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***Stratigraphy, structure, and tectonics: An east-to-west transect of the Blue Ridge and Valley and Ridge provinces of northern Virginia and West Virginia***

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**ABSTRACT**

**This field guide covers a two-day east-to-west transect of the Blue Ridge and Valley and Ridge provinces of northwestern Virginia and eastern West Virginia, in the context of an integrated approach to teaching stratigraphy, structural analysis, and regional tectonics. Holistic, systems-based approaches to these topics incorporate both deductive (stratigraphic, structural, and tectonic theoretical models) and inductive (field observations and data collection) perspectives. Discussions of these pedagogic approaches are integral to this field trip.**

**Day 1 of the field trip focuses on Mesoproterozoic granitoid basement (associated with the Grenville orogeny) and overlying Neoproterozoic to Early Cambrian cover rocks (Iapetan rifting) of the greater Blue Ridge province. These units collectively form a basement-cored anticlinorium that was thrust over Paleozoic strata of the Valley and Ridge province during Alleghanian contractional tectonics. Day 2 traverses a foreland thrust belt that consists of Cambrian to Ordovician carbonates (Iapetan divergent continental margin), Middle to Upper Ordovician immature clastics (associated with the Taconic orogeny), Silurian to Lower Devonian quartz arenites and carbonates (inter-orogenic tectonic calm), and Upper Devonian to Lower Mississippian clastic rocks (associated with the Acadian orogeny). Alleghanian structural features include the Little North Mountain thrust, Cacapon Mountain anticlinorium, Broad Top synclinorium, and Wills Mountain anticlinorium. Within the road log of this field guide we include both planned and optional stops, so that readers can explore the pedagogic concepts discussed herein in more detail, if desired.**

## INTRODUCTION

This field guide focuses on an east-to-west, cross-orogen transect of the Blue Ridge and Valley and Ridge provinces of northwestern Virginia and eastern West Virginia, generally following Route 33 from Ruckersville, Virginia, to the Allegheny Front near Judy Gap, West Virginia. Over the past few decades several field trip guides have documented the stratigraphy and depositional environments of this region (e.g., Diecchio, 1986; Fichter, 1986; Fichter and Diecchio, 1993), as well as the structural geometry and tectonic history of this part of the Appalachian orogen (e.g., Perry and DeWitt, 1977; Spencer *et al.*, 1989; Bailey *et al.*, 2006). It is not the purpose of this field guide to reiterate all of this prior work, except to briefly summarize pertinent models and interpretations in the context of field locations that are highlighted. Instead, this field guide focuses on the pedagogy of an integrated approach to teaching stratigraphy and structural analysis within the overarching framework of tectonics. In the text that follows we present a holistic, systems approach to teaching these topics from both inductive and deductive perspectives that are rooted in field observations and data collection.

In 2007, the James Madison University Geology and Environmental Science Department initiated a new course for earth science majors, entitled “Stratigraphy, Structure, Tectonics,” or “SST.” The course builds on a central theme of the earth science degree, which is to simultaneously think about, evaluate, and integrate the relative importance of many variables that influenced the geology and natural history of a region. In general, we want students to learn to evaluate how different systems influence each other, rather than think about each system individually. Thus, components of traditional stratigraphic and structural analyses techniques are incorporated within the broad umbrella of tectonics, in a course co-taught by specialists in these respective fields.

A major component of the SST course is a semester-long project based on several field trips that collectively transect the Blue Ridge and Valley and Ridge geologic provinces of northern Virginia and West Virginia. During the field trips, structural and stratigraphic data are collected at each outcrop, with students and instructors evaluating the data to assemble a regional tectonic history. Stratigraphic data include detailed facies analysis and environmental interpretations; structural data include orientation measurements and geometric relationships. Students incorporate field observations, data, and interpretations into a final report that consists of two principal parts: (1) a cross section from the Blue Ridge to the Allegheny Front that incorporates multiple scales of stratigraphic and structural field evidence, and (2) a comprehensive tectonic and geologic history of the region that uses stratigraphic and structural field observations and is informed by theoretical models. For this report it is not enough to simply recognize and identify specific outcrop features. Observations and conclusions must be both inductively and deductively valid, and to the degree possible, internally consistent and rooted in the overarching mechanisms and driving forces of tectonics.

The Geological Society of America (GSA) field trip described in this guidebook is based on the SST semester-long project described above. We hope that this field guide provides a provocative way of thinking about student field trips and field education in general, as well as serving as a useful resource for educators leading their own field trips through this region.

## GEOLOGIC SETTING

### Blue Ridge

The first day of this field trip begins south of Madison, Virginia, and proceeds west to Route 33, crosses the Blue Ridge at Swift Run Gap, and ends in Harrisonburg, Virginia. In north-central Virginia, the Blue Ridge province forms a basement-cored anticlinorium that was thrust over Paleozoic strata of the Valley and Ridge province during late Paleozoic (Alleghanian) contractional tectonics. Mesoproterozoic granitoid basement and a cover sequence of Neoproterozoic to Early Cambrian rocks underlie the Blue Ridge. The basement complex formed at middle to lower crustal depths during and after the assembly of the Rodinian supercontinent, while the cover sequence records rifting, Rodinian breakup, and the subsequent transgression of the Iapetus Ocean at the onset of the Phanerozoic.

The basement suite formed between 1.2 and 1.0 Ga and includes three temporally distinct groups of granitoids (Fig. 1). The oldest group crystallized between 1190 and 1150 Ma, the middle group between 1120 and 1110 Ma, and the youngest group between 1090 and 1020 Ma (Aleinikoff *et al.*, 2000; Tollo *et al.*, 2004; Southworth *et al.*, 2009). The older group is gneissic and characterized by a high-grade compositional layering. Both the older and younger groups are chemically diverse and range from low-silica charnockites to alkali feldspar leucogranitoids. The volumetrically less significant middle group is restricted to orthopyroxene-bearing granites.

The felsic 730–700 Ma Robertson River plutonic and volcanic complex cuts Mesoproterozoic basement and a thick sequence of Neoproterozoic metasedimentary rocks (Lynchburg, Fauquier, and Mechum River units) overlies older rocks (Tollo and Aleinikoff, 1996; Bailey *et al.*, 2007). This sequence of plutonic, volcanic, and sedimentary rocks formed during an episode of rifting that created significant accommodation space but did not generate ocean crust.

A later Neoproterozoic cover sequence of metasedimentary and metavolcanic rocks unconformably overlies the basement complex in the western Blue Ridge and includes the clastic Swift Run Formation and predominantly basaltic greenstones of the Catoctin Formation (Fig. 1). The Swift Run Formation is heterogeneous with a highly variable thickness. The Catoctin Formation forms a thick unit extruded over a large area (>4000 km<sup>2</sup>) and was generated from mantle-derived tholeiitic magmas (Badger and Sinha, 2004). Metadiabase dikes of similar composition to Catoctin metabasalts intrude the basement complex (and older Neoproterozoic rocks) and are likely feeder dikes for the

overlying Catoctin lava flows. Badger and Sinha (1988) report a Rb-Sr isochron age of  $570 \pm 36$  Ma, and zircons from metarhyolite tuffs and dikes in the Catoctin Formation yield U-Pb ages between 570 and 550 Ma (Aleinikoff et al., 1995).

The Early Cambrian Chilhowee Group overlies the Catoctin Formation and in north-central Virginia includes the Weverton, Harpers, and Antietam formations (Figs. 1 and 2). The contact

between the underlying Catoctin metabasalts and the overlying Chilhowee Group has traditionally been interpreted as an unconformity, but its significance remains uncertain (King, 1950; Gathright, 1976; Southworth et al., 2009). The Weverton Formation includes quartz metasandstone, metaconglomerate, laminated metasilstone, and quartzose phyllite. The Harpers Formation is dominated by phyllite and thinly bedded metasandstone with

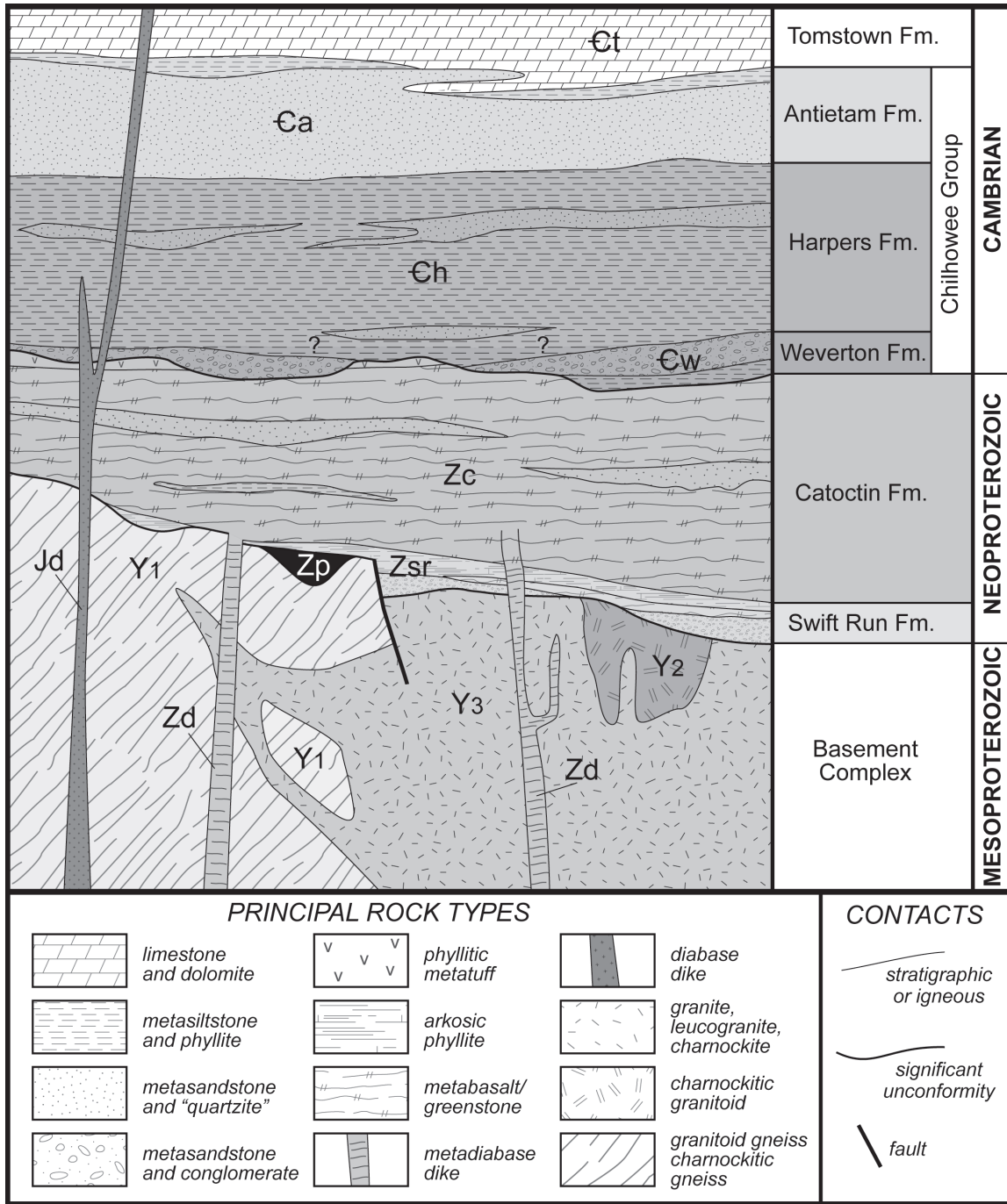


Figure 1. Generalized stratigraphic section of rock formations in the western Blue Ridge anticlinorium, Virginia. Based in part on figure 6 from Gathright (1976). Zp—Neoproterozoic garnet-graphite paragneiss.

Sequence	AGE	West	FORMATION	East	Thick-ness	DESCRIPTION	Interpretation		
KASKASKIA	Miss.		<b>MAUCH CHUNK</b>			Coarse ss, silt, shale. Channels. Plant fossils common in places. Coal	Begin Alleghenian Orogeny		
			<b>GREENBRIAR</b>			Carbonate dominated (oolites, biosparites)	Orogenic Calm		
			<b>POCONO</b>			300-1700'	Quartz sandstone & conglomerate; coarse, thick, large cross beds	Acadian Orogeny	
	Devonian		<b>HAMPSHIRE</b> (Catskill)			2000'	Point Bar Sequences; red		
			<b>GREENLAND GAP GROUP</b> (former Chemung)	<b>FOREKNOBS SCHEER</b>		2000'	Thick hummocky sequences; at top interbedded red and green fine sands and silts		
			<b>BRALLIER</b>		(Portage in Pa.)	1500-1700'	Bouma sequences		
			<b>MILLBORO</b> (Used south of Shenandoah Co.)		Tully Harrel Mahantango Marcellus	900'	Dark gray to black silts and fine sands		
			<b>NEEDMORE</b>		Tioga bentonite	100-530'	Olive gray fine sands, silts, and shales; fossils abundant in places		
		<i>Wallbridge Unconformity</i>							
			<b>ORISKANY</b>			10-125'	Quartz arenite; white, gray, tan; abundant fossils	Orogenic Calm	
Silurian		<b>HELDERBERG GROUP</b>		LICKING CREEK MANDATA NEW SCOTLAND NEW CREEK KEYSER	70-150' 17-50' 70-600'	Carbonates of many kinds; sometimes with cherts, or interbedded with shale or quartz arenites; fossils very abundant			
		(Salina in WVa.)	<b>TONOLOWAY</b>			50-250'	Tidal carbonates; ALM, ALD; mud cracks; salt casts; evaporitic to west		
		<b>CLINTON CAYUGA</b> WILLS CREEK WILLIAMSPORT MCKENZIE	<b>BLOOMSBURG</b>			0-400'	Bloomsburg: red very fine sands/silts/shale		
TIPPECANOE	Silurian		<b>KEEFER</b>			70'	Massanutten: coarse friable quartz arenites and conglomerates with large planar X-beds Tuscarora/Keefe: quartz arenites; ripples Skolithus. Rose Hill: red fine - coarse sands and shales; loads, ripples, trace fossils	Taconic Orogeny	
			<b>ROSE HILL</b>			650'			
			<b>TUSCARORA</b>			50-250'			
			<b>MASSA-NUTTEN</b>			700-1200'			
			<b>JUNIATA</b>		"Cub ss"	0-200'			Red X-bedded ss; Skolithus; bedded w/sh
	Ordovician		<b>OSWEGO</b>			0-375'	Gray/white, coarse X-bedded sands	Hum-mocky	
			<b>REEDSVILLE</b>		<b>MARTINSBURG</b>	3000'	Clastic hummocky sequences	Feldspathic/lithic Bouma sequences	
			"TRENTON GROUP"		Oranda (Liberty Hall)	40-60'	Carbonate hummocky sequences	Gray silty/shale	
			"BLACK RIVER GROUP"		<b>EDINBURG</b> (Lantz Mills)	425-600'	Carbonate hummocky sequences	Black massive micrites and shale	
				<b>LINCOLNSHIRE</b>			25-170'	Micrites, bio- and pelmicrites, chert	
			<b>NEW MARKET</b>			40-250'	abundant fossils, darkens up section Very pure micrites; tidal features		
SAUK	Cambrian	<i>Knox Unconformity</i>							
			<b>BEEKMANTOWN</b> (Rockdale Run)			2500'	Thick bedded dolomite, black chert; tidal	Divergent Continental Margin	
			<b>STONEHENGE</b> (Chepultepec)			500'	Thick bedded micrite, blue; tidal features		
			<b>CONOCOCHEAQUE</b>			2500'	LS/dolo/qtz arenite ; abndt tidal structures		
			<b>ELBROOK</b>			2000'	LS/dolo/ blue-gray; tidal features		
			<b>ROME</b> (Waynesboro)			2000'	Red/green shale/dolo/micrite; very variable		
			<b>SHADY</b>			1600'	Dolomite (granular); LS at top and bottom		
			<b>CHIL-HOWE</b> <b>ANTIETAM</b>			500-1500'	Quartz arenite; abndt X-beds Skolithus		Thin bedded
			<b>WEVERTON</b>		<b>HARPERS</b>		2000'		Crs feldspathic sands; large planar X-beds
						800'			shale and graded sandstones

Figure 2. Generalized stratigraphic column for the central and northern Shenandoah Valley of Virginia and eastern West Virginia, encompassing the lithologic units visited on Day 2 of the field trip. After Fichter and Diecchio (1993).



minor well-cemented quartz arenite and ferruginous metasediment. The Antietam Formation consists of well-cemented quartz arenite with abundant *Skolithos*. Collectively, the Chilhowee Group records shallow-marine sequences along the Laurentian margin during the Cambrian (Simpson and Eriksson, 1989). A thick package of Cambrian to Ordovician carbonate and shale stratigraphically overlies the Chilhowee Group and crops out in the Shenandoah Valley west of the Blue Ridge (Figs. 1 and 2).

Unmetamorphosed diabase dikes cut Mesoproterozoic basement and Neoproterozoic to early Cambrian cover rocks. The olivine normative, low-titanium diabase is similar to mafic dikes and sills exposed in the Mesozoic Culpeper basin east of Shenandoah National Park. A diabase dike along the Potomac River, ~100 km north of the Park, yielded an Ar-Ar age of 200 Ma (Kunk et al., 1992).

The Blue Ridge anticlinorium is an imbricated stack of basement thrust sheets emplaced over Valley and Ridge rocks along a family of related, low-angle thrusts. The frontal Blue Ridge fault system truncates early fold structures and penetrative fabrics in both the hanging-wall and footwall rocks; the deformation style is typically brittle, and breccias are well developed at a number of localities. In the core of the anticlinorium mylonitic rocks occur in km-thick anastomosing zones. Asymmetric structures in these high-strain zones consistently record a top-to-the-northwest sense of shear (i.e., hanging wall up movement). Displacement across Blue Ridge mylonite zones accommodated crustal contraction enabling the relatively stiff basement complex to shorten while cover rocks were folded. Folds in western Blue Ridge cover rocks are typically asymmetric northwest-verging structures. Axial planar foliation (cleavage) is well developed in fine-grained rocks and dips gently to moderately southeast.

A distinctive coarse foliation or compositional banding is developed in the older Mesoproterozoic basement units (>1150 Ma) and formed at upper amphibolite- to granulite-facies conditions. Younger Mesoproterozoic basement units (Group 3, <1090 Ma) typically lack a high-temperature fabric. A younger foliation is variably developed in both the basement and cover sequence, this foliation characteristically strikes northeast, dips to the southeast, and is defined by aligned greenschist-facies minerals. New Ar-Ar geochronology indicates that pervasive deformation

in the basement and cover sequence occurred between ~380 and 310 Ma (late Devonian to Pennsylvanian). A suite of north-northwest (330°–350°) and west-northwest (280°–300°) transverse faults cut the regional structural grain and may be related to transtensional stresses during Mesozoic rifting.

### Valley and Ridge

The second day of this field trip begins in Harrisonburg, Virginia, and follows Route. 33 west to Judy Gap, West Virginia, before terminating at the Allegheny Front at Briery Gap. Lithologic units west of the frontal Blue Ridge fault system include Cambrian and Ordovician carbonate rocks of the Iapetus (proto-Atlantic) Ocean, deposited after the rifting of Rodinia (Fig. 2). West of Elkton, Virginia, these change into clastic sequences of the mid- to late Ordovician Taconic orogeny (Cooper and Cooper, 1946; Woodward, 1951; Diecchio, 1993), and in Fort Valley of the Massanutten synclinorium, Devonian black shales of the Acadian orogeny (Rader and Biggs, 1975, 1976). West of Harrisonburg, Cambrian to Ordovician carbonates are again apparent in the hanging wall of the west-directed Little North Mountain thrust fault. West of the Little North Mountain fault, lithologies are characterized by Upper Ordovician clastic rocks of the Taconic sequence (strikingly different from those exposed east of the fault), Silurian to Lower Devonian quartz arenites and carbonates deposited during the orogenic calm between the Taconic and Acadian orogenies (Dennison and Head, 1975; Rader and Perry, 1976; Smosna et al., 1977), and a thick sequence of Upper Devonian to Lower Mississippian clastic rocks (the Catskill clastic wedge) that represent the dominant expression of the Acadian orogeny in the mid-Atlantic region (Woodward, 1943; Dennison, 1970).

This region is considered a type example of a foreland thrust belt, representing the foreland of the Alleghanian collision of the African part of Gondwana with Laurentia (ancestral North America). Major structural features include the Little North Mountain thrust in the east, progressing west through the Cacapon Mountain anticlinorium, Broad Top synclinorium, and Wills Mountain anticlinorium to the Allegheny Front (Fig. 3). The major fold structures are underlain by duplexes of Cambrian to Ordovician carbonate and clastic rocks (Kulander and Dean, 1986; Mitra, 1986; Evans,

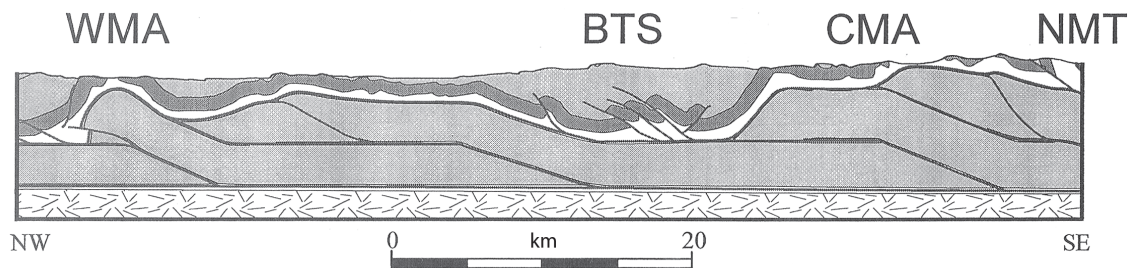


Figure 3. NW-SE cross section across the central Appalachian foreland from Dunne (1996) that shows the subsurface imbricate duplex structure, interpreted to underlie the surface fold and fault pattern traversed during Day 2. WMA—Wills Mountain anticlinorium, BTS—Broad Top synclinorium, CMA—Cacapon Mountain anticlinorium, NMT—North Mountain thrust.

1989), which implies that the surface rocks are the roof sequence of a blind thrust that likely propagates into the subsurface of the Allegheny Plateau (Rogers, 1970; Wilson and Shumaker, 1992; Dunne, 1996). Surface structures are apparent throughout the region at many scales, from outcrop-scale folds and thrusts with centimeters to meters of displacement, to folds with a wavelength of several kilometers, such as the breached Wills Mountain anticline where the floor of Germany Valley is exposed. The scale and geometry of structural features are controlled, in part, by mechanical aspects of alternating strong and weak lithologic sequences, such that significant westward transport likely occurs along weak, shale-dominated units (Martinsburg, Rose Hill, and Wills Creek formations), while outcrop structures are more apparent in the stronger sandstone and dolomitic units (Oswego, Tuscarora, Williamsport, and Oriskany formations).

## INTRODUCTION TO PEDAGOGIC APPROACHES

Stratigraphy and structural geology are often presented as distinctly different subjects within the geoscience curriculum. Their vocabularies are distinct, and each requires examination of different features at the outcrop. For a stratigrapher, structural deformation is commonly viewed as “noise” that masks or gets in the way of the pertinent information, while structural geologists view stratigraphic units as mechanical layers that respond differentially to external stress, with little regard to specific depositional features. Yet what is common to both stratigraphic and structural analyses is that everything we observe in the rocks has resulted from energy transfer driven by tectonics.

For many geologists, energy transfer is a partially abstract concept. The final products of the transfer of energy are apparent, but there are typically many pathways that energy could have traveled, as addressed by Chamberlin’s (1890) method of multiple working hypotheses. Conceptually, stratigraphic and structural analyses provide two distinct, but interrelated, approaches to evaluating tectonic evidence. In structural analyses the evidence of energy transfer is often direct: folds and faults are visually apparent or extrapolated from outcrop measurements, and energy transfer can be inferred from the degree of deformation or strain seen in the rocks. Conversely, in stratigraphic analyses based on flow regimes (the energy required to transport and deposit sediments), interpretations are not obvious from outcrop evidence. Most interpretations must be based on observations of modern depositional processes that may or may not be correlative with ancient environments.

Stratigraphic interpretations that are further removed from direct outcrop evidence include the size, shape, and history of the basins in which sediments were originally deposited. General characteristics of basin subsidence may be apparent, but specific details on how far, how fast, and how deep the basin subsided are not directly obvious. Tectonic processes that cause depositional basins to subside also result in structural deformation of the rocks, but generally these large-scale processes cannot be fully analyzed from evidence in a single outcrop. Nevertheless,

the tectonic history of a region underpins fundamental questions that structural geologists and stratigraphers consider when evaluating data from individual outcrops. The approach taken in this field guide is to present outcrop-based stratigraphic and structural analyses techniques jointly in the larger context of tectonics, reflecting the approaches developed in the SST course.

## DEDUCTIVE (TOP-DOWN) AND INDUCTIVE (BOTTOM-UP) STRATEGIES

This field guide includes a brief description of the theoretical framework and pedagogic strategies used in the SST course, where stratigraphy and structural analysis are synthesized in the service of tectonics and basin interpretation. It is not meant to be a theoretical and/or historical summary of the geology for professionals, but rather a pedagogic framework for field-oriented investigations and education. With this in mind, we consider two strategies for interpreting geology: deductive (top-down) and inductive (bottom-up). In our experience we have found that students often have trouble distinguishing between these two approaches, especially on the outcrop.

A deductive approach is predominantly theoretical and revolves around conceptual models, such as plate tectonic regimes, geophysical models based on remote sensing data, and basin development models derived from ancient and modern examples. In the field, theoretical models are used in two ways: first, to guide observations on the outcrop by taking fragmentary information apparent in single outcrops and placing them in a regional context; and second, to test theoretical models by making predictions of what should be observed based on what has already been observed. For example, after observing an outcrop containing hummocky units, one could predict that down section the features would devolve into deep shelf or submarine fan deposits, while up section they would evolve into shoreline and terrestrial deposits. Correspondingly, structural analysis integrates theories of stress and strain with rheologic models of materials to interpret and predict deformed structures at all scales of observation. For example, small-scale folds theoretically mimic regional-scale folds that are too large to be seen at a single outcrop, such that Z and S folds in an outcrop are often used to infer the location of the axis of a larger fold.

An inductive approach is empirical, where observations on the outcrop are the primary data for developing an understanding of geologic processes and larger-scale features. In addition, bottom-up observations are used to test the inferences and predictions of theoretical models. In practice real-world observations may diverge far enough from theoretical models for us to suspect that the theoretical models are either incomplete or wrong. This discrepancy often opens avenues to refining or expanding our understanding.

The pedagogic strategy advocated here is to continuously pit top-down deductions and bottom-up inductions against each other until a logical contradiction emerges, or evidence and/or theory have been exhausted. This approach forces us to rethink theoretical models and/or gather more observational data from the

outcrop. For the professors, the ideal outcome of these investigations is for each student, informed by their knowledge of theoretical models and using their stratigraphic and structural field observations, to build a complete and comprehensive tectonic and geologic history of the region. In the sections below we develop stratigraphic and structural theoretical models pertinent to this field trip and then discuss their pedagogic application in the field.

### THE TECTONICS OF STRATIGRAPHY: BASIN ANALYSIS

Sedimentation requires the creation of accommodation space, and the creation and filling of accommodation space requires the transfer of energy. This energy is of two kinds: (1) *tectonic energy*, including heat from the Earth's interior that drives plate motion, and associated gravitational energy; and (2) *solar energy* that drives atmospheric circulation, powers the hydrologic cycle, and results in climatic zonation. Once accommodation space is created, deposition at any one locality is controlled by these two sources of energy: (1) *dip-fed energy* of tectonic origin: water flowing down a slope, whether subaerial or subaqueous; and (2) *strike-fed energy* of solar origin: water flowing more or less horizontally, as along a beach (acknowledging tidal currents are also important).

The production of accommodation space is controlled by five processes, although these typically work together.

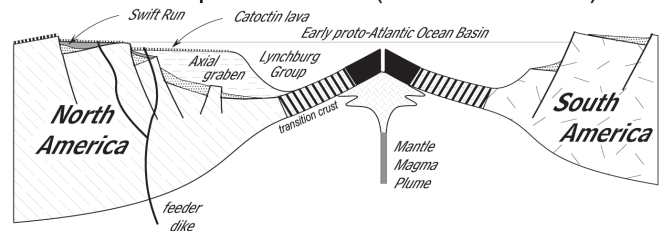
- (1) Isostatic control—vertical response to loading and unloading of the crust.
- (2) Tectonic control—plate tectonic energy expressed in cycles of collision and extension, producing uplift and subsidence (basin formation).
- (3) Eustatic control—worldwide sea level changes, driven by both tectonics and climate.
- (4) Sediment supply—affecting how fast the accommodation space is filled.
- (5) Climate—most obviously during glacial cycles, but in lesser ways under other conditions.

Basin analysis is the investigation and classification of basins based on how they form, how they evolve, what controls their evolution, and their geologic records. The depositional records occur in a nested hierarchy of patterns (called signatures) beginning with individual laminations, and working up through beds, bedsets, parasequences, systems tracts, sequences, and basin-filling sequences. The filling sequence of any basin results from several energy sources. The initial driving energy is tectonic, influencing the rate and degree of subsidence, followed by dip-fed and strike-fed processes that fill the accommodation space, influenced by sediment supply and sea level changes. In this field guide we focus on two regional examples of basin development: (1) the rift-to-drift sequence, as represented by the Chilhowee group that overlies Blue Ridge basement rocks in north-central Virginia, and (2) the evolution of a foreland basin, as represented by the Silurian–Devonian clastic wedge in the Valley and Ridge province of western Virginia and eastern West Virginia.

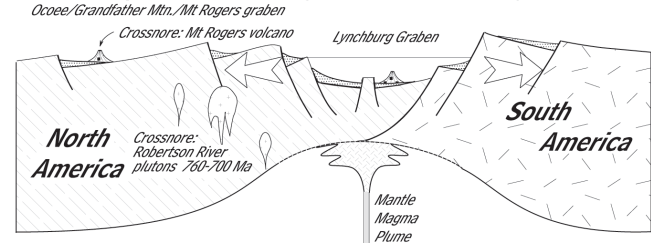
### Theoretical Rift-to-Drift Stratigraphic Basin Evolution

The theoretical model for a typical rift-to-drift sequence begins with uplift associated with the initiation of a hot spot. This produces tensional stresses, which results in horizontal extension and the formation of a horst (highland) and graben (rift) system (Fig. 4). A typical rift system consists of an axial graben and parallel lateral half-graben that lie on either side of the axial graben. The central axial graben may initiate as a subaerial feature, but it ultimately collapses below sea level (Fig. 4A). Shortly thereafter the drift phase commences, where oceanic crust starts to upwell along one of the central rifts, forming a new ocean basin (Fig. 4B). As this occurs the source of heat that lifted the hot spot migrates out to the center of the opening ocean, away from the new continental margins, which cool and subside. Initially, the subsidence is driven by thermal decay (cooling leading to increasing density and isostatic sinking), but as time goes by sediment loading contributes to the subsidence. Subsidence decays exponentially, such that subsidence in the rift phase is very rapid and slows progressively into the drift

#### C - Late Neoproterozoic (~700 - 570 Ma)



#### B - Neoproterozoic (~760 - 700 Ma)



#### A - Neoproterozoic (~800 Ma)

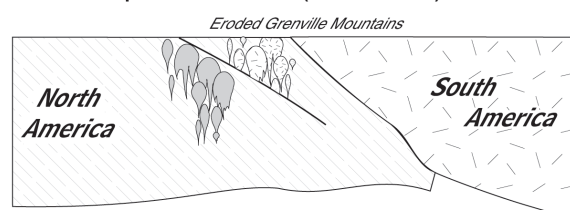


Figure 4. Theoretical model of a rift sequence (cross sections A, B, and C), broadly applicable to the Catoclin, Swift Run, and Chilhowee Group (Weverton, Harpers, Antietam) stratigraphic record.



phase (Fig. 4C). Correspondingly, in the rift phase accommodation increases very rapidly, more rapidly than sediment can keep up with, leading to a deep water environment. Then, as subsidence slows, sediment filling catches up with the accommodation space, leading to a coarsening and shallowing upward sequence. The transition of the rift phase to the drift phase produces a divergent continental margin (DCM) and a transgression of the shoreline across the former location of the rift. At this stage deposition is able to keep up with subsidence, and mostly coastal and shallow to deep shelf deposition results.

### ***Predictive Stratigraphic Model***

The predictive stratigraphic model presented here (based on Fichter and Diecchio, 1986) assumes that several dynamic processes are going on simultaneously, or at least overlap in time. First assumption: stratigraphic development in the rift-to-drift system is basically a coarsening and shallowing upward sequence. Second assumption: the Chilhowee Group stratigraphic record we are dealing with spans both the uplift and subsidence stages of the rifting. Third assumption: graben-filling occurred on the Blue Ridge western flank, based on visible Bouma sequences. Fourth assumption: unlike a typical fan delta system that finishes with a subaerial alluvial fan (which could still be there based on large planar cross-bedding in the Weverton Formation), the submarine fan grades up section into a shallow storm shelf (based on hummocky sequences in the Harpers Formation), and then beach facies of the Antietam Formation. The sequence below accounts for all of these conditions and processes.

- (1) Initial horst uplift and graben subsidence stemming from hot spot activity results in high relief. Depositional systems develop on both sides of the rift continental terrace (horst that borders the axial rift on each side) and flow in opposite directions, one toward the axial rift, the other toward the continent. Toward the rift, fan deltas develop in the graben, while on the opposite side rivers flow toward the continent. To our knowledge, no remnants of such river systems have been described for the mid-Atlantic region. The graben fill results in a coarsening upward sequence, from basin shales, through submarine fan, and (ideally) into an alluvial fan. High relief results in rapid erosion and deposition.
- (2) With time, erosion lowers the horsts and deposition fills the accommodation space, lessening the relief. Submarine fan turbidite deposits (Bouma sequences) shallow upward.
- (3) At about the same time, the continental margin is subsiding, eventually sinking below sea level resulting in a transgression. Shallow marine shelf deposits appear in the section. These may deposit on top of submarine fan Bouma sequences, or may transgress across fluvial systems (top of the fan delta). Both are possible in different locations. Tops of horsts may appear as islands.
- (4) As the continental margin subsides and the horsts erode (and/or are buried in debris) continental drainage

reverses. Where the gradient and flow used to be toward the continent, the gradient and flow are now toward the DCM. This taps the deposits of lag quartz sands found on continental cratons and brings them down to the new coastal systems.

- (5) Finally, as the relief diminishes, the continental margin subsides and the shore transgresses. Sea level fluctuations begin to more strongly influence the stratigraphic record.

### ***Local Rift Stratigraphic Record***

On the west flank of the Blue Ridge anticlinorium, the formations representing rift events are the Catoctin metabasalts (initiation of proto-Atlantic oceanic crust formation), Swift Run siliciclastics (interlayered with metabasalts), Weverton submarine fan (Bouma sequences), Harpers shelf (hummocky sequences), Antietam (beach system), and Shady (tidal dolomite). Outcrops of the Swift Run, Weverton, Harpers, and Antietam formations are sparse and not contiguous. On this field trip, we will see all of these formations except the Shady dolomite. A Harpers outcrop on Route 211 near Luray (north of our field trip route) contains hummocky sequences. However, we will visit a Harpers locality at the base of the Blue Ridge on Route 33 that contains Bouma sequences (Stop 1-8).

### **Theoretical Foreland Basin Stratigraphic Basin Evolution**

In our theoretical model, foreland basin development is preceded by a tectonic calm, either a divergent continental margin (DCM) or an interorogenic calm (Fig. 5, Stage I). Tectonic calms are recognized by quartz arenite and/or carbonates, both of which are stratigraphically thin (tens to hundreds of feet), as compared with the stratigraphic thickness of orogenic events (thousands of feet).

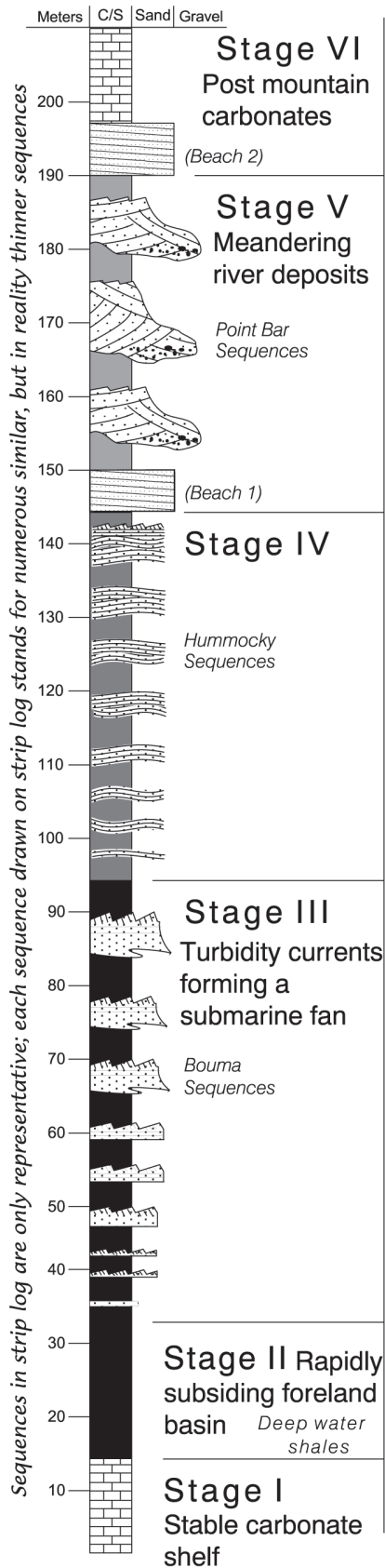
The early stages of a collisional orogeny produce rapid foreland subsidence (Fig. 5; Stages II–III) that exponentially slows with time. Similar to rift basins, foreland basins initiate with the formation of deep water environments followed by long-term filling of the accommodation space by progradation and filling (Fig. 5; Stages IV–V). This pattern is best developed adjacent to the maximum relief produced by mountain building and diminishes as one moves away from the orogenic core.

### ***Predictive Stratigraphic Model***

The ideal model of a progradation and filling sequence follows Walther's Law: the horizontal sequence of environments will stack vertically in the same order during a transgression or regression (Middleton, 1973; Fig. 6). The order of environments is controlled by the systematic changes in the way energy is transferred. Following initial tectonic subsidence, the main energy driving the system switches to sedimentation (dip-fed and strike-fed) and sea level changes. Figure 6 shows the preferential stacking order for the filling sequence of an ideal foreland basin. This sequence becomes the top-down basis for making interpretations and predictions on the outcrop.



*Strip Log and Interpretation*



*Sequential History of Basin*

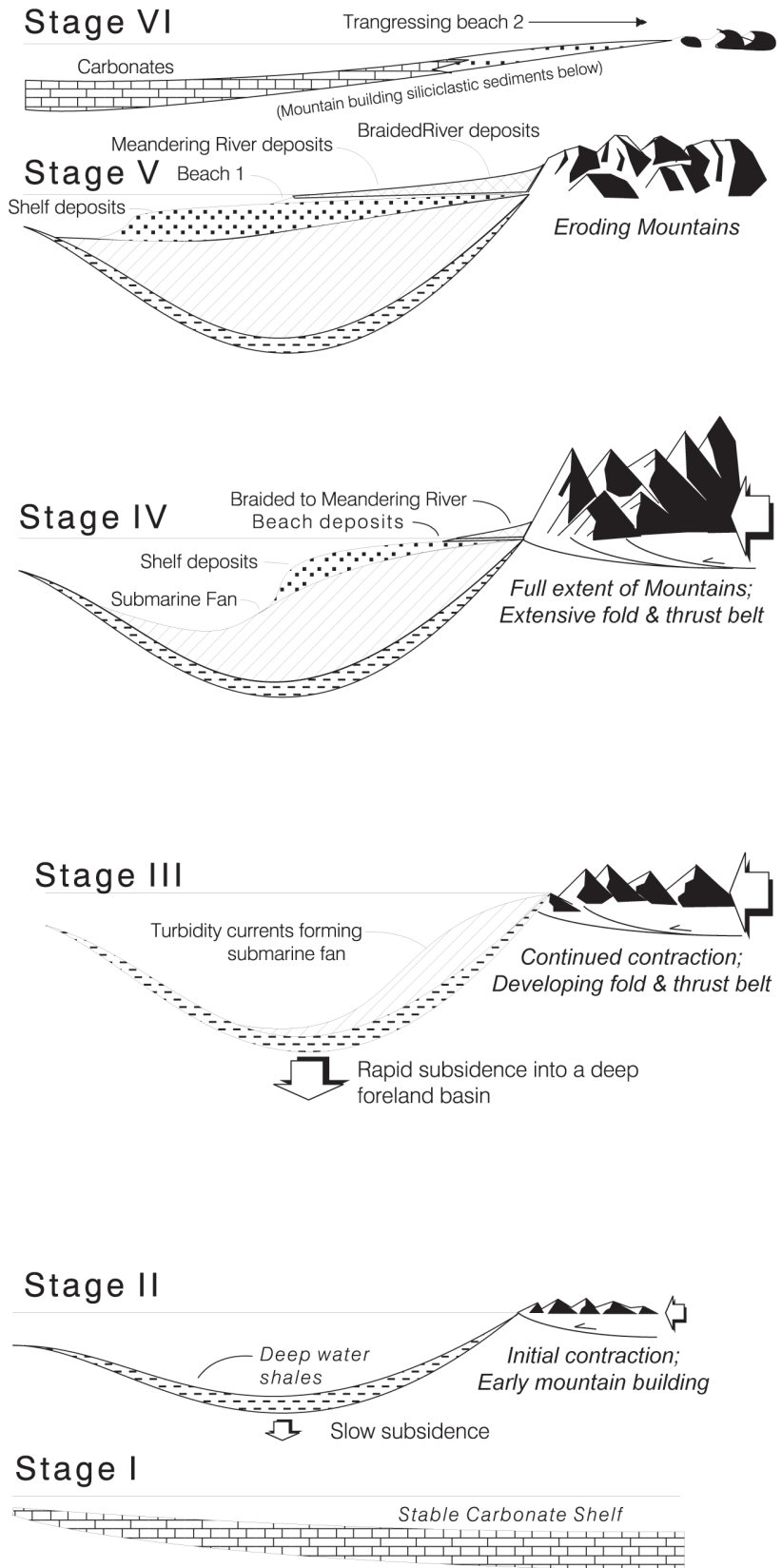


Figure 5. History of an ideal foreland basin stratigraphic filling sequence; after Fichter and Poché (2001).

**Local Foreland Basin Stratigraphic Record**

Two distinct foreland basin records are encountered within the region covered by this field guide, one for the Ordovician Taconic orogeny and the other for the Devonian Acadian orogeny (Fig. 2). The Acadian sequence (Catskill clastic wedge) in this part of Virginia and West Virginia is almost a perfect match for the theoretical model (Fichter, 1986). The Needmore Formation shows anoxic features, fossil rich layers, and condensed sections that collectively represent the early stages of a rapidly subsiding basin. The Millboro Formation is composed of anoxic, thinly laminated shales that indicate the deepest environment of the section. The laminated shales grade up section into Bouma sequences of the Brallier Formation, which transition into hummocky sequences of the Greenland Gap Formation and then point bar sequences of the Hampshire Formation. The red beds of the Hampshire Formation indicate a muddy shoreline environment, which is a slight deviation from the theoretical model. Simplistically we would expect to see a sandy shoreline, either because that is what most people see when they visit the beach or because many coastlines today consist of sandy beach and barrier island systems. The absence of a sandy beach and presence of a muddy shoreline is useful pedagogically as it prompts on-the-outcrop discussions of coastal energy regimes and climatic zones.

In contrast to the almost ideal Acadian foreland basin record, the Taconic stratigraphic record deviates substantially from the theoretical model. Three distinct Taconic sequences occur along a west-to-east transect of the Valley and Ridge province: Germany Valley (westernmost section), Brocks Gap (middle section along Little North Mountain), and the Massanutten Synclinorium section (Fig. 7). Due to time constraints, we only see the Germany Valley section on this field trip. Oblique collisions of the Taconic terrane(s) left the present-day northern Virginia region in a protected reentrant that experienced only slight flexure fold-

ing (Thomas, 1977; Drake et al., 1989). This divided the Taconic foreland basin into a rapidly subsiding deep water eastern basin and a slowly subsiding shallower western basin (Diecchio, 1986, 1993). These basins remained isolated from each other until deposition of the Oswego Formation in the late Ordovician. Thus, the western basin (the Germany Valley section of this field guide) never developed a deep water system. Instead, carbonate hummocky sequences (Black River and Trenton groups) grade into clastic hummocky sequences (Reedsville Formation), and shoreline sandbars (Oswego Formation). This is overlain by a clastic tidal system (Juniata Formation red beds) that does not transition into a fluvial system, but rather transitions into a beach and barrier island system (Tuscarora Formation). The details of the Taconic stratigraphic sequence are compared and contrasted with the Acadian sequence, which prompts discussions of the relative merits of deductive versus inductive analysis techniques and their relative applicability to field investigations.

**Equating Inductive and Deductive Approaches to Stratigraphic Analysis**

One of the consequences of evaluating the geologic record as an energy-transferring evolutionary system is that stratigraphic sequences can be viewed as patterns that are replicated at many scales: an example of natural fractal organization. For large-scale tectonic synthesis, geologists and students need to know where they are in the hierarchy of stratigraphic sequences, know the energy processes that produced each sequence, and know how and why the sequences are nested in a particular order. On the outcrop this can be evaluated inductively (bottom-up). For example, fining upward Bouma sequences that are nested within fining upward parasequences (representing sea level changes), that are nested within composite parasequence sets (systems tracts, either

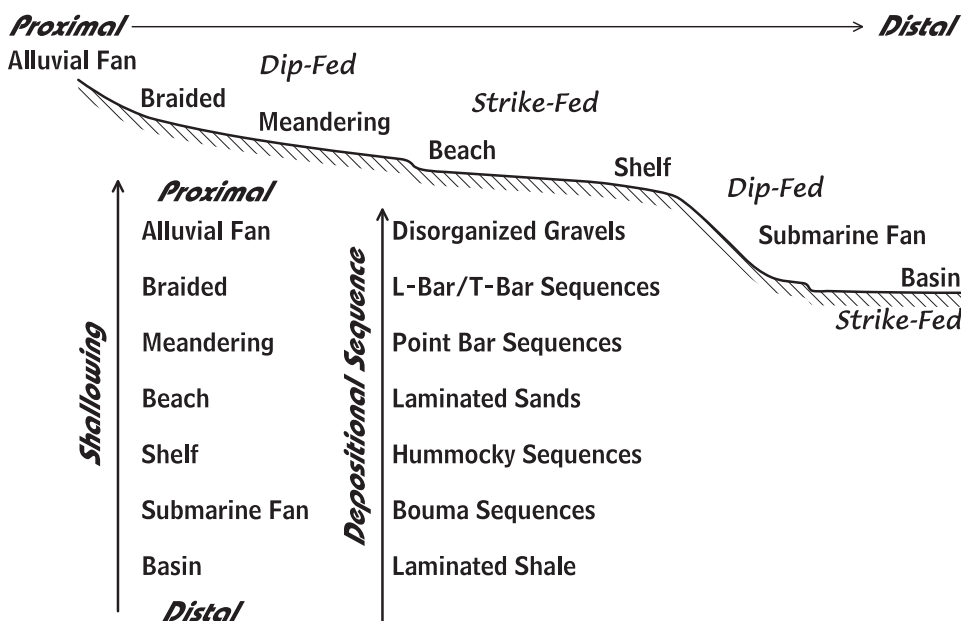


Figure 6. Ideal progradational and corresponding stacking sequence of depositional environments.

coarsening or fining upward), that are nested within an overall coarsening upward sequence, collectively represent a prograding submarine fan environment. Similar patterns exist in shelf sequences, tidal sequences, and fluvial sequences. However, by the time larger scale components of this hierarchy are considered, the patterns can no longer be viewed at a single outcrop. At this point, patterns are deductively evaluated within the framework of a large-scale theoretical model to see how effectively they correspond to the outcrop evidence.

Stratigraphic sequences in the Blue Ridge and Valley and Ridge provinces of northern Virginia and West Virginia exhibit a rift-to-drift sequence followed by several orogenic events (Taconic, Acadian, and Alleghanian), followed by a second rift-to-drift sequence (opening of the Atlantic Ocean). Each of the orogenic events represents a pulse of tectonic activity that decays exponentially over time and includes systematic filling of the accommodation space during the decay periods. With each pulse

of tectonic activity the stratigraphic record responds in generally predictable ways. Thus, theoretical models that are based on how energies are transferred predict that particular sequences (e.g., Bouma sequences; Fig. 8) will not appear haphazardly in the stratigraphic column. By evaluating outcrop evidence bottom-up, with ideal basin-filling sequences as testable models, we and our students can build plausible regional-scale tectonic histories from the visible stratigraphic record.

**THE TECTONICS OF STRUCTURAL ANALYSIS: DEFORMATION AT MULTIPLE SCALES**

In the late nineteenth century, Raphael Pumpelly articulated his “rule” that the axes of minor folds are typically congruent with major fold structures of the same phase of deformation (Pumpelly et al., 1894). This is often generalized by stating that small-scale structures mimic larger scale structures, a theoretical

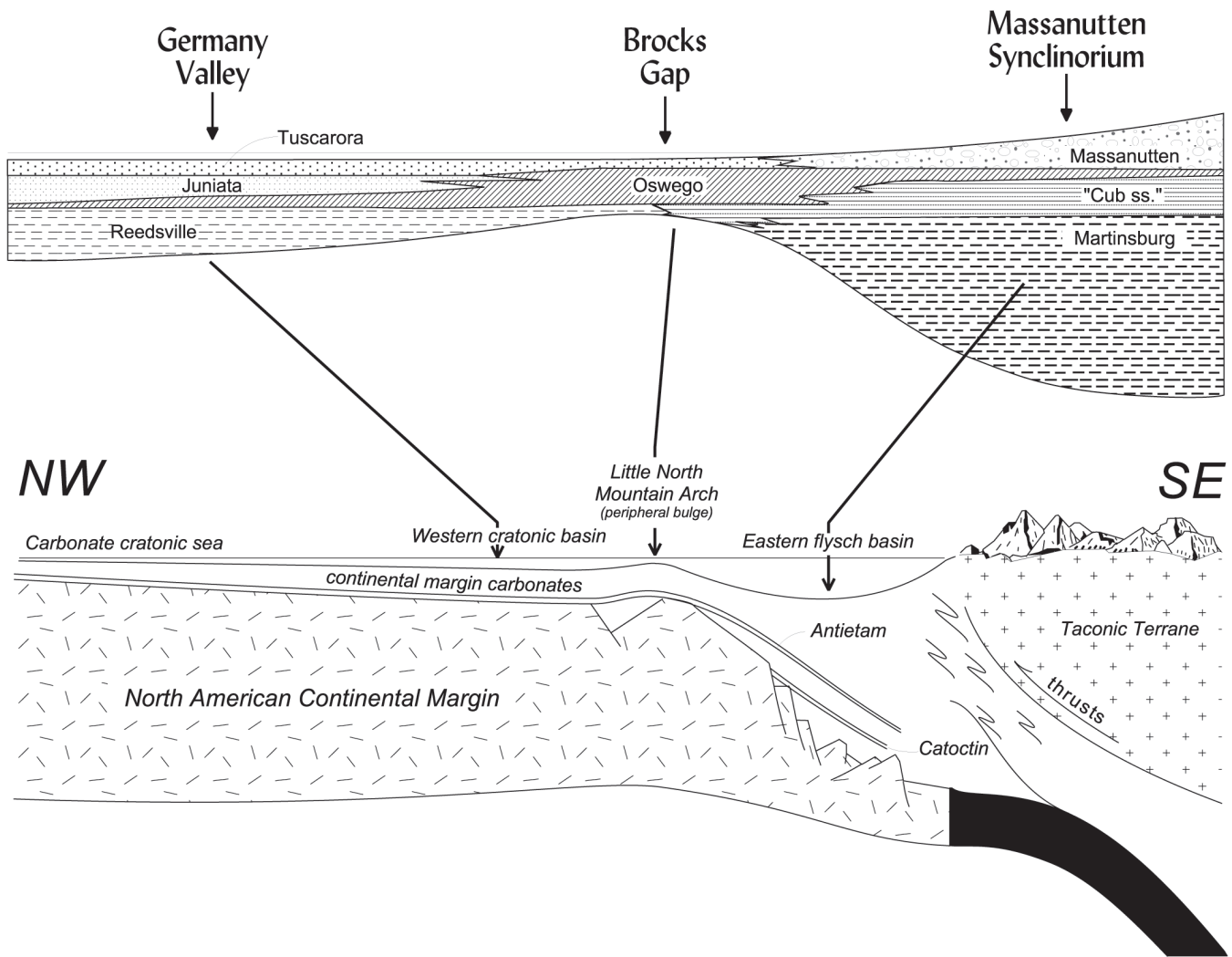


Figure 7. Interpretive stratigraphic and tectonic cross sections for the Taconic sequences of Germany Valley, Little North Mountain (Brocks Gap), and the Massanutten Synclinorium. Top: cross section after Diecchio (1993).

principal that fits within fractal analyses. Structural geologists use Pumpelly's Rule to infer regional structures that are not observable at a single outcrop from detailed outcrop measurements, an example of integrating theoretical models with inductive observations. However, a critical assumption is that structures at all scales resulted from a single tectonic event.

This principle of patterns of deformation at multiple scales is abundantly in evidence along the Valley and Ridge transect described by this field guide, where folds and faults are apparent at the outcrop scale and inferred at larger, regional scales. The concept of energy transfer is demonstrable along the east-to-west progression of field stops, such that the WNW-directed collision of Gondwana with this region of eastern Laurentia produced deep-rooted, penetrative deformation in the basement rocks of the Blue Ridge, which shallows to thin-skinned deformation across the Valley and Ridge, before finally dissipating in the subsurface of the Allegheny Plateau.

Ductile deformation is primarily observed in basement rocks east of the Blue Ridge thrust system along the western margin of Shenandoah National Park. Mylonitic shear zones have a similar NE-SW orientation to, and can be temporally equated with, brittle faults of the foreland thrust belt of the Valley and Ridge to the west (Bailey et al., 2006). The geometry of folds and faults is controlled, in part, by the mechanical strength of rock units, with most of the westward transport accommodated along shale-dominated units like the Martinsburg Formation (Dunne, 1996). The scale of deformation structures range from those visible at a single outcrop (e.g., Stop 2-19), to folds that span several kilometers (e.g., Germany Valley anticline, Stop 2-24). Seismic data suggests that multiple-scale deformation patterns extend into the subsurface, where fault-bounded horses underlie much of the visible surface patterns (Evans, 1989; Wilson and Shumaker, 1992; Fig. 3).

This field guide documents stops that exhibit ductile and brittle folds and faults, of at least three distinguishable orders of magni-

tude. We consider first-order structures to be at the several-kilometer scale, and thus not directly observable at a single outcrop; the Germany Valley anticline (Stop 2-24) is a good example. Evidence for second-order structures is apparent at several outcrops (Stops 2-12 and 2-19), and the scale of a specific structure may be tens of meters to a kilometer. Third-order structures are a few meters in scale and readily apparent at a single outcrop, such as Stops 2-10 and 2-19. Mega-scale structures, like the subsurface duplexes in Figure 3, and microscopic-scale structures are inferred from other data sets, such as the mylonitic structures in Blue Ridge basement rocks from Day 1, but will not be directly observed on this field trip.

**CONCLUSIONS**

The deductive and inductive approaches to stratigraphic and structural analyses outlined above provide a multifaceted toolbox for outcrop-based field investigations. Our integrated approach forces novice geoscientists to utilize all of these techniques for the overarching goal of synthesizing the tectonic history of the northwestern Virginia and eastern West Virginia region. As students work toward this goal, it becomes apparent to them that outcrop evidence exists not only at several spatial scales but also at several temporal scales. Stratigraphic data provide information about the Taconic and Acadian orogenic events, while structural data predominantly reflect deformation from the Alleghanian orogeny. The task of interpreting and synthesizing observations at multiple spatial and temporal scales is daunting for both novices and experts alike, but it is ultimately what geoscientists are required to do in order to build compelling tectonic histories. It is our good fortune that this region is rich in outcrops that facilitate multidisciplinary investigations of several tectonic episodes that collectively cover most of the Appalachian orogenic cycle.

For students completing the SST course, the expectation is that the theoretical models and concepts presented here, once

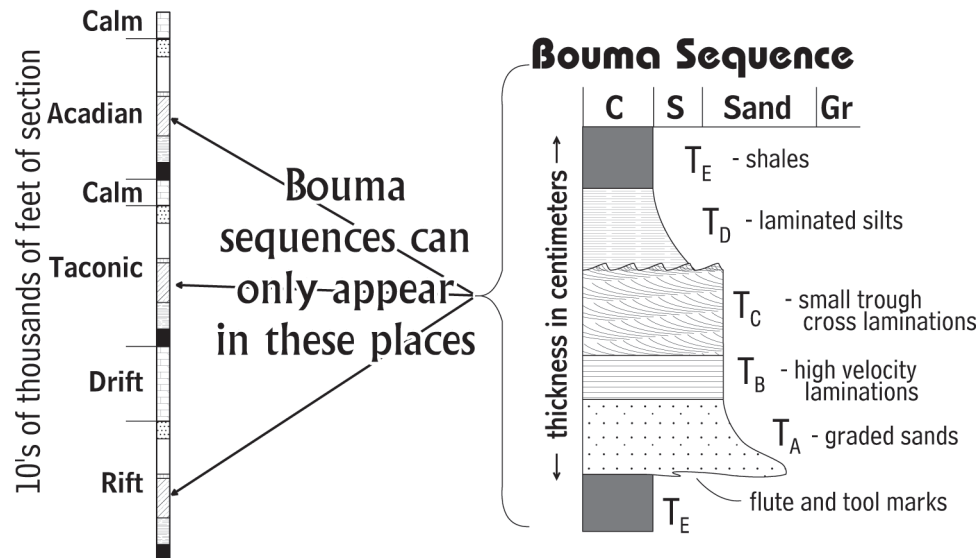


Figure 8. Theoretical model showing how specific sequences, such as Bouma sequences, are predicted from the transfer of tectonic and stratigraphic energy.



absorbed, allow one to evaluate the preserved stratigraphic and structural record, and then predict what might be seen laterally in nearby outcrops. The deductive experiences on the outcrop temper this expectation with the reality that theoretical models do not always match field observations. However, these discrepancies between models and outcrop evidence provide an opportunity to refine the models. From a pedagogic perspective, what is important about this approach is that students begin to construct a framework of interpretation and understanding, and with more and more experience, begin to think about the geologic and tectonic record in terms of linked systems and energy.

**ROAD LOG, DAY 1: BLUE RIDGE**

The road log for the Blue Ridge part of the field trip (Day 1) starts at the junction of U.S. Route 29 and Virginia Route 230, in Ruckersville, south of Madison, Virginia (N38° 20' 50", W78° 17' 06"; mile 0.0). Day 1 stops are shown on a relief map of the area (Fig. 9) and on a simplified geologic map (Fig. 10).

**Stop 1-1. Pavement Outcrops in Stanardsville Yard (Older Pyroxene-Bearing Gneiss)**

*Mile 10.4 (N38° 18' 02", W78° 26' 06")*

Home of Jackie Pamerter. Pavement outcrops in center of driveway loop and behind outbuilding of coarse-grained, orthopyroxene-bearing Mesoproterozoic granitoid gneiss that is one of the older basement lithologies in this part of the Blue Ridge, with a crystallization age of 1177 + 11 Ma. The gneiss displays a well-developed, high-temperature tectonic foliation, defined by mm- to cm-scale feldspar and quartz aggregates with elongate clots of orthopyroxene and hornblende—lithologies with ages <1100 Ma lack such a strong foliation. The gneissic foliation strikes northeast and dips to the northwest; elsewhere in the Blue Ridge, northwest strikes are not uncommon for rocks with similar gneissic fabrics of “Grenville” age. Note orange-weathering boulders to left of shed—this distinctive weathering rind is characteristic of pyroxene-bearing granitoid rocks. The sculpture in the center of the loop features a piece of Catoctin metabasalt.

Cumulative mileage	Point-to-point mileage	Directions and comments
0.0		Proceed westbound on VA Rt. 230.
7.2	3.2	Cross Conway River; enter Greene County.
10.4	3.2	Turn right into driveway; proceed to driveway loop and park.

Cumulative mileage	Point-to-point mileage	Directions and comments
10.4	0.0	Turn left (north) on VA Rt. 230 (Otonia Road).
11.0	0.6	Turn left (northwest) onto Rt. 637.
12.2	1.2	Turn left (south) onto Tall Pines Drive.

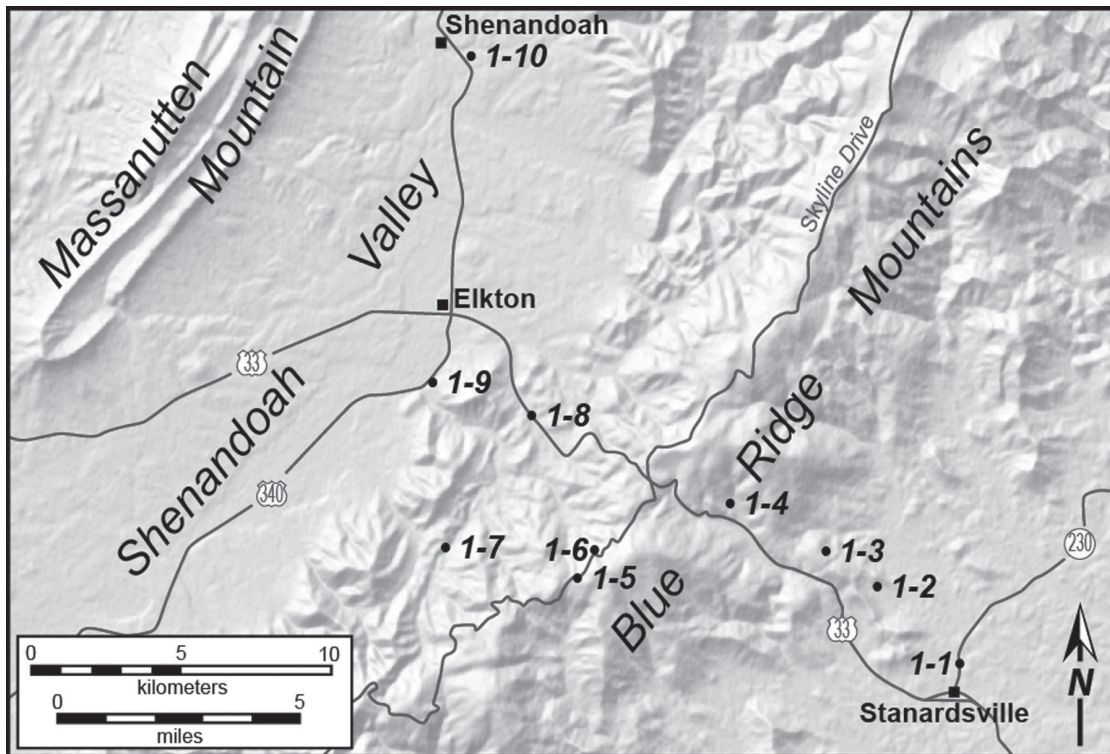


Figure 9. Shaded relief map with major towns and roads, showing the field trip stops for Day 1.

- 12.5 0.3 Bear right onto Greene Acres Road North.
- 13.6 1.1 Park on left.

**Stop 1-2. Roadcut on Greene Acres Road North (Basement-Derived Mylonite)**

Mile 13.6 (N38° 19' 42", W78° 27' 54")

Protomylonite and mylonite are well exposed in this cut. The protolith for these strongly deformed rocks is younger Mesoproterozoic charnockite (see next stop), and this high-strain zone can be traced for 10 km to the north. Foliation dips to the east and a strongly developed penetrative lineation plunges obliquely down-dip. Kinematic indicators such as asymmetric porphyroclasts and shear bands indicate a top-to-the west shear sense (reverse fault); small, enigmatic outliers nearby of Catoctin metabasalt on basement suggest that the shear zone had an earlier, top-to-the-east shear sense (normal fault).

Cumulative mileage	Point-to-point mileage	Directions and comments
13.6	0.0	Continue west on Greene Acres Road North.
13.8	0.2	Turn right (west) onto Greene Acres Road South.
14.5	0.7	Turn right (north) onto Rt. 638 (Turkey Ridge Road).
15.0	0.5	Pull off on right at slight bend.

**Stop 1-3. Roadside Outcrop on Turkey Ridge Road (Younger Mesoproterozoic Charnockite)**

Mile 15.0 (N38° 20'22", W78° 27' 58")

This exposure shows massive-weathering, coarse-grained, orthopyroxene-bearing granitoid, also known as charnockite. This lithology is one of the youngest Mesoproterozoic lithologies in the Blue Ridge, with a crystallization age of ~1050 Ma that indicates emplacement near the end of the Grenville orogeny. Accordingly, the rock lacks a tectonic foliation; faint foliation observed in some charnockite outcrops is probably magmatic in origin. The contacts between this young charnockite and the older gneisses are primarily intrusive in nature; in a roadcut on U.S. Route 33, a narrow dike of this type of charnockite intrudes well-foliated granitoid gneiss. Similar to the rocks at Stop 1-1, this pyroxene-bearing rock weathers to produce a distinctive orange rind, as seen in nearby boulders.

Cumulative mileage	Point-to-point mileage	Directions and comments
15.8	0.7	Turn left (west) onto Rt. 634 (Bull Yearling Road).
18.5	2.7	Turn right (west) onto U.S. Rt. 33.
20.2	1.7	Pull off into small area on the right (north) side of U.S. Rt. 33. Walk northward for 0.3 mi. to the exposure.

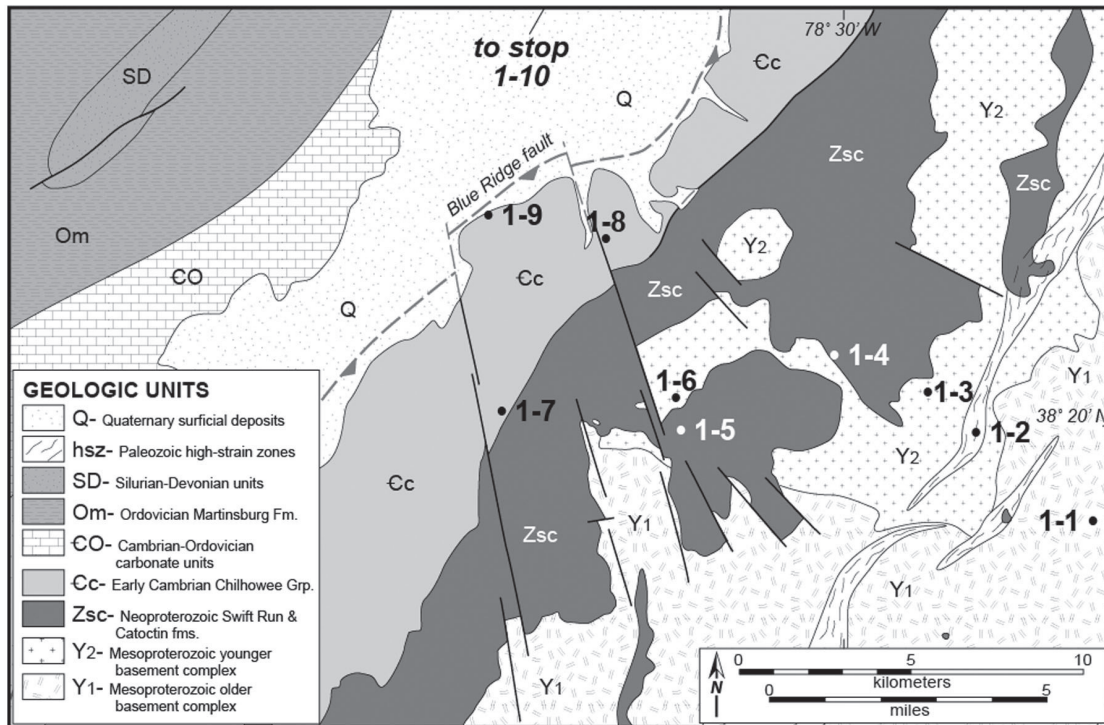


Figure 10. Simplified geologic map of a region of north-central Virginia. Field trip stops for Day 1 are indicated.

**Stop 1-4. Cliffs along Tributary of East Swift Run (Swift Run Formation)***Mile 20.2 (N38° 20' 56", W78° 30' 53")*

The low cliffs form one of the best exposures of the Swift Run Formation in Shenandoah National Park. The original type location (Jonas and Stose, 1939) was 1.6 km to the west, but that outcrop was destroyed during the widening of U.S. Rt. 33, and this outcrop makes an admirable neostatotype for the Swift Run Formation. Approximately 10–12 m of arkosic metasandstone, metaconglomerate, and mudstone are exposed. Bedding dips gently southeast and is cut by a more steeply dipping foliation. Cross and plane bedding is common, and graded bedding and mudstone rip-up clasts are evident at a few locations. Coarse sandstone layers commonly truncate layers of maroon mudstone. The provenance for these sediments is the granitic basement complex, and sedimentary structures are consistent with a fluvial to fluvial braidplain depositional environment. Cores were drilled for paleomagnetic analysis in an effort to determine the paleolatitude during Swift Run deposition, but the remnant magnetic signature in these rocks is complex.

<i>Cumulative mileage</i>	<i>Point-to-point mileage</i>	<i>Directions and comments</i>
20.2	0.0	Bear right (northwest) onto U.S. Rt. 33.
22.5	2.3	Swift Run Gap cross under the Skyline Drive.
22.8	0.3	Turn right into Shenandoah National Park entrance and proceed through entrance station.
23.1	0.3	Turn right (south) on the Skyline Drive.
26.1	3.0	Turn left into Smith Roach Gap parking area. Hike eastward on old road for 0.3 mi to outcrop.

**Stop 1-5. South Flank of Hightop Mountain (Catoctin Formation)***Mile 26.1 (N38° 19' 35", W78° 34' 11")*

The walk from the parking area takes us across foliated greenstone interlayered with thin layers of arkosic phyllite in the Catoctin Formation. At ~400 m a large outcrop of greenstone crops out immediately to the north of the trail. Columnar joints are well developed and transected by a southeast-dipping foliation. The long axes of the columns plunge steeply to the southeast, consistent with a gently dipping flow geometry. On the south flank of Hightop the Catoctin Formation dips gently to the southeast.

<i>Cumulative mileage</i>	<i>Point-to-point mileage</i>	<i>Directions and comments</i>
26.1	0.0	Turn right (north) onto Skyline Drive.

26.9	0.8	Turn left into Sandy Bottom Overlook.
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**Stop 1-6. Sandy Bottom Overlook (Charnockite in the Basement Complex)***Mile 26.9 (N38° 20' 10", W78° 33' 57")*

Sandy Bottom Overlook provides a commanding view of the Blue Ridge (northeast), the Shenandoah Valley (west), and Massanutten Mountain (west/northwest). Well-cemented quartz arenites of Silurian age underlie the long linear ridges of the Massanutten Mountain complex. The canoe-shaped prow at the southwestern end of Massanutten reflects the geometry of this gently plunging syncline. The mountain front between the Elkton area and north to Stanley is sinuous and likely reflects the low-angle nature of the Blue Ridge fault and offset associated with younger transverse faults.

The “great unconformity” between Mesoproterozoic basement and the Neoproterozoic cover sequence occurs above the Skyline Drive. Basement is overlain by arkosic phyllite of the Swift Run Formation and at least 250 m of Catoctin metabasalts capping Hightop Mountain. Sandy Bottom (immediately to the northwest) is underlain by a northwest-striking transverse fault that places basement against the Catoctin Formation. The large roadcut across from the overlook exposes a distinctive orthopyroxene-bearing monzogranite. A U-Pb zircon age of  $1049 \pm 9$  Ma was obtained from rock at this location and is interpreted as a crystallization age (Southworth et al., 2009). This charnockitic pluton is part of the younger group of Grenvillian granitoids.

<i>Cumulative mileage</i>	<i>Point-to-point mileage</i>	<i>Directions and comments</i>
26.9	0.0	Turn left (north) onto Skyline Drive.
29.1	2.2	Turn left onto Shenandoah National Park entrance road.
29.4	0.3	Turn right (west) onto U.S. Rt. 33.
31.6	2.2	Turn left (southwest) onto Rt. 628.
34.9	3.3	Park on the right across from driveway.

**Stop 1-7. Roadcut on Route 628 (Weverton Formation)***Mile 34.9 (N38° 20' 14", W78° 37' 16")*

The long roadcut exposes a coarse arkosic metasandstone and quartzose phyllite of the Weverton Formation. Bedding is upright and dips 15° to 25° to the northwest. A southeast-dipping foliation is well developed in the phyllite. In the Elkton area fine-grained rocks are common in both the Weverton and overlying Harpers Formation making the distinction between units difficult. Fine-grained white mica in the quartzose phyllite yields an Ar/Ar plateau age of ~340 Ma and is interpreted to be either a cooling or growth age. In either case, penetrative deformation in this rock occurred prior to the Alleghanian orogeny.



Two sets of fractures cut the Weverton Formation at these exposures. The older set strikes to the northeast and dips normal to bedding, consistent with fracturing prior to folding. The younger subvertical set strikes to the northwest, and fractures are adorned with plumose structure; this set may have developed under a west-northwest oriented principal stress associated with late Paleozoic contraction.

<i>Cumulative mileage</i>	<i>Point-to-point mileage</i>	<i>Directions and comments</i>
34.9	0.0	Retrace route to the northeast on Rt. 628.
38.2	3.3	Turn left (west) on U.S. Rt. 33.
39.0	0.8	Park on right shoulder, cross to south side of the divided highway.

### Stop 1-8. Roadcut on U.S. Route 33 (Harpers Formation)

*Mile 39.0 (N38° 22' 31", W78° 35' 18")*

This roadcut exposes laminated quartzose metasandstone of the Harpers Formation. Bedding dips gently to the northwest, and a southeast-dipping penetrative foliation (cleavage) is well developed in the fine-grained rocks. Depositional units are proximal Bouma sequences, mostly T<sub>AE</sub> and T<sub>ABE</sub>, from one to a few dm thick. T<sub>A</sub> units with scoured bottoms, ranging from coarse quartzose sands to granule and pebble gravels with graded bedding; all consistent with a steep gradient and deeper water marine depositional environment.

<i>Cumulative mileage</i>	<i>Point-to-point mileage</i>	<i>Directions and comments</i>
39.0	0.0	Continue northwest of U.S. Rt. 33.
41.8	2.8	Exit to the right off U.S. Rt. 33.
42.0	0.2	Turn left onto U.S. Rt. 340 at the end of ramp.
45.7	1.7	Park on the right (northwest), and carefully cross road.

### Stop 1-9. Roadcut on U.S. Route 340, South of Elkton (Antietam Formation)

*Mile 45.7 (N38° 23' 03", W78° 37' 42")*

The exposure to the southeast side of U.S. Rt. 340 is cut into extensively fractured and brecciated quartz arenite of the Antietam Formation. These rocks are in the hanging wall of the Blue Ridge fault that is buried beneath alluvium of the South Fork of the Shenandoah River immediately to the northwest. Wells drilled on the Merck chemical plant penetrated middle Cambrian rocks of the Elbrook Formation (King, 1950) within 0.5 km of this outcrop, and the intervening Waynesboro and Tomstown formations are absent.

<i>Cumulative mileage</i>	<i>Point-to-point mileage</i>	<i>Directions and comments</i>
45.7	0.0	U-turn and go north on U.S. Rt. 340.

47.4	1.7	Cross under U.S. Rt. 33 and enter Elkton.
52.9	5.5	Turn right into Shenandoah town park.

### Stop 1-10. Outcrops in Shenandoah Town Park (Beekmantown Group and Conococheague Formation)

*Mile 52.9 (N38° 28' 56", W78° 37' 02")*

Exposures of strongly deformed limestone, with abundant sheared stylolites, crop out on the north side of Gem pond, in Shenandoah town park on the east side of Rt. 340. Outcrops at the west end of the pond are interpreted as the Stonehenge member of the Beekmantown Group, while outcrops at the eastern end of the pond are Conococheague Formation. Cliffs along the eastern side of the pond exhibit several layer-parallel zones of fault gouge, interpreted to be splays of the northwest-directed Stanley fault. The main fault surface is probably the erosional notch at the northeastern corner of the pond; this is also potentially the contact between the Ordovician Beekmantown Group and the Cambrian Conococheague Formation.

End of Day 1 field stops. Drive back south on Rt. 340 (5.4 miles), and turn right onto ramp to join Rt. 33 west. Drive ~17 miles to Harrisonburg, Virginia. At about mile 10 along this drive you will pass the prow of Massanutten Mountain, just north of Rt. 33, which is defined by Silurian Massanutten Formation sandstones overlying the Ordovician Cub sandstone (hummocky sequences) and Martinsburg Formation (Bouma sequences) and represents the western syncline of the Massanutten Synclinorium. The eastern syncline is apparent as the mountain of Lairds Knob, which is east and a bit north of Massanutten Mountain. At about mile 13 you cross over the west-directed Staunton thrust fault (not exposed), which juxtaposes Cambrian Elbrook Formation limestones (hanging wall) against Ordovician Beekmantown Group carbonates (footwall). The city of Harrisonburg predominantly sits on subhorizontal Ordovician carbonates and shales of the Edinburg and Martinsburg formations.

### ROAD LOG, DAY 2: VALLEY AND RIDGE

The road log for the Valley and Ridge part of the field trip (Day 2) includes many more stops than we will have time to visit in a single day. We have included optional stops for the possible future use of field trip participants and field guide readers. Day 2 stops we hope to visit are shown on a relief map of the area (Fig. 11) and on a simplified geologic map (Fig. 12).

Note that we visit all of the stops listed below in the SST course, but it takes us two to three days to accomplish this. Readers will also note that the stop descriptions are extremely terse. This format mimics the information given to the SST students, where most of the details are deciphered during examinations and discussions on location at



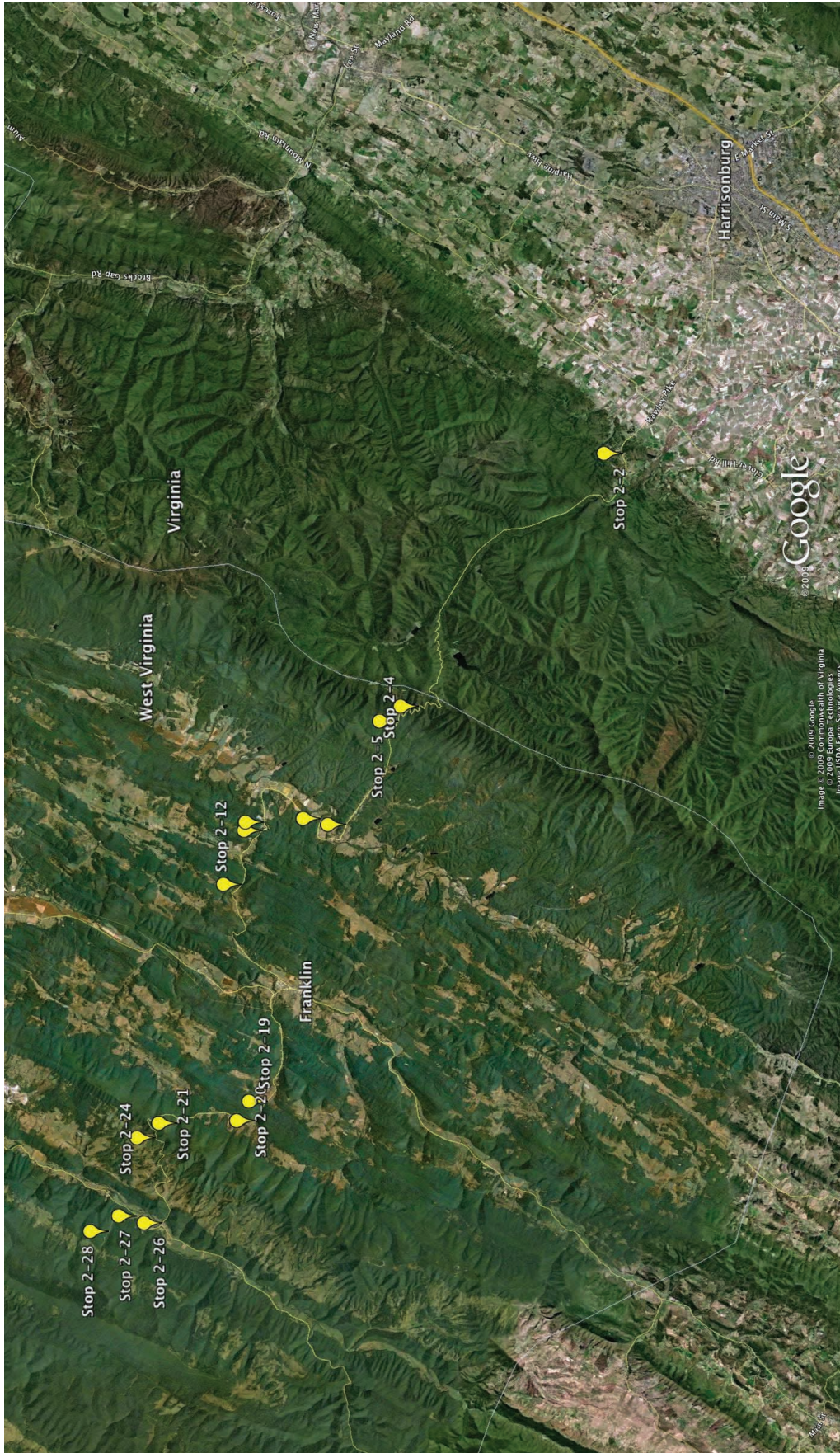


Figure 11. Google Earth relief map showing the field trip stops for Day 2.



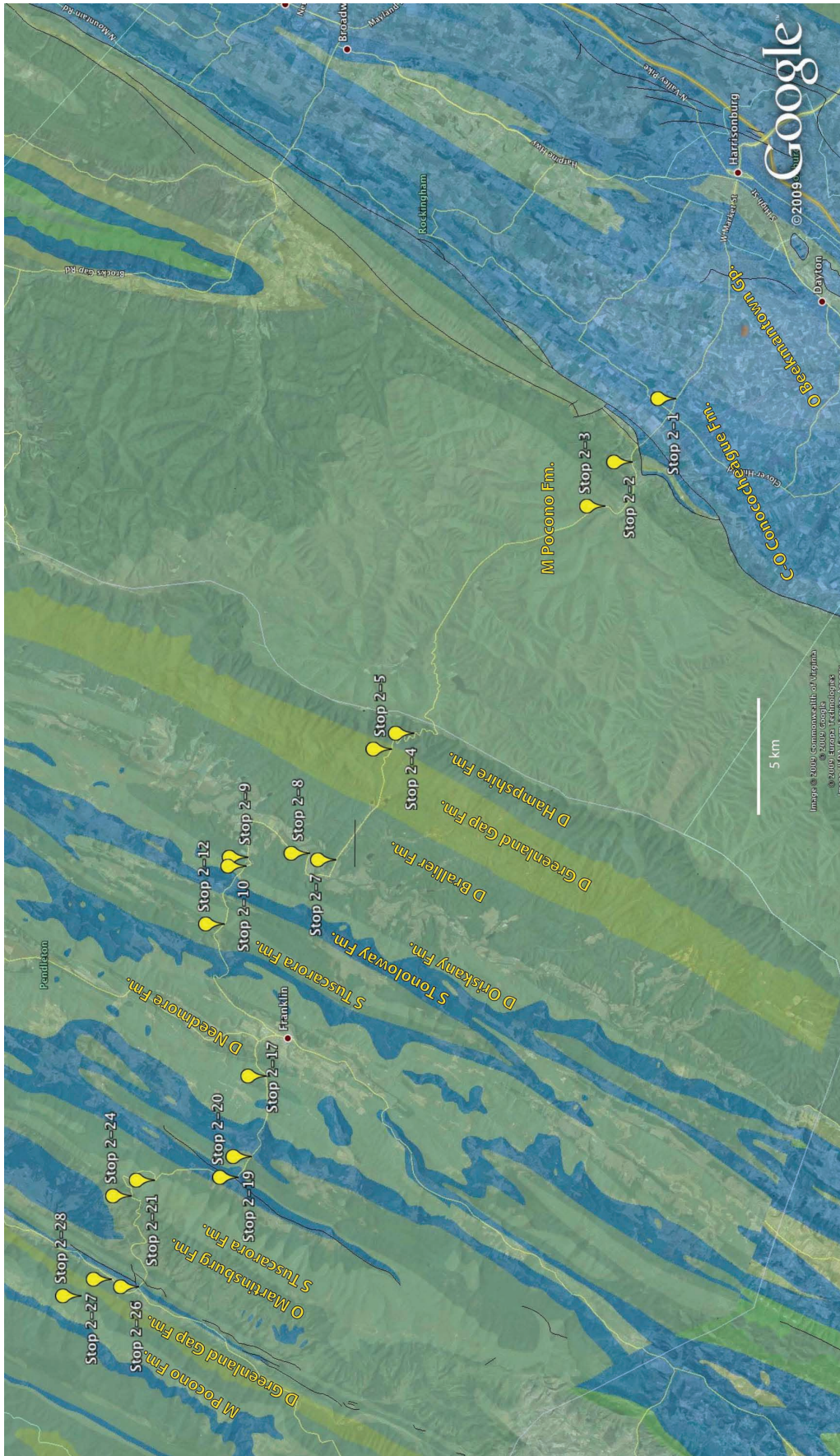


Figure 12. Simplified geologic map of a region of northwestern Virginia (after VDMR, 2003) and eastern West Virginia (after WVGES, 1998), draped over Google Earth relief map. Field trip stops for Day 2 are indicated.

each outcrop. Our intention is to duplicate this approach during this field trip, and therefore we have limited these stop descriptions to only enough basic information to get discussions initiated.

Day 2 of the field trip starts in Harrisonburg, Virginia, at the junction of High St. and Rt. 33 (N38° 27' 00", W78° 52' 22"; mile 0.0). Drive west on Rt. 33 (Rawley Springs Rd.), passing the Frazier quarry on the right (mile 0.7) in the Ordovician Edinburg Formation. Black, micritic limestones are quarried here, known locally as "bluestone." Continue driving west down section through carbonate rocks dipping shallowly east.

Pass Mole Hill in the left (mile 3.9), an Eocene basaltic volcanic plug that exhibits pyroxene ± olivine phenocrysts and occasional quartz sandstone(?) xenoliths.

**Stop 2-1 (Optional). Small Outcrop along the North Side of Route 33 (Conococheague Formation)**

*Mile 7.0 (N38° 28' 37", W78° 59' 24")*

Small limestone outcrop of Cambrian–Ordovician Conococheague Formation. This is the hanging wall of the North Mountain thrust; footwall rocks can be seen in the ridges just west of here.

Pass very small limestone outcrop of Conococheague Formation along the south side of Rt. 33 at mile 7.7.

**Stop 2-2. Small Abandoned Quarry on the North Side of Route 33 (Greenland Gap Formation)**

*Mile 9.3 (N38° 29' 45", W79° 01' 26")*

You have just crossed over the west-directed North Mountain thrust and are now at an old quarry in the Devonian Greenland Gap Formation (hummocky sequences). This is the proximal footwall to the thrust, and the footwall syncline drag fold can be seen at the eastern end of the quarry. Beds are steeply overturned along the eastern wall of the quarry and transition to subhorizontal at the western end.

**Stop 2-3 (Optional). Cliffs on the North Side of Route 33 (Pocono Formation)**

*Mile 11.4 (N38° 30' 27", W79° 02' 51")*

Cross-bedded sandstone of the Mississippian Pocono Formation, dipping shallowly to the east. The Pocono Formation is the youngest unit along this traverse.

Proceed west on Rt. 33 up the long incline that leads to the top of Shenandoah Mountain, passing many outcrops of Pocono Formation and dark-red Hampshire Formation (Devonian). Note that the incline of the road is roughly equivalent to the shallow east dip of the rocks, thus you don't cross much section through here. The crest of Shenandoah Mountain (mile 21.6; N38° 34' 44", W79° 10' 04") is Hampshire Formation and also the Virginia–West Virginia state boundary.

**Stop 2-4. Extensive Roadcut on the North Side of Route 33 (Hampshire Formation)**

*Mile 22.6 (N38° 35' 19", W79° 10' 05")*

Shallowly east-dipping siltstones, sandstones, and gravel conglomerates, featuring point bars, levees, and crevasse splays of a meandering river system. Chlorite slickenlines can be seen on some bedding planes. The next few stops progress down stratigraphically through the Devonian clastic wedge.

**Stop 2-5. Large Roadcut on the North Side of Route 33 (Contact between Greenland Gap and Hampshire Formations)**

*Mile 24.2 (N38° 35' 53", W79° 10' 35")*

Variable shales, siltstones, sandstones, and a thick quartz pebble conglomerate of the Greenland Gap Formation transition into red sands and gravels of the Hampshire Formation. This location represents the transition from a marine shelf to a muddy shoreline depositional environment. Small contraction faults can be seen at the western end of the roadcut.

**Stop 2-6 (Optional). Overgrown Roadcut on the North Side of Route 33 (Greenland Gap Formation)**

*Mile 26.8 (N38° 36' 41", W79° 13' 01")*

Open anticline of shale, siltstone, and sandstone beds of the Greenland Gap Formation, with a possible east-directed, high-angle backthrust at the eastern end of the roadcut.

**Stop 2-7. Quarried Outcrop behind the West Virginia Department of Transportation (WV DOT) Shed on the North Side of Route 33 (Brallier Formation)**

*Mile 28.0 (N38° 37' 19", W79° 14' 08")*

Abundant Bouma (turbidite) sequences are apparent in the large quarried cliff face behind the equipment shed and gravel piles. Dip is shallow to the east.

Turn right at small town of Brandywine (mile 28.6), staying on Rt. 33.

**Stop 2-8. Large Roadcuts on Both Sides of Route 33 (Millboro Formation)**

*Mile 29.9 (N38° 37' 59", W79° 13' 55")*

Park on east side of Rt. 33, just south of the roadcuts, where the road curves. Dark-gray to black shale and siltstone beds dip shallowly to the east. Abundant fauna can be seen on some bedding planes, including dwarf brachiopods, clams, and nautiloids. Occasional concretions are apparent, and convolute bedding (soft-sediment deformation) can be seen in the brown, silty beds near the base of the outcrop on the east side of Rt. 33.



**Stop 2-9. Large Roadcut on the South Side of Route 33 (Needmore Formation)***Mile 33.1 (N38° 39' 32", W79° 14' 01")*

Subhorizontal dark-gray shales and silts of the Needmore Formation with condensed sections (black) and fossiliferous horizons (gastropods, cephalopods, brachiopods, and trilobites). Laminated sands occur near the top of the outcrop.

**Stop 2-10. Long Outcrop of Cliffs on South Side of Uphill Section of Route 33 (Oriskany Formation, Helderberg Group, Tonoloway Formation)***Mile 33.5 (N38° 39' 34", W79° 14' 18")*

The base of the uphill road incline consists of cliffs of Oriskany Formation quartz arenite dipping steeply to the east; brachiopod molds are apparent on bedding planes. Progressing uphill to the northwest along the south side of the road, the beach and near-shore facies of the Oriskany Formation transition into subtidal units of the Helderberg Group. These include (moving uphill, but down section): the Licking Creek and Mandata formations (poorly exposed cherts and carbonates), New Scotland Formation (thick-bedded, fossiliferous limestone with chert bands), Coeymans Formation (bryozoan-rich calcareous siltstones), and Keyser Formation (two zones of coarse-grained calcarenite, separated by the poorly exposed Big Mountain shale). The top of the hill consists of algal-laminated micritic limestone of the Tonoloway Formation. Tonoloway beds at the top of the hill are horizontal, indicating the core of an anticline. Parasitic, west-vergent folds are also apparent just before the top of the incline. Note that the Helderberg Group is the base of the Devonian, and the Tonoloway Formation is the uppermost Silurian unit. This is the eastern flank of a first-order fold, the western flank of which is apparent at Stop 2-14.

**Stop 2-11 (Optional). Outcrop on North Side of Route 33 (Tuscarora Formation)***Mile 35.0 (N38° 40' 01", W79° 15' 41")*

Clean white sandstones of the Tuscarora Formation, dipping steeply to the east.

**Stop 2-12. Low Cliffs Just behind the Trees on the North Side of Route 33 (Tuscarora Formation)***Mile 35.5 (N38° 40' 08", W79° 16' 09")*

Clean white sandstone of the Silurian Tuscarora Formation dipping steeply to the west. You have just driven through an anticline cored by the red shale and sandstone of the Juniata Formation, which were visible in roadcuts on the north side of Rt. 33. Note the subhorizontal Tuscarora cliffs at the top of the distant hillside above you to the east.

**Stop 2-13 (Optional). Roadcuts on Both Sides of 90° Bend in Route 33 (Rose Hill Formation)***Mile 36.0 (N38° 40' 24", W79° 16' 34")*

Dangerous location along Rt. 33, but access problems can be mitigated by parking on Ravenswood Lane just west of the roadcut, and hiking above the roadcut on the south side of Rt. 33 to view the roadcut on the north side of Rt. 33. A somewhat eroded example of a complex anticlinal structure of small-scale (third-order) folds and faults.

Pass small-scale folds in the Helderberg Group carbonate rocks at mile 36.9.

**Stop 2-14 (Optional). Cliffs on the South Side of Route 33 (Contact between Oriskany and Needmore Formations)***Mile 37.7 (N38° 40' 25", W79° 17' 55")*

Sandstone beds (cliff formers) of the Oriskany Formation and shales of the Needmore Formation all dip steeply to the west. This is the western flank of a first-order fold, for which the eastern flank is apparent at Stop 2-10.

**Stop 2-15 (Optional). Low Roadcuts on Both Sides of Route 33 (Needmore Formation)***Mile 38.6 (N38° 39' 57", W79° 18' 46")*

Moderately southeast-dipping shales of the Needmore Formation; last Devonian outcrop until the final Briery Gap section. Lunch in Franklin.

**Stop 2-16 (Optional). Roadcuts on Both Sides of Route 33 at Western Outskirts of Franklin, West Virginia. Subhorizontal Beds of Oriskany Formation Sandstones***Mile 40.6 (N38° 39' 11", W79° 19' 51")***Stop 2-17 (Optional). Roadcuts on North Side of Route 33 (Contact between Helderberg Group and Oriskany Formation)***Mile 41.9 (N38° 39' 07", W79° 21' 04")*

Carbonate and sandstone beds dip steeply to the west.

This section of the traverse has several small outcrops of Oriskany Formation and/or Helderberg Group, with dips that often alternate between east and west, suggesting undulating small-scale folds.

**Stop 2-18 (Optional). Quarry on North Side of Route 33 (Tonoloway Formation)***Mile 43.6 (N38° 39' 19", W79° 22' 51")*

Moderately east-dipping beds of algal-laminated micrites.



**Stop 2-19. Roadcut on North Side of Route 33 (Keefer Formation)***Mile 44.4 (N38° 39' 30", W79° 23' 38")*

Park at small pullout on south side of Rt. 33. The roadcut shows an outcrop-scale faulted fold in sandstone beds of the Silurian Keefer Formation. The faulted fold is a breakthrough, with a well-defined hanging-wall anticline and footwall syncline. This is a good example of the smallest scale (third-order) deformation structure that we will see during the Day 2 traverse.

Pass an outcrop of east-dipping Tuscarora Formation sandstone at mile 44.8.

**Stop 2-20. Roadcut on North Side of Route 33 (Juniata Formation)***Mile 45.1 (N38° 39' 50", W79° 24' 17")*

Parking is problematic; best to park around the bend in the road (west of the outcrop) and then walk back to the roadcut. Juniata Formation red shale and sandstone beds show a well-defined anticline, interpreted as a ramp anticline over a cryptic west-directed thrust. The fault trace is probably located at the northward bend in Rt. 33, just west of the roadcut. This is an example of intermediate scale (second-order) deformation structures along the Day 2 traverse.

**Stop 2-21. Roadcuts on East Slope of North Fork Mountain (Contact between Juniata and Tuscarora Formations)***Mile 47.8 (N38° 41' 54", W79° 24' 18")*

Juniata red beds (south end of outcrop) transition into clean quartz arenite of the Tuscarora Formation. This contact is considered the Ordovician–Silurian boundary. Vertical *Skolithos* burrows occur near the base of the Tuscarora Formation, followed by massive cross-beds, followed by more *Skolithos* burrows. An interval of thin sandstone and dark-gray shale beds contain *Arthropycus* (bedding plane trails). Dip is moderately to the east.

Follow Rt. 33 west over the crest of the North Fork Mountain ridge (Tuscarora Formation).

**Stop 2-22 (Optional). Roadcuts on East Side of Route 33 (Juniata Formation)***Mile 49.3 (N38° 42' 32", W79° 24' 29")*

Juniata Formation red beds of alternating shale and sandstone dip shallowly to the east. The beds are cyclical, with cross-bedded, fine-grained sublitharenite at the base, followed by sublithic wacke with vertical burrows, and culminating with a bioturbated mudstone. These are interpreted as fining-upward tidal parasequences.

**Stop 2-23 (Optional). Roadcut on South Side of Route 33 (Contact between Reedsville Formation and Oswego Formation)***Mile 49.5 (N38° 42' 29", W79° 24' 39")*

This outcrop shows the gradational transition between the upper Reedsville Formation, a bioturbated, fossiliferous mudstone, and the Oswego sandstone. The Oswego is an immature sandstone (sublitharenite) that represents the culmination of a marine coarsening-upward sequence that started at the base of the Reedsville.

**Stop 2-24. Germany Valley Overlook on North Side of Route 33***Mile 49.7 (N38° 42' 29", W79° 24' 47")*

The view to the north shows a several kilometer-scale breached anticline (Wills Mountain anticlinorium), with Germany Valley visible below. Ridges to the east and west are Silurian Tuscarora Formation, and the valley is composed of Ordovician carbonates. Closure of the anticline is visible along the horizon to the north where the ridges connect. This is representative of the largest scale (first-order) deformation structures that we see during the Day 2 traverse. At this locality we can see the whole structure from one overlook.

**Roadcuts on South Side of Route 33 (Middle Reedsville Formation)**

Shale and calcareous siltstone that represent mid-shelf deposition; includes thin beds of bioclastic calcarenite.

**Stop 2-25 (Optional). Roadcut on South Side of Route 33 (Trenton Formation)***Mile 50.4 (N38° 42' 22", W79° 25' 21")*

Subhorizontal, thin hummocky sequences (distal shelf) with zones of fossil hash.

**Stop 2-26. Judy Gap (Tuscarora and Juniata Formations)***Mile 53.6 (N38° 42' 22", W79° 27' 50")*

Parallel bands of vertical cliffs on both sides of Rt. 33 consist of clean Tuscarora sandstone and red beds of the Juniata Formation, apparently duplicated. Contraction fault visible in streambed on the north side of Rt. 33. Vertical beds of the Tonoloway Formation are found to the west in a quarry on the south side of Rt. 33.

Turn right at intersection to follow Rt. 33 to the north.

**Stop 2-27. Junction of Route 33 and Briery Gap Road (Oriskany Formation)***Mile 54.7 (N38° 43' 03", W79° 27' 35")*

Vertical to slightly overturned (east-dipping) beds of Oriskany Formation sandstone; brachiopod molds apparent on bedding planes.

Turn left (west) onto Briery Gap road (leave Rt. 33).

### Stop 2-28. Partway up Hill on Briery Gap Road (Greenland Gap and Hampshire Formations)

*Mile 55.7 (N38° 43' 48", W79° 28' 04")*

Park at pullout on north side of road. Just east of the pullout (downhill) is the contact between the Greenland Gap Formation and Hampshire Formation (mid-shelf parasequences). Note that the beds gradually dip more shallowly to the west as you drive uphill.

### Stop 2-29 (Optional). Just below T Intersection at the Top of Briery Gap Road (Pocono Formation)

*Mile 56.3 (N38° 44' 01", W79° 28' 37")*

Shallowly west-dipping, cross-bedded quartz conglomerate sandstone. This is essentially the Allegheny Front: the western boundary of the Valley and Ridge province and the western limit of visible Alleghanian deformation.

End of field trip! Turn around, and head back to Baltimore.

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