juniata Formation (Fig. 14a). It does not exist in the southern or westernmost locations (Red Rock Mountain, Gap Mills, Narrows, and South Gap). Facies Association B typically interfingers with Facies Association C (Fig. 12). At the New Castle location, however, Facies Association B is overlain by Facies Association A (Fig. 14b). The cross sections show that Facies Association B is only developed in the eastern-most locations, with the one exception being North Fork Mountain where the facies association is present towards the base of the formation (Fig. 12).

Facies Association B consists of multiple sets of quartz arenite or argillaceous sandstone beds, which are commonly drab to tan in color, with much lesser amounts of siltstone or mudstone (Fig. 17a, b; Cove Mountain locality in Fig. 15). Red coloration is less common in this facies association than in the other facies associations. Quartz arenites are the most commonly lithology, but sublithic arenites and argillaceous

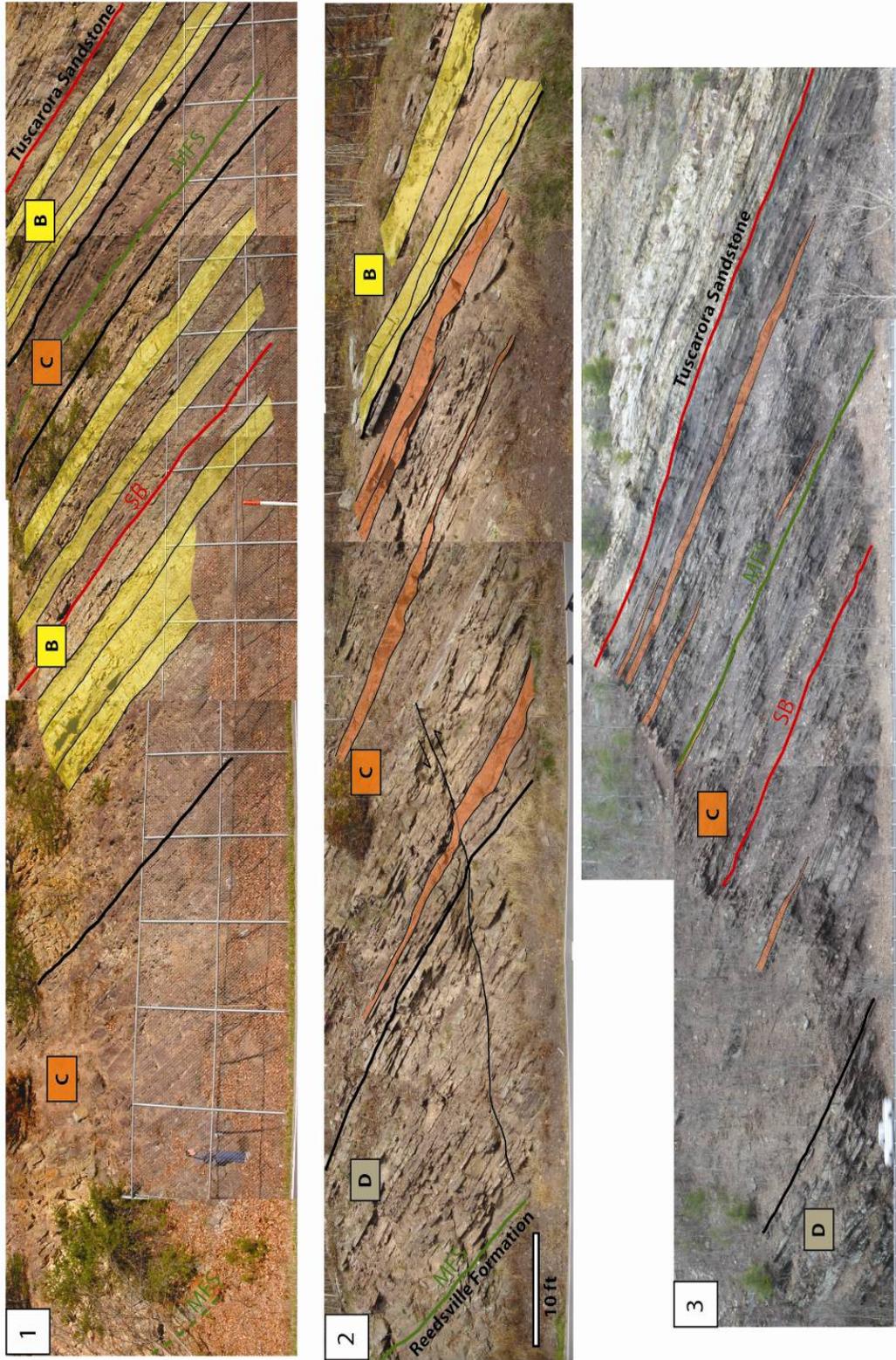


Figure 17: Distribution and geometries of Facies Associations B, C, and D at three localities. 1) Cove Mountain, Va. Laterally continuous arenites (yellow) of Facies Association B are the most abundant facies at this location. Person in foreground is approximately 6 feet tall. 2) New Castle, Va. Facies Association B exhibits minor pinching and swelling, as well as wedging of beds (yellow). Channeling and irregular erosional surfaces are abundant in Facies Association C (orange). 3) South Gap, Va. Facies Association C comprises the majority of the outcrop, and fine-grained facies dominate the stratigraphy. Sandstones are generally wedge-shaped (orange). Facies Association boundaries are black, maximum flooding surfaces (MFS) are green, and sequence boundaries (SB) are red.

sandstones also are rarely present. This facies association contains less than 10% of mudstone or silty mudstone.

Sandstones are massive to cross-bedded, and cross-bedding is much more common in comparison to other facies associations. Trough cross-beds are the most common type of cross-bedding and low-angle cross lamination and parallel lamination also are developed. Symmetrical ripples are commonly present along the top of sandstone beds where a bedding surface is exposed. These rippled surfaces are rarely spotted with *Skolithos* or *Monocriterion* burrows. Bioturbation rarely is present in massive sandstones. Overall, bioturbation is less common in these sandstones than sandstones of other facies associations, and only vertical burrows have been observed. Sandstone beds are usually laterally continuous throughout the outcrop (Fig. 17a), but pinching and swelling of beds and wedging also rarely occurs (Fig. 17b). Bases of beds commonly exhibit a sharp, planar contact (Fig. 17a), but slight scouring with up to 6 inches of relief at the base is also common, especially in beds of irregular thickness (Fig. 17b). A representative stratigraphic succession of Facies Association B is shown in Figure 18.

This facies association is distinct in outcrop as well as in gamma-ray logs. The low concentration of clay within the sandstone units results in a low total gamma count. These values are generally lower than most of the other sandstones in the formation. Small variations in total gamma count occur where thicker beds of mudstone or siltstone are present within sandstone intervals (see the Cove Mountain locality in Fig. 15). These variations are even more common where the sandstones are argillaceous. Rare spikes in uranium content in some sandstone beds also results in an anomalously high total gamma-ray count, but the overall distribution shows a fairly continuous, blocky pattern.

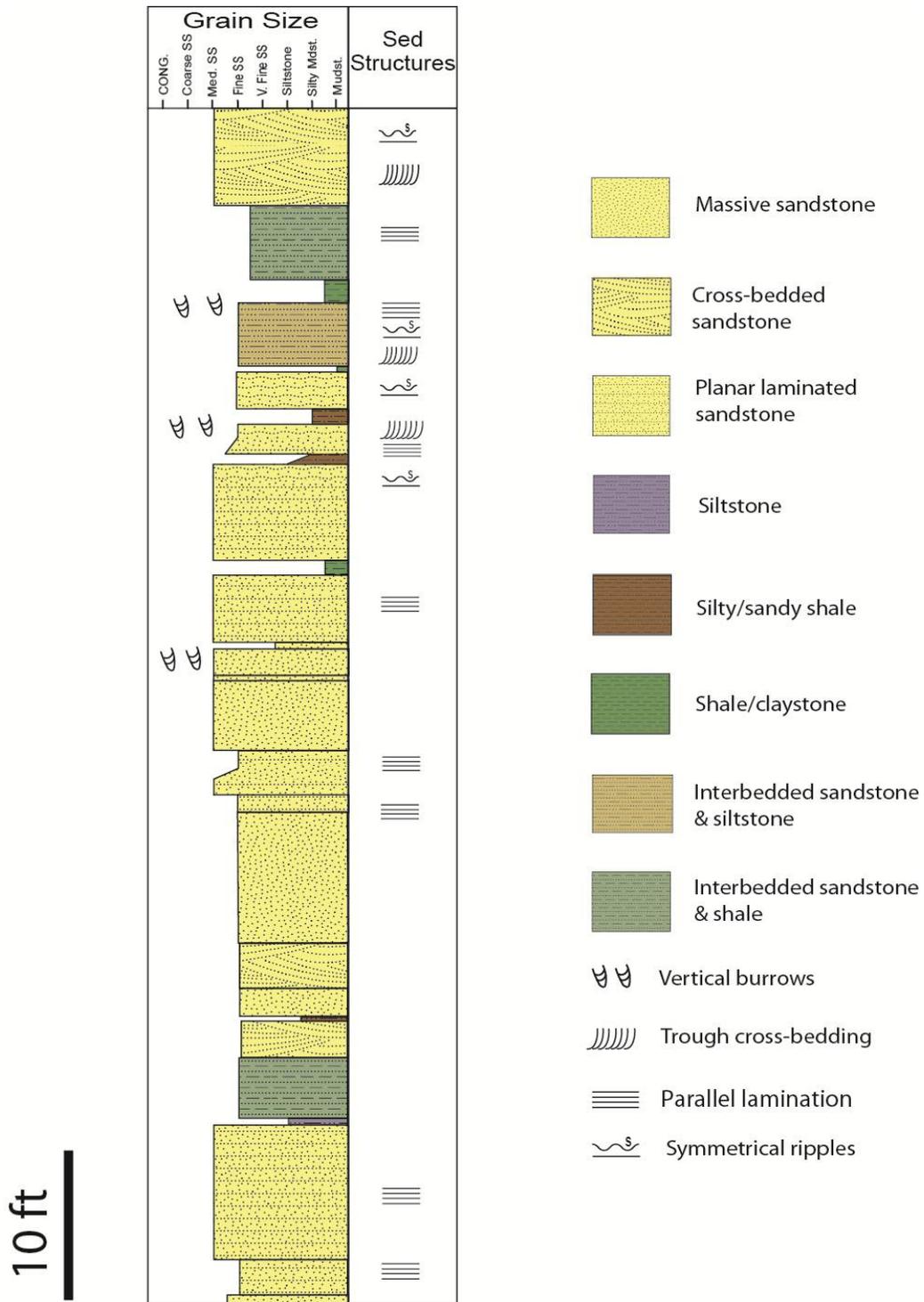


Figure 18: Representative stacking patterns of Facies Association B. Section is from Cove Mountain, Va (location shown in red box on Fig. 15).

### 5.3.2. Interpretation

The most likely depositional environment for Facies Association B is that of discontinuous, nearshore sandbars. The high concentration of sand, along with the sedimentary structures and bioturbation exhibited in this facies association, suggests a proximal location to the shoreline, but below low tide. There is no evidence for subaerial exposure, or aeolian dune formation, so it is interpreted that these sandbars developed in the middle-to-upper shoreface zone along the coast. Models for nearshore bars, based upon modern analogs, contain a succession of facies, including: an offshore or inner-shelf shoreface transition, a seaward slope, a bar crest, a landward slope, a rip-channel or trough, and foreshore deposits (Hunter et al., 1979; Ly, 1982; Harms et al., 1982; Greenwood & Mittler, 1985; Clifton, 2006). Preservation of all of these facies, however, is quite rare due to constant reworking in the nearshore environment, and progradation would likely only preserve the inner-shelf shoreface transition, the seaward slope, and rip-channel or trough—which would be separated by a sub-horizontal erosional surface (Davidson-Arnott & Greenwood, 1976; Hunter et al., 1979; Greenwood & Mittler, 1985; Clifton, 2006). Nearshore bar-trough systems essentially enhance the unidirectional flow of rip currents and longshore currents, so a progradational succession should contain abundant cross-bedding with a dominantly unimodal transport direction (Harms et al., 1982; Clifton, 2006).

Within Facies Association B, trough cross-bedding, low-angle bedding/lamination, planar bedding, and symmetrical ripple bedding are characteristic sedimentary structures (Fig. 18). The combination of these structures reflects current and wave movement along different parts of the bar. In general, trough cross-bedding, low-

angle bedding, and planar bedding (to some degree) are the result of longshore and/or offshore-directed currents, and symmetrical ripples and planar bedding (to some degree) represent reworking by oscillatory flow (Harms et al., 1982; Clifton, 2006). Trough cross-bedding and low-angle bedding/lamination most likely are the result of deposition along the seaward-side of the bar, where currents generally transport sediment in the offshore and longshore direction and result in the preservation of beds during progradation (Greenwood & Mittler, 1985; van de Meene, 1996; Clifton, 2006). Wedge-shaped sandstone bodies are likely the result of deposition along the seaward slope as well. On modern coasts, wedge-shaped facies on nearshore bars have been attributed to the variation of the profile of the bar as it moves seaward and landward, in response to both storms and alongshore migration (Greenwood & Mittler, 1985). Rare wave ripple cross-lamination also can develop on the seaward side of nearshore bars as a result fair-weather-wave reworking (Ly, 1982; van de Meene, 1996).

Planar bedding and medium-scale trough cross-bedding likely reflect deposition within the trough or rip-channel, where current velocity is the highest and current and wave direction is the most variable (Davidson-Arnott, 1976; Ly, 1982; Harms, 1982). The erosional surfaces (planar and scoured) within Facies Association B (Fig. 17a, 17b) represent erosion of the bar crest and the other missing facies of the bar. Some scouring is also the result of erosional processes that occur within the trough and/or rip channel. Although quartz and sublithic arenite are the main component within Facies Association B, minor amount of finer-grained facies occur as well. This can be attributed to both the type of sediment being supplied to the coast and the overall energy regime of the coast. Fine-grained facies are common throughout the Juniata Formation in the study area, and

it can be concluded that there was an abundant supply of silt and clay that was deposited in a fairly low energy setting that did not provide enough turbulence to prevent mud deposition. Interbedded silts and muds within Facies Association B could reflect periods of quiescence when the fine particles were able to settle out of suspension, possibly within a trough.

The rarity of bioturbation within this facies association supports deposition in a shallow-water, high-energy environment such as found along a bar within the middle and upper shoreface. The constant shifting of the substrate would allow only vertical burrowing organisms to establish themselves, hence the singular presence of *Skolithos* burrows within this facies association. Since the upper shoreface is affected by waves in the onshore and offshore direction, as well as by the wave-driven longshore current, a variety of paleocurrent directions would be expected. Because this facies association exhibits a variety of cross-bed orientations, a significant portion of variable and longshore-oriented paleocurrent directions recorded by previous workers (Diecchio, 1985; Kreisa, 1980; Dorsch, 1993) were likely the result of the wave activity along these shore parallel-to-oblique bars.

The inherent lateral movement of nearshore bars during deposition makes their preserved position in an outcrop highly variable, and difficult to map regionally. The thickness pattern of Facies Association B (Figs. 12, 14a, 14b) suggests that the thickness varies according to the proximity of the source area. Therefore, the closer a location was to a source of sand, the more likely a sequence of longshore bars would develop. Longshore sand bars are particularly susceptible to storm reworking (Davidson-Arnott & Greenwood, 1976; Hunter et al., 1979; Greenwood & Mittler, 1985; Clifton, 2006), and

therefore are rare within the Juniata Formation. They are likely to be reworked into the further offshore after major storm events by strong seaward-directed currents and wave action that occur on the nearshore (Suter, 2006). The paucity of this facies in the more distal (southerly and westerly) outcrops (Fig. 15a, b) is due to either a lesser amount of sand supplied to these areas, or the sequence being destroyed by storm reworking. Although the more distal outcrops do contain a slightly higher ratio of shale-to-sand, there is still a significant amount of sand contained within the formation at these locations. Therefore, the storm reworking hypothesis is favored.

Published data from Cotter (1983) and Davies et al. (2010) suggest a dominance of this facies association around the depocenter in central Pennsylvania, which has been interpreted as both a fluvial (Cotter, 1983) and shallow marine (Davies et al., 2010) deposit. Kreisa (1980) recognized this facies association at various locations in southwestern Virginia and interpreted it to be strandline sandstone body that flanked delta-plain mudflats. The vertical succession of facies within this strandline sandstone body was interpreted by Kreisa (1980) to be a barrier beach deposit. Kreisa proposed a model in which short, isolated barrier islands were separated by tidal channels and inlets. However, concrete evidence for these sandstone successions being part of a barrier island sequence was not found in this study. Clear evidence for tidal inlets or tidal channels was not observed, and no characteristic barrier island sedimentation patterns, such as foreshore, back barrier, and lagoonal facies, were documented.

The interpretation of Facies Association B as a wave-dominated deposit reveals a basic classification dilemma for the coastal system. Facies Association A is interpreted to be the result of tidal processes, but Facies Association B is dominated by wave processes.

Along modern coasts, tidal effects are more common behind barriers or bars along an overall wave-dominated coast (van de Meene et al., 1996; Cooper, 2000; Harris et al., 2002). In addition, different parts of a coastline may be dominated by different processes based upon the morphology of the coastline, seasonal climatic changes, tectonics, and sea-level changes (Boyd et al., 1992; Suter, 2006). It is suggested that this juxtaposition, along with evidence from other facies associations discussed in the following sections, means that the coast was a mixed wave- and tide-dominated system. Anthony and Orford (2002) concluded that mixed wave- and tide-dominated coasts are much more prevalent than previously recognized, and may make up a significant portion of the of the rock record. Their work showed that wave-dominated, mixed-energy, or tide-dominated morphologies may develop along any particular stretch of coastline, with little difference in parameters. These authors also concluded that coasts with mesotidal ranges are more likely to be mixed-energy systems rather than either wave- or tide-dominated systems.

#### 5.4. *Facies Association C: Heterolithic Facies*

##### 5.4.1. Description

Facies Association C (Cs and Cf) is the most common association within the Juniata Formation and its characteristics are the most variable. Facies Association C tends to be the thickest of all facies associations, although locally this is not the case (i.e. Cove Mountain in Fig. 14a, and Gap Mills in Fig. 12). The thickness of this facies association tends to vary proportionally to the regional isopach trend (Fig. 12). Stratigraphic location within the formation is also variable, but it is normally underlain by Facies Association D at the bottom of the formation, and interfingers with Facies Association B or A throughout the rest of the formation (Fig. 12). Figure 12 shows a

regional trend in which Facies Association C predominates to the south and is intercalated with Facies Association A to the north. Facies Association C is the most abundant facies association at the Red Rock Mountain, South Gap, and Narrows localities (Figs. 12 and 19). The transition between Facies Association A and Facies Association C is gradational throughout the study area.

Facies Association C consists of significant proportions of both the fine-grained facies (mudstone and siltstone: Cf) and coarse-grained facies (sandstone and conglomerate: Cs). Overall, the finer-grained facies make up around 60 percent or more of Facies Association C, but there are rare, thin intervals that contain mostly coarse-grained constituents (e.g. Narrows locality in Fig. 19). Mudstone and silty mudstone with interbedded sandstones are highly variable in thickness (approximately 1 foot to tens of feet), but the sublithic or quartz arenites beds are much thinner (maximum of 5 feet) than in the other facies associations. Argillaceous sandstone is also common, and the majority of lithic sandstones and conglomerates (6 inches to 2 feet thick) are developed within this facies association.

Facies Association C contains a variety of sedimentary structures, along with a wide range of geometries. Within the mudstones and silty mudstone with interbedded sandstones, parallel lamination is the most common primary sedimentary structure. Within argillaceous sandstones, flaser or wavy bedding is rarely exhibited. Quartz and sublithic arenites rarely contain trough cross-beds and low-angle cross-stratification, and symmetrical ripples are commonly developed along the tops of beds. Despite the occurrence of these sedimentary structures, massive beds of argillaceous sandstone and

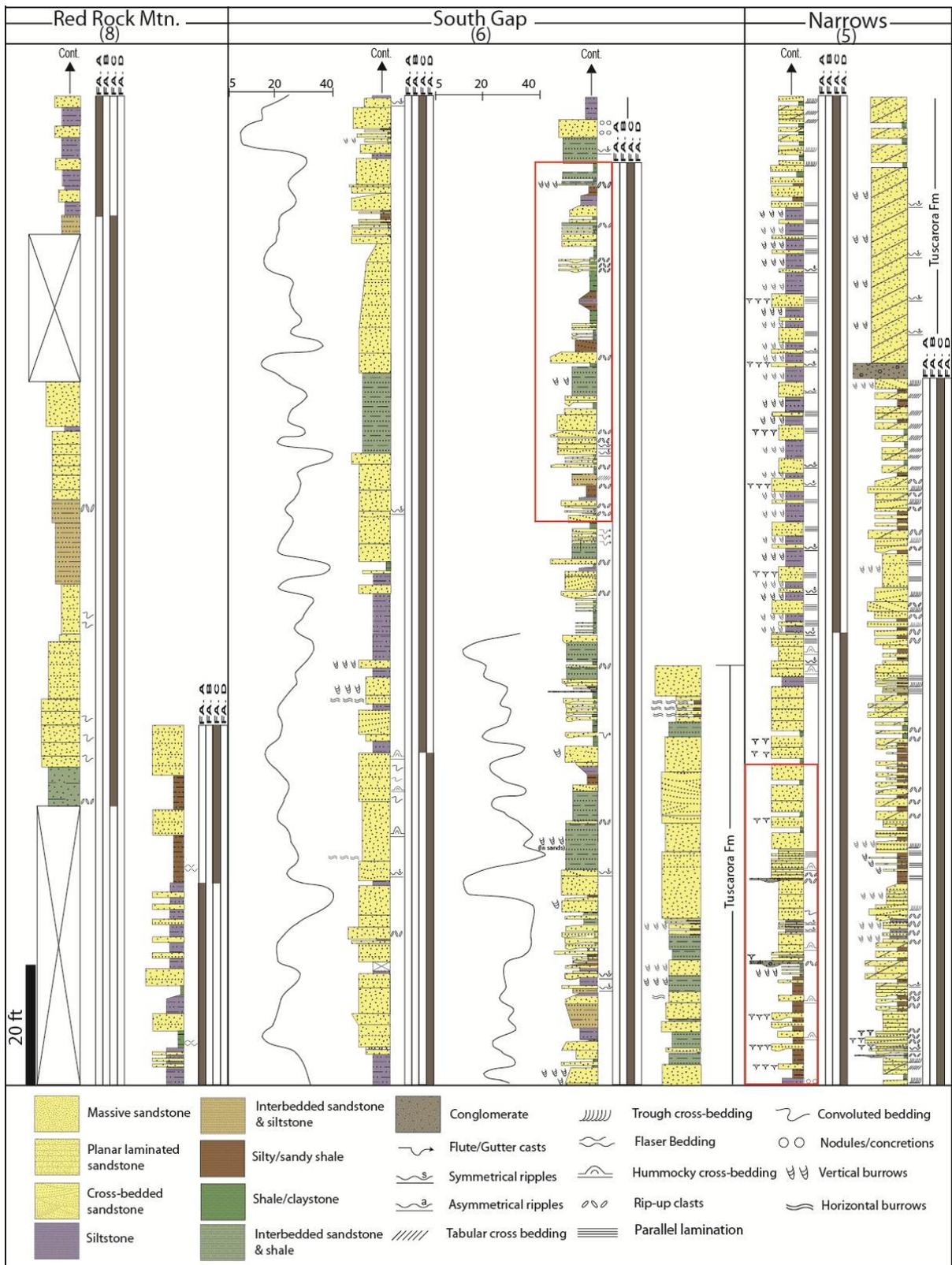


Figure 19: Distribution of Facies Associations: Red Rock Mtn., VA; South Gap, VA; Narrows, VA. Gamma ray curve is to the left of the strat columns and facies associations are shaded to the right. Red boxes denote location of section in Figures 20 and 22.

quartz or sublithic arenites are the most common. Contacts between sandstones and finer-grained lithologies are almost always sharp, and scouring is abundant. Tool marks, along with flute or gutter casts are commonly found on the bottom of beds. Mudstone rip-up clasts are commonly present in argillaceous sandstone beds as well as in sublithic or quartz arenite beds and these rarely appear to be lag deposits. All facies are laterally variable in thickness, and thick continuous beds are quite rare. Channeled beds and pinching and swelling of beds (Fig. 17b) are common, as is wedging of sandstone beds, interfingering of facies, and gradational facies changes (Fig. 17c; Fig. 20).

Bioturbation is much more abundant in Facies Association C than the other facies associations. The types of bioturbation are also much more diverse, including *Planolites*, *Cruziana*, *Skolithos*, *Monocriterion*, and *Arenicolites*. Vertical burrowing is the most abundant, but horizontal burrows are also common. Bioturbation tends to be concentrated in the fine-grained facies, but vertical burrows are commonly developed throughout many of the thinner sandstone beds, especially along the tops of the beds. However, where packages of quartz and sublithic arenites are thicker bioturbation is rare. The majority of massive, argillaceous sandstones within this facies association are due to abundant bioturbation.

Two different types of stacking patterns are exhibited in this facies association: both coarsening-upward and fining-upward. Thick (approximately 20-40 feet thick) fining-upward successions are exhibited at South Gap (Fig. 17c; Fig. 20). In this stacking pattern, the thickness and frequency of sandstones within interbedded sandstones, siltstones, and mudstones gradually decreases until the succession is capped by a thick red mudstone interval (Fig. 20). Sandstone beds typically decrease in thickness from as

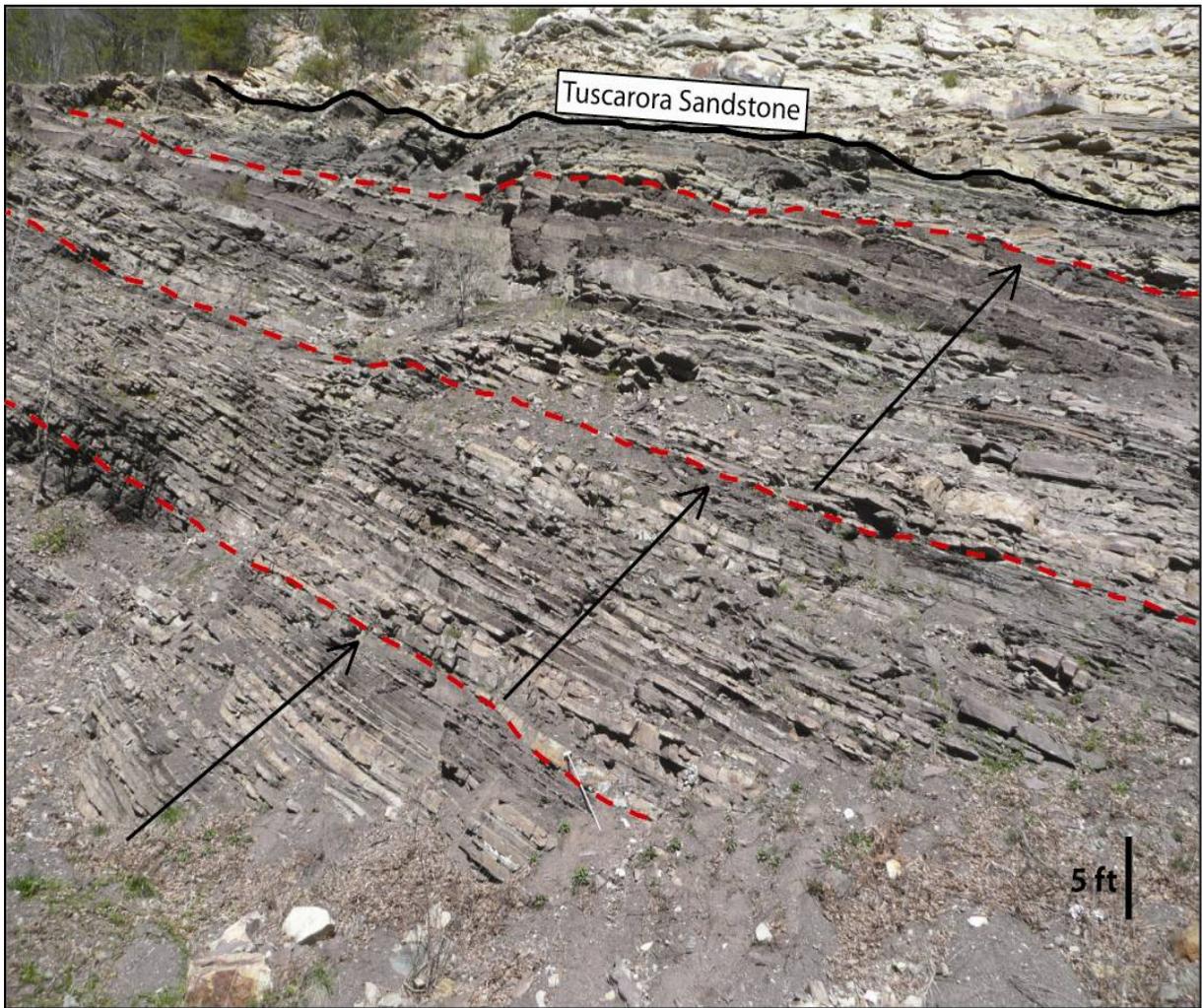


Figure 20: Facies stacking patterns and geometries of Facies Association C at South Gap, VA. Black arrows denote upward-fining sequences capped by red mudstone. Note the lateral variation in sandstone and mudstone beds.

much as 5 feet to as little as 6 inches within these fining-upward packages.

Another stacking pattern in the lower-to-middle part of the formation consists of quartz/sublithic arenites that cap coarsening-upward successions averaging 15 feet thick (Fig. 17b; Fig. 21). These coarsening-upward sequences stack into a unit that is generally 30 to 50 feet thick and dominated by argillaceous sandstone and silty mudstone with interbedded sandstones. The lower parts of the coarsening-upward successions contain thin (6 inches or less), argillaceous sandstone beds separated by thicker (approximately 1

foot) beds of silty mudstone and siltstone that are commonly bioturbated. The proportion of sandstone increases upward within successions where heterolithic scour-fills, flaser bedding, oscillatory ripples, and channel forms are developed (Fig. 17b, Fig. 21) These two stacking patterns are commonly seen within Facies Association C throughout the study area, but they are not ubiquitous. Facies Association C also may exhibit no preferred stratigraphic succession, with stacking of facies mostly random (see North Fork Mountain locality in Fig. 13)

The gamma-ray scintillometer signature of Facies Association C is much less distinctive than that of the other facies associations. Due to the highly variable nature of lithologies and stacking patterns, gamma-ray curves vary by location. In fact, the simplest way to pick out this facies association from the others is that it does not exhibit conspicuous, predictable changes. In general, the gamma-ray curve tends to fluctuate with a much higher and it contains local spikes and drops that may (or may not) correlate to thicker intervals of mudstone and sandstone, respectively. The lateral variability of facies also causes a problem in recognizing dominant lithologies in the gamma-ray log.

#### 5.4.2. Interpretation

The density of bioturbation, the predominance of fine-grained facies, and the lateral and vertically variability of facies within Facies Association C suggests that it was deposited in a deeper environment than Facies Associations A and B. Facies Association C most likely reflects deposition in the middle to lower shoreface, and locally, the upper offshore zone. Due to the complexity of facies stacking patterns and lateral variability within this facies association, discrete sedimentation processes (e.g. tide, wave, storm, current) are difficult to distinguish and are often superimposed on each other.

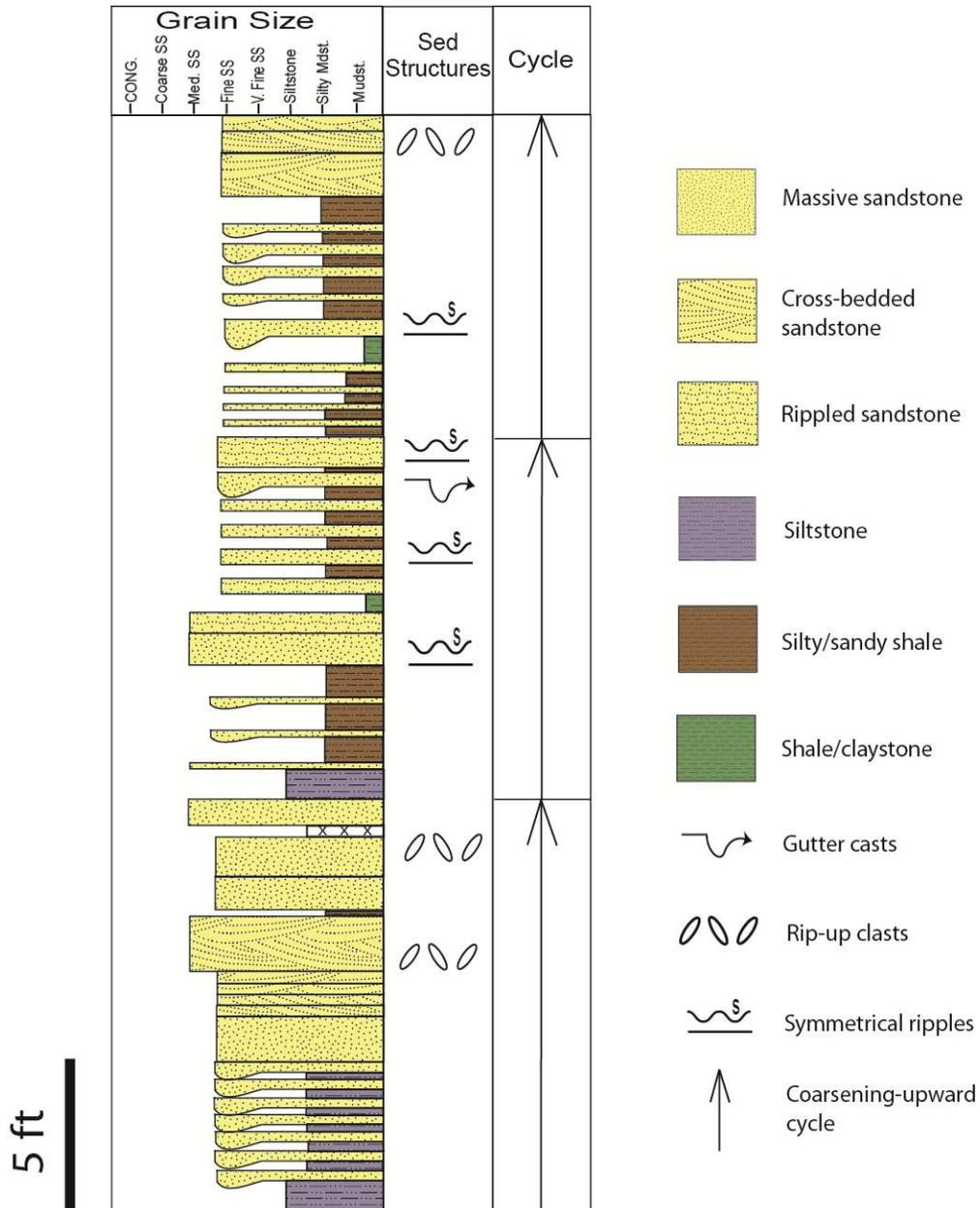


Figure 21: Representative coarsening-upward stacking pattern of Facies Association C. Section is from New Castle, VA (location shown in red box in Fig. 15).

Distribution of sand in this zone is also controlled by the presence of strong tidal and rip-currents, which move sand in the offshore direction, as well as along shore due to Coriolis force (Suter, 2006). The lower-to-middle shoreface zone is also consistently

impacted by storms, which generally remove sand and redistribute the material to the offshore and shelf environments (Galloway & Hobday, 1996; Suter, 2006).

The alternation of sandstone and mudstone in this facies association is likely the result of alternating storm and fair weather conditions (Harms et al., 1982; Clifton, 2006). Sedimentary structures exhibited in Facies Association C can be attributed to the interaction of multiple processes. Symmetrical ripples in sandstone beds reflect oscillatory flow during fair weather conditions (Galloway & Hobday, 1996; Clifton, 2006). Flaser and wavy bedding likely reflect alternating bedload and suspension deposition possibly related to fluctuating tidal currents (Klein, 1971; Clifton, 2006; Davies et al., 2010). Channeling and scour features could represent erosion and deposition due to rip-currents or storm events (Harms et al., 1982; Galloway & Hobday, 1996).

In order to understand the primary depositional processes of Facies Association C, the stacking patterns of individual facies must be examined in detail. The two main stacking patterns exhibited in Facies Association C are thinner coarsening upward and thicker fining upward successions. The coarsening-upward successions exhibited at New Castle, Va, as well as Narrows, Va (Dorsch, 1993), suggest a shoaling trend. The presence of heterolithic scour-fills, flaser bedding, alternating beds of sandstone and mudstone, oscillatory ripples, and channel forms (Fig. 17b, Fig. 21) exhibited in upper sandstone units may be evidence for increased tidal influence on sedimentation (Davies et al., 2010). Bioturbation also becomes less common toward the top of these successions suggesting higher depositional energies. Therefore, it is interpreted that the coarsening-upward successions are related to the transition from the lower shoreface to the middle-

to-upper shoreface, where sedimentation becomes increasingly influenced by fair weather waves and tides.

Fining-upward successions, such as at South Gap, Va, are developed in the upper half of the Juniata Formation (Fig 17c; Fig 20). Sandstone makes up a much lower percentage of this part of the formation, and bioturbation becomes increasingly abundant. In addition, the sandstone beds are characteristically thin and discontinuous and bear no signature of upper shoreface deposition. It is interpreted that the cycles at this location developed only in the upper offshore to lower shoreface zone. The highly variable thickness and distribution of the sandstone and mudstone beds suggests that this area remained deep and sedimentation was dominated by the interplay of storm and fair weather processes (Dorsch, 1993). The fine-grained facies were most likely deposited as a result of fair weather wave and current dispersion (oscillatory flow), whereas the sands were deposited through more focused storm deposition (advective transport) (Galloway & Hobday, 1996; Clifton, 2006). Although the sandstone beds do not always display features characteristic of storm deposition, such as hummocky cross-bedding and normal grading, it is possible that the heavy bioturbation exhibited in this zone may have obliterated these features (Suter, 2006). This stacking pattern was only seen at one location and it seems to be a local phenomenon. The origin of these fining-upward successions is puzzling. The most likely hypothesis is that the fining-upward successions represent local deepening events, due to the fact that South Gap was probably located in a small, restricted depocenter (Dorsch, 1993).

Dorsch (1993) interpreted his heterolithic facies association (Facies Association C in this study) as a middle shoreface to offshore marine deposit, with the majority

representing an offshore setting. For southwestern Virginia, Dorsch (1993) envisioned the facies association to represent deposition within a shallow epicontinental sea, in which facies development was controlled by the ambient storm system. No tidal signatures or cyclic bedding were documented by Dorsch (1993). Kreisa (1980), however, interpreted this facies association to represent sequences of tidal inlet and channel-fill in southwestern Virginia. Citing the abundance of heterolithic facies, channel structures, and gently dipping accreted cross-beds, Kreisa (1980) suggested a strong tidal influence on sedimentation. He also noted the presence of both coarsening- and fining-upward cycles. The former was attributed tidal channel migration and the latter was not specifically addressed. In all likelihood, Facies Association C actually represents a continuum of these depositional environments depending on the stratigraphic and geographic position of the facies association. For example, coarsening-upward successions (which represent shoaling) are more common in the northern and eastern localities, whereas fining-upward successions are developed only in southern and western localities.

#### 5.5. *Facies Association D: Hummocky Sandstone-Dominated Facies*

##### 5.5.1. Description

Facies Association D is generally the thinnest of all the facies associations seen in the Juniata Formation (Fig. 12). No repetitive vertical successions or predictable stacking patterns have been observed in Facies Association D, and facies appear to be randomly distributed. This facies association is thickest at the South Gap and Narrows locations (Fig. 12), which are located the furthest southwest. Facies Association D was not observed at the Gap Mills location because the lower-most interval of the Juniata

Formation was covered. In addition, this facies association was not observed at North Fork Mountain due to the presence of a facies change to the Oswego Sandstone below the basal Juniata beds. Where this facies association is present, it is always located at the base of the formation and overlain by Facies Association C. The basal contact with the Martinsburg or Reedsville Formation is gradational, and this facies association is very similar to the lithological and sedimentological characteristics of the top of these formations.

Facies Association D consists of siltstone/silty mudstone with interbedded sandstone, argillaceous sandstone, hummocky bedded sandstones, and rare lithic conglomerates. Very fine to fine-grained sandstone is the most dominant lithology (~70%), and it is commonly interbedded with thin siltstone units (6 in to 1 ft). Smaller proportions of mudstone or silty mudstone (<25%) have also been observed within this facies association. The facies association generally becomes redder up-section as the amount of finer-grained material increases. In fact, the change to a dominantly red coloration within this facies association is one of the characteristics used to identify the boundary between the Juniata Formation and the underlying Martinsburg/Reedsville Formations.

Sedimentary structures within this facies association include parallel lamination in siltstone and sandstone, tabular cross-beds in sandstones, hummocky bedding in sandstones and siltstone (Fig. 10B), and convolute bedding and ball-and-pillow structures (Fig 10C). The hummocky beds and convolute structures are unique to this facies association. Intraformational mudstone and siltstone rip-up clasts are also commonly seen along the base of sandstone beds as well. Bases of beds are commonly sharp and scoured,

but gradational changes to fine-grained lithologies are also exhibited. Bioturbation tends to be less abundant than Facies Association C, but it is still common. Horizontal burrows, especially *Cruziana* traces, are more dominant in Facies Association D than in other facies associations, and *Skolithos* burrows have also been documented. Bioturbation, however, is most commonly expressed in massive and mottled argillaceous sandstone and siltstone beds. Rare occurrences of the inarticulate brachiopod, *Lingula*, have also been observed locally (see Narrows locality in Fig. 19) and are more common toward the base of the Juniata Formation. A representative stratigraphic section of Facies Association D can be found in Figure 22.

The gamma-ray signature of this facies association is highly variable due to the random distribution and thickness of facies. The only regional trend observed is that the total gamma-ray counts tend to be higher, on average, throughout this facies association than those seen in other facies associations. In well logs that penetrate the underlying Martinsburg or Reedsville Formation, the gamma-ray curves are almost identical to those seen at the top of the Martinsburg or Reedsville Formation, suggesting a subtle, gradational change in facies between the two formations.

#### 5.5.2. Interpretation

The presence of hummocky cross-beds, the density of bioturbation, and the lack of any observable stacking pattern suggests that Facies Association D was deposited in the inner shelf to lower shoreface transition zone. It is widely agreed upon that hummocky cross-bedding is the result of storm waves (Kreisa, 1981; Harms et al., 1982; Galloway & Hobday, 1996; Suter, 2006), and the transfer of storm wave energy is more effective as water shallows. However, large storms have the power to transport sediment

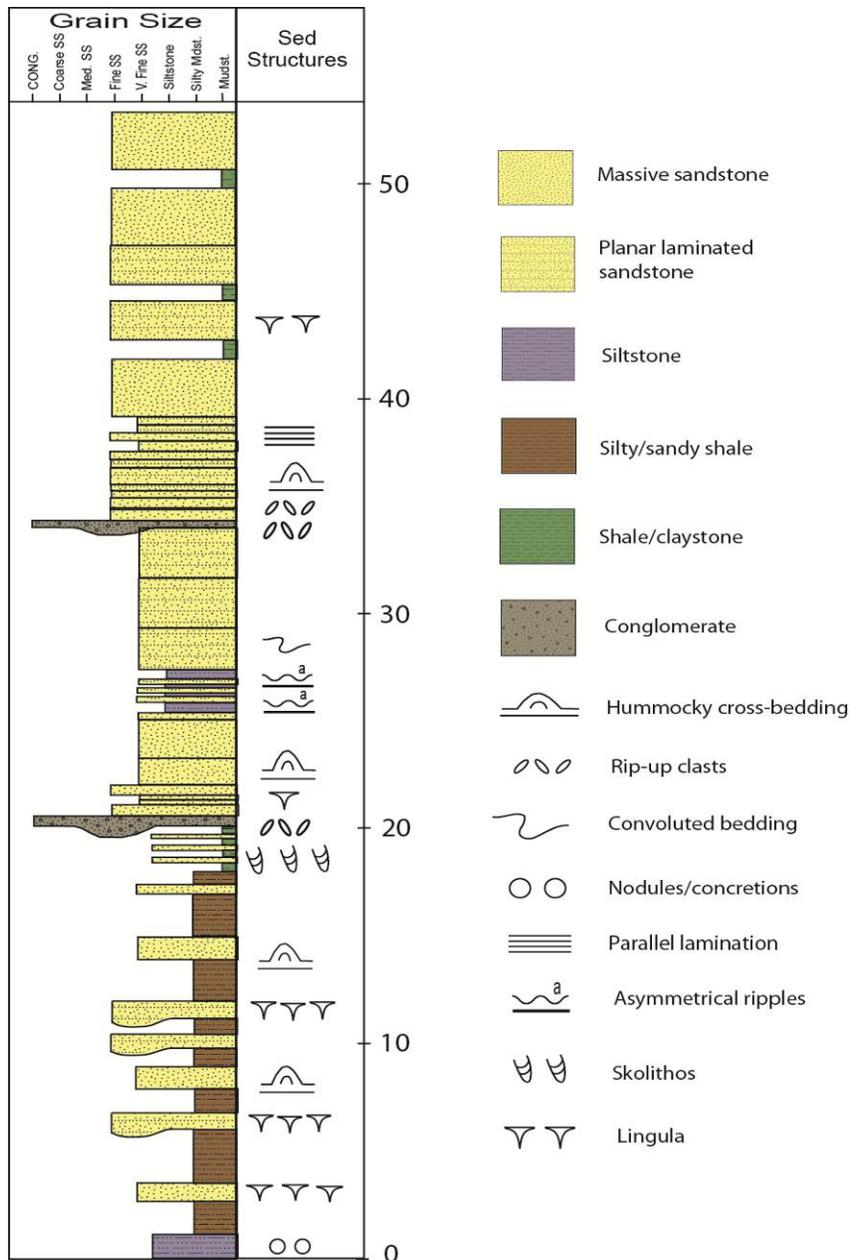


Figure 22: Representative stratigraphic succession of Facies Association D. Section is from Narrows, VA (location shown in red box in Fig. 19).

to depths to over 100 meters (Suter, 2006), so deposition of hummocky cross-bedding can still occur in shelf environments. Therefore, the inner shelf to lower shoreface transition zone is an ideal location for the formation of hummocky cross-bedding due to its location between storm wave base on the inner shelf and fair weather wave base on the shoreface (Galloway & Hobday, 1996). Hummocky cross-bedding has been documented

as being restricted to silt and very fine sand (Leckie, 1988), and that was also observed in the rocks in this study. The characteristic combination of *Skolithos* and proximal *Cruziana* ichnofacies in the upper part of sandy storm beds also suggest an inner shelf to lower shoreface transitional environment (Suter, 2006).

Within the inner shelf to lower shoreface transition zone, facies development was dictated by storms and the resulting re-working during fair weather deposition (Kreisa, 1980; Dorsch, 1993). Sedimentary structures such as hummocky cross-bedding, rip-up clasts, parallel lamination, and heterolithic facies suggest deposition as a result of and storm processes, mainly from high amplitude waves (Harms et al., 1982). Convolute bedding may also be a result of storm waves which cause in situ liquefaction in sands (Galloway & Hobday, 1996). The combination of hummocky cross-bedding, rip-up clasts, and convolute bedding is a strong argument for storm deposition. Hummocky cross-stratification has been the focus of some controversy since it has mostly been observed in laboratory studies, but there has been one example where hummocky cross-stratification was observed in nature, and it was the result of a storm event (Greenwood & Sherman, 1986). Fair weather depositional processes include suspension fall-out of fine grains, which is reflected in parallel laminations in siltstones and mudstones, and abundant bioturbation by burrowing organisms (Suter, 2006). Reworking of the sediment due to bioturbation causes a scrambled bedding style, and it is the dominant feature of the majority of argillaceous sandstones as well as siltstones in this facies association. The result is combination of storm-generated sedimentary structures interbedded with bioturbated sandstones and siltstones within Facies Association D.

The transition between the upper Martinsburg/Reedsville Formations and Facies Association D of the Juniata Formation is gradational. The bottom contact is quite difficult to distinguish in outcrop as well as in the subsurface due to the striking similarity in lithologies and sedimentary structures. Traditionally, the boundary is placed at the beginning of dominant red coloration within beds and the point of increasing proportions of sandstone to finer-grained facies (Kreisa, 1980; Diecchio, 1985; Dorsch, 1993). The lower-most Juniata Formation, represented in most locations by Facies Association D, exhibits many similar sedimentary structures of the upper Martinsburg or Reedsville Formation, but the proportion of sandstone to mudstone increases substantially. Within the study area, workers have interpreted the upper part of the Martinsburg/Reedsville Formations as inner shelf deposits (Kreisa, 1980; Diecchio, 1985). The abundance of horizontal as well as vertical burrows and the higher amounts of sandstone in Facies Association D compared to the Martinsburg/Reedsville Formations places this facies association within the offshore-lower shoreface transition zone. It should be noted that the boundary between the Martinsburg/Reedsville Formation and Facies Association D marks an important facies change, but it is time-transgressive throughout the basin. This contact becomes younger to the west (Kreisa, 1980; Diecchio, 1985; Dorsch, 1993).

All previous workers generally agree on the depositional setting of Facies Association D. Kreisa (1980), Diecchio (1985), and Dorsch (1993), attribute the characteristics of this facies association to deposition within the offshore-to-shoreface transition zone. Kreisa (1981) conducted a detailed study on the Martinsburg Formation of southwest Virginia and concluded that the upper Martinsburg is composed of storm and fair weather deposits in a shallow offshore setting. A series of storm-generated

structures, including hummocky bedding, re-worked fauna, thickening and thinning of lenticular beds, weakly graded beds, and laminated beds with upward-thinning laminae were documented within the Martinsburg Formation (Kreisa, 1981). Fine-grained beds such as siltstone and mudstone are much more dominant within the Martinsburg Formation and bioturbation and fossil fragments are much more abundant. Facies Association D marks the beginning of the coarsening-upward and shallowing-upward trend within the Juniata Formation. Overlying facies associations contain similar or higher portions of sandstone than Facies Association D, and all overlying facies associations are interpreted to have formed in shallower environments, as discussed earlier.

Table 1. Summary of interpreted depositional environments for facies associations

<b>Facies Association</b>	<b>Facies Exhibited</b>	<b>Sedimentary Structures</b>	<b>Stacking Patterns</b>	<b>Depositional Environment</b>
A	<ol style="list-style-type: none"> <li>1. "Proto-vertisols"</li> <li>2. Red shale/mudstone</li> <li>3. Siltstone/silty mudstone with interbedded sandstone</li> <li>4. Quartz &amp; sublithic arenite</li> </ol>	<p>Massive beds, tabular cross-beds, trough cross-beds, flaser/wavy bedding, reactivation surfaces, flute/gutter casts, parallel lamination, intraformational mudstone clasts, <i>Skolithos</i></p>	<p>Fining-upward cycles of facies 1-4. Thickness ranges from 3 to 10 feet.</p>	<p>Prograding tidal flat</p>
B	<ol style="list-style-type: none"> <li>2. Red shale/mudstone (&lt;10%)</li> <li>4. Quartz &amp; sublithic arenite</li> <li>5. Argillaceous sandstone</li> </ol>	<p>Trough &amp; tabular cross-beds, low-angle cross-lamination, parallel lamination, symmetrical ripples, <i>Skolithos</i>, <i>Monocriterion</i></p>	<p>Multiple beds of quartz (rarely sublithic) arenites. Sharp, planar contacts and slight scouring common</p>	<p>Discontinuous nearshore bars</p>
C	<ol style="list-style-type: none"> <li>2. Red shale/mudstone</li> <li>3. Siltstone/silty mudstone with interbedded sandstone</li> <li>4. Quartz/sublithic arenite</li> <li>5. Argillaceous sandstone</li> <li>6. Lithic conglomerate</li> </ol>	<p>Parallel lamination, symmetrical ripples, tool marks, flute/gutter casts, trough cross-beds (rare), low-angle cross-stratification (rare), flaser/wavy bedding (rare), massive, bioturbated beds, <i>Planolites</i>, <i>Cruziana</i>, <i>Skolithos</i>, <i>Monocriterion</i>, <i>Arenicolites</i></p>	<p>Higher percentage of fine-grained facies. Coarsening-upward and fining-upward patterns expressed. Channeling, interfingering of facies, and gradational changes common.</p>	<p>Lower-middle shoreface</p>
D	<ol style="list-style-type: none"> <li>2. Red shale/mudstone (&lt;25%)</li> <li>3. Siltstone/silty mudstone with interbedded sandstone</li> <li>5. Argillaceous sandstone</li> <li>6. Hummocky bedded sandstone and siltstone</li> <li>7. Lithic conglomerate (rare)</li> </ol>	<p>Parallel lamination, tabular cross-beds, hummocky bedding, convolute bedding (ball and pillow structures), rip-up clasts, <i>Cruziana</i>, <i>Skolithos</i>, <i>Lingula</i> fragments</p>	<p>No discrete stacking patterns. Mostly amalgamated hummocky sandstones and siltstones with interbedded fines</p>	<p>Inner shelf-lower shoreface transition zone</p>

## 6. PALEO GEOGRAPHY AND SEQUENCE STRATIGRAPHY

### 6.1. *Paleogeographic Reconstruction*

#### 6.1.1. Central Appalachian Basin

It is extremely difficult to differentiate among various shallow water environments of the Juniata Formation. One reason is because the lack of vascular plants during the late Ordovician did not allow environments such as channels and marshes to stabilize. Therefore, many environments what would be distinct on a modern coastline seem to mesh together in the ancient rock record. The lack of any body fossils—except for a few scattered *Lingula* fragments in the lower part of the Juniata Formation—also makes it nearly impossible to separate such inter-related environments with confidence. This is especially true for identifying estuary or lagoonal settings, since the most obvious evidence for a brackish water environment is an impoverished marine signal in the fossil record (Dalrymple, 1992). As a result, the facies stacking patterns, sedimentary structures, and knowledge of the tectonic and paleoclimatic setting of the region is all that can be used to reconstruct this ancient environment. This leaves a great deal to interpretation, and to the quality of the outcrops that display these features.

There have been few paleogeographic reconstructions of the Juniata Formation, especially for the Central Appalachians. Kreisa (1980) was the first to attempt such an exercise, and he concluded that the lowermost Juniata Formation of southwest Virginia is a shoreface and beach deposit overlain by non-marine mudflat and coastal plain deposits of the middle and upper Juniata Formation. Diecchio (1985) presented a generalized reconstruction, and emphasized the abundance of trace fossils within the Juniata Formation, as well as the meter-scale fining-upward cycles. He depicted the Juniata

Formation as deposits of broad coastal lowlands or delta plains. Dorsch (1993) explained that the interpretations by Kreisa (1980) and Diecchio (1985) did not agree with the results of his study, but he did not present a reconstruction. He concluded that the Juniata Formation in southwestern Virginia, along with the “Lower” Tuscarora Sandstone, is a storm-dominated shallow marine (lower to middle shoreface) deposit.

Figure 23 illustrates a paleogeographic reconstruction for the Juniata Formation developed based on this study. The reconstruction shows a gently-sloping coastal plain with discontinuous longshore bars of facies association B that mark the transition from storm-dominated deposits of Facies Associations D and C to tidally-influenced deposits of Facies Associations C and A. The alluvial environments to the east, which was the source of sediments from the newly-formed Taconic Highlands, were not observed in outcrop in this study but their existence is inferred. These environments were likely eroded away as a result of the degradation vacuity represented by the Tuscarora Unconformity (Diecchio, 1985; Dorsch, 1993). Net paleocurrent directions (Fig. 6) show both an offshore distribution and a component of longshore sediment transport. The Appalachian Basin was oriented in a NE-SW direction during the Late Ordovician (Scotese, 2004), and the Taconic Highlands—which were the major source of sediment to the basin—were located to the East of the basin (Rodgers, 1971; Ettensohn, 1994). Paleocurrents directed toward the west reflect sediment distribution offshore from the highlands, and paleocurrents oriented along the strike of the basin record the net longshore sediment transport direction, which was likely controlled by the trade winds.

During the Late Ordovician, the Central Appalachian Basin was located around 20 degrees south latitude (Scotese, 2004). Within this zone during the Late Ordovician,

net atmospheric circulation patterns would have driven winds to the southwest on the eastern side of Laurentia (Parrish, 1982). This is due to the presence of a high pressure cell in the atmosphere just east of Laurentia (Parrish, 1982). Therefore, these southern trade winds are likely responsible for driving longshore sediment transport to the southwest in the study area. A study by Challands et al. (2009) on the occurrence of Late Ordovician black shales within the Welsh Basin cited an increase in upwelling in the area prior to the Hirnantian Glaciation. Challands et al. (2009) interpreted this intensified upwelling to be the result of strengthening of the southern trade winds, due to the changes in ice volume and a more arid climate. During the Late Ordovician, the Welsh Basin was located around 30 degrees south latitude, just beneath the prevailing trade winds.

Together, the isopach map (Fig. 11) and the paleogeographic reconstruction for the Central Appalachians (Fig. 23) suggest deposition along the shoreface of a gently-sloping, broad shelf in the Central Appalachians. Given that sediment size largely determines the slope of a nearshore system (Clifton, 2006), and the Juniata Formation is composed mostly of fine-grained sand, silt, and mud, it is interpreted that the slope of the nearshore was gently inclined. Gentle slopes allows waves to break farther from the shoreline and dissipate their energy over a wide zone (Clifton, 2006), hence the increased tidal signature in the shallowest facies associations in the Juniata Formation.

Sediment was likely derived from two source areas: one to the north in Pennsylvania, and one to the east from the Taconic Highlands. The isopach map (Fig. 11) shows a depocenter around southern Pennsylvania and western Maryland, which likely supplied sediment to the southwestern regions of the basin (Fig. 6). In addition, the pattern of the Juniata Formation becoming coarser to the east, as well as the presence of

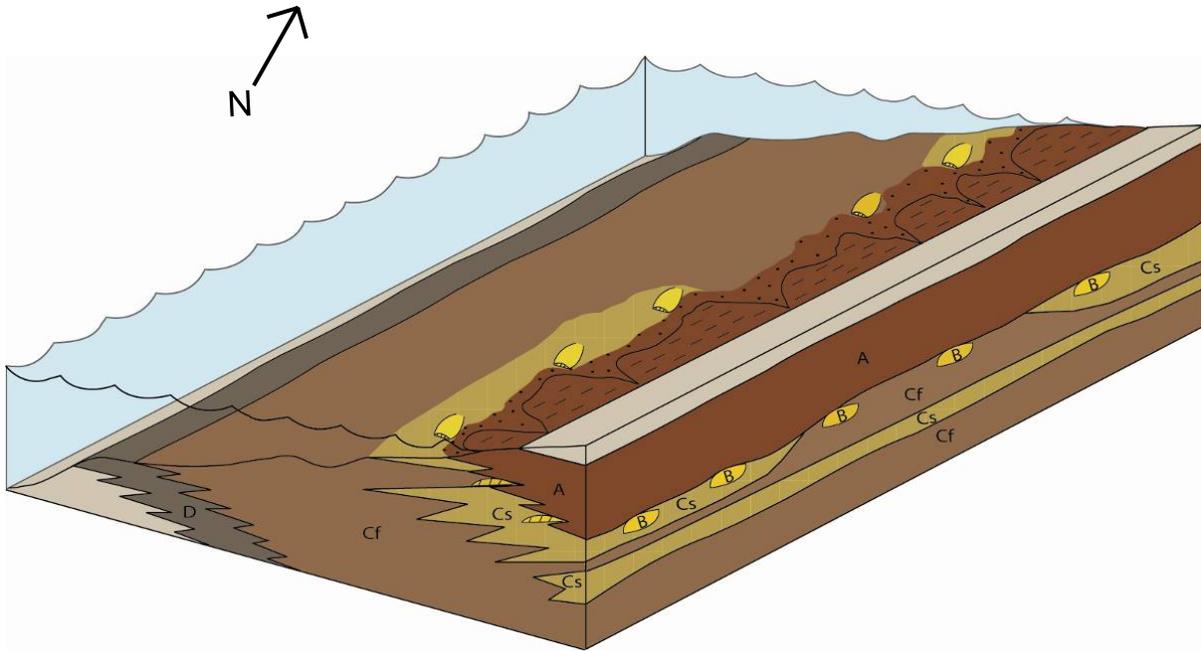


Figure 23: Generalized block diagram of depositional environments for the Juniata Formation within the Central Appalachians. Letters and colors correspond to the facies associations as shown in the cross-sections. The distribution of Facies Association C<sub>s</sub> varies along the strike and dip of the basin according to depth and proximity to a sand source. Location within the Appalachian Basin is shown by the red box in figure 24.

the “Lower” Tuscarora Sandstone in southeastern locations (discussed in the next chapter) points to an eastern source for sediment as well. Although the isopach map (Fig. 11) shows a pattern of abrupt thinning to the east, this is largely an artifact of the “Tuscarora Unconformity,” which represents more removed sediment to the east (Diecchio, 1985; Etensohn, 1994). In the central Pennsylvania and western Maryland region, the thickness pattern (Fig. 11), paleocurrent directions (Fig. 6), and facies descriptions (Cotter, 1983; Castle 1998, Davies et al., 2010) point toward the possibility of deltaic sedimentation. In fact, the Juniata Formation in Pennsylvania was referred to as a part of the “Queenston Delta Complex” by Dennison (1976). Sediments in this region were likely sourced from the highlands in the east and then distributed southwestward in a prograding delta system (Diecchio, 1985).

The presence of a delta system in the central Pennsylvania and western Maryland region would have resulted in the formation of an embayment in the northern Virginia eastern West Virginia area (Fig. 11). Diecchio (1985) noted this pattern as well and documented Eurypterid impressions within the Oswego Formation, which suggest more brackish water conditions in this area. Further evidence for the dispersal of sediments from the north and east to the southwest and west, respectively, is the presence of coeval carbonate formations in southwestern parts of the basin (Fig. 24). The Sequatchie Formation occurs in extreme southwestern Virginia and eastern Tennessee and is a biomicrite and a biomicrudite that represents offshore-to-subtidal deposition on a shallow, open-marine shelf (Thompson, 1970c; Milici & Wedow, 1977). Moving further southwest, the Sequatchie Formation transitions to the Shellmound Formation (Fig. 24). The Shellmound Formation contains an even more diverse fauna and less siliciclastic components than the Sequatchie Formation, and it represents mostly open marine carbonate sedimentation (Milici & Wedow, 1977). This decrease in the amount of siliciclastics to the southwest points to a more northeastern source for detrital sediment.

#### 6.1.2. Comparison to other parts of the basin

Figure 24 depicts the relationship of the Juniata Formation of the Central Appalachians to the formations in the other parts of the Appalachian Basin. The generalized block diagram shows fluvial deltaic facies of the Juniata Formation of northeastern Pennsylvania passing into the shallow-marine facies of the Juniata Formation in Virginia and West Virginia. The more distal siliciclastic formations in the basin include the Queenston Shale and the Richmond Group of Ohio and Kentucky. To the southwest, the siliciclastic formations pass into the carbonate Sequatchie and

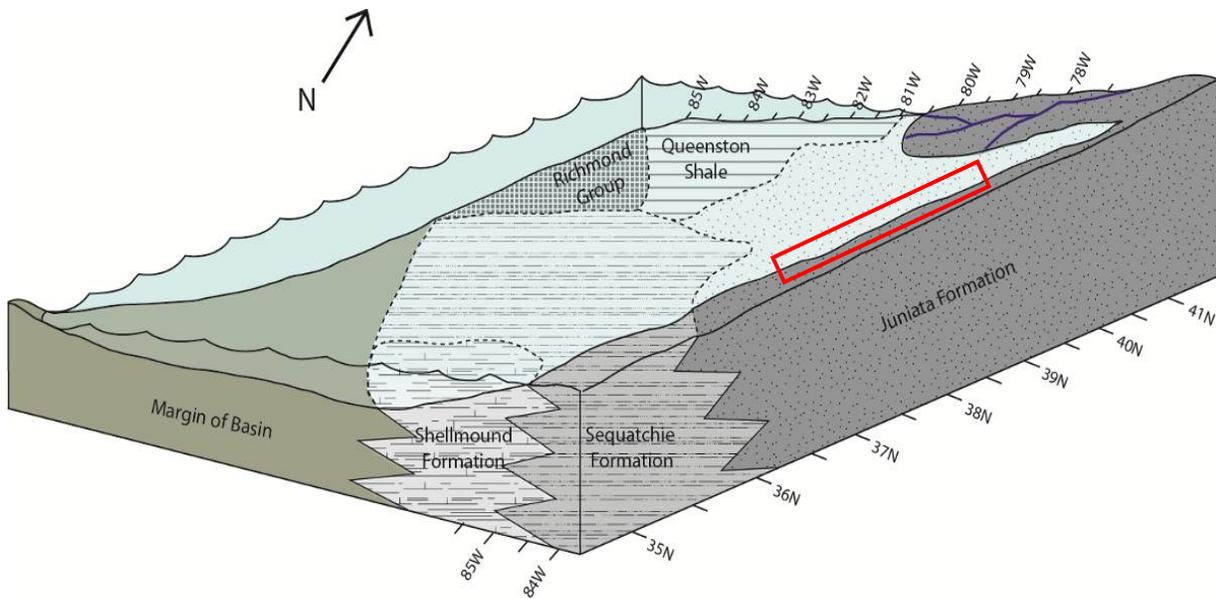


Figure 24. Paleogeographic reconstruction of the Appalachian Basin during the Late Ordovician. Red box denotes general location of Figure 23 along the shoreline. Latitude and longitude lines are based upon the palinspastic base of Dennison and Woodward, 1963. The southwestern basin margin grades into the carbonates of the Cincinnati Arch and Nashville Dome, and those formations are not represented in the figure.

Shellmound Formations of Kentucky, Tennessee, and Alabama. To the west of the main basin (and not pictured in Fig. 24) are the carbonates of the Nashville Dome and Cincinnati Arch. This reconstruction clearly shows that the source of siliclastics to the basin were from the east/northeast which were distributed to the west/southwest. Carbonate sedimentation persisted in the southwestern portions of the basin in locations starved of clastic input.

In the northernmost part of the basin, the coarser, fluvial facies of the Juniata Formation are located along the eastern margin (Yeakel, 1962; Castle, 2001) and they pass into the lower delta-plain facies of the Juniata Formation and then the Queenston Shale to the west (Keith, 1989). The Queenston Shale represents the most distal facies of the “Queenston Delta Complex” and it interfingers with the Richmond group, which is a mixed-lithology facies of a carbonate platform, in the western-most region of the basin

(Dennison, 1976; Keith, 1989). Within the Central Appalachian region, sediment supply was high (and sea-level was low) which prevented a distal shale facies from forming. It has been suggested that oxygen-deficient conditions occurred in the deep, extreme northern part of the basin during the Late Ordovician due to a humid climate and stagnant ocean conditions (Hay & Cisne, 1989). The occurrence of inceptisols in the Juniata Formation support the hypothesis for a humid climate in the northern part of the region (Retallack, 1992), but the existence of oxygen-deficient conditions could not be evaluated based on the facies of the Central Appalachians.

Moving into the southwestern part of the basin, the Juniata Formation grades into the mixed carbonate-siliciclastic Sequatchie Formation (Fig. 24). The geographic boundary between the Juniata Formation and the Sequatchie Formation is based on the presence of marine fossils and the proportion of calcareous and terrigenous material (Milici & Wedow, 1977), and is therefore subjective. Overall, the Sequatchie Formation is a peritidal, calcareous mudflat deposit that contains abundant burrowing but rare skeletal fossils (Thompson, 1970c; Milici & Wedow, 1977). Rocks that are intermediate between the Juniata and Sequatchie Formations tend to be extensively bioturbated and mottled (Thompson, 1970c; Milici & Wedow, 1977), and this was documented in this study as well. Red Rock Mountain, Virginia (Fig. 19)—a location that had never been logged before this study—may represent the furthest southern extent of the Juniata Formation before it changes facies into the Sequatchie Formation. The outcrop was heavily bioturbated and mottled, it was much more argillaceous than the other Juniata study locations, and it did not contain any traces of carbonate or body fossils. Further to the southwest, the Sequatchie Formation transitions into the Shellmound Formation of

southern Tennessee and northern Alabama. The Shellmound Formation is a gray fossiliferous limestone of subtidal, normal marine origin and contains relatively little clastic material (Milici & Wedow, 1977).

Even further west, and outside the region of interest for this study, the carbonate platform of the Nashville Dome and Cincinnati Arch is developed. These formations have been extensively studied for the sequence stratigraphy and paleoclimatic conditions of the Late Ordovician (Holland, 1993; Holland & Patzkowsky 1996, 1997, 1998; Pope & Read, 1997, 1998), and the author suggests referring to these papers for a review on the subject. The characteristic that is of particular interest in this study is the occurrence of meter-scale shallowing-upward cycles that occur in some of these peritidal limestones (Pope & Read, 1998). These cycles have been interpreted to be a result of climatic and eustatic fluctuations that may reflect the build-up and waning of the Gondwana ice sheets before the Hirnantian Glaciation (Pope & Read, 1998). This interpretation may also fit the model for the shallowing-upward cycles of Facies Association A in this study, and warrants further investigation.

## 6.2. *Sequence Stratigraphy*

The stacking pattern of the facies associations within the Juniata Formation reveals two overall shallowing-upward trends toward the top of the formation. This shallowing-upward trend has been documented by many other workers (Dennison, 1976; Kreisa, 1980; Diecchio, 1985; Castle, 1998; Davies et al., 2010). In this study, the Juniata Formation is interpreted to shallow-upward from the inner shelf-lower shoreface transition zone of Facies Association D to a prograding tidal flat environment of Facies Association A (Fig. 23). Therefore, the Juniata Formation is interpreted to represent and

overall progradational shallow-marine system. The along-strike cross-section (Fig. 12) suggests more than one episode of progradation. Facies Association A, which represents the shallowest depositional environment, commonly interfingers with Facies Association C, which is interpreted as a lower to middle shoreface deposit. Therefore, periods of progradation appear to have been punctuated by shorter transgressive events. In addition, the lack of Facies Association B in some locations may be a result of erosion due to repeated transgressive events, in which case nearshore bars are not likely to be preserved. Overall, the Juniata Formation within the Central Appalachians represents a regressive phase of deposition in the Appalachian Basin. High sedimentation rates, as well as favorable eustatic conditions, were likely the driver (Kreisa, 1980; Diecchio, 1985).

There has been relatively little work done on the sequence stratigraphy of the Juniata Formation, and on upper Ordovician strata in general, within the Appalachian Basin. Most sequence stratigraphic studies have been conducted on the carbonate units within the Nashville Dome and the Cincinnati Arch (Holland & Patzkowsky, 1996; Pope & Read, 1997; Holland & Patzkowsky, 1998). Thus, the Juniata Formation and time equivalent siliciclastic strata have been loosely tied to the sequences within the Nashville Dome and Cincinnati Arch. Upper Middle Ordovician to Upper Ordovician strata of Virginia and West Virginia fall within Supersequence O-3, which is primarily a coarsening-upward siliciclastic succession (Read & Eriksson, in press). There are four to five major sequences within Supersequence O-3, with two to three recognized within the Oswego/Juniata/"Lower" Tuscarora interval (Diecchio & Brodersen, 1994; Holland & Patzkowsky, 1996; Read & Eriksson, in press).

Diecchio and Broderson (1994) conducted a study using well logs and modified Fisher Plots to delineate sea-level fluctuations throughout the Ordovician and found sea-level cycles that averaged about 5 my. Two to three of these regional sea-level cycles were found in the Juniata Formation of West Virginia (Diecchio & Broderson, 1994). Holland and Patzkowsky (1996) defined six sequences within the Cincinnati Series of the Nashville Dome, Cincinnati Arch, and surrounding areas. Depending upon the location within the basin, the Juniata Formation may contain parts of Sequences C4 and C5 (Holland & Patzkowsky, 1996). Figure 25a illustrates the sequence stratigraphic correlations within the Juniata Formation in the study area. Regardless of the name or number of sequences within the Juniata Formation, it is generally agreed that the formation composes part of a second order late highstand deposit in the basin (Read & Eriksson, in press). The interpretation in this study that the Juniata Formation mainly represents regressive deposits as a result of high sedimentation rate and relative sea-level fall fits well into the framework of a late highstand of sea-level. The along-strike cross-section also shows two major shallowing cycles in the Juniata Formation (Fig. 25b). Based upon the estimated duration of the Juniata Formation in the study area (~5 Ma), these cycles are 3<sup>rd</sup> Order with an approximate span of 2.5 Ma. In addition, the “Lower” Tuscarora Sandstone in Virginia appears to represent another phase of transgression before the occurrence of the Tuscarora Unconformity (Dorsch, 1993; Read & Eriksson, in press). The Tuscarora Unconformity (Ordovician–Silurian Boundary) may either represent erosion from a glacioeustatic drop in sea-level (Dennison, 1976; Diecchio, 1985; Ettensohn, 1994) or a renewed phase of tectonism (Dorsch, et al., 1994), or a combination of the two.



### 6.3. *Modern Analogs*

Identifying an exact modern analog for the depositional environment of the Juniata Formation is difficult due to the inherent differences in the Earth system at that time. Although the Appalachian foreland basin was located slightly south of the equator during the Late Ordovician (Scotese, 2004), the coast was devoid of vascular land plants. The earliest terrestrial plant yet discovered is an ancient liverwort from eastern Gondwana that is Middle Ordovician in age (Rubinstein et al., 2010). In addition, modern sea-levels are generally in a transgressive phase due to post-glacial eustatic sea-level rise (Suter, 2006). Therefore, an exact modern analog does not exist in the world today. Similarities are found in modern coastal environments, however. One such example is the Gulf of Carpentaria in northern Australia and the adjacent Arafura Sea (Chivas et al., 2001; Harris et al., 2002).

The Gulf of Carpentaria is located between Australia and New Guinea and the body of water spans from approximately 10°S to 18°S. Essentially, the Gulf of Carpentaria and the adjacent Arafura Sea comprise a shallow epicontinental sea (maximum depth around 70 meters) with a fairly well-constrained climatic and depositional history from the Late Quaternary (Chivas et al., 2001). The region experiences both diurnal and semidiurnal tides and has a tropical climate with heavy summer rains, relatively dry winters, and common tropical cyclones and seasonal monsoons (Preda & Cox, 2004). The coast is a mixed siliciclastic-carbonate system, with detrital sediments (mostly dispersed through small deltas in the eastern portions of the gulf and shallow carbonate sedimentation becoming more prominent to the west (Preda & Cox, 2004). Strandplains (and chenier plains), tidal flats, and tidal-dominated deltas are

the most prominent geomorphic features of the coastline (Harris et al., 2002). It has been documented in places along the southern part of the Gulf of Carpentaria that the tidal flats and chenier plains have migrated more than 30 km since the Middle Holocene (Rhodes, 1982). In the deeper portions of the gulf, however, muds dominate and the morphology is controlled mainly by tropical storms that generate high current velocities (Preda & Cox, 2004). This example of a tropical epicontinental sea with a tide-dominated upper shoreface and a storm-dominated lower shoreface and shelf may be one of the closest modern analogs to the Juniata Formation (and possibly Sequatchie Formation) of the Central Appalachians.

There are other possibilities for modern analogs for the Juniata Formation. Parts of the North Sea have traditionally been used to describe conditions that were similar to the depositional setting of the Juniata Formation (Kreisa, 1980; Dorsch, 1993). Other possible analog are the tidal flats that developed in the East China Sea, where increased riverine sediment load has caused tidal flat progradation of up to 17 meters per year in some locations (Yang et al., 2001). Unfortunately, other than the Gulf of Carpentaria, the North Sea, and the East China Sea, there are few other modern analogs that come close to mimicking the depositional environment of the Juniata Formation.

## 7. DISCUSSION

### 7.1. *Tectonic versus Eustatic Influences on Sedimentation*

The relative roles of tectonics and eustasy on the stratigraphic architecture of foreland basin deposits can be difficult to distinguish. When evaluating eustatic and tectonic influences on sedimentation, it is important to recognize that these processes operate on different scales of length and time (Castle, 2001). Ultimately, basin fill geometry is dictated by tectonic setting and phases. The basin-fill pattern of the Appalachian Basin during and after the Taconic orogeny progresses from fine-grained, deep-water siliciclastic facies of the Martinsburg Formation (or shallow- water siliciclastic facies of the Reedsville Formation) to near-shore and fluvial siliciclastic facies of the Juniata and Tuscarora Formation. The commencement of fine-grained sedimentation followed by coarser fluvial deposits was suggested by Blair & Bilodeau (1988) to be an indicator of renewed tectonic activity, and this model is consistent with the deposits of the Taconic Orogeny. Other workers have noted that the basin fill patterns of the Ordovician–Silurian Appalachian Basin mimic predicted pulses of tectonic activity within a peripheral foreland basin as well (Ettensohn, 1994; Castle, 2001).

There is a strong tectonic overprint on the basin fill patterns of the Appalachian Basin. In a foreland basin, the primary control on accommodation space is subsidence and the primary control of sediment supply is uplift (Castle, 2001). These controls direct the facies tracts that then develop within the basin. In the Ordovician Appalachian Basin, five major facies tracts have been recognized which correlate to various phases of tectonic activity in the basin (Ettensohn, 1994; Castle, 2001). Facies tracts range from shallow water carbonates which represent interorogenic quiescence (e.g. the

Lower/Middle Ordovician carbonates) to progradational shoreline sandstones and fluvial sandstones which represent filling of the proximal foreland during loading and relaxation of the basin (e.g. The Juniata Formation and Tuscarora Sandstone) (Castle, 2001). It is important to note that significant along-strike variations can occur within these deposits (Castle, 2001), and evidence for this is seen within the Juniata Formation. Structural salients and recesses cause sequences to be thicker and thinner, respectively. For example, the Juniata Formation is many times thicker in the Pennsylvania salient than in the Virginia recess (Fig. 11). Therefore, a sea-level fall is going to have a greater impact in a structural recess than in a salient.

Not only are there varying expressions of eustasy along strike, but there is also a significant difference in the expression of eustatic changes along depositional dip. In the more distal parts of a basin, which are not affected by high subsidence rates, eustatic influences on sedimentation are much clearer than in the proximal parts of the basin (Castle, 2001). Therefore, it is generally accepted that regional, widespread sea-level changes in the rock record are usually the result of eustasy and short, isolated sea-level changes in the rock record are the result of local tectonic events. This has also been the case for the majority of interpretations about the stratigraphy of the Juniata Formation and the Ordovician–Silurian Boundary in the Central Appalachians (Dennison, 1976; Kreisa, 1980; Diecchio, 1985; Bambach, 1987; Dorsch, 1993).

There is an alternative hypothesis related to basin morphology that explains the variable stratigraphic architecture of Upper Ordovician strata within the Central Appalachian basin. Diecchio (1991) recognized two distinct types of basins—deep and shallow—in the Central Appalachians based upon regional stratigraphy and isopach data.

Deep basins are recognized based upon the presences deep siliclastics facies, and they are interpreted to have been topographic lows during deposition (Diecchio, 1991). Shallow basins, however, do not contain major lithofacies changes but are expressed as depocenters in an isopach map (Diecchio, 1991). Subsidence due to sediment loading is invoked as the causative mechanism for forming shallow basins (Diecchio, 1991). Therefore, the only true thrust load-induced foredeep occurred in the deep basins, which is limited to the eastern-most outcrop belt of the Central Appalachians (Diecchio, 1993). Between the deep basins and the shallow basins is an axis of thinning, which is interpreted to represent a peripheral bulge (Diecchio, 1993). The outcrops in this study are located either along the peripheral bulge or in the western shallow basins of Diecchio (1991, 1993).

In this study, outcrops were located entirely within the proximal part of the Appalachian Basin, along the Virginia recess. Therefore, there was little evidence for a strong eustatic influence on sedimentation. The one exception may be the cycles present in Facies Association A, which are widespread as well as generally consistent in cycle thickness across the region. The similarity of these cycles to other glacioeustatic peritidal deposits (Tankard & Hobday, 1977; Pope & Read, 1998) lends strong support to a eustatic signature. More distal deposits of the Juniata Formation, such as those in the subsurface of central West Virginia, may display more evidence for eustatic changes.

### *7.2. Nature of the Ordovician-Silurian Boundary in the Study Area*

Perhaps the most debated tectonic versus eustatic event in the basin is the cause of the unconformity at the Ordovician–Silurian Boundary. The regional occurrence of the unconformity, along with the timing of a major world glaciation event, has convinced

many workers it was created by a eustatic drop in sea-level (Dennison, 1976; Diecchio, 1985; Castle, 2001). Others have noted the local differences in the magnitude and expression of the unconformity pointed to a tectonic driver or overprint (Bambach, 1987; Dorsch et al., 1994; Ettensohn, 1994). The Ordovician–Silurian boundary has traditionally been placed at the lithological boundary between the Juniata Formation and the Tuscarora Formation (Dennison, 1970; Diecchio, 1985; Bambach, 1987). The major lithologic change from successions of red sandstone and mudstone to successions of white quartz arenite suggests an obvious change in sedimentation patterns, and it is a convenient place to put the boundary. The only biostratigraphic control on the ages of the formations come from brachiopods in the Reedsville Formation (Upper Ordovician), located below the Juniata Formation, and in the Rose Hill Formation (Lower Silurian), located above the Tuscarora Sandstone. Considering these constraints, the placing of the Ordovician-Silurian boundary at the contact between the Juniata Formation and the Tuscarora Sandstone has been widely accepted.

Although identifying the Ordovician-Silurian in this way may seem simple, recognizing this boundary can actually be quite difficult. In the northern and central parts of the study area, the Tuscarora Sandstone does indeed rest above the Juniata Formation, but the contact is an unconformity (Fig. 26a). This makes the boundary easy to distinguish, but precise dating much more difficult. In the more southern parts of the study area, however, the Juniata Formation grades into the “Lower” Tuscarora Sandstone (Fig. 26b) which is most likely Late Ordovician in age (Dorsch, 1993). Therefore, in locations like Cove Mountain, South Gap, and Narrows, the Ordovician-Silurian boundary is actually located between the “Lower” Tuscarora Sandstone and the Upper

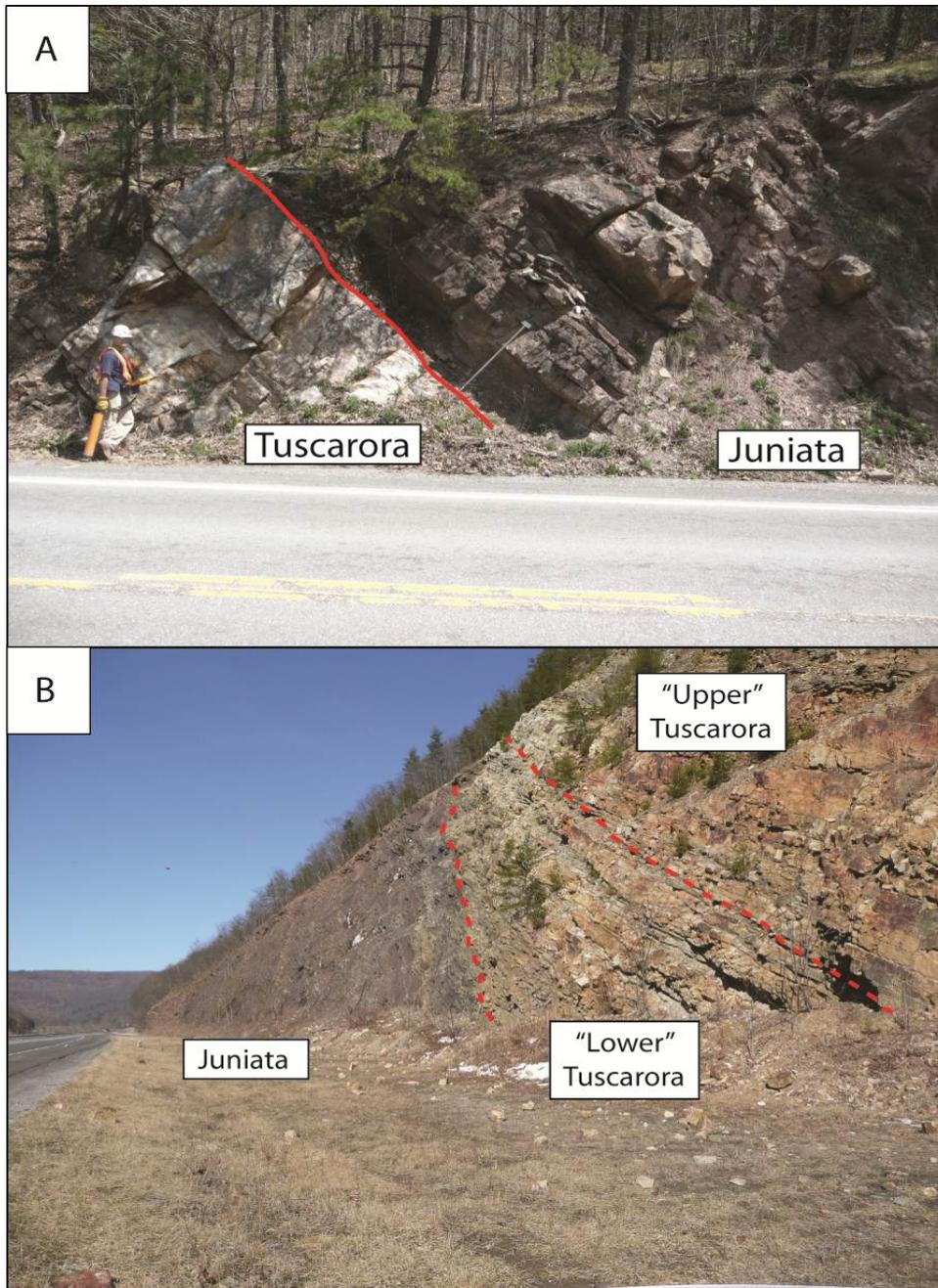


Figure 26. Various expressions of the Juniata/Tuscarora contact (Ordovician–Silurian boundary) in the study area. A) The “Tuscarora Unconformity” expressed at Gap Mills, WV. The top of the Juniata Formation is represented by red shale, and the base of the Tuscarora Sandstone is a white, conglomeritic sandstone (section is overturned). B) Gradational changes between the Juniata Formation and the “Lower” Tuscarora Sandstone, and the “Lower” Tuscarora Sandstone and the “Upper” Tuscarora Sandstone at South Gap, VA. The Ordovician–Silurian boundary is most likely located between the “Lower” and “Upper” Tuscarora Sandstone.

Tuscarora Sandstone. This contact has also been described as a disconformity (Diecchio, 1985; Dorsch, 1993), but it is much less obvious and probably represents less missing time. In places the “Upper” Tuscarora Sandstone unconformably overlies the Juniata Formation, in which case the boundary is located at this unconformity (Dorsch et al., 1995).

In the extreme southwest Virginia, such as in the vicinity of Red Rock Mountain, the Upper Tuscarora is referred to as the Clinch Sandstone (Bambach, 1987), but the Ordovician-Silurian boundary is still located beneath it. Moving into central Pennsylvania, the contact between the Juniata Formation and the Tuscarora Sandstone is gradational, and the record is complete across the boundary (Dennison, 1976; Davies et al., 2010). It has been suggested that this may also be the case in parts of Tennessee where the Sequatchie grades into the Hagan shale and the Clinch Sandstone (Milici & Wedow, 1977), but it has yet to be evaluated. As a result, the location and the character of the Ordovician–Silurian boundary vary according to the location along the strike of the basin.

In all locations in this study, the Ordovician–Silurian boundary is represented by an unconformity of varying magnitude (Fig. 26). This unconformity has been given many names throughout the Appalachian Basin: “The Taconic Discontinuity” (Wheeler, 1963), “The Cherokee Discontinuity” (Dennison and Head, 1975), and “The Tuscarora Unconformity” (Dorsch et al., 1994). It is the suggestion of this study to use the name “Tuscarora Unconformity” since it best describes the location of the unconformity throughout the study area. This unconformity spans more time to the north and to the east of the basin, where the Juniata is completely absent in some locations (Diecchio, 1985).

Due to the extensive nature and the timing of the unconformity in the study area, there is still much debate as to whether it was caused by eustatic lowering of sea level at the end of the Ordovician, or a renewed phase of tectonism within the basin. Most researchers generally favor a eustatic origin for the unconformity, citing that the Ordovician–Silurian unconformity is global (Dennison, 1976; Diecchio, 1985; Castle, 2001), but others that suggest a tectonic overprint in some areas (Bambach, 1987; Ettensohn, 1994) or relate the unconformity to a large isostatic rebound event (Dorsch et al., 1994).

Based upon the evidence collected in this study, it is interpreted the Tuscarora Unconformity is most likely the result of a combination of these two factors, depending on the location along the strike of the basin. For the majority of study locations, the unconformity exhibits evidence of a eustatic driver. The unconformity is expressed as disconformity between a red shale or siltstone of the Juniata Formation and a white sandstone or conglomerate of the Tuscarora Formation (Fig. 26a). More stratigraphy is missing in the proximal parts of the study area, which is what is expected for a eustatic sea-level fall. However, in a few areas the unconformity appears much more gradational (Cove Mountain and South Gap) and a few of the most proximal areas show evidence of an angular unconformity (Diecchio, 1985). These characteristics suggest a tectonic driver, perhaps from a renewed phase of thrusting (Dorsch et al., 1994). The more gradational changes around the boundary could be caused by antiperipheral bulge formation, which would cause local deepening (Ettensohn, 1994). Formation of this antiperipheral bulge could also explain the local deepening seen in the Juniata Formation at South Gap (Fig. 20). Therefore, along-strike variations in the structural setting of the

basin may be more important on the development of the unconformity than previously recognized.

The argument that the Hirnantian Glaciation at the end of the Ordovician may have been the eustatic driver for the Tuscarora Unconformity (Read & Eriksson, in press) could not be evaluated in this study. Without precise dating, a direct link to the Hirnantian Glaciation cannot be made. However, it is very likely that the unconformity spanned this time interval at most locations across the basin. In addition, it has recently been shown that there was a longer period glacial build-up around Gondwana than previously thought during the Late Ordovician (Brenchley et al., 2003; Saltzman & Young, 2005). Therefore, the case for glacioeustatic signatures within the Juniata Formation, and the likelihood for a glacioeustatic origin for the Tuscarora Unconformity, has become more convincing. If a record of the Hirnantian Glaciation is to be found within the basin, it would most likely be contained within the carbonates in the Sequatchie Formation of Tennessee. Carbon and oxygen isotopes from these carbonate units could provide a correlation to the well-documented excursions in the global signal.

## 8. CONCLUSIONS

1. Seven facies comprise the Juniata Formation in the study area; these are: (1) “proto-vertisols”, (2) red shale/mudstone, (3) siltstone/silty mudstone with interbedded sandstones, (4) quartz arenite and sublithic arenite, (5) argillaceous sandstone, (6) hummocky-bedded sandstones and siltstones, and (7) lithic sandstones and conglomerates.
2. Facies within the Juniata Formation are grouped into four facies associations (A, B, C, and D). Facies Association A was deposited in a prograding tidal flat environment, Facies Association B represents discontinuous nearshore bars, Facies Association C contains lower-to-middle shoreface deposits, and Facies Association D was deposited in the inner shelf-to-lower shoreface transition zone.
3. In the Central Appalachians, the Juniata Formation was deposited along the shoreface of a gently-sloping, broad shelf. The shoreline was oriented NE–SW, along the strike of the basin, and there were two sediment source areas: one from the east and one from the north. Detrital sediment was dispersed west and southwest across the basin.
4. Both tectonics and eustasy influenced the stratigraphic architecture of the Juniata Formation. Tectonics controlled the overall basin-fill pattern within the formation (which varies along strike), and eustatic changes are likely expressed in the more distal deposits of the formation and possibly in the cycles of Facies Association A.
5. The Ordovician–Silurian boundary is expressed as an unconformity of varying magnitude throughout the study area. Along-strike variations in the structural setting of the basin may be more important in the development of the unconformity than previously recognized.

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## **Appendix A: Photo Mosaics**

The following photo mosaics were compiled during field reconnaissance to Cove Mountain, VA, New Castle, VA, and South Gap, VA from 2007–2009. These three locations were the only outcrop sections that were feasible to photograph and make into a montage. The photo mosaics are raw and contain no interpretative information (except for formation contacts). For interpretations refer to Figures 9 and 17.

Photo Mosaic 1: Cove Mountain, Virginia. Person in foreground is approximately six feet tall. The lower contact with the Martinsburg Formation is just outside the left edge of the mosaic. The upper contact with the Tuscarora Formation is denoted with a red line. Red coloring in the rock usually represents finer-grained material, but not always. Some sandstones still appear red in this outcrop.

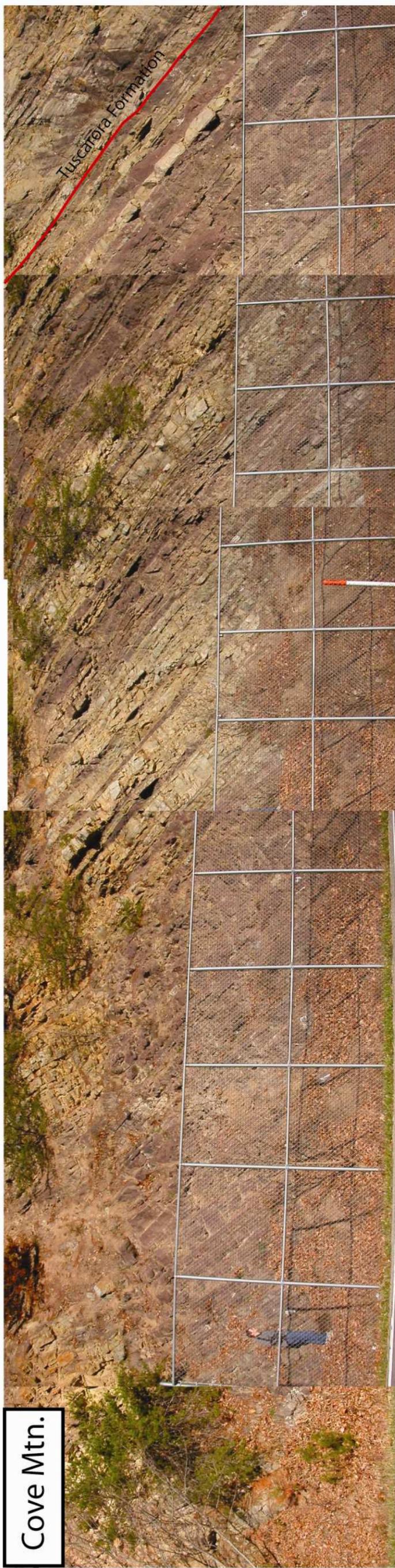


Photo Mosaic 2: New Castle, Virginia. The lower contact with the Reedsville Formation is denoted by a black line in the upper picture. There is about 40 feet of cover between the two mosaics. The upper contact with the Tuscarora Formation is covered at this location.



Photo Mosaic 3: South Gap, Virginia. The lower contact with the Martinsburg Formation is outside the frame of the mosaic by about 20 ft. The upper contact with the Tuscarora Formation is denoted with a red line.



## Appendix B: Cross-Sections

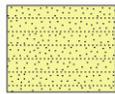
The following cross-sections were constructed based upon logged outcrop data and gamma ray scintillometer measurements. Interpreted facies associations and sequence stratigraphy are projected onto the cross-sections. Dashed lines indicate inferred lines of correlation.

### Stratigraphic Column Legend

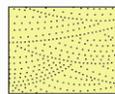
#### Lithology



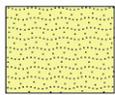
Massive sandstone



Planar laminated sandstone



Cross-bedded sandstone



Ripple-bedded sandstone



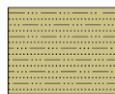
Siltstone



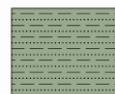
Silty/sandy shale



Shale/claystone



Interbedded sandstone & siltstone



Interbedded sandstone & shale



Interbedded ripple-bedded sandstone & shale



Conglomerate

#### Sedimentary Structures



Flute/Gutter casts



Tool marks



Symmetrical ripples



Parallel lamination



Tabular cross bedding



Trough cross-bedding



Flaser Bedding



Hummocky cross-bedding



Rip-up clasts



Convoluted bedding



Nodules/concretions

#### Bioturbation



Rare



Common



Abundant

#### Trace Fossils



Cruziana

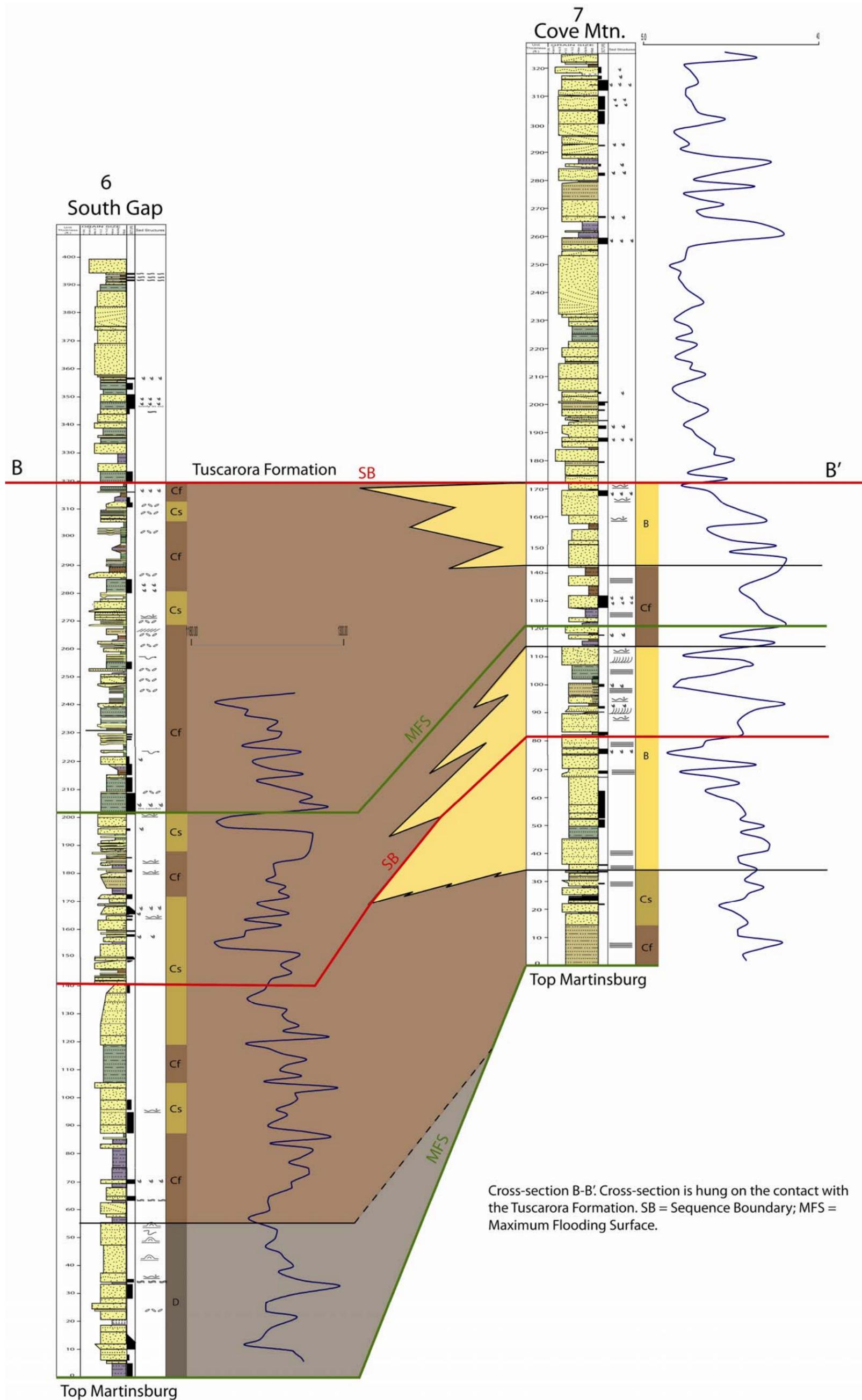


Skolithos



Lingula Fragments





Cross-section B-B'. Cross-section is hung on the contact with the Tuscarora Formation. SB = Sequence Boundary; MFS = Maximum Flooding Surface.

