Active features along a “passive” margin: The intriguing interplay between Silurian–Devonian stratigraphy, Alleghanian deformation, and Eocene magmatism of Highland and Bath Counties, Virginia

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ABSTRACT

This two-day trip highlights new findings from structural, stratigraphic, and petrologic research in the Valley and Ridge province of Highland, Bath, and Augusta Counties, Virginia, and Pendleton County, West Virginia. The structural emphasis on Days 1 and 2 will be at several scales, from the regional scale of folds and faults across the Valley and Ridge, to outcrop- and hand sample-scale structures. Stops will highlight deformation associated with previously unmapped faults and a second-order anticline in Silurian and Lower Devonian carbonate and siliciclastic strata, specifically the Silurian Tonoloway Limestone, the Silurian–Devonian Helderberg Group, and the Devonian Needmore Shale. The stops on Day 1 will also focus on facies changes in Silurian sandstones, the stratigraphy of the Keyser–Tonoloway formational contact, and new discoveries relevant to the depositional setting and regional facies of the McKenzie Formation in southern Highland County. The focus of the stops on Day 2 will be on the petrology and geochemistry of several exposures of the youngest known volcanic rocks (Eocene) in the eastern United States. Discussions will include the possible structural controls on emplacement of these igneous rocks, how these magmas and their xenoliths constrain the depth and temperature of the lower crust and mantle, and the tectonic environment that facilitated their emplacement.

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INTRODUCTION

Recent and ongoing bedrock mapping in western Virginia and eastern West Virginia has clarified several stratigraphic and structural relationships in the Ordovician, Silurian, and Devonian sequence. This work has added to our understanding of stratigraphic and sedimentologic relationships, and to our knowledge of local structures formed during late Paleozoic Alleghanian orogenesis. In addition, recent and ongoing petrologic and geochemical analyses have furthered our understanding of igneous activity that occurred during the Eocene in this region. Collectively, these research efforts have led us to contemplate some new ideas about the geologic history of this region while simultaneously revisiting and refining old ideas and models. The purpose of this field trip and the selected stops along its route (Fig. 1) is to showcase new findings and interpretations, as well as to raise questions for lively discussion.

OVERVIEW

Sedimentary strata in the Appalachian orogen have a long and interesting history. They have been deposited, buried, lithified, deformed, eroded, buried again, intruded, uplifted, and eroded again. This field trip will look at the effects of some of those processes in what we infer to be their chronological order, beginning with an overview of the sedimentology and stratigraphy, followed by igneous petrology and geochemistry, and concluding with deformation and structural relationships.

Principal Stratigraphic Findings

The three major stratigraphic findings and/or reinterpretations and their various components that will be highlighted on Day 1, as we examine several exposures of Lower Paleozoic strata are as follows:

(1) Facies changes and detailed lateral relationships in the Silurian and Lower Devonian sandstones of this region are now better understood as a result of our work.

(2) Quartz sandstones and quartzose oolitic grainstones that occur in the McKenzie Formation of this area are identified as the easternmost exposures known thus far of the unnamed middle sandstone member of the McKenzie Formation and of the oolitic facies that comprise the upper beds of the Lockport Member of the McKenzie Formation in the subsurface to the west.

(3) The complicated and unconformable nature of the stratigraphic contact between the Tonoloway Limestone and the overlying Keyser Limestone in this area is now better understood.

Principal Igneous Petrology and Geochemistry Findings

At least 150 dikes, plugs, sills, and diatremes are exposed in the Valley and Ridge province of Virginia and West Virginia in Rockingham, Augusta, Highland, and Pendleton Counties. These igneous rocks have been observed and studied by field geologists for more than 100 years (Darton, 1899; Garnar, 1956; Kapnicky, 1956; Kettren, 1970; Johnson et al., 1971; Rader et al., 1986; Southworth et al., 1993; Tso et al., 2004; Tso and Surber, 2006), but it was not until the 1960s that the first paleomagnetic data implied these igneous rocks were Eocene in age (Fullagar and Bottino, 1969). On Day 2 we will examine several exposures of these igneous rocks, and we will discuss textures and compositions of mafic, intermediate, and felsic rocks, and recent geochemical data:

(1) The petrology and mineralogy of the mafic, intermediate, and felsic rocks have been determined in appreciably more detail from our recent studies.

(2) Geothermobarometers have been used to determine temperature and depth from mantle xenocrysts and lower crustal xenoliths.

Principal Structural Findings

In addition to discussion throughout the field trip of local and regional structures of interest, the major structural findings and/or reinterpretations that will be highlighted on this field trip include:

(1) Detailed geologic mapping and structural analyses along Virginia State Highway 42, 9.5 km south of Millboro Springs in southeastern Bath County have confirmed an ~6-km-long, northeast-trending hill as the surface expression of a ramp anticline that overlies a cryptic fault. The doubly plunging “breadloaf”-shaped fold is interpreted as a fault bend fold in the proximal hanging wall of a shallowly southeast-dipping, northwest-directed thrust fault.

(2) Deformation features in the hinge region of the “breadloaf” anticline change along trend. Wedge faults with complex, small-scale folds are apparent in the southwest-plunging hinge region of the anticline (Stop 3), but are less prominent to the northeast (Stop 4).

(3) Igneous dikes and plugs align with regional structural fabrics, suggesting that magma exploited faults and fractures to ascend through the crust.

SUMMARY OF STRATIGRAPHIC UNITS OF INTEREST

Figures 2 and 3 show the various Ordovician, Silurian, and Devonian stratigraphic units and stratigraphic relationships that are of interest at the stops on this trip. These units are summarized below.

Ordovician Carbonate Sequence Undivided

(Beekmantown Formation undivided, Lurich Formation of Kay [1956], Blackford Formation of Butts [1940], Elway...
Limestone of Cooper [1945], Five Oaks Limestone of Cooper and Prouty [1943], New Market Limestone of Cooper and Cooper [1946], Lincolnshire Limestone of Cooper and Prouty [1943], Big Valley Formation of Bick [1962], Benbolt Limestone of Cooper and Prouty [1943], McGlone Limestone of Kay [1956], McGraw Limestone of Kay [1956], and Nealmont Limestone of Kay [1944]).

The oldest exposed strata of interest in the field trip area are a thick sequence of Ordovician carbonate rocks. These underlie the Shenandoah Valley, and they also crop out along the axes of the several anticlinal valleys of the Valley and Ridge (Kay, 1956) including the Warm Springs, Bolar (Big), and Hightown Valleys (Fig. 1). These are of interest because of several thermal springs emanating from these carbonates in the Warm Springs

Figure 1. Generalized geology of the field trip area showing stop locations and several major folds and faults (modified from Diecchio, 1986). Inset map (upper left) shows the location of the field trip area relative to Blacksburg.
and Bolar Valleys (alternate Stop 4B) and because of the igneous intrusions in some of these carbonates in the Hightown Valley (Stops 8 and 9) and the Bolar Valley (Darton, 1899; Rader and Wilkes, 2001; Haynes and Diecchio, 2013).

The lengthy and exceedingly complex history of nomenclature that has been variously applied to these carbonate strata is hinted at by the various authors included in the above list of formation names. Each of these authors made an effort to subdivide this carbonate sequence, usually on the basis of fossil content. That approach to the naming of stratigraphic units is now forbidden by the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983, 2005), so there is a real need in this region to identify workable lithostratigraphic, rather than biostratigraphic, differences that can be used to distinguish one unit from another in the field.

Based on our most recent mapping efforts in the field trip area (Haynes and Diecchio, 2013), we recognize at the present time that the Nealmont Limestone with its interbedded bluish gray slabs of bioclastic wackestone and packstone contrasts sufficiently with the overlying Dolly Ridge Formation to make a useful and recognizable contact in the field. The marked unconformity and associated overlying chert-rich breccias that elsewhere in this region are so prominent at the base of the Blackford Formation or New Market Limestone (Mussman and Read, 1986), which can be used as an unambiguous contact to separate the underlying Beekmantown or Knox Group dolomitic carbonate rocks from the overlying units that are predominantly limestones, can likewise be a recognizable contact in many areas. In the Hightown Valley, Germany Valley, and the north end of the Big Valley, however, we have not yet identified that unconformity with any certainty. Although Wilkes (2011) mapped the Beekmantown separately from the overlying limestones, he noted nonetheless (p. 3) that “Contact of the Beekmantown with the overlying middle Ordovician limestone unit was not observed but is assumed to be unconformable…” Therefore, pending additional fieldwork in the region that is needed to delineate this stratigraphic contact more conclusively, we have included the upper beds of Beekmantown with the overlying units as an undivided sequence of Ordovician carbonate strata in central and northern Highland County (Haynes and Diecchio, 2013).

**Ordovician Dolly Ridge Formation (80–130 m thick)**

The type section of the Dolly Ridge Formation is at Dolly Ridge in Germany Valley, the northern extension of the Hightown Valley in Pendleton County, West Virginia (Perry, 1972). These strata were initially mapped by Darton (1899) as part of the Shenandoah Limestone. Kay (1956) designated a new member (the Onego Member) of the Salona Formation for part of this stratigraphic interval, and Bick (1962) assigned these strata to the Edinburg Formation. Perry (1971, 1972) noted that in Pendleton County, these strata do not resemble the Salona...
Formation or Edinburg Formation at their respective type sections, and he concluded that a new name was warranted. Subsequent publications have used the name Dolly Ridge Formation (Rader and Wilkes, 2001; Haynes and Diecchio, 2013).

Much of the Dolly Ridge Formation consists of thin beds of dark gray to black lime mudstones, many of which weather white, and interbedded dark greenish-gray shales, some of which are K-bentonite beds (altered tephras). The lower 30–40 m has several cobbly weathering zones that produce small nodules of white weathering, black lime mudstones that are common to abundant on some hillslopes underlain by this interval.

**Ordovician Reedsville Shale (300–400 m thick)**

The type section of the Reedsville Shale is at Reedsville in Mifflin County, Pennsylvania (Ulrich, 1911). Darton (1899), Kay (1956), and Bick (1962) mapped these strata in Bath and Highland Counties as the Martinsburg Shale or the Martinsburg Formation. Because the Martinsburg Shale of the Shenandoah Valley area is a thick sequence of siliciclastic turbidites with only a few tens of meters of carbonate strata at its base, all deposited in open basin to basin margin settings (McBride, 1962), whereas the strata of equivalent age west of the North Mountain front are mixed carbonate and siliciclastic sediments deposited in a storm-dominated shelf setting (Kreisa, 1981), Diecchio (1991) recommended that the name Reedsville Shale be used for these strata on the west side of the North Mountain front (marked by the North Mountain fault system along the west side of the Shenandoah Valley) and that the name Martinsburg Formation should be restricted in its usage to equivalent strata in exposures east of the North Mountain front. Reedsville Shale has been used to refer to these strata throughout most of the field trip area (Rader and Wilkes, 2001; Haynes and Whitmeyer, 2010; Wilkes, 2011; Haynes and Diecchio, 2013). It is the oldest formation shown in the regional cross section (Fig. 3), which includes specific stratigraphic information for the field trip stops at Eagle Rock (Stop 1), the Bullpasture River (Stop 5), and Bluegrass and Forks of Waters (Stop 6).

Thin greenish-gray to gray mudrock with thin interbeds of fine-grained sandstones, siltstones, and bioclastic limestones comprise this interval. A prominent brachiopod-rich horizon known regionally as the Orthorhynchula zone occurs in the upper 3–4 m of the Reedsville, and is a useful marker bed for identifying the contact between the Reedsville Shale and the overlying Oswego Sandstone or Juniata Formation.

**Ordovician Oswego Sandstone (8–25 m thick)**

The Oswego Sandstone was named by Prosser (1888) for outcrops in Oswego County, New York, although a specific type section was not specified. These strata were mapped by Darton (1899) as part of the Juniata Formation. Butts (1940) identified a thin outcrop of the Oswego Sandstone in northwestern Highland County, but Bick (1962) did not recognize the Oswego. Subsequently the Oswego has been recognized at several exposures in this region (Rader, 1984; Diecchio, 1985; Wilkes, 2011; Haynes and Diecchio, 2013).

Greenish-gray to brown beds of fine- to medium- to coarse-grained sublithic arenites up to 1 m thick, and cross-beded in places, characterize the Oswego Sandstone. A common and distinctive character of these sandstones on a fresh surface is the presence of limonite as small yellowish-orange specks. Thin interbeds of green mudrock are also generally present.

**Ordovician Juniata Formation (100–250 m thick)**

The Juniata Formation was named by Darton and Taff (1896), and a type section was designated by Clark (1897). Darton (1899) mapped the Juniata Formation in this region, and this stratigraphic name has been in essentially continuous use in this region ever since (Butts, 1940; Bick, 1962; Dennison, 1976; Diecchio, 1985; Rader and Wilkes, 2001; Wilkes, 2011; Haynes and Diecchio, 2013).

Interbedded yellowish-brown to reddish-brown sublithic arenites up to 1 m thick, some with cross-bedding, and olive-gray and red mudrocks are the major lithologies in the Juniata Formation. *Skolithos* (trace fossils of vertical burrows) occurs in some of the sandstone beds. In many sections, the top of the Juniata is characterized by several pink quartz to sublithic arenite beds up to ~1.5 m thick that are transitional with the overlying quartz arenites of the Tuscarora Formation.

**Silurian Tuscarora Formation (15–25 m thick)**

The type section of the Tuscarora Formation is at Tuscarora Mountain in Pennsylvania. It was named by Darton and Taff (1896), and soon thereafter Darton (1899) mapped these strata in Bath and Highland Counties as the Tuscarora Quartzite. Woodward (1941) referred to these strata regionally as the Tuscarora Sandstone, whereas Bick (1962) mapped them as the Clinch Sandstone. Subsequent publications have generally referred to these strata as the Tuscarora Formation (e.g., Bick, 1973; Rader and Wilkes, 2001).

Thick to massively bedded white to grayish-white to pale-yellow to pale-pink silica-cemented supermature quartz arenites, some with prominent cross beds, are the principal lithology of the Tuscarora. Because of its extreme durability, ledges of Tuscarora Sandstone are the dominant ridge-forming stratigraphic unit of the central Appalachians. Thin beds of quartz-pebble conglomerate occur in the lower half of the formation at many exposures, and at a few locations, notably along the west limb of the Wills Mountain anticline, a thin black shale is present in the middle of the unit. Trace fossils including *Skolithos* and *Arthrophytes* (single to compound elongate burrows) can be found in some beds and on some bedding planes.
Figure 3. Facies changes in Upper Ordovician and Silurian strata between selected exposures in and near the field trip area, including Eagle Rock (Stop 1), the Bullpasture River Gorge (Stop 5), and Bluegrass and Forks of Waters (Stop 6). The lateral and vertical facies changes in the stratigraphic interval above the Tuscarora (TUSC) and below the Tonoloway will be a major part of the discussions at our stops on Day 1.
Silurian Rose Hill Formation (80–250 m thick)

The type section of the Rose Hill Formation is at Rose Hill in the city of Cumberland, Allegany County, Maryland (Swartz, 1923). The earlier name for this stratigraphic unit was the Cacapon Sandstone (Darton and Taff, 1896), and in Bath and Highland Counties that name was used by Darton (1899). Woodward (1941) noted that strata previously mapped as the Cacapon Sandstone in western Virginia should be mapped as the Rose Hill Formation, and although Bick (1962) mapped these strata as the Cacapon Member of the Clinton Formation, subsequent publications (e.g., Rader, 1984; Rader and Wilkes, 2001) have nearly uniformly referred to this interval as the Rose Hill Formation. The name Cacapon sandstone is still widely used in this region, however, in reference to the distinctive dark-maroon to purplish hematitic sandstones, some of which are ripple marked. These are the most recognizable lithology in the Rose Hill Formation and invariably are a major, and commonly the major, component of colluvial and alluvial deposits that blanket the dip slopes of ridges in this region that are underlain by the Tuscarora Formation.

In addition to the distinctive dark-maroon to purplish hematitic sandstones, there are thin-bedded olive to gray mudrocks interbedded with reddish shales and siltstones in the Rose Hill, some of which are sparsely to moderately fossiliferous with ostracodes, brachiopods, and trilobites.

The character of the Rose Hill Formation along the field trip route is relatively consistent, as we will see at Eagle Rock (Stop 1), the Bullpasture River (Stop 5), and Bluegrass (Stop 6).

Silurian “Eagle Rock sandstone” (125 m thick)

The “Eagle Rock sandstone” was named by Lampiris (1975), and the not yet formalized type section is the series of cuts at Eagle Rock in Botetourt County (Stop 1, Fig. 4) where the James River has cut a steep-walled gorge that bisects a prominent ridge into two separate ridges, Rathole Mountain and Crawford Mountain. The thickness of the Silurian sandstones at Eagle Rock is in marked contrast to the exposure at Fagg farther southeast (Fig. 3), where the entire Silurian is only a 1–3-m-thick bed of pebbly Tuscarora Sandstone that unconformably overlies bioclastic beds of the Martinsburg Formation and is unconformably overlain by the Rocky Gap Sandstone (Diecchio, 1985). The “Eagle Rock sandstone” is the modern name of this thick unit, which collectively includes the stratigraphic equivalents of the Keefer, McKenzie, Williamsport, and Wills Creek Formations that are separable into discrete stratigraphic units at sections farther northwest (Figs. 2, 3), as we will see in exposures at Crizer Gap (Stop 4), the gorge of the Bullpasture River (Stop 5), and in the vicinity of Bluegrass and Forks of Waters (Stop 6).

Silurian Keefer Formation (<1–8 m thick)

The type section of the Keefer Formation is at Keefer Mountain, a few kilometers northeast of Hancock in Washington County, Maryland (Stose and Swartz, 1912). In Bath and Highland Counties, this stratigraphic interval was mapped by Darton (1899) as part of the Rockwood Formation.

There is appreciable nomenclatural complexity to this stratigraphic interval, which in its restricted stratigraphic sense refers to a white to grayish-white to pale-pink to red silica-cemented quartz arenite, known informally in the region as the “true” Keefer. In the Clifton Forge area southward, the name “Keefer” has been used to refer to what is more appropriately referred to as “Eagle Rock sandstone.” Woodward (1941) referred to these strata regionally as the Keefer Sandstone; Bick (1962) mapped these strata as the Keefer Member of the Clinton Formation; Perry (1971) mapped these strata in Germany Valley, Pendleton County, West Virginia, as the Mifflintown Formation and included the McKenzie Formation and the Williamsport Sandstone. Helfrich (1975, 1980) mapped these strata at the Bluegrass section in northern Highland County (Stop 6) as the lower hematitic member of the Mifflintown Formation and the overlying Cosner Gap Member of the Mifflintown Formation, and stated that the Cosner Gap Member is a limey equivalent of the Keefer Sandstone. The Pennsylvania formation name “Mifflintown” has not subsequently been used in this region, and Rader and Wilkes (2001) mapped these strata as the Keefer Formation.

Figure 4. Sketch of the exposure at Eagle Rock (Stop 1) that shows formational boundaries, and how thick the Silurian “Eagle Rock sandstone” is at this location relative to the other stratigraphic units present. View is to the southwest. Omb—Martinsburg Formation; Os—Oswe-ego Sandstone; Stu—Tuscarora Formation; Srh—Rose Hill Formation; Ser—Eagle Rock sandstone. Not shown is the Tonoloway Limestone at the northwest end of the exposure (modified from figure 4 of Rader and Gathright, 1986).
Haynes and Whitmeyer (2010) and Hazelwood et al. (2012) found that in southern Highland and northern Bath Counties (Stop 5) the Keefer is a mappable unit, but in west-central and northwestern Highland County, Wilkes (2011) and Haynes and Diecchio (2013) found that the Keefer is too thin to map as a separate unit, and so it was included with the underlying Rose Hill Formation. In a petrographic investigation of the exposure at Bluegrass (Stop 6), Haynes et al. (2011) noted that little or no quartz arenite is present, and instead there is appreciable ferroan dolomite as well as ooids that are composed of hematite and berthierite and/or chamosite.

The character of the Keefer changes significantly along the route of this field trip (Figs. 2, 3), from a massive, thick, and erosionally resistant quartz arenite that comprises the lower part of the “Eagle Rock sandstone” (Stop 1) to a thinner but still resistant ledge of quartz arenite (Stop 5) to thin ferruginous dolomites and mudrocks (Stop 6).

**Silurian McKenzie Formation (60–80 m thick)**

The type section of the McKenzie Formation is at McKenzie Station on the Baltimore and Ohio Railroad in Allegany County, Maryland (Stose and Swartz, 1912). The unit was first mapped in Bath and Highland Counties as the lower part of the Lewistown Limestone (Darton, 1899). Woodward (1941) referred to this stratigraphic interval as the McKenzie Formation. Bick (1962) mapped these strata in Bath and Highland Counties as the “McKensie [sic] Limestone” of the Cayuga Group, but the name “Cayuga Group” has since been abandoned as a lithostratigraphic term (http://ngmdb.usgs.gov/Geol-ex/NewRefsmy/sumry_937.html). Perry (1971) and Helfrich (1975, 1980) mapped these strata in Highland and Pendleton Counties as the McKenzie Member of the Mifflintown Formation, but as noted above that name has not subsequently been widely used, and these strata have since been mapped in this area as the McKenzie Formation (Diecchio and Dennison, 1996; Rader and Wilkes, 2001; Haynes and Whitmeyer, 2010; Haynes and Diecchio, 2013).

Where the McKenzie is recognized as a distinct stratigraphic unit in the field trip area (Stops 2–6) it is a heterogeneous sequence of thinly bedded and laminated dark-gray lime mudstones (Stop 4), oolitic and bioclastic (primarily ostracode) grainstones, tan to green to blue-gray to gray to black shales, and the aforementioned thick to massively bedded medium-to-coarse-grained, silica-cemented, yellowish-white quartz arenite beds that collectively comprise the middle sandstone member and are ~5 m thick in the Bullpasture River Gorge (Stop 5), and almost 10 m thick along Muddy Run to the southwest (Whitehurst, 1982).

**Silurian Williamsport Sandstone (9–10 m thick)**

The type section of the Williamsport Sandstone is on a branch of Patterson Creek, 1 km east of Williamsport in Grant County, West Virginia (Reger, 1924). Darton (1899) mapped this sandstone as part of the Lewistown Limestone. Butts (1940) included it as part of the Wills Creek Formation, which he defined as all of the strata between the McKenzie Limestone below and the Tonoloway Limestone above. Woodward (1941) first identified this sandstone as a separate formation in this region, which he mapped as the Williamsport Sandstone. Although Bick (1962) mapped this sandstone as part of the Wills Creek Formation, subsequent publications have mapped these strata in Highland County as the Williamsport Sandstone (Helfrich, 1975; Diecchio and Dennison, 1996; Wilkes, 2011), and our mapping efforts have also shown that the Williamsport is a persistent and useful marker bed in this area (Haynes and Whitmeyer, 2010; Hazelwood et al., 2012; Haynes and Diecchio, 2013).

The Williamsport Sandstone is a tough, erosion-resistant, silica-cemented quartz arenite that weathers variously white to tan to orange-brown to brown. Like the quartz arenites of the Tuscarora, the “Eagle Rock,” and the Keefer, the Williamsport is generally very resistant and it makes prominent flatirons on many of the dip slopes in this region, but because it is typically medium bedded it commonly (but not always) breaks into smaller blocks than if it were more massively bedded, as the Tuscarora tends to be. It is common to find some bedding planes with prominent ripple marks (Stop 5), a sedimentary structure that seems to be far less common in the otherwise petrologically similar quartz arenites of the Tuscarora, Keefer, and McKenzie Formations. In some intervals, isolated ostracodes to ostracode coquinas are present. On more weathered exposures, the ostracodes are now just shell moldic pores that are commonly lined by orange limonite, but ostracode shells in unweathered samples are commonly extensively pyritized, and it is the oxidation of this pyrite that contributes to the yellowish-brown limonite staining and patina that is common on the surface of ledges and blocks of the Williamsport throughout this region.

The Keefer of Lesure (1957, his Table 8, p. 39) includes 52 ft (15.8 m) of “resistant…light-brown to grayish-orange” sandstone as its uppermost bed, a description that is consistent with typical Williamsport Sandstone of this region, further suggesting that the expanded Keefer, i.e., “Keefer” of previous reports includes the Williamsport.

**Silurian Wills Creek Formation (<1–70 m thick)**

The type section of the Wills Creek Formation is at Wills Creek in Cumberland, Allegany County, Maryland (Uhler, 1905). In this region, Darton (1899) included these strata as part of the Lewistown Limestone, and Butts (1940) mapped them as the Wills Creek Formation, which he defined as all of the strata between the McKenzie Limestone below and the Tonoloway Limestone above (thus his definition would include the Williamsport Sandstone). Woodward (1941) assigned these strata to the Wills Creek Limestone, and then Bick (1962) mapped them as the Wills Creek Formation, the name that has been used in this region by most authors since
Brown to green mudrocks are the principal Wills Creek lithology, with interbedded sandstone, sandy limestone, and lime mudstone present in the Wills Creek as well. Ripple structures, algal laminations, desiccation cracks, rip-up clasts, and molds of evaporite crystals are present in some of these beds. Fossils are not abundant, but include leperditian ostracodes, stromatolites, and brachiopods.

The thickness of the Wills Creek Formation changes significantly from south to north in the field trip area (Fig. 2), from < 2 m thick in the Bullpasture River Gorge (Stop 5) to ~70 m thick at the Bluegrass and Forks of Waters exposures (Stop 6).

### Silurian Tonoloway Limestone (50–180 m thick)

The type section of the Tonoloway Limestone is at Tonoloway Ridge in Washington County, Maryland (Ulrich, 1911). This thick sequence of predominantly thin-bedded limestones was mapped by Darton (1899) as part of the Lewistown Limestone. Swartz (1930) mapped these strata as the Tonoloway Limestone of the Cayuga Group, whereas Butts (1940) and Woodward (1941) referred to these carbonates as the Tonoloway Limestone, the name that is used for this interval of strata in this region today (Bick, 1962; Perry, 1971; Helfrich, 1975; Diecchio and Dennison, 1996; Bell and Smosna, 1999; Wilkes, 2011; Haynes and Diecchio, 2013).

In this region, the Tonoloway Limestone consists of three unnamed members (Woodward, 1941; Perry, 1971; Bell and Smosna, 1999) that are laterally persistent across Pendleton, Highland, and northern Bath Counties:

1. The lower member is up to 60 m thick and it consists primarily of thin-bedded and laminated gray to black lime mudstones, commonly peloidal and usually cut by many prominent orthogonal fractures; in some of these limestones, there are zones in which prominent pink to red to reddish-brown argillaceous and dolomitic partings are present. This member also contains two to three calcite- and quartz-cemented calcarenitic quartz arenites in the area around the gorge of the Bullpasture River (Stop 5) that are up to 3 m thick and have recently been found to have been mistaken for tongues of the Clifton Forge Sandstone in this area for decades (White and Hess, 1982; Swezey et al., 2013). There are also a few thin beds of ostracode and gastropod packstones and grainstones, and thin oolitic grainstones in this member.

2. The middle member is up to 20 m thick and it consists of thick to massively bedded bioclastic grainstones in which abundant crinoid fragments and lesser sponge, brachiopod, coral, and bryozoan debris are most common, along with sparse boundstones and coral-stromatoporoid framstones.

3. The upper member is up to 100 m thick and it consists of thin-bedded and laminated gray lime mudstones that have some to abundant and prominent orthogonal fractures that cut individual beds; many of these lime mudstones are also peloidal, and mud cracked and algal laminated, and in a few beds thin intraclast grainstones and packstones are present. This member also contains 3–4 thin beds of calcite-cemented quartz arenites up to 4 m thick. At four exposures in this region (near Oak Flat on U.S. 33 in Pendleton County, West Virginia; at the north end of Burnsville Cove along SR 609 in Bath County; just north of the junction of Muddy Run Road and U.S. 220 in an unused quarry on the east side of U.S. 220 in Bath County; and in the bed of the stream in Crizer Gap [Stop 4] south of Millboro Springs in Bath County), there is a vuggy bed, brecciated in places, and with rare “gypsum daisies” that are now pseudomorphed by calcite. This bed, which is likely laterally persistent from this region westward, was originally an evaporite horizon of mostly gypsum or anhydrite that has now been modified by diagenetic processes and largely replaced by calcite, but with some of the original evaporite textures still present, which are an eastward extension of the widespread evaporites of the Salina facies in the subsurface of the Appalachian basin farther west (Dennison and Head, 1975; Smosna et al., 1977). The contact with the overlying Keyser Limestone is sharp, and in places consists of an intraclastic grainstone and packstone (“flat-pebble conglomerate”) that varies in thickness from 0 to 1.4 m over short distances (Stop 5).

### Silurian–Devonian Keyser Limestone of the Helderberg Group (15–70 m thick)

The type section of the Keyser Limestone is at a quarry near the town of Keyser in Mineral County, West Virginia (Ulrich, 1911). Darton (1899) included these strata as part of the Lewistown Limestone, Swartz (1930) assigned them to the Keyser Limestone of the Helderberg Group, Woodward (1943) identified them as the Keyser Limestone of the Helderberg Group, and Bick (1962) mapped this unit as the Keyser Limestone and considered it to be a separate formation below the Helderberg Group. Most subsequent publications have mapped these strata in Bath and Highland Counties as the Keyser Limestone of the Helderberg Group (Dorobek and Read, 1986). In this area, five named members have been identified, and their stratigraphic relations are complicated because of regional facies changes and pinchouts.

### Byers Island Limestone Member of the Keyser Limestone of the Helderberg Group (0–20 m thick)

The type section of the Byers Island Limestone Member of the Keyser Limestone is a series of outcrops along the Susquehanna River northeast of Selinsgrove in Snyder County, Pennsylvania (Head, 1972). In the field trip area it includes gray to pink bioclastic wackestones to grainstones and bryozoan and stromatoporoid boundstones, and argillaceous limestone; crinoid debris is abundant. We will see the Byers Island at Coronation (Stop 3), where it is a massive grainstone to boundstone between the Tonoloway Limestone below and the Clifton Forge Sandstone above. The Byers Island is discontinuous over relatively short
distances, as we will see from Coronation (Stop 3) to Crizer Gap (Stop 4), a distance of just under 3.5 km.

**Clifton Forge Sandstone Member of the Keyser Limestone of the Helderberg Group (0–25 m thick)**

The type section of the Clifton Forge Sandstone Member is at Clifton Forge in Alleghany County, Virginia (Swartz, 1930). North of the type section, the Clifton Forge Sandstone Member splits into two sandy beds (Woodward, 1943). The lower of these sandy beds merges in south-central Highland County with the Big Mountain Shale Member of the Keyser Limestone, whereas the upper of these sandy beds extends north into Highland County and presumably pinches out (Dorobek and Read, 1986).

The Clifton Forge is a calcarenaceous quartz arenite, with crinoid fragments as the primary non-quartz framework grains but with some distinctive pink corals and/or stromatoporoids as well. Cross bedding is prominent in some horizons. At Coronation (Stop 3) and Crizer Gap (Stop 4) it is ~20 m thick, and in and near the Bullpasture River (Stop 5) where much of the Clifton Forge is actually a quartzose limestone, it is ~10 m thick. From southern Highland County northward the Clifton Forge Sandstone Member changes facies laterally into green calcareous shale that is identified as the Big Mountain Shale Member of the Keyser Limestone (Swartz, 1930).

Deike (1960) considered the prominent and erosional resistant sandstone beds that form the floor and ceiling of Breathing Cave in northern Bath County (near Stop 5) to be the same two sandstone beds that Woodward (1943) identified as tongues of the Clifton Forge Sandstone Member, and he informally named these beds the “lower Breathing sandstone” and the “upper Breathing sandstone.” White and Hess (1982) applied the name lower Clifton Forge Sandstone to the lower bed and the name upper Clifton Forge Sandstone to the upper bed. Our mapping efforts in this area (Walker et al., 2010; Haynes and Whitmeyer, 2010; Hazelwood et al., 2012; Swezey et al., 2013) indicate that the “upper Breathing sandstone” and “lower Breathing sandstone” of Deike (1960) are instead correlative with two sandstones in the lower member of the Tonoloway Limestone, and thus they cannot be tongues of the Clifton Forge Sandstone Member of the Keyser Limestone.

**Big Mountain Shale Member of the Keyser Limestone of the Helderberg Group (0–10 m thick)**

The type section of the Big Mountain Shale Member of the Keyser Limestone is at Big Mountain, ~2.5 km west of the community of Upper Tract in Pendleton County, West Virginia. It was named by Swartz (1930), who identified these strata as a separate, mappable unit within the Keyser Limestone in Highland County that are characterized by olive-gray shales and some thin beds of sandstone and sandy limestone. Swartz (1930), Woodward (1943), and Dorobek and Read (1986) recognized the facies relationship that these shales have with the Clifton Forge Sandstone Member to the south.

**Jersey Shore Limestone Member of the Keyser Limestone of the Helderberg Group (8–45 m thick)**

The type section of the Jersey Shore Limestone Member of the Keyser Limestone is near the community of Jersey Shore in Lycoming County, Pennsylvania (Head, 1972). In the field trip area, the Jersey Shore Member is lithologically heterogeneous and it includes gray to blue-gray to pink bioclastic packstones and grainstones with abundant crinoid, brachiopod, and bryozoan debris; shaly mudstones with sparse black chert nodules and lenses and more abundant siliceous beds that weather similar to chert but are not yet fully silicified (we refer to these horizons in the field as the “Keyser faux chert”); nodular bedded bioclastic wackestones and packstones; and, in many areas, two prominent beds of stromatoporoid-coral boundstones, rudstones, grainstones, and packstones (Dorobek and Read, 1986). A bed of nodular limestone above the Clifton Forge Sandstone at Crizer Gap (Stop 4) is a common Jersey Shore lithology.

**LaVale Limestone Member of the Keyser Limestone of the Helderberg Group (<1–9 m thick)**

The type section of the LaVale Limestone Member of the Keyser Limestone is at the Corriganville Quarry near the town of La Vale in Allegany County, Maryland (Head, 1972). The LaVale Member is a laminated blue-gray to gray sandy limestone to calcite-cemented calcarenaceous sandstone, which can be confused with the Healing Springs Sandstone in this region because the quartz sand laminae, stringers, lenses, and thin beds are commonly wavy to anastomosing, although the sandy beds in the Healing Springs are generally thicker and more laterally persistent than those in the LaVale.

**Devonian New Creek Limestone of the Helderberg Group (<1–10 m thick)**

The type section of the New Creek Limestone is a quarry on the north side of U.S. Route 50, ~0.8 km south of the town of New Creek in Mineral County, West Virginia (Bowen, 1967). Darton (1899) mapped these strata as part of the Lewistown Limestone. Subsequently Swartz (1930) identified these strata as the Coeymans Limestone of the Helderberg Group, Butts (1940) identified them as the Coeymans Limestone Member of the Helderberg Limestone, Woodward (1943) identified them as the Coeymans Formation of the Helderberg Group, and Bick (1962) mapped these strata as the Coeymans Limestone of the Helderberg Group. Bowen (1967) demonstrated that these strata cannot be traced continuously from Virginia through intervening areas to the type section of the Coeymans Limestone in New York, and so use of the name Coeymans Limestone has been discontinued in areas south of central Pennsylvania, and the name New Creek Limestone is used instead.

The New Creek Limestone is thick to massively bedded light-gray to pink crinoidal grainstone, and in some exposures the crinoid columnals can be noticeably pink and up to 3 cm in diameter.
Devonian Corriganville Limestone of the Helderberg Group (0–8 m thick)

The type section of the Corriganville Limestone is at a road cut 0.5 km southeast of the town of Corriganville in Allegany County, Maryland (Head, 1972). Darton (1899) mapped these strata as part of the Lewistown Limestone, Swartz (1930) identified these strata as the New Scotland Limestone of the Helderberg Group, and Woodward (1943) and Bick (1962) likewise used the name New Scotland Limestone of the Helderberg Group. Head (1972) demonstrated that these strata cannot be traced continuously from Virginia through intervening areas to the type section of the New Scotland Limestone in New York, and so the name New Scotland Limestone has been discontinued in areas south of central Pennsylvania, and the name Corriganville Limestone is used instead.

The Corriganville Limestone is recognizable by its common and distinctive light-gray chert nodules and lenses, and common large curved brachiopod shell fragments that can be up to 6 cm in length. From southern Highland County southward the Corriganville becomes less cherty and more quartzose as it changes facies into the Healing Springs Sandstone (Swartz, 1930; Perry, 1971; Dorobek and Read, 1986).

Devonian Healing Springs Sandstone Member of the Corriganville Limestone of the Helderberg Group

The type section of the Healing Springs Sandstone Member is at Healing Springs in Bath County, Virginia. Swartz (1930) first identified these strata as a separate unit, which he named the Healing Springs Sandstone Member of the New Scotland Limestone of the Helderberg Group. Woodward (1943) and Bick (1962) mapped these strata as the Healing Springs Sandstone Member of the New Scotland Limestone of the Helderberg Group, but because Head (1972) indicated that the name Corriganville Limestone should be used instead of New Scotland Limestone in Virginia, these strata are more appropriately mapped as the Healing Springs Sandstone Member of the Corriganville Limestone of the Helderberg Group. The Healing Springs changes facies laterally northward from northern Bath County into the cherty Corriganville Limestone (Dorobek and Read, 1986).

The Healing Springs Sandstone is a calcarenaceous quartz arenite to sandy limestone in which bioclastic debris is common. It is distinctive for its wavy laminae and thin beds of quartz grains that typically stand 1–2 mm in relief above the enclosing limestone.

Devonian Licking Creek Limestone of the Helderberg Group (10–40 m thick)

The type section of the Licking Creek Limestone is at a bluff on the south side of Licking Creek ~1.6 kilometers east of Warren Point in Franklin County, Pennsylvania (Swartz, 1939). This sequence of cherty and sandy limestones has a complex nomenclatural history, and almost equally complex stratigraphic relationships. Darton (1899) mapped them as part of the Lewistown Limestone, and both Swartz (1930) and Butts (1940) identified these strata as the Becraft Limestone of the Helderberg Group. Woodward (1943) abandoned the name Licking Creek, and instead used the names Port Jervis Limestone and Port Ewen Chert, which he stated were equivalent in part to the Becraft Limestone and Shriver Chert of previous reports. Lesure (1957) revived the name Licking Creek Limestone for the distinctive sequence of limestones that contain common to abundant nodules and lenses of black chert and which are stratigraphically below the Oriskany Sandstone. Bick (1962) subsequently mapped these strata in Bath and Highland Counties as the Licking Creek Limestone of the Helderberg Group.

Head (1974) redefined the Licking Creek Limestone so as to comprise all limestone and cherty limestone above the Corriganville Limestone and below the Oriskany Sandstone, and he defined two members of the Licking Creek (below). In this region, these cherty and sandy limestones are presently mapped as the Licking Creek Limestone of the Helderberg Group.

In the vicinity of Burnsville Cove, the Licking Creek Limestone is an ~25–60-m-thick unit of gray cherty limestone and argillaceous limestone, overlain by gray limestone and sandy limestone. In Bath and Highland Counties, these strata were mapped by Darton (1899) as part of the Lewistown Limestone.

Devonian Cherry Run Member of the Licking Creek Limestone of the Helderberg Group (5–30 m thick)

The type section of the Cherry Run Member of the Licking Creek Limestone is near Cherry Run in Washington County, Maryland (Head, 1974). The Cherry Run Member comprises the lower and middle Licking Creek Limestone and is characterized by lime mudstones to bioclastic wackestones and some packstones with minor argillaceous and shaly lime mudstones, all of which have common to abundant nodules, lenses, beds, and irregular masses of tough black chert. The Cherry Run Member is equivalent to the Port Ewen Chert of Woodward (1943).

At Porters Cave (Stop 2), the Cherry Run Member is not present along Virginia State Highway 42 because it has been cut out by the fault that places the Little Cove Member of the Licking Creek on the Needmore Shale. But, just a few tens of meters to the east from the exposures along Highway 42 are superb subterranean exposures of the Licking Creek in the passages of Porters Cave. Exploration of that cave shows that the fault seen along the highway is not exposed in the cave. Furthermore, a complete composite section of the Little Cove Member and several meters of the underlying cherty Cherry Run Member are present in Porters Cave, thus suggesting that the shallowly dipping fault seen along the highway must dip more steeply approaching the cave to the east.
Devonian Little Cove Member of the Licking Creek Limestone of the Helderberg Group (8–12 m thick)

The type section of the Little Cove Member of the Licking Creek Limestone is near Franklin County, Pennsylvania (Head, 1974). The Little Cove Member, which is equivalent to the Port Jervis Limestone of Woodward (1943), can be distinguished from the underlying Cherry Run Member by the commonly abrupt disappearance vertically of the black chert nodules and lenses that are so prevalent in the underlying limestones and are the distinguishing lithology of the Cherry Run. The Little Cove Member is a thick-bedded quartzose bioclastic wackestone to packstone that commonly weathers massively, to such an extent in some places that bedding can be difficult to identify, as is the case along much of the exposed length of the massive bluffs at Stop 2.

At Porters Cave (Stop 2, along the road) the Little Cove Member forms the hanging wall of a low(?)-angle thrust fault over the younger Needmore Shale. At Coronation (Stop 3), the Little Cove and Cherry Run Members are characterized by appreciable small scale folds and contractional features by virtue of their being in the footwall immediately beneath a fault that has placed the Byers Island and Clifton Forge Members of the Keysor above the Licking Creek Limestone. Quartz sand grains in samples of the Little Cove Member from the footwall beneath this fault have been pervasively fractured.

There is an interesting and unusual stratigraphic story associated with Head’s (1974) naming of this member. In his dissertation, Head (1969) divided the Licking Creek into a lower Cherry Run Member and an upper Warren Point Member, and the name “Warren Point Member” was used by Whitehurst (1982) in his detailed study of the Muddy Run area in Bath County, and it was also shown in the stratigraphic column for the Burnsville area of Bath and Highland Counties by White and Hess (1982, p. 69), just west of the Bullpasture River Gorge (Stop 5). The stratigraphic column of White and Hess (1982) has even been used as recently as 2010 (Chess et al., 2010). Since 1925, however, the name “Warren Point” has been used for a Pennsylvanian sandstone in the southern Appalachians from Virginia to Georgia (Culbertson, 1963). So according to the rules of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983, 2005), its use by Head (1969) was invalid. As a result, Head revisited this stratigraphic matter, and resolved it when he applied the name Little Cove Member (Head, 1974) to the upper and mostly chert-free limestones of the Licking Creek Limestone, a name that is in use at the present time (e.g., Wilkes, 2011).

Devonian Oriskany Sandstone (3–25 m thick)

The type section of the Oriskany Sandstone is at Oriskany Falls in New York (Vanuxem, 1839). This stratigraphic unit, like some of the other formations we will see, has had a fairly complex nomenclatural history since it was first named almost 180 years ago. Darton (1899) mapped this distinctive sandstone as the Monterey Sandstone, which he stated was approximately equivalent to the Oriskany Sandstone. Kindle (1911) identified these strata in Bath County as the Oriskany Sandstone, but shortly thereafter Schuchert et al. (1913) mapped equivalent strata in West Virginia and Maryland as the Ridgeley Sandstone Member of the Oriskany Formation. Schuchert et al. (1913) divided the Oriskany into a lower member named the Shriver Chert Member of the Oriskany Formation, and an upper member named the Ridgeley Sandstone Member of the Oriskany Formation. They designated a type section for the Ridgeley Sandstone Member at the town of Ridgely [spelling later changed to “Ridgeley”] in Mineral County, West Virginia. Swartz (1930) later identified these strata as the Ridgeley Sandstone of the Oriskany Group, but Butts (1940) used the name Oriskany Sandstone for these strata, stating that the Oriskany Sandstone “corresponds exactly with the Ridgeley Sandstone” (Butts, 1940, p. 291); Butts also indicated that the Oriskany Sandstone is the same as the Monterey Sandstone of Darton (1899). Bick (1962) mapped these strata in Bath and Highland Counties as the Ridgeley Sandstone, but Avary and Dennison (1980) assigned these strata in Highland County to the Oriskany Sandstone. In subsequent publications, however, the name Ridgeley Sandstone has persisted for these strata in Bath and Highland Counties (e.g., Rader and Wilkes, 2001), but the existing rules of stratigraphic nomenclature (North American Commission on Stratigraphic Nomenclature, 1983, 2005) dictate that that name Oriskany Sandstone has priority and thus is the name that should be given to these strata throughout this region. Therefore, this is the name we are using in our mapping efforts across this region (Haynes and Whitmeyer, 2010; Hazelwood et al., 2012; Haynes and Diecchio, 2013).

The Oriskany is a calcareous to calcarenaceous quartz arenite, with some pebbly zones, and one of its principal characteristics throughout the central Appalachian region is the abundance in some beds of prominent biomicidic pores formed by dissolution of large spiriferid brachiopod shells.

Devonian Needmore Shale (6–45 m thick)

The type section of the Needmore Shale is located between the towns of Needmore and Warfordsburg in southern Fulton County, Pennsylvania (Willard, 1939). Darton (1899) mapped these shales as part of the Romney Shale, but Butts (1940) stated that the name Romney Shale should be abandoned, and he mapped these strata at Bullpasture Mountain in Highland County as the Onondaga Formation. Woodward (1943) assigned these strata to the Needmore Shale of the Onondaga Group, and Bick (1962) described these strata in Bath and Highland Counties as predominantly shale, which he mapped as the Onondaga Formation. Avary and Dennison (1980) used the name Needmore Shale for these strata, and that name is now widely used in this region.

The Needmore Shale is a sequence of greenish-gray to gray to black fissile to blocky weathering mudrock, with some beds
of gray lime mudstone that commonly have bioclastic debris weathering in relief. Intact Phacops sp. trilobites are not infrequently found in weathered exposures of the blocky weathering mudrocks of the Needmore; discovery of a Phacops in the Needmore Shale of the footwall at Porters Cave (Stop 2) helped to confirm that those shales are most likely the Needmore.

At many exposures, the lowermost few meters of the Needmore Shale are notably darker than the overlying shales, and Dennison (1961) named these black mudrocks the Beaver Dam black shale subfacies of the Needmore Shale. Hasson and Dennison (1988) later mapped these strata in Bath and Highland Counties as the Beaverdam Shale Member of the Needmore Shale.

Devonian Millboro Shale (70–400? m thick)

The type section of the Millboro Shale is at Millboro Springs in Bath County, Virginia, along the route of this field trip (Cooper, 1939; Butts, 1940; Hasson and Dennison, 1988). Darton (1899) mapped these black fissile mudrocks as part of the Romney Shale. Butts (1940) stated that the name Romney Shale should be abandoned, and he mapped the upper portion of the Romney Shale in Bath and Highland Counties as a separate formation he named the Millboro Shale after a name that had been used by Cooper (1939). Farther north in Pennsylvania and New York, these strata are mapped collectively as the Marcellus Shale, Mahantango Formation, Harrell Shale, and (or) Hamilton Formation, but Butts (1940) had difficulty differentiating these units in Virginia, so he proposed the name Millboro Shale for these strata in Virginia. Woodward (1943) used the names Millboro Shale and Harrell Shale for these strata and he also noted that Butts had proposed the name Millboro Shale instead for the entire sequence of shales. The name Millboro is now widely used in this region (Bick, 1962; Avary and Dennison, 1988; Rader and Wilkes, 2001).

The Millboro Shale is a sequence primarily of black mudrock (shale) that is fissile and typically weathers to thin platy chips. Calcareous concretions are locally present, as are occasional silt- to sand-rich layers, some of which display convolute bedding. Trimble Knob (Stop 7) and several other igneous intrusions in Highland and Pendleton Counties are emplaced in the Millboro Shale.

STRATIGRAPHY AND SEDIMENTOLOGY

Facies Changes in the Silurian Sandstones

Local and regional stratigraphic relationships among the various Silurian sandstones are complex, especially those in the Keefer–McKenzie–Williamsport–Wills Creek interval, and correlations have been puzzled over by geologists in this region for decades, even before Woodward (1941, p. 103, 169) aptly referred to exposures in the Eagle Rock and Clifton Forge area (Stop 1) as a stratigraphic “tangle of Silurian sandstones.” From a tectonic perspective, the stratigraphic and sedimentologic details that this thick sequence of Lower Silurian quartz arenites preserves may ultimately support a basin rebound hypothesis for the depositional environment of these sandstones (Driese et al., 1991; Dorsch et al., 1994; Dorsch and Driese, 1995), as well as the hypothesis that the Taconic Orogeny persisted into the Silurian (Ettensohn and Brett, 2002). They may also help improve our understanding of the Late Ordovician glaciation (Hambrey, 1985).

At Eagle Rock (Stop 1), near the eastern margin of the depositional basin, an amalgamated 125-m-thick sequence of Silurian quartz arenites comprises the “Eagle Rock sandstone” (Fig. 3), the modern name for Woodward’s stratigraphic “tangle.” It is worth noting that in the Massanutten Synclinalion to the northeast of the field trip area (Fig. 1), another thick Silurian sandstone, the Massanutten Sandstone, is present. Its stratigraphic relations have been understood for some time, as it is recognized as the equivalent of the Tuscarora, Rose Hill, and Keefer Formations in the field trip area (Roberts and Kite, 1978). That contrasts with the difficulties geologists have had in working out the regional stratigraphic relations of the “Eagle Rock sandstone” over the decades.

A few of the many fundamental questions about these Silurian sandstones that can be asked as we examine and discuss some of the changes that are evident in a southeast to northwest traverse across part of the depositional basin include: (1) What might the subtle petrographic details of these quartz arenites tell us about the provenance of all the sand that was transported to the Eagle Rock depocenter? (2) What tectonic or eustatic event(s) accompanied or preceded the erosion, transport, and deposition of this quantity of quartz sand? (3) Are any/all of these sandstones first-cycle quartz arenites (Johnsson et al., 1988)? (4) How does the composition of the silt and clay fraction in the mudrocks vary across the region (Taylor and McLennan, 1985). And, (5) how and why did accommodation space vary so significantly from Fagg to Eagle Rock (Fig. 3)?

Our recent and ongoing mapping efforts in this area (Haynes and Whitmeyer, 2010; Walker et al., 2010; Hazelwood et al., 2012; Haynes and Diecchio, 2013; Haynes et al., 2010, 2011) have led to the development of a working stratigraphic model that evolves as we continue to map and trace out these several Silurian (and Lower Devonian) sandstones across this region (Fig. 3), from the area of Woodward’s “tangle” northwest in Bath County and southern Highland County, the individual sandstones become progressively more stratigraphically distinct and “untangled” as the overall volume of mudrocks and carbonates in the section increases relative to quartz arenites. This change in lithologic ratios effectively divides and separates what at Eagle Rock is the massive and undifferentiated “Eagle Rock sandstone” (Stop 1, Fig. 3) into the readily differentiated Keefer, McKenzie, and Williamsport quartz arenites that comprise discrete stratigraphic horizons at other exposures such as Crizer Gap (Stop 4).

Each of these sandstones makes obvious ledges in the gorge of the Bullpasture River (Stop 5), but when our mapping in this
region began, we found that identifying which sandstone ledge was which is no simple task. This fundamental stratigraphic issue evidently eluded previous geologists who worked in this region as well (e.g., Bick, 1962), perhaps because no stratigraphic column for the gorge and nearby areas that is based on one or more measured sections has ever been published, a situation that we have rectified (Fig. 3). One major advance in our understanding of the Bullpasture Gorge is the identification of the McKenzie sandstone, discussed in more detail below.

At Stops 1, 5, and 6, we will also discuss an intriguing stratigraphic aspect of the Keefer Formation, specifically what is true Keefer Sandstone versus “Keefer Sandstone” versus “Eagle Rock sandstone.” Woodward (1936) may have been the first to refer to the thick sequence of sandstones in the Roanoke area and vicinity (including Eagle Rock) as Keefer, and several authors since then (e.g., Lesure, 1957; Rader, 1967, 1984; Patchen, 1974; Dennison et al., 1992) have used the expanded Keefer or “Keefer” as a convenient name and useful mapping unit, but one that is stratigraphically inappropriate vis-à-vis the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983, 2005), because the restricted Keefer is a well-defined stratigraphic unit.

We favor discontinuing the use of “Keefer Sandstone” in the central Appalachians and substituting instead the “Eagle Rock Sandstone” of Lampiris (1975) as an acceptable alternative name (and one that is far less stratigraphically confusing) for this markedly thickened sequence of Silurian sandstones at exposures in this area where its use would be appropriate. This would be analogous to the way that the Massanutten Sandstone is used farther north. “Eagle Rock” as a stratigraphic name is available, because the term Eagle Rock tuff in Idaho, named by Stearns (1936), has been abandoned (Stearns and Isotoff, 1956). For this to happen, though, the name “Eagle Rock Sandstone” will need to be formally proposed as a stratigraphic unit in accordance with the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983, 2005).

Initial study of the petrographic characteristics of these sandstones has helped us begin to identify criteria that are useful in helping to distinguish one from another on the basis of more than just stratigraphic position. Petrographic study has also helped with our efforts to identify these sandstones at three additional and previously unmeasured exposures in Highland County: Lower Gap, Trimble, and McDowell (Fig. 3).

In addition to these sandstones, we will see and discuss some of the facies changes that occur in other Silurian and Lower Devonian sandstones of this area, several of which are calcarenaceous quartz arenites (“calcarenaceous” refers to a siliciclastic sediment in which 10%–50% of the total framework grains are carbonate allochems, e.g., peloids or bioclasts; Pettijohn et al., 1972, p. 190; Riley et al., 1997, p. 437) in contrast to the predominantly quartz arenites of the Tuscarora, Keefer, and Williamsport (in which quartz framework grains comprise ≥95% of the total framework grains). These include unnamed sandstones in the lower member of the Tonoloway Limestone (Stops 4 and 5) that for almost 50 years were mistakenly identified in the Bullpasture River Gorge and nearby areas as upper and lower tongues of the Clifton Forge Sandstone (White and Hess, 1982; Walker et al., 2010; Swezey et al., 2013). Other calcarenaceous sandstones we will see include the “real” Clifton Forge Sandstone Member of the Keyser Limestone (Stops 3, 4, and 5), the Healing Springs Sandstone Member (Stop 3 and alternate Stop 4A), the sandy limestones of the Little Cove Member of the Licking Creek Limestone (Stops 2, 3, and 4), and the Oriskany Sandstone (Stops 2, 3, and 5 and alternate Stop 4A).

### Quartz Sandstones and Quartzose Oolitic Grainstones in the McKenzie Formation

A second stratigraphic finding that has come from our mapping is that we now recognize that the unnamed middle sandstone member of the McKenzie Formation (Travis, 1962; Patchen, 1974) extends ~25 km northward of the exposures along Muddy Run (Fig. 3), which is the previously identified northern limit of that sandstone (Whitehurst, 1982; Diechcio, 1986; Diechcio and Dennison, 1996). It is a thick bed in the Bullpasture River Gorge (Stop 5), and it thins northward from there (Fig. 3) toward McDowell and Monterey, but it can be recognized as a thin bed on Jack Mountain west of McDowell.

In addition, our mapping has led us to conclude that the exposures of oolitic limestones in the gorge of the Bullpasture River and along nearby Tower Hill, and which form prominent ledges that total ~8 m in thickness along State Road 678 (Stop 5), are quite likely an older and earlier eastern equivalent of the oolitic facies that in the subsurface farther west comprises the upper part of the Lockport Member of the McKenzie (Patchen and Smosna, 1975; Smosna and Patchen 1978; Smosna, 1984). And, because these oolitic limestones in the McKenzie Formation along the Bath–Highland County line are stratigraphically below the unnamed middle sandstone member of the McKenzie, in contrast to the oolitic carbonates in the Lockport Member farther west that overlie the middle sandstone, we conclude that these oolitic limestones represent an earlier development of the sandy oolitic lithofacies in the basin.

Thin sections of these oolitic grainstones and related bioclastic grainstones from the Bullpasture River Gorge and Lower Gap indicate that dolomitization has not been as pervasive in this area as in many of the cores described by Smosna (1984), but the cementation history of these carbonates is complex nonetheless, with a later diagenetic ferroan baroque dolomite (Spötl and Pitman, 1998) that effectively reduced any remaining interparticle pore spaces in these sediments.

Our discovery that the middle sandstone and the oolitic grainstones in the McKenzie Formation extend into central and southern Highland County and northern Bath County could be of some significance in the search for hydrocarbons in the Silurian of this region. The presence of baroque dolomite in these...
and other Silurian and Devonian strata of this region (Dorobek, 1987; Haynes et al., 2010, 2011) is evidence that these strata have been in the oil window (Spötl and Pitman, 1998). There is a long history of natural gas production in the central Appalachian basin from the Lockport oolite facies (Patchen and Smosna, 1975) and more recently from the Williamsport Sandstone (Patchen, 1974); Patchen (1974) noted that thicknesses of the Williamsport Sandstone were inversely proportional to the thickness of the underlying McKenzie Formation. Given the proximity of these McKenzie exposures in the Bullpasture River Gorge to the scattered gas production in neighboring Pocahontas County (Limerick et al., 2005), further study of these units may be warranted at some future time for their potential to assist in identification of drilling prospects in the Silurian of this area.

Stratigraphically, this sequence of oolitic limestones and the overlying unnamed middle sandstone member have turned out to be useful marker beds. This has been especially helpful to our ongoing mapping efforts in central and northern Highland County, an area where the Keefer sandstone thins to such an extent that it is no longer mappable, and the sequence becomes an otherwise shale-dominated stratigraphic interval from the middle Rose Hill Formation up section to the Williamsport Sandstone.

Unconformable Nature of the Tonoloway–Keyser Contact

In the central Appalachians, the oldest of five named members of the Keyser Limestone is the Byers Island Member of Head (1972, 1974). Our mapping efforts have shown that the thickness of the Byers Island varies greatly and abruptly over relatively short distances in the area of this field trip, as shown on the detailed stratigraphic column that is applicable to Stops 2, 3, and 4 (Figs. 5, 6). This abrupt thinning and discontinuous nature of the Byers Island Member in this area, which we will see at Coronation and Crizer Gap (Stops 3 and 4), has apparently not been recognized previously. At Coronation (Stop 3), the Byers Island is at least 18 m thick, and it separates the older Tonoloway Limestone (below) from the younger Clifton Forge Sandstone (above), but just less than 3.5 km to the northeast, at Crizer Gap (Stop 4), the Byers Island is absent, and the upper beds of the Tonoloway Limestone are overlain instead by the Clifton Forge Sandstone.

Our mapping (Haynes and Whitmeyer, 2010; Hazelwood et al., 2012) has shown that a similar stratigraphic relationship also occurs in southernmost Highland County, where the Clifton Forge unconformably overlies the Tonoloway in and around the gorge of the Bullpasture River (Stop 5), but that in central and northern Highland County (vicinity of Stop 6 although not exposed at our stop there) the Byers Island unconformably overlies the Tonoloway. In northern Highland County and northward into adjacent Pendleton County, the Keyser stratigraphy is further complicated by the facies change in the middle Keyser, as the Clifton Forge Sandstone passes laterally into the Big Mountain Shale Member.

The nature of the Tonoloway–Keyser contact has not been discussed in any appreciable detail in previous studies. Woodward (1941, 1943) observed flat-pebble conglomerates discontinuously at the contact in some of his many measured sections, and Dorobek and Read (1986) noted that the lowest beds of the Keyser represent a deepening of the water column and development of more open marine conditions compared to the
Figure 6. Elevated cross section showing our interpretation of the geology in the vicinity of Stops 2 and 3. Note that the top of the cross section represents the ground surface, and the colored units represent subsurface geology. Smc—McKenzie Formation; Swp—Williamsport Sandstone, Stw—Tonoloway Limestone; SDk—Keyser Formation (mostly the Clifton Forge Sandstone Member); Dolh—Oriskany Sandstone, Licking Creek Limestone, and Healing Springs Sandstone undivided; Dmn—Millboro and Needmore Shales undivided. Landscape imagery is from Google Earth. The inset shows the cross-section interpretation of Kozak (1965) in the vicinity of Stop 3 (Dhl—Helderberg Group; Dm—Millboro and Needmore Shales; Do—Oriskany Sandstone; Sc1—Clinton Group; Scy—Cayuga Group; Sk—Keyser Limestone). Note that the west-directed ramp-to-flat thrust fault is missing from Kozak’s interpretation.
restricted conditions that prevailed during deposition of much of the underlying Tonoloway (Smosna et al., 1977), and that were described in more detail by Bell and Smosna (1999).

PETROLOGY AND GEOCHEMISTRY

Overview

The Eocene volcanic rocks of western Virginia and West Virginia are the expression of the youngest-known magmatic event in the eastern United States. Why these Eocene magmas erupted is an especially intriguing question, because then, as today, the eastern United States was a passive margin, far from the Mid-Atlantic Ridge. The answer to this question must involve the long and complicated tectonic history of the Appalachian region (i.e., Hatcher, 1989). The Eocene dikes as well as the ca.150 Ma Late Jurassic dikes in the area (Southworth et al., 1993) also contain crustal and mantle xenoliths that help constrain the deeper stratigraphy of the lower crust and mantle. These volcanic rocks hold important keys to the interpretation of structural and seismic data in the region and our understanding of the long-term, continued evolution of the rift-to-drift transition for eastern North America, as well as for rift margins worldwide.

Geochronology of the Eocene (and Late Jurassic) Igneous Rocks

The Eocene volcanic swarm (Fig. 7) was originally assumed by initial investigators to be a part of Central Atlantic magmatic province volcanism (May, 1971; Ragland et al., 1983; Philpotts and Martello, 1986; McHone et al., 1987; Ragland, 1991; Marzoli et al., 1999; McHone, 2000, 2002). The Central Atlantic magmatic province volcanic activity occurred at ca. 190–200 Ma along the East Coast of the United States, during the breakup of Pangea (Nomade et al., 2007; Marzoli et al., 1999). It was not until the 1960s that the first paleomagnetic data implied these igneous rocks were Eocene in age (Elvers et al., 1967; Fullagar and Bottino, 1969). Limited K-Ar and Ar-Ar dates (Core et al., 1974; Wampler and Dooley, 1975; Ressetar and Martin, 1980; Southworth et al., 1993) confirmed the young age of these igneous rocks with reported ages ranging from 48 to 35 Ma. The most recent Ar-Ar dates constrain Eocene eruption ages to 47–48 Ma (Bulas and Johnson, 2012).

The region of Eocene volcanic rocks overlaps with an area (Fig. 7) that includes ca. 150 Ma Late Jurassic dikes which postdate the opening of Pangea by 50 Ma (Zartman et al., 1967; Johnson et al., 1971; Southworth et al., 1993). Although only...
three of the Late Jurassic dikes have been dated using K-Ar and Ar-Ar geochronology (Zartman et al., 1967; Johnson et al., 1971; Southworth et al., 1993), dikes with similar-trace element geochemistry and orientation are assumed to be Late Jurassic in age (e.g., Furman and Gittings, 2003) and are common within Augusta and adjacent Rockingham and Pendleton Counties (Fig. 7).

Whole-Rock Geochronology and Petrology

Whole-rock geochemical data for the Eocene volcanics are compiled in Southworth et al. (1993) and additional data are reported in Tso et al. (2004) and Furman and Gittings (2003). The Eocene volcanics form a bimodal alkaline series ranging from microbasalts and basanites to trachydacites and rhyolites. The mafic volcanics have LREE (light rare earth element)-enriched REE (rare earth element) patterns with steep negative slopes similar to those of oceanic-island basalts (OIBs), and the felsic rocks have even more highly enriched LREE (Southworth et al., 1993; Furman and Gittings, 2003) than the mafic magmas. Extremely limited Sr, Nd, and Pb isotopic data from Mole Hill (Furman and Gittings, 2003) and a composite Sr isotope analysis of felsic rocks from Highland County (Fullagar and Bottino, 1969) indicate little interaction of the Eocene magmas with the crust.

The mafic rocks are generally aphanitic to porphyritic and contain microcrystalline plagioclase and olivine or clinopyroxene within the groundmass. Phenocrysts of olivine and clinopyroxene are common within the mafic magmas. Vesicles and/or amygdules filled with carbonates, sulfides, and zeolites are often present (Kearns, 1993). The intermediate and felsic rocks typically have a devitrified glassy groundmass, sometimes including microcrystals of plagioclase, with phenocrysts of plagioclase, alkali feldspar, amphibole, and biotite. Some of the felsic dikes have glassy chilled margins.

Geochemistry of Xenoliths and Xenocrysts

Geochemical analyses of lower crustal xenoliths and mantle xenocrysts that occur within the Eocene and Late Jurassic volcanic rocks can be used to understand the vertical cross section of the lower crust and mantle underneath western Virginia and eastern West Virginia.

Lower crustal xenoliths of paragneiss and anorthosite-gabbro are included within several dikes in the area (Fig. 7B). The gneisses contain a granulite-facies mineral assemblage of quartz + alkali feldspar + garnet + rutile + sillimanite + zircon ± apatite ± graphite with secondary chlorite, ilmenite, monazite, sulfides, and barite along grain boundaries and fractures (Helsley et al., 2013). Metamorphic temperatures were determined using Zr-in-rutile thermometry (Tomkins et al., 2007) on rutile inclusions within garnets that record maximum temperatures, as well as rutile grains within the matrix of the xenolith that record resetting during infiltration of hydrous fluids from the magma into the xenolith during ascent. Calculated temperatures (637–984 °C; Helsley et al., 2013) extend into the ultra-high temperature (UHT) field of metamorphism. This is only the second reported occurrence of UHT rocks in the eastern United States (Ague et al., 2013). The depth (pressure) of origin of the xenoliths is not as well constrained, but a pseudosection from Ague et al. (2013) implies that maximum pressure was at least 7.25 kbar and no more than 14.5 kbar. The gneiss xenoliths record Grenvillian detrital U-Pb zircon ages (Rossi et al., 2013) with no evidence for zircon rim growth during subsequent orogenic events. In contrast, the anorthosite and gabbro xenoliths have igneous U-Pb ages of ca. 150 Ma.

Two studies (Sacco et al., 2011; Jones et al., 2012) have used olivine-melt, clinopyroxene-only, and clinopyroxene-melt geothermobarometers to determine temperature and depth from mantle xenocrysts. At Mole Hill, the xenocrysts record a temperature of 1230 °C and a pressure of 13 kbar, corresponding to ~39 km depth (Sacco et al., 2011). These conditions fall close to the solidus within the spinel peridotite stability field, consistent with the assemblage of olivine, high Al-augite, and spinel xenocrysts found within the basalt. The recorded depth is close to the 40 km depth of the Moho (Benoit and Long, 2009). Clinopyroxene megacrysts from a Highland County picrobasalt record a pressure similar to that at Mole Hill ($P = 14.1 \pm 1.8$ kbar), but a significantly higher temperature of 1371 °C (Jones et al., 2012). Preliminary calculations using olivine melt inclusion compositions from Mole Hill estimate the depth of melting to be 60–70 km at that location (O’Reilly et al., 2012), which would likely lie within the garnet peridotite stability field. Further geothermobarometric work is needed to completely interpret these preliminary results.

STRUCTURAL GEOLOGY

Alleghanian Deformation

This field trip visits excellent exposures that characterize outcrop- to mountain-scale fold and fault structures commonly associated with thin-skinned tectonics. The region is commonly viewed as a type example of a foreland fold-and-thrust belt (Rodgers, 1970), as it represents the foreland of the late Paleozoic collision of Gondwana with eastern Laurentia. The region highlighted by this field trip is dominated by a series of large-scale anticlines and synclines, bounded by the west-directed Pulaski and North Mountain fault systems to the east, and dissipating at the Allegheny structural front to the west (Fig. 1). From west to east the major fold structures include the Wills Mountain anticline, Warm Springs–Bolar anticline (Kulander and Dean, 1986; Rader and Wilkes, 2001), and Rough Mountain syncline. These and other large-scale fold structures are interpreted to overlie a series of duplexes of Cambrian to Ordovician clastic and carbonate rocks (Kulander and Dean, 1986; Mitra, 1986). Second-order deformation features occur as parasitic folds on the large-scale structures, and as fault bend folds or ramp anticlines (e.g., the “breadloaf”-shaped anticline of Stots...
from structural interfinger can produce elevated hills that are
by folding. The resulting increased thickness of hinge regions
(Perry, 1978; Fichter et al., 2010) as a mechanical accommo-
dation; monly exhibit contractional wedge faults in the hinge regions
(e.g., Kropp et al., 2013). Outcrop- and larger-scale folds com-
tomations probably cut through more competent lithologies at depth
(e.g., Kropp et al., 2013). Outcrop- and larger-scale folds commonly exhibit contractional wedge faults in the hinge regions
(Perry, 1978; Fichter et al., 2010) as a mechanical accommodation
by brittle lithologies to the reduction of space precipitated by
folding. The resulting increased thickness of hinge regions from structural interfinger can produce elevated hills that are
resistant to weathering (Fig. 6), in contrast to the more typi-
cal inverted topography of kilometer-scale breached anticlines
(e.g., the Germany Valley region of the Wills Mountain anticline; Fichter et al., 2010).
In general, differential weathering in the southeastern Valley
and Ridge province has resulted in northeast-trending mountain
ridges that are underlain by resistant Silurian and Devonian sand-
stones, and valleys that are typically underlain by weak Devonian shales (e.g., Enomoto et al., 2012) or Ordovician carbonates (e.g., Diecchio, 1985, 1986). Smaller-scale, fault-related folds can add intriguing complexities to regional topographic patterns. How-
ever, the lack of exposed deformational features across much of
the Valley and Ridge province can lead to underestimates of the complexity of deformation in this region. On this field trip, we are fortunate to have several key outcrops that we can use as a proxy for the style and intensity of deformation that likely pervaded much of the Appalachian foreland.

Structural Controls on Eocene Magmatism

Eocene volcanic rocks are generally exposed within Ordovician, Silurian, and Devonian limestones and shales (Darton, 1899; Wilkes, 2011), and the intrusions mostly (but not always) seem to have avoided intrusive pathways through the stronger sandstone units. The shales and limestones are generally more complexly deformed than the sandstones, and there is usually evidence for many parasitic folds within larger-scale fold structures (Tso and Surber, 2006). Exposures of Eocene volcanic rocks are generally aligned along or around fold axes and noses of plunging folds in the region (Darton, 1899; Wilkes, 2011). This contrasts with Late Jurassic dikes, which generally strike northwest (Southworth et al., 1993). The strike orientations of individual bodies, where determined, have been shown to align with jointing within the sedimentary unit(s) into which they intrude (Tso and Surber, 2006).

It is reasonable to hypothesize that the Eocene dikes and plugs exploited preexisting fracture and fault systems to ascend to the surface, especially considering our findings which indicate that magma ascent rates were rapid (Stempniewicz and Johnson, 2011). For example, even though Mole Hill (Stop 13) is exposed within carbonates of the Ordovician Beekman-town Formation, xenoliths of a sandstone unit beneath Mole Hill were brought to the surface during eruption. Petrographic analyses (texture, grain size, and composition) indicate that the Silurian Tuscarora Formation is the most likely stratigraphic unit from which the sandstone xenoliths were derived (Johnson et al., 2013). We hypothesize that the Eocene Mole Hill magma exploited splay of the North Mountain fault system (exposed ~8 km to the west) to ascend to the surface.

Eocene Tectonics

Several hypotheses have been proposed to explain the Eocene magmatism on a plate tectonic scale. Southworth et al. (1993) proposed that a shift in worldwide plate tectonic motion at ca. 50 Ma may have resulted in a change in the stress field in the North American plate, reactivating fault and fracture sys-
tems in the deep and shallow crust and inducing magmatism. The 38th parallel fracture zone (Dennison and Johnson, 1971) has recently been extended and reinterpreted as a hotspot track produced by linear regions of lower lithospheric thinning and asthenospheric upwelling (Chu et al., 2013). This proposed hotspot track crosses directly through the Virginia–West Vir-
ginia Eocene volcanic swarm (Fig. 7A), although Chu et al. (2013) places the hot spot in this area at ca. 65 Ma rather than at 50 Ma.

Other hypotheses combine mantle dynamics with plate tectonics. Asthenospheric upwelling and melting could have occurred underneath Virginia as a response to the Farallon plate sinking into the deep mantle below the eastern United States (Moucha et al., 2008; Forte et al., 2010). Edge-driven convec-
tion of the asthenosphere at the edge of the continental litho-
sphere also could have caused upwelling and melting to occur (King and Anderson, 1998). Helium isotope data obtained from waters at Warm Springs (R/Ra > 1) record a mantle component (Baedke and Silvis, 2009), implying that at least some fractures in the shallow crust are connected in some way to the mantle below, perhaps by deeper fractures in the lower crust.

These scenarios might be able to explain upwelling at a distance from the continental margin that corresponds to western Virginia, but they are less able to explain the unique location of young volcanic rocks along the edge of eastern North America. Preexisting structural and thermal conditions caused by prior orogenic and rifting events might help to explain why magmatism occurred only in the western Valley and Ridge during the Eocene. For example, Wagner et al. (2012) interpret their seismic data to show a remnant subducted slab and evidence for crustal delamination below the Piedmont and Blue Ridge of North Carolina. Regional variations in the lower crustal and lithospheric mantle structure could have produced magmatism in western Virginia. At present, existing hypotheses for these
enigmatic intrusions are poorly constrained and await future investigations to improve our understanding of Eocene tectonic conditions in the eastern United States region.

**ROAD LOG AND STOP DESCRIPTIONS**


The road log begins at Christiansburg, just east of Blacksburg, where U.S. 460 intersects I-81. The coordinates for latitude and longitude for all stops are given in the WGS 84 system.

**Day 1**

<table>
<thead>
<tr>
<th>Mileage (Cumulative)</th>
<th>Directions</th>
</tr>
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<tbody>
<tr>
<td>0.0</td>
<td>Intersection of U.S. 460 and I-81 (Mile Marker 118 on I-81). Proceed north on I-81.</td>
</tr>
<tr>
<td>20.7 (52.7)</td>
<td>Eagle Rock, and the long exposure along the southwest side of U.S. 220 at the bridge over the James River.</td>
</tr>
</tbody>
</table>

**Stop 1. Eagle Rock**  
37.64125° N, 79.80735° W

At this exposure (Fig. 4), the prominent ridge-forming sandstone is the Silurian “Eagle Rock sandstone” of Lampiris (1975). It is underlain by the Rose Hill Formation and overlain by the Tonoloway Limestone. Gathright and Rader (1981) and Rader and Gathright (1984) correlated the middle red zone of the “Eagle Rock sandstone” with the Bloomsburg Formation, which in the Massanutten Synclinorium to the northeast is at the approximate stratigraphic level of the McKenzie Formation and Williamsport Sandstone (Figs. 2, 3). Because the Tuscarora Formation underlies the Rose Hill Formation here at Eagle Rock, the “Eagle Rock sandstone” cannot be completely correlative with the thick Massanutten Sandstone of that area, which includes the Tuscarora and Rose Hill equivalents. Furthermore, there is no nearby exposure of the Bloomsburg along strike toward the Massanutten Synclinorium, and there is no Bloomsburg in the western Valley and Ridge, but rather the sequence of McKenzie, Williamsport, and Wills Creek formations.

The structural complexity of Eagle Rock has been well documented in other field guides (Gathright and Rader, 1981; Rader and Gathright, 1986; Spencer et al., 1989), and thus we will provide only a few highlights. Steeply inclined to overturned sandstones and shales, as outlined in the preceding paragraph, are folded and cut by several faults (McGuire, 1970; Kattenhorn and McConnell, 1994; McConnell et al., 1997). Hanging wall anticlines and footwall synclines are manifest as both fault propagation folds and fault bend folds. Fault-bounded horse blocks are apparent in the hanging wall of the main thrust surface, the footwall of which also exhibits secondary thrust splays (McConnell et al., 1997). This locality is incorporated within the Eagle Rock allochthon (a thrust-bounded klippe; Bartholomew, 1987) produced by west-directed thrusting of the Pulaski fault system. Similar geometries of thrust bounded horses and interrelated folds are in evidence along the North Mountain fault system (Orndorff, 2012), and perhaps apparent in part as the doubly plunging fault bend antcline that we will examine at Stops 2, 3, and 4.

At this exposure, look for trace fossils in the “Eagle Rock sandstone,” look for criteria that distinguish the “Eagle Rock” from the Rose Hill and the Tuscarora, and for the more subtle differences in texture and composition that occur in the almost 130-m-thick sequence of quartz sandstone that comprises the “Eagle Rock Sandstone” and that might be useful for helping understand Woodward’s “tangle” of Silurian sandstones in this region.

<table>
<thead>
<tr>
<th>Mileage (Cumulative)</th>
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<tbody>
<tr>
<td>0.0 (52.7)</td>
<td>Continue north from Eagle Rock on U.S. 220.</td>
</tr>
<tr>
<td>22.5 (75.2)</td>
<td>Junction with I-64. Take the entrance ramp onto I-64 East (right).</td>
</tr>
<tr>
<td>1.4 (76.6)</td>
<td>Exit 29 on I-64 and the junction with Virginia State Highway 42. Leave I-64 and drive on State Highway 42 heading north (left).</td>
</tr>
<tr>
<td>10.2 (86.8)</td>
<td>Arrive at the pullout on the west side of Highway 42 across from the trail to Porters Cave. This is a relatively busy road, so cross it cautiously.</td>
</tr>
</tbody>
</table>

**Stop 2. Porters Cave**  
37.91743° N, 79.72533° W

At this exposure along the eastern side of the broad Cowpasture River Valley, a low-angle, west-directed thrust fault has emplaced chert-free limestones of the Little Cove Member of the Devonian Licking Creek Limestone over the younger Devonian Needmore Shale (Figs. 5, 6, 8A), yet there is a significant spring that emerges at the base of the embankment, apparently from beneath the shale, suggesting that there are karstic limestones present, at this lower elevation and lower structural position. The stratigraphic sequence of shale-limestone-shale at this location was first noted by Holsinger (1961), who aptly described it thusly:

Limestone outcrop just west of the entrance to Porter’s Cave. Note the well defined contact between the limestone (upper bed) and the shale (lower bed). The shale layer here is about 15 ft thick while the limestone layer is about 50 ft. Overlying the limestone is another layer of shale averaging from 20 to 25 ft thick. (Holsinger, 1961, p. 67)
Holsinger’s (1961) Figure 3 shows this contact, which we now interpret as a fault, as a normal stratigraphic contact. Although Holsinger did not attempt to name or correlate either of the two shale horizons regionally as to their stratigraphic position, he did conclude that Porters Cave is formed in the New Scotland Limestone of the Helderberg (Holsinger, 1961, p. 66), which is the Corriganville Limestone of current regional stratigraphic usage.

By contrast, our fieldwork here indicates that (1) the Healing Springs Sandstone, not the facies equivalent cherty Corriganville Limestone, is present in this area and in fact forms the ceiling of nearby Black Oak Cave; and (2) Porters Cave is developed in the Licking Creek Limestone (both the Little Cove and Cherry Run Members, Fig. 5), rather than the Corriganville Limestone. Between here and Highland County to the north (Stops 5 and 6), the Healing Springs changes facies into the cherty Corriganville Limestone, and this is one of the several significant facies changes that occur in the Silurian–Devonian sequence of this region (Figs. 3, 8, 9, 10).

This km-long outcrop is at the south end of a southwest-plunging anticline that is located between regionally extensive synclines in which Rough Mountain (to the east) and Beard Mountain (to the west) are the most prominent features. The exposures are astride the axis (nose) of the anticline. The fault, which crops out along the east side of Virginia State Highway 42 at this locality, exhibits cm-scale deformation bands and drag structures indicating top-to-the-west movement. The geometry of hanging wall rocks defines an anticline with a wavelength of several tens of meters, plunging gently to the southwest.

Several trips into Porters Cave, 50 m east of the road, have thus far failed to locate the fault plane in the lower cave passages. Instead, a good composite section of the Licking Creek Limestone can be seen in the cave, with the ceiling of many of the cave passages in the upper levels being either the basal Oriskany Sandstone (exposed in the south wall of the sinkhole in which the cave’s only known entrance occurs) or the uppermost sandy limestones of the Little Cove Member of the Licking Creek. A complete section of the Little Cove Member is present in the cave, and it is underlain by a nearly complete section of the underlying Cherry Run Member of the Licking Creek, with its distinctive and relatively abundant lenses and nodules of black chert. These stratigraphic relations, in combination with local structural features (i.e., Little Cove Member faulted on Needmore Shale along the highway), suggest that the shallowly dipping fault plane apparent along Highway 42 steepens to the east, perhaps in a flat-to-ramp geometry (Fig. 6).

At this exposure, look for bedding in the massive bluffs of the Little Cove Member, for evidence of movement and slippage along the fault plane, for fossils including *Phacops* (Fig. 8A) in the Needmore Shale beneath the fault plane, and, at the southern end of the exposure, look at the thin Oriskany Sandstone and the overlying Needmore Shale in normal sequence. In addition, we welcome discussion and speculation on the hydrogeologic relationship of the (presumably) karst spring at the base of the embankment to the structure and stratigraphy at this stop.

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<th>Mileage</th>
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<tbody>
<tr>
<td>0.0 (86.8)</td>
<td>Continue northward on Virginia State Highway 42.</td>
</tr>
<tr>
<td>0.7 (87.5)</td>
<td>Pull off along the right (south) side after the sharp bend to the east. The sharp, blind curves in both directions make this a particularly treacherous road to traverse, so as at Stop 2, cross the road cautiously.</td>
</tr>
</tbody>
</table>

**Stop 3. Coronation**

37.92466° N, 79.72002° W

At this exposure, previously documented by Montgomery (1967) and by Rader and Gathright (1984) as a stop in their road log, a complexly deformed sequence of strata that includes Tonoloway limestones, Byers Island and Clifton Forge Members of the Keyser Formation, and Licking Creek limestones, is present in the core of a broad anticline. The upper 6–8 m of thinly bedded, laminated and algal-laminated, and in places mud-cracked lime mudstones of the Silurian Tonoloway Limestone are the oldest strata exposed. In the old roadside quarry at the east end of this exposure, the approximate contact of the uppermost thin beds of Tonoloway lime mudstones with the overlying massive bryozoan and crinoidal grainstones and in places boundstones of the Byers Island Limestone Member of the Keyser Formation can be found with little difficulty. The massive Byers Island is the principal limestone in the old quarry, and it is overlain by cross-bedded calcarenaceous sandstones of the Clifton Forge Sandstone Member of the Keyser (Fig. 11B), with the contact being well exposed at the east end of the quarry.

Deformation features become more apparent to the west, with abundant small-scale folding apparent in the Tonoloway limestones adjacent to a shallowly east-dipping fault that truncates the unit. The fault continues upward to the west, where it underlies a wedge of lighter gray Byers Island limestone. These limestones are, in turn, emplaced over darker-gray deformed cherty and sandy limestones of the Licking Creek Limestone along a second subhorizontal fault. Pervasively fractured quartz sand grains with numerous fracture lamellae (Fig. 11A) like those discussed at length by Perry (1971) in Pendleton County, West Virginia, are adjacent to the fault plane. Near the western end of the outcrop, the overlying Clifton Forge sandstone dips westward, defining the western part of the broad anticlinal structure, but exhibiting none of the internal deformation seen in the underlying limestone units. The western part of this exposure is a steeply dipping succession of Healing Springs Sandstone, Licking Creek Limestone, Oriskany Sandstone (Fig. 11C), and a meter or two of Needmore Shale, all in normal stratigraphic sequence (Figs. 5, 6). Overall, the geometry of interfingered,
thrust-bounded wedges of limestone overlain by gently folded but otherwise undeformed sandstone beds suggests that a series of contraction faults accommodated reduced space in the hinge of a broad anticline. This anticline likely overlies a northeastward continuation of the west-directed thrust apparent at Stop 2.

At this exposure, look for the lithologic criteria that indicate that the lowest limestones in this section are Tonoloway limestones, look for bryozoa and other fossils in the Byers Island, compare and contrast the Clifton Forge and Healing Springs and Oriskany Sandstones, and look at the contact between the cherty Cherry Run Member of the Licking Creek and the overlying Little Cove Member. Questions to consider at this exposure: Why is the Oriskany relatively thin in this area (generally less than 4 m thick)? What caused this anticline to develop between the two wide and regionally extensive synclines to the east and west. And, why is there apparently so little Keyser and evidently no New Creek between the Clifton Forge and the Healing Springs?

Coronation, the name of this location, is also a curiosity. There is no such town now shown on maps of this region, and there are no road signs directing travelers in this area to it either. Coronation is shown on the 1928 *Geologic Map of Virginia* and the accompanying topographic map, and Woodward (1941, 1943) referred to this exposure as the Coronation section, but since then the town seems to have disappeared. The apparent fate of Coronation seems to be connected with a tornado:

May 2, 1929, Virginia’s “Deadliest Tornado Outbreak”: It has been said that tornadoes do not occur in mountainous areas. This is false. It was a warm May day with a cold front moving in from the west. The first tornado hit Rye Cove in Scott County in extreme southwest Virginia... In Bath and Alleghany Counties lies Cowpasture Valley. This valley is at an elevation of 1500 feet and lies between two ridges that rise 1000 feet above the valley. A tornado struck around 6 p.m. Property losses in Coronation and Sotlington were great. At least 10 people were injured, but none were killed. An eyewitness watched the tornado form near his home. He described everything within 250–800 yards of the tornado’s path being destroyed. The postmaster at Covington followed the storm 17 miles. He watched it take out 150 apple trees, lift the roof off a house, and sweep away a barn. In the barn, a woman was milking a cow. She was found some distance from where the barn had stood, under its floor. One edge of the barn floor was resting on a stone wall and she, miraculously, was not injured, nor were the six cows that had been in the barn. Poultry houses were swept away and chickens were found dead and almost featherless. (Historical Virginia Tornadoes [NOAA]; www.erh.noaa.gov/lwx/Historic_Events/va-tors.html [accessed 10 January 2014])

The town of Sitlington mentioned in the above quote likewise no longer seems to exist. So it is possible these two communities were damaged so significantly by this 1929 tornado that they were either not resettled, or the inhabitants eventually moved away.

<table>
<thead>
<tr>
<th>Mileage (Cumulative)</th>
<th>Directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 (87.5)</td>
<td>Continue northward along Virginia State Highway 42.</td>
</tr>
<tr>
<td>2.2 (89.7)</td>
<td>At the T-intersection with VA 632 (Crizer Gap Road), which comes from the west (left), note the exposed ledges of cherty limestones of the Cherry Run Member of the Licking Creek Limestone along the east (right) side of the road. Turn west (left) onto VA 632.</td>
</tr>
<tr>
<td>0.6 (90.3)</td>
<td>Drive to the pullout on the west side of the bridge over the creek.</td>
</tr>
</tbody>
</table>

Stop 4. Crizer Gap
37.95041° N, 79.69866° W

(Weather permitting, this will be our lunch stop.)

At this location, a creek has cut an erosional window through a broad anticline defined by Oriskany Sandstone and

Figure 8. Outcrops of Silurian and Devonian strata in and around the field stops by Porters Cave (Stop 2), Coronation (Stop 3), Crizer Gap (Stop 4), and Windy Cove Gap (alternate Stop 4A). (A) Fault contact between quartzose chert-free limestones of the Little Cove Member of the Devonian Licking Creek Limestone and the underlying but younger Devonian Needmore Shale along State Highway 42 by Porters Cave (Stop 2). Inset (lower right) shows part of a *Phacops* sp. found in the Needmore below the fault plane. The Licking Creek is overlain here by a normal stratigraphic sequence of the Oriskany Sandstone, Needmore Shale, and Millboro Shale, each of which is exposed on the hillside above this outcrop and above the nearby sinkhole entrance to the cave. Photo by P. Lucas. (B) Wedge fault in algal laminated limestones of the Silurian Upper McKenzie Formation in the axis of the anticlinal arch in Crizer Gap (Stop 4). Photo by J. Haynes. (C) Ledges of the Silurian Williamsport Sandstone on the west limb of the anticline exposed in Crizer Gap (Stop 4); these are underlain by the upper several meters of the McKenzie Formation, and overlain by a complete exposure of the Silurian Tonoloway Limestone. Photo by J. Haynes. (D) Arrow points to the base of a thick, calcarenaceous, and in places cross-bedded (inset, upper left) sandstone in the undivided Tonoloway Limestone at Crizer Gap (Stop 4). We are tentatively correlating this sandstone with a Tonoloway sandstone in Highland and northern Bath Counties (Stop 5, Fig. 10F), which in that region separates the lower and middle members of the Tonoloway, and is known informally as the “upper Breathing Cave sandstone” (Swezey et al., 2013). Photos by J. Haynes. (E) Contact between the lowest exposed bed of the Clifton Forge Sandstone Member of the Keyser Formation (arrow #1), which is cross-bedded (inset, upper right), and the uppermost exposed thin-bedded lime mudstones of the Tonoloway Limestone (arrow # 2) in the streambed at Crizer Gap (Stop 4). The Byers Island Member of the Keyser, which 3.4 kilometers away at Coronation (Stop 3) separates the Clifton Forge and the Tonoloway and is ~15 m thick, is absent here. Photos by J. Haynes. (F) Exposure of the Devonian Healing Springs Sandstone along State Highway 39 in Windy Cove Gap (alternate Stop 4A), which in this area typically exhibits these distinctive wavy laminae and thin beds of calcarenaceous sandstone, which weather in relief and contrast with the surrounding sandy limestone. Photo by J. Haynes.
Active features along a “passive” margin, Highland and Bath Counties, Virginia

Figure 8.
Licking Creek Limestone. An evidently unfaulted sequence is present from the Licking Creek Limestone down section to the upper McKenzie Formation, which is exposed along the road in the anticlinal axis (note the wedge fault in the McKenzie here, Fig. 8B). The massive rock arch (Fig. 8C) is formed by the resistant quartz arenite ledges of the ~15-m-thick Williamsport Sandstone, which overlies the McKenzie. The Williamsport–Tonoloway contact on the west limb is covered at the pull-off, but it is exposed in the creek bed on the east limb. The Wills Creek Formation, which elsewhere in the region separates the Williamsport Sandstone and the Tonoloway Limestone (e.g., Stop 6), is absent here. The Tonoloway is recognizable by its thinly bedded, laminated limestones, a thick sandstone (Fig. 8D) that we tentatively correlate with a Tonoloway sandstone in the Burnsville area of Bath and Highland Counties, and by a distinct vuggy bed that is likely related to deposition and subsequent dissolution of evaporites.

Of particular interest is the Tonoloway–Keyser contact, which is exposed just downstream from the pullout (Fig. 8E). The lowest bed of the Clifton Forge Sandstone is just a meter or two up section from the uppermost exposed thin Tonoloway limestones, and the Byers Island Member is either very thin and not exposed, or it is absent, which is also what is seen in the vicinity of the Bullpasture River Gorge (Stop 5, Figs. 10E, 10G).

Above the Clifton Forge are just a few meters of nodular Keyser limestones that are overlain by another sandstone, which is in the right stratigraphic position to be the Healing Springs Sandstone based on the section at Windy Cove Gap to the north (Fig. 8F). The New Creek Limestone that elsewhere occurs between the Keyser and the Healing Springs or the cherty Corriganville Limestone, is very thin or absent. The Healing Springs Sandstone is overlain by the cherty limestones of the Cherry Run Member of the Licking Creek, and above that is the sandy chert-free Little Cove Member. The Oriskany is either very thin here or completely absent, as no exposures can be found in the creek bed below the first exposures of Needmore and/or Millboro Shale.

In the interval of the Tonoloway Limestone to Helderberg Group part of the sequence at this exposure (i.e., above the Williamsport Sandstone and below the Millboro Shale), it is useful to determine the number of discrete sandstone-dominated beds that are present in the section. In addition, consider how the McKenzie Formation and Williamsport Sandstone here differ lithologically from the equivalent interval that we saw at Stop 1 where the “Eagle Rock sandstone” occupied much of this same stratigraphic interval. In addition, note the difference in small-scale structures here (a single wedge fault in the McKenzie Formation, Fig. 8B) versus the intricate wedge faulting and complexity of structures we saw at Stop 3 (Figs. 6, 8B).

Figure 9. Aerial view of the ledges of Silurian Rose Hill, Keefer, McKenzie, and Williamsport sandstones that form rapids in the gorge of the Bullpasture River, and as identified in the stratigraphic column shown in Figure 2. Images from Google Earth. (A) West limb of the Bullpasture Mountain anticline at the mouth of White Oak Draft. (B) East limb of the Bullpasture Mountain anticline just upriver from Williamsville (Stop 5).
Figure 10. Outcrops of Rose Hill, Keefer, McKenzie, Williamsport, Tomoloway, and Clifton Forge sandstones (Silurian) in and near the gorge of the Bullpasture River (Stop 5). (A) Nearly horizontal ledges of the Cacapon sandstone facies of the Rose Hill Formation in the Bullpasture River along the axis of the Bullpasture Mountain anticline. Photo by J. Haynes. (B) The massive ledge of Keefer sandstone on the east limb of the Bullpasture Mountain anticline on the north bank of the Bullpasture River. Photo by J. Haynes. (C) The massive ledge of McKenzie sandstone that forms Beaver Dam Falls in the Bullpasture River above Williamsville. Photo by J. Haynes. (D) The Williamsport Sandstone along State Road 678 in the Bullpasture River Gorge. Inset shows bedding planes with numerous ripple marks, which are a common sedimentary structure on many bedding surfaces of the Williamsport in this region. Photos by J. Haynes. (E) Flat-pebble conglomerate at the base of the Clifton Forge Sandstone where it unconformably overlies the uppermost lime mudstones of the Tonoloway Limestone in the Water Sinks Subway Cave west of the Bullpasture River Gorge (Stop 5). Photo by P. Lucas. (F) Cross-bedded calcarenaceous quartz arenite that separates the lower and middle members of the Tonoloway Limestone along State Road 614 near Burnsville southwest of the Bullpasture River Gorge (Stop 5), and which we correlate with the sandstone in the Tonoloway Limestone at Crizer Gap (Fig. 8D). Photo by J. Haynes. (G) Cross-bedded Clifton Forge Sandstone in the main stream passage of Aqua Cave at the west end of the Bullpasture River Gorge. This is near the northern extent of the Clifton Forge and its transition into the Big Mountain Shale, and most beds within the Clifton Forge in this vicinity are sandy limestones rather than sandstones (Stop 5). Photo by J. Haynes.
Alternate Stop 4B. The Jefferson Pools at Warm Springs
11.9 (109.1) Warm Springs, and the junction with U.S. 220.
0.0 (97.2) Continue west on State Highway 39.

Directions to Alternate Stop 4A and Alternate Stop 4B
(These are options if the weather limits our time at Crizer Gap.)

Alternate Stop 4A. Windy Cove Gap and Blowing Cave
38.00477° N, 79.63801° W

At this location, the upper Helderberg Group limestones are exposed both in the quarry and along the roadcut, as well as in the passages of Blowing Cave (a cave that was described in some detail by Thomas Jefferson in his 1785 publication Notes on the State of Virginia including a comment about the airflow at the cave entrance from which the cave takes its name), the entrances to which are in the quarry. The oldest unit exposed is the very thin New Creek Limestone with its large pink crinoids, which is overlain by the Healing Springs Sandstone and its distinctive anastomosing sandy laminae and beds (Fig. 8F). Above the Healing Springs Sandstone is the Licking Creek Limestone with the lower cherty Cherry Run Member and the upper sandy, and in places fossiliferous, Little Cove Member. Above this is the Oriskany Sandstone, and there are a few scattered hillside exposures of the Needmore Shale.

If we visit this exposure, things to consider in comparison with the prior four stops are the increased thickness of the Oriskany here and the presence of a prominent bed of collophane grains and pebbles in it, the very gradational nature of the Licking Creek–Oriskany contact, the change in the quartz-calcite ratio in the Healing Springs such that there is much more limestone in the Healing Springs here, and the extreme thinness (10s of cm) of the New Creek Limestone here.

Alternate Stop 4B. The Jefferson Pools at Warm Springs
38.05417° N, 79.78051° W

Like Blowing Cave, the thermal springs here were also mentioned by Thomas Jefferson in his 1785 publication Notes on the State of Virginia. These springs are some of the several thermal springs that occur along the length of the Warm Springs anticline, which topographically forms an anticlinal valley as it is floored by the soluble Ordovician carbonates from the Beekmantown Formation stratigraphically up section through the Nealmont Formation. At ~36 °C (96 °F) the springs here at Warm Springs are among the warmest in the valley, exceeded only by the thermal stream in Mud Pot in Alleghany County that was measured at 37 °C (99 °F) by James Madison University student Meghan Moss in January 2013, and the several thermal springs at Hot Springs, the hottest of which is “The Boiler” at 41 °C (106 °F).

The source of heat that warms these waters has been a source of speculation for decades, with one hypothesis (Dennison and Johnson, 1971) being heat that is radiated by the cooling of the magma chamber(s) associated with the igneous intrusions we will see on Day 2. The other prevailing hypothesis (Perry et al., 1979; Severini and Hunley, 1983) is that deeply circulating waters enter the Ordovician sequence at the Browns Mountain anticline (Fig. 1) in West Virginia, at elevations...
Active features along a “passive” margin, Highland and Bath Counties, Virginia

Figure 11.
~260 m higher than the floor of the Warm Springs Valley, and are then confined to the Ordovician stratigraphic interval and on their journey toward the various thermal resurgences in the Warm Springs Valley, are heated by the geothermal gradient.

**Mileage Directions (Cumulative)**

**Stop 5. Bullpasture River Gorge**
38.19913° N, 79.57322° W

At the roadcuts and riverbed exposures we will visit here on the east limb of the Bullpasture Mountain anticline, we will see all of the strata that at Eagle Rock (Stop 1) in Botetourt County were part of the massive “Eagle Rock sandstone” as well as the underlying Rose Hill Formation (Fig. 10A). Here at the Bath–Highland County line, there are now three distinct quartz arenites above the Rose Hill (Figs. 2, 3, 9, 10B, 10C, 10D), and their aggregate thickness is far less than the “Eagle Rock sandstone” at Stop 1. We will first examine the youngest of the three, the Williamsport Sandstone, along VA 678. At this exposure there is not a massive ledge as at Crizer Gap (Stop 4), but instead there are medium-bedded sandstones, many with ripple-marked bedding planes (Fig. 10D) and some with ostracode molds (Fig. 11D) that are variably filled with limonite derived from oxidation of pyrite that commonly has replaced the ostracode shells in the McKenzie and Williamsport of this region (Fig. 12B). There is appreciably more mudrock in the Williamsport here than at Crizer Gap (Stop 4) or in the “Eagle Rock sandstone” at Eagle Rock (Stop 1).

The second sandstone we will see is the unnamed middle sandstone member of the McKenzie (Figs. 2, 3, 9, 10C, 12A) that we have identified in this region, thus pushing its known geographic extent well into Highland County several tens of km north of its prior known northernmost extent, at Muddy Run in central Bath County (Fig. 3). Here the sandstone is a silica-cemented quartz arenite that forms the prominent ledges at Beaver Dam Falls in the Bullpasture River as well as one of the prominent ledges along VA 678.

The third sandstone we will see is the Keefer Sandstone, which likewise forms a prominent ledge in the riverbed (Fig. 9) and along VA 678. It is also a silica-cemented quartz arenite, and it is underlain by hematite-cemented maroon quartz arenites of the Cacapon lithofacies of the Rose Hill Formation (Figs. 9, 10A). The Cacapon sandstones are colored thusly from the strong pigmenting action of the hematite, even though the hematite is just a coating on the quartz framework grains as seen in thin section (Fig. 11F). The thin section also shows why these sandstones have no value as an iron ore—a question asked not infrequently by students and others—and the answer is very straightforward: The ratio of hematite to quartz is uneconomically low. Along VA 678 we will also examine the dark-gray quartzose oolitic grainstones of the lower McKenzie that overlie the Keefer and are 6–8 m thick (Figs. 12C, 12D). These form prominent ledges with small solution openings along the road, and just a few km south of the road atop Round Hill, there are additional small caves developed in these oolitic McKenzie limestones. The presence of this oolitic grainstone lithofacies here suggests that it may likewise be present in the subsurface to the west between this outcrop and the core described by Smosna (1984) from an area where active hydrocarbon production in the Silurian occurs.

At these exposures, compare and contrast the stratigraphic sequence with what we saw at Eagle Rock (Stop 1) and Crizer Gap (Stop 4), and look for the lithologic criteria (some of them being quite subtle) that along with stratigraphic position might be used to identify and differentiate these sandstones from each other. It is also worthwhile to look at the thin-bedded shales which occur at the Rose Hill–Keefer contact and which may represent a feather edge of the Rochester Shale.

**Stop 6. Bluegrass and Forks of Waters**
38.48811° N, 79.52744° W

At this long series of roadcuts (Fig. 13) on the east limb of the Wills Mountain anticline, we will see a long section of the Silurian from the Rose Hill up into the Tonoloway, with very good although not continuous exposures. Our focus will be on the hematitic ferroan dolomite of the Keefer at the west end of the exposures, the shaly McKenzie, the quartz arenites of the Williamsport, the thick Wills Creek Formation, and the lime mudstones of the lower Tonoloway. The Keefer here consists of some quartz grains, but they are cemented by ferroan dolomite (Fig. 11E), not silica. In addition, ooids of chamosite and/or berthierine (Fig. 11E) and hematite are present, making this exposure a thin but distinctly unambiguous occurrence of the Clinton iron ore lithofacies (Brett et al., 1998) that elsewhere in the Appalachians, e.g., upstate New York and Birmingham, Alabama, has been mined for many decades.

The McKenzie at this stop has no sandstone, only shales and shaly limestones, which are not well exposed. The uppermost McKenzie that is exposed immediately beneath the lowest quartz
Figure 12. Photomicrographs of the middle sandstone and oolitic and bioclastic grainstones in the McKenzie Formation from Highland County. All samples have been stained with the standard Dickson method. (A) Bimodal texture of quartz framework grains, with the larger grains being more rounded than the smaller grains. Middle sandstone, plane-polarized light (PPL), Jack Mountain west of McDowell, Highland County. (B) Moderately to extensively pyritized ostracode shells, typical of these bioclastic grainstones. Note the presence of late stage ferroan dolomite cements that reduced much of the remaining interparticle pore spaces that had initially been reduced by non-ferroan calcite. Limestones in the lower McKenzie, PPL, from Lower Gap, Highland County. (C) Quartzose oolitic grainstone in which many ooids have radial textures that probably indicate elevated salinity. A few ooids are superficial, some have cores of echinoderm fragments, and others have cores of siltstone SRFs (sedimentary rock fragments) or quartz silt grains. Limestones in the lower McKenzie, PPL, from the gorge of the Bullpasture River along State Road 678 (Stop 5). (D) Quartzose oolitic grainstone showing a variety of cements that reduced interparticle pores during diagenesis. Cementation by carbonate minerals began with an initial non-ferroan and probably meniscus fibrous cement (pink colored) that formed thin coatings on many of the ooids. It was followed by ferroan calcite (lilac colored) that appreciably reduced much of the remaining interparticle porosity, and the final cement is baroque ferroan dolomite (patchy blue color). Many of the quartz grains have some quartz overgrowths on them. Compare this photomicrograph and Figure 12C above with the photomicrographs in figures 6C and 8D of Smosna (1984, p. 33, 45), which show texturally similar ooids in the Lockport oolite complex of West Virginia. Although these ooids in the McKenzie of Highland County are probably older than the Lockport oolites, they were evidently deposited in a very similar facies as the oolitic grainstones of the Lockport farther west, implying a westward transgression of the oolite complex with time. Limestones in the lower McKenzie, PPL, gorge of the Bullpasture River along State Road 678 (Stop 5).
arenite of the Williamsport is a green mudrock with abundant white speckles that give this bed a texture consistent with a paleosol, possibly one in a semi-arid environment in which calcite or even some evaporite minerals formed small clumps and nodules in the soil.

The Williamsport forms a low hogback in this vicinity by virtue of the sandstone’s erosional resistance, but the total thickness of quartz arenites is less than 10 m, vastly diminished from the “Eagle Rock sandstone” at Eagle Rock (Stop 1) and the Williamsport at Crizer Gap (Stop 4). Above the Williamsport here is the ~60-m-thick Wills Creek Formation, which we have not seen at other stops because it is thin to absent in areas south of here, and the thinning seems to occur quite abruptly (Fig. 3). It is a heterogeneous unit that consists of ostracode grainstones and laminated lime mudstones, and siliciclastic mudrocks and thin calcarenaceous quartz arenites with common ostracode shell fragments as framework grains. Look for sedimentary structures in the Wills Creek including domal LLH (laterally linked hemispherical) stromatolites, gutter casts, ripple marks, lenses of ostracode debris, and possibly some hummocky cross-stratification. Collectively, these structures suggest shifting depositional environments from a storm-dominated shelf to supratidal flats with stromatolitic microbial mats. The Wills Creek–Tonoloway contact is readily identified by the change from a sequence of shaly weathering strata to a sequence of thin- to medium-bedded bluish-gray lime mudstones.

Figure 13. Sketch of the exposure along VA 642 in northern Highland County between Forks of Waters and Bluegrass (Stop 6), showing formational boundaries of the stratigraphic units and selected lithologic features in certain beds. Compare the thickness (or thinness) of the Williamsport Sandstone here with the “Eagle Rock sandstone” at Eagle Rock (Stop 1). The Williamsport and thinner sandstones in the Wills Creek Formation are the only quartz arenites at this location in the “Eagle Rock sandstone” stratigraphic interval, as the Keefer and McKenzie have changed facies into other lithologies (modified from figure 10 of Diecchio and Dennison, 1996).

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<td>0.0 (144.5)</td>
<td>Turn around and drive east on VA 642.</td>
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<tr>
<td>7.2 (151.7)</td>
<td>Return to Monterey via VA 642 and U.S. 220. Monterey, and the junction with U.S. 250. Turn west (right) on U.S. 250 and park in front of the Highland Inn (68 West Main Street, Monterey, Virginia).</td>
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<td>0.2 (151.9)</td>
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END OF DAY 1 ROAD LOG.

Day 2

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<td>Depart Highland Inn on U.S. 250 heading west.</td>
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<td>0.1 (0.1)</td>
<td>Junction with VA 636 (Spruce Street). Turn south (left) on VA 636.</td>
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<td>0.6 (0.7)</td>
<td>Park at base of hill on private property.</td>
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Stop 7. Trimble Knob Diatreme
38.4048° N, 79.5881° W

Trimble Knob is on private property. Request permission from landowner for access.

Trimble Knob was previously called Pyramid Hill due to its angular shape (Darton, 1899; Rader et al., 1986). A transect from west to east reveals a texturally heterogeneous cross section that likely influenced the resulting geomorphology of the hill. On the western side of the peak of the hill is exposed aphanitic-porphyritic basalt containing augite and olivine phenocrysts in a devitrified matrix containing microphenocrysts of plagioclase. The basalt forms poor- to moderately developed nocrysts in a devitrified matrix containing microphenocrysts of plagioclase. The basalt exhibits complex columnar jointing patterns, including a set of subhorizontal, curving columns that extend across the central portion of the outcrop (Fig. 16A). It has been suggested (Johnson et al., 1971; Rader et al., 1986) that this dike changes to a

Stop 8. Hightown Dike
38.4295° N, 79.6167° W

At this location in the Hightown and Blue Grass Valleys along the Wills Mountain anticline, a cross section through an aphanitic basaltic dike within the Ordovician Beekmantown Formation is observed in outcrop. The dike is visible to the west within a creek bed, and also extends up the hillside to the east of the outcrop. The dike has an orientation of N53°W that is nearly perpendicular to the orientation of the Wills Mountain anticline fold hinge (approximately N30°E) and clearly cross-cuts the prevalent bedding orientation. This is in contrast to the sills and dikes oriented roughly parallel to the fold hinges and bedding that we will observe nearby, including within the Hightown Quarry (Stop 9). Southworth et al. (1993) proposed that dikes such as this one oriented perpendicular to the regional strike exploited deep fracture systems within the lower crust during ascent. While such deep fracture systems are likely to exist, we hypothesize that formation of a doubly plunging fold, such as the Wills Mountain anticline, would produce fractures perpendicular to the fold hinge, and this dike could have exploited one of these fractures within the shallow crust.

Miarolitic cavities >2 cm across and smaller amygdules containing calcite and zeolites (Johnson et al., 1971; Rader et al., 1986) are observed within the dike. Small ~1 cm xenoliths of limestone are also entrained within the basalt. The dike exhibits complex columnar jointing patterns, including a set of subhorizontal, curving columns that extend across the central portion of the outcrop (Fig. 16A). It has been suggested (Johnson et al., 1971; Rader et al., 1986) that this dike changes to a...
more andesitic composition on its eastern end, but given the adjacent exposure of bimodal compositions elsewhere in the Blue Grass Valley, and the lack of outcrop between the basaltic and andesitic segments (Rader et al., 1986), we prefer to interpret any nearby felsic rocks as separate intrusions.

Along the way to the quarry we will observe low-lying hills to the west of Blue Grass Valley Road; these hills contain multiple felsic and mafic dikes and plugs intruded into the Ordovician Beekmantown Formation. These dikes, sills, and plugs align roughly parallel to the regional strike, and are interpreted to intrude an overturned anticline (Wilkes, 2011). Within the abandoned quarry, at least three felsic sills and a basaltic dike intrude the carbonate rocks of the Beekmantown Formation. Bedding is near-vertical and dipping to the NW on the west side of the quarry, but beds dip more shallowly to the SE near the top of the quarry (Wilkes, 2011). A thin basaltic dike cross-cuts the Beekmantown bedding planes, and is offset just above the debris slope. Two felsic dikes run across the quarry wall.

Exposed on the north end of the quarry is a highly brecciated felsic sill and a small 15–20-cm-wide felsic sill, which intrude parallel to the near-vertical bedding of the Beekmantown. Fingers of obsidian extend from the brecciated sill, and

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**Mileage Directions (Cumulative)**

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<td>0.8 (7.4)</td>
<td>Junction with VA 640, Blue Grass Valley Road. Turn north (right) on VA 640.</td>
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<td>2.2 (9.6)</td>
<td>Park in wide pullout on the east (right) side of the road in front of quarry.</td>
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**Stop 9. Hightown Quarry**

38.4554° N, 79.6075° W
both sills exhibit glassy chill margins at contacts with the country rock (Fig. 16B).

The felsic dikes at this location are trachydacites containing phenocrysts of alkali and plagioclase feldspar as well as biotite and amphibole (Fig. 14). The amphibole phenocrysts show little evidence of dehydration reaction rims with the magma, suggesting rapid ascent during the last stage of eruption from at least 7 km depth (Rutherford and Hill, 1993; Bulas and Johnson, 2012).

### Mileage Directions

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<td>Junction with U.S. 250. Turn east (left).</td>
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<td>5.7 (17.5)</td>
<td>Stop in Monterey for restrooms. Continue east on U.S. 250.</td>
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<tr>
<td>13.9 (31.4)</td>
<td>Junction with VA 614, Cowpasture River Road. Turn north (left) on VA 614.</td>
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<td>8.5 (39.9)</td>
<td>Virginia/West Virginia state line. VA 614 becomes WV 21, Sugar Grove Road. Continue north on WV 21.</td>
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<tr>
<td>1.7 (41.6)</td>
<td>Park on left side of road just south of the basalt outcrop.</td>
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**Stop 10. Steeply Dipping Sill or Dike near Turkey Farm**

38.4479° N, 79.3563° W

At this location, a basaltic sill or dike intrudes the Devonian Millboro Shale (Fig. 16C) on the western limb of a complex antiformal structure (McDowell et al., 2004). The Millboro Shale at this location dips 44° SE, toward the road, and it contains 60–120° jointing. The igneous body is intruded parallel to bedding as a sill in the cross-sectional exposure, but it dips below the shale to the south, and it also disappears beneath the surface exposure at the top of the hill, thus giving it characteristics of a dike as well. The intrusion exhibits jointing perpendicular to the contact with the shale.

Miarolitic cavities and amygdules within the basalt are aligned in bands that are roughly parallel to the edges of the intrusion. These cavities contain calcite, aragonite, barite, pyrite, and many zeolites including notronite, analcites, thomposonite, mesolite, harmotome, and chabazite (Kearns, 1993).

### Mileage Directions

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<td>0.0 (41.6)</td>
<td>Continue north on WV 21 (Sugar Grove Road).</td>
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<tr>
<td>2.4 (44.0)</td>
<td>Park in pullout across from church.</td>
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**Stop 11. Trachybasalt Plug at Wilfsong (St. Michael) Church (Optional)**

38.4743° N, 79.3323° W

A trachybasalt containing clinopyroxene, plagioclase, and olivine is visible at this location. It is intruded near the contact of the Devonian Millboro/Needmore Shale and the overlying Devonian Brallier Formation. The brecciated contact zone between the igneous rock and shale is exposed in places along on the south side of the intrusion and at the top of the small hill. The trachybasalt has massive, blocky jointing, and is Eocene in age. The rock might be more properly called a gabbro, as it is composed of interlocking plagioclase and clinopyroxene crystals. Some augite crystals exhibit carbonate inclusions in thin section, similar to those found at Trimble Knob.

### Mileage Directions

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<td>0.0 (44.0)</td>
<td>Continue north on WV 21 (Sugar Grove Road).</td>
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<td>1.1 (45.1)</td>
<td>Park near outcrop; only limited turnout space is available.</td>
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</table>

**Stop 12. “Mica Pyroxenite” Basanite Dike Containing Crustal Xenoliths near Sugar Grove**

38.4869° N, 79.3249° W

The dike at this location cross-cuts the sandstone and shale of the Devonian Brallier Formation (McDowell et al., 2004) and has blocky jointing. It has been dated at 149 Ma using Ar-Ar geochronology (Southworth et al., 1993) and is therefore 100 m.y. older than the other igneous rocks observed on this trip. This dike is similar in age to other Late Jurassic dikes exposed in Augusta County, Virginia, to the southeast of this location (Johnson et al., 1971; Southworth et al., 1993). The origin of these Late Jurassic dikes is also puzzling, because they postdate the 200 Ma Central Atlantic magmatic province (McHone, 2000) magmatism associated with the rifting of Pangea by 50 m.y.
In addition to its perplexing age, the mineralogy and appearance of this igneous rock is unusual. Garnar (1956) referred to this rock as a “mica pyroxenite” due to its mineralogy, but it would likely be classified as a hydrous basanite using the modern International Union of Geological Sciences classification. The rock contains abundant microphenocrysts of mica and plagioclase as well as larger mica, almost colorless pyroxene (Garnar, 1956), and amphibole phenocrysts. The cleavage planes of the mica and plagioclase give the rock a sparkling appearance in hand sample. Small (>0.5 cm) vesicles and amygdules are common.

Also within the dike are large (>1 cm) xenocrysts of black augite, and felsic lower crustal xenoliths that range from <1 cm up to several cm in width (Fig. 16D). The xenoliths are either igneous granitoids or granulite-facies gneiss, and they contain feldspar and quartz and are granular in appearance.

Figure 16. Exposures of igneous rocks in Highland and Pendleton Counties. (A) Subhorizontal curved columnar jointing in the Hightown basaltic dike (Stop 8). Rock hammer ~40 cm long is at the center of the image. (B) Contact between a trachydacite sill and the limestone of the Beekmantown Formation in the Hightown Quarry at Stop 9. A chilled margin of black obsidian is present near the contact. (C) Steeply dipping basaltic sill (top) in contact with the Millboro Shale (bottom) near Sugar Grove at Stop 12. A rock hammer ~40 cm long lies on the cleavage surface of the shale at mid-to lower-left of the image. (D) Angular granitic xenolith (light color, center-right of image) within a mica pyroxenite dike just south of Sugar Grove at Stop 12.

Mileage | Directions (Cumulative)
---|---
0.0 (45.1) | Continue north on WV 21 (Sugar Grove Road).
12.5 (57.6) | Brandywine, and the junction with U.S. 33. Turn east (right) on U.S. 33.
24.4 (82.0) | Junction with VA 734 (Bank Church Road). Turn south (right) on VA 734.
Active features along a “passive” margin, Highland and Bath Counties, Virginia

0.0 (87.0) Turn right onto South High Street from Memorial Hall parking lot.
0.4 (87.4) Turn left onto Port Republic Road.
0.9 (88.3) Turn right to merge onto I-81 south, and drive back to Blacksburg.

END OF DAY 2 ROAD LOG.

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