Appalachian Basin Stratigraphy, Tectonics, and Eustasy from the Blue Ridge to the Allegheny Front, Virginia and West Virginia

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Field Trip Guide FTG-10

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FRONT COVER: The Silurian Tuscarora Sandstone cropping out on the northwest limb of the Hanging Rock anticline at Baker, West Virginia, **Stop 1-3** of the field trip

INTRODUCTION

This two-day field trip was organized in conjunction with the 2015 Geological Society of America annual meeting in Baltimore, Maryland. The field trip explores the tectonic, eustatic, and depositional history of Paleozoic strata in the Appalachian Basin through examination of selected exposures of sedimentary strata along a southeast to northwest traverse across regional strike of the Appalachian Basin in the Blue Ridge, Valley and Ridge, and Appalachian Plateau provinces of western Virginia and eastern West Virginia (**Figure 1**). By visits to exposures of Neoproterozoic through Pennsylvanian strata (**Figure 2**), this field trip examines evidence that supports current interpretations of some of the major tectonic events in the history of eastern North America, including the rifting of Rodinia, and the Taconian, Acadian, and Alleghanian orogenies. These particular events were accompanied by the accumulation of appreciable volumes of siliciclastic sediments in diverse depositional environments (fluvial, deltaic, beach, shallow shelf, basin margin) along the eastern margin of Laurentia. This contrasts with the intervening periods of relative tectonic quiescence, times during which thick sequences of carbonate sediments accumulated over very widespread areas of the Appalachian Basin, also in a diverse array of depositional environments (sabkha, peritidal, shelf, slope, basin margin). The field trip stops focus on key intervals that record major tectonic and/or eustatic events of this region including the Sauk, Tippecanoe, and Kaskaskia sequences of Sloss (1963) and Wheeler (1963), and their bounding unconformities.

Eight of the ten stops on this trip are located at road cuts along the recently constructed US Highway 48 (also known as Corridor H), which are just a selection of the many spectacular exposures along this road. At the time of writing, this field trip guidebook showcases much of the stratigraphic section in the central Appalachian Basin in a nearly unweathered state. The humid, temperate climate of this region results in relatively rapid weathering of road cuts, and so there are relatively few localities in the Appalachian Basin where superb exposures of stratigraphic sections such as these can be examined over long distances.

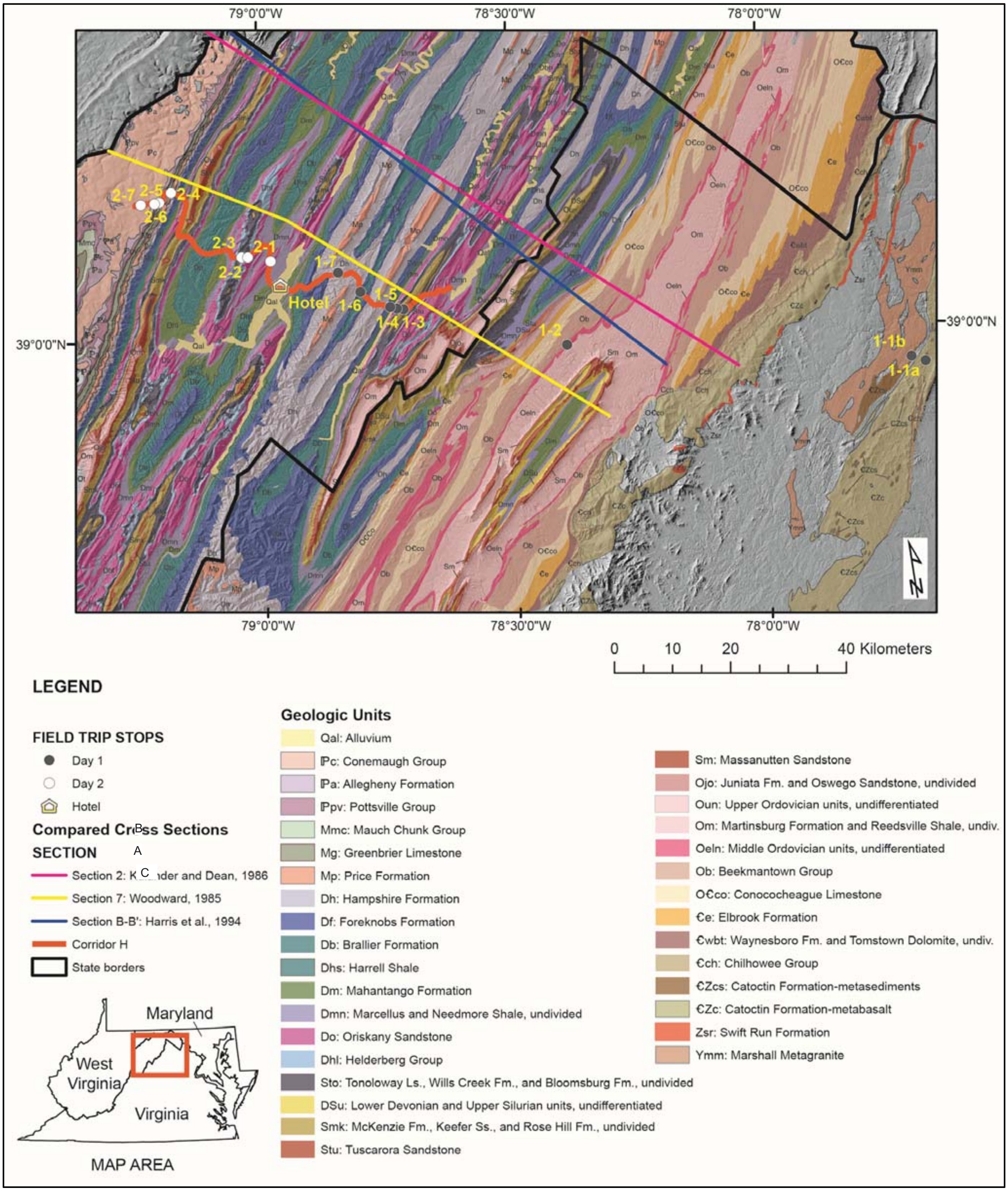


Figure 1: Field-trip stops on geologic map of West Virginia (Cardwell, et al, 1986). Lines of cross section presented in Figure 3 are also shown.

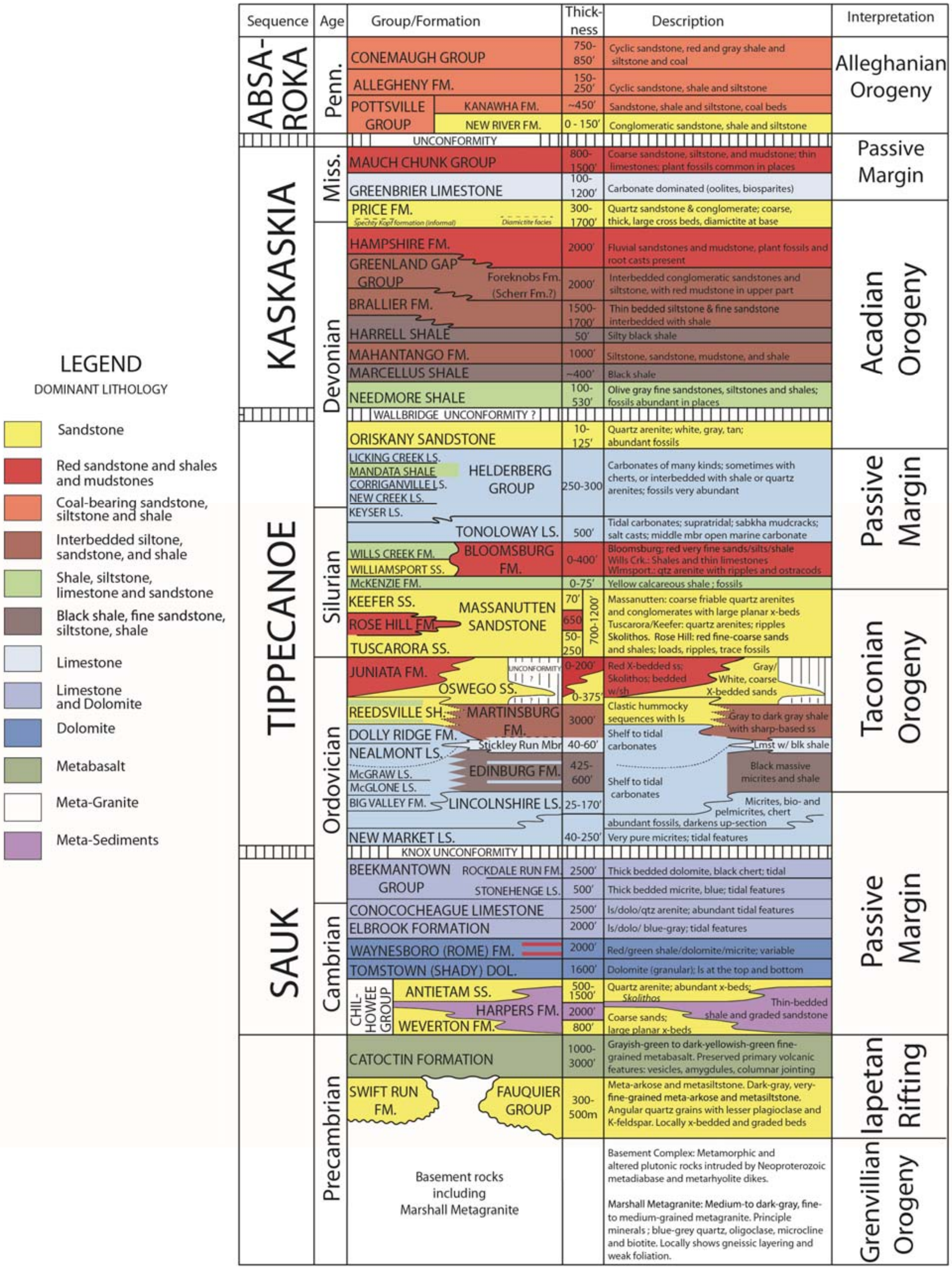


Figure 2: Generalized stratigraphic chart for the central Appalachian Basin and units seen on this trip (modified from Fichter and Diecchio, 1993).

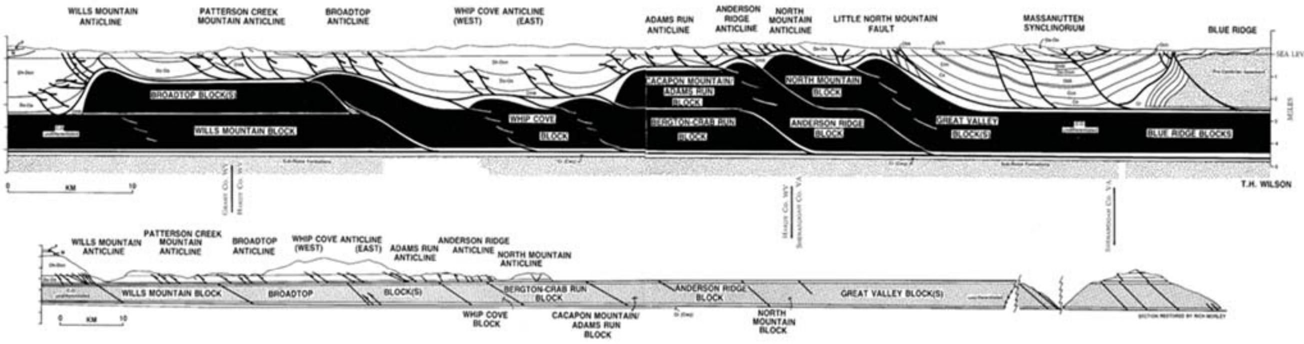
At the stops on this field trip, there is evidence for deformation at multiple scales, including faults and folds in hand samples, anticlines and synclines in individual road cuts, and larger regional structures such as the Blue Ridge anticlinorium, the Hanging Rock anticline (Front Cover), the Patterson Creek Mountain anticline, and the Whipcove anticline (**Figure 3**). Please note that the stratigraphic nomenclature used herein is that recognized and used by the West Virginia Geological and Economic Survey; the nomenclatural usage in surrounding states and by the US Geological Survey can – and sometimes does – vary from the stratigraphic nomenclature used in this field guidebook.

BACKGROUND AND GEOLOGIC SETTING

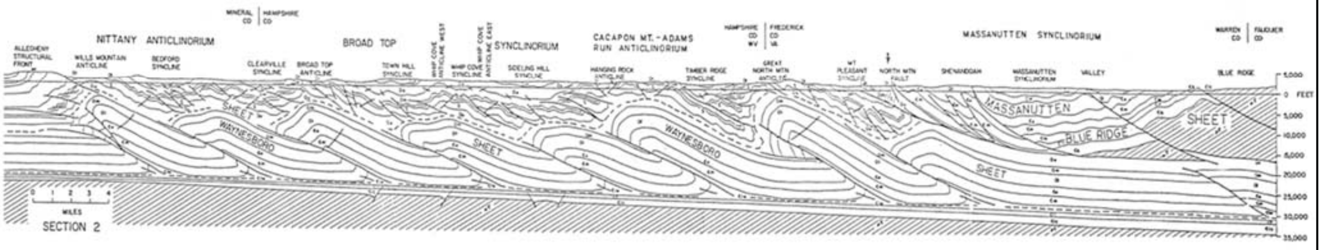
In the mid-Atlantic region, the Appalachian Highlands are divided into four distinct physiographic provinces, which from east to west are: the Piedmont, the Blue Ridge, the Valley and Ridge, and the Appalachian Plateaus (Fenneman and Johnson, 1946). This trip traverses parts of each of these provinces, and makes stops in the latter three. Major geologic aspects of the Blue Ridge, Valley and Ridge, and Appalachian Plateaus provinces are summarized and discussed below, and the stratigraphic succession is shown in **Figure 2**.

Blue Ridge Province

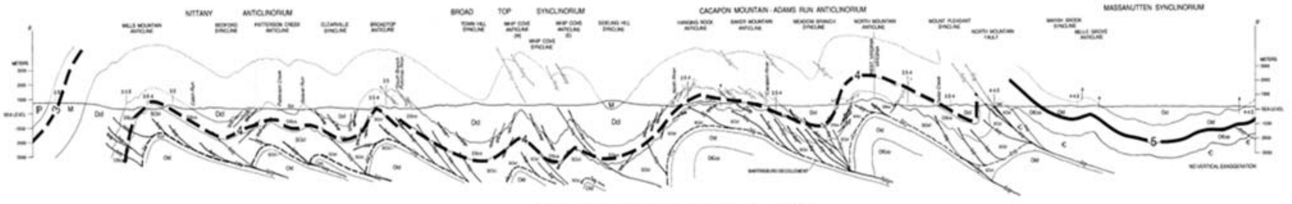
The basement rocks of the central Appalachian Basin are exposed in the Blue Ridge province. These are among the older rocks in the entire Appalachian Mountain belt, with granitic gneisses and charnockites in the Blue Ridge having crystallization ages that range from 1198 Ma to ~1040 Ma (Bailey et al., 2006; Whitmeyer et al., 2015). From its northern terminus near Carlisle, Pennsylvania, southward to the vicinity of Lynchburg, Virginia, the Blue Ridge Province can be characterized structurally as an anticlinorium. Therefore, in much of this region the Blue Ridge province (which continues southward to Georgia) consists of a regionally persistent antiformal metamorphic basement complex and Cambrian cover rocks that have been detached and thrust to the west and northwest over younger Paleozoic rocks (**Figure 3**). Within the core of the Blue Ridge anticlinorium are metamorphosed Mesoproterozoic granitoids, which are overlain by a Neoproterozoic to Lower Cambrian cover sequence of metasedimentary rocks, including arkosic sandstone and mudrock (seen at **Stop 1-1)**. Metamorphism of up to lower greenschist facies has extensively altered and recrystallized the phyllosilicate minerals of the matrix in the arkosic sandstone and in the mudrock (many of which are true slate and phyllite). In contrast, metamorphism had less effect on the quartz and feldspar framework grains, with the most notable effects being recrystallization of grain edges, as seen in thin sections of the Lower Cambrian cover including the Swift Run Formation and Weverton Formation (Johnson et al., 2013). Strain shadows, a product of deformation, can likewise be observed in the same thin sections.



A. Section from Woodward (ed.), 1985



B. Section from Kulander and Dean, 1986



C. Section from Harris et al., 1994

Figure 3: Interpretive structural cross sections through the Valley and Ridge province in the area of the field trip, from the reference cited below each cross section.

Valley and Ridge Province

The Valley and Ridge province is a classic fold-and-thrust belt (**Figures 1 and 3**) that is characterized physiographically by a series of northeast-trending linear parallel ridges and valleys. With very few exceptions, these ridges are held up by erosionally resistant sandstone, and throughout the region the main ridge-forming stratigraphic unit is the Silurian Tuscarora Sandstone. Subordinate ridges with lower elevation ridge crests are held up by other sandstones, most commonly the Devonian Oriskany Sandstone, the Devonian Hampshire Formation, or the Devonian-Mississippian Price Formation. The valleys are underlain either by mudrock, which is more susceptible to physical weathering and erosion, or by carbonate rocks, which are more susceptible to chemical weathering and erosion. There are two principal valley-forming mudrock sequences, the Ordovician Martinsburg Formation (McBride, 1962) and its partial facies equivalent to the west, the Reedsville Shale and the Devonian Marcellus Shale and Mahantango Formation (Zagorski et al., 2012). There are three principal valley-forming carbonate sequences: (1) the Cambrian and Ordovician carbonate sequence that includes (from oldest to youngest) the Tomstown (Shady) Dolomite, the Waynesboro (Rome) Formation, the Elbrook Formation, the Conococheague Limestone, the Beekmantown Group, the New Market Limestone, the Lincolnshire Limestone, and the Edinburg Formation and its facies equivalents to the west, the Big Valley Formation, and the McGlone, McGraw, and Nealmont Limestones (Read, 1980, 1989; Read and Repetski, 2012; Haynes et al., 2014); (2) the Silurian and Devonian carbonate sequence that includes the Tonoloway Limestone and the Helderberg Group (Dorobek and Read, 1986; Bell and Smosna, 1999); and (3) the Mississippian carbonate sequence that includes the Greenbrier Limestone and its regional equivalents (Brezinski, 1989; Wynn and Read, 2007, 2008). These Paleozoic sedimentary strata now exposed along the valley bottoms, flanks, and ridge crests in the Valley and Ridge have undergone a long history of deposition, burial, deformation, and now exhumation (Bailey et al., 2006; Whitmeyer et al., 2015). As a result, the valleys and the ridges that form strikingly parallel landforms today result in a very distinctive landscape that is the product of differential weathering of a thick sequence of variably erosionally resistant siliciclastic and carbonate strata.

Appalachian Plateaus Province

The Allegheny Plateau, which is seen during only a small part on this trip, is a major part of the Appalachian Plateaus province. The Allegheny Plateau is underlain by essentially flat-lying strata, and in much of the region these strata are predominately of Mississippian and Pennsylvanian age (**Figure 1, Figure 3 A, B**). Throughout the region, the strata of the Allegheny Plateau have been broadly uplifted and in some areas broadly folded as well, but in general these strata are only minimally deformed. This minimal deformation is in great contrast to the strata of the adjacent Valley and Ridge province, which have been deformed by extensive folding and faulting. The relatively abrupt transition from the Valley and Ridge to the Allegheny Plateau occurs at a regionally extensive structural transition known as the Allegheny Front, which extends from north-central Pennsylvania southwestward into Tennessee and which marks the westward limit of deformation associated with the compressional events that produced the folding and faulting in the Valley and Ridge province (**Figures 1 and 3**). The Allegheny Front in West Virginia marks the eastern and highest part of the "eastern high plateau," which stands in contrast to the lower western plateau and the lower Valley and Ridge province.

TECTONIC AND EUSTATIC HISTORY

Several stratigraphic intervals will be seen at the stops on this field trip. The outcrops at each stop help us understand the large-scale tectonic events during Appalachian history and provide a broad view of more than a billion years of geologic history.

Precambrian Iapetan Rifting: The Breakup of Rodinia

Our tectonic-eustatic narrative begins with the rifting of the supercontinent Rodinia, an event that occurred at approximately 800 Ma (Bailey et al., 2006). This widespread rifting along the eastern margin of Rodinia is recorded initially by deposition of arkosic sand and mud of the Neoproterozoic Fauquier Group and its stratigraphic equivalent, the Swift Run Formation, into low areas on the eroded surface of the crystalline basement rocks, which in this area include granitic gneisses of the Marshall Metagranite. **Stop 1-1b** is a series of discontinuous exposures of the Marshall Metagranite and the Fauquier Group, including a Mesozoic diabase dike that cuts the Marshall Metagranite. During and subsequent to deposition of the Fauquier Group rifting of Rodinia continued and sea-floor spreading began along the rifts. This resulted in eruptions of voluminous flood basalts of the Catoctin Formation (**Stop 1-1a**) across an extensive area of the eastern margin of Laurentia. These basalts (now metabasalts) of the Catoctin Formation are a major part of the Catoctin volcanic province (Badger and Sinha, 2004) and they occur as a discrete unit in the Blue Ridge province from southern Pennsylvania to central Virginia, and as metabasalts of the same approximate age interbedded with the Unicoi Formation of southwestern Virginia and northeastern Tennessee (Brown and Van der Voo, 1982).

Cambrian-Ordovician Passive Margin: Development of the Great Laurentian Carbonate Bank

As rift-related sedimentation and volcanism waned and eventually ended in the Early Cambrian, marine waters of the Iapetan Sea transgressed much of the Laurentian shelf and a passive margin setting developed as the landmass that became the eastern edge of Laurentia continued to drift away from the rest of the Rodinia landmass. This setting persisted from about 560 Ma to 475 Ma, and during this time a carbonate depositional regime slowly replaced the initial siliciclastic-dominated depositional regime. The super-mature quartz arenites of the Antietam Sandstone (the uppermost unit of the Chilhowee Group) were the last predominantly siliciclastic sediments that accumulated along the Laurentian margin during the next tens of millions of years (**Figure 2**).

The Cambrian and Ordovician carbonates were deposited primarily in shallow shelf to nearshore peritidal environments (Read and Repetski, 2012). In fact, carbonates of similar origin accumulated across much of Laurentia during this time. Ordovician peritidal carbonate strata are capped by the regionally widespread Knox unconformity, which developed on top of the Beekmantown Group and correlative carbonate units throughout much of eastern North America (Mussman and Read, 1986; Swezey, 2002). In the area of this field trip, the Knox unconformity is overlain by carbonates of the New Market Limestone and Lincolnshire Limestone, which are interpreted in Virginia as deeper water tidal flat to open shelf deposits (Read, 1980). Above the Lincolnshire is the Edinburg Formation, a sequence of limestones and mudrocks interpreted as deeper ramp and slope deposits (Read, 1980). Several thin beds of altered volcanic ash at its base are evidence of subduction-related volcanism along a magmatic arc (Haynes et al., 1998), which suggests that the passive margin – in existence since the Early Cambrian – was transitioning into an active margin. In eastern West Virginia, the Edinburg Formation is correlated with carbonates of the Big Valley Formation, the McGlone Limestone, the McGraw Limestone, and the Nealmont Limestone (Kay, 1956; Perry, 1972; Haynes et al., 2015b)

The Ordovician-Silurian Taconian Orogeny

Siliciclastic strata become more prevalent above the Edinburg Formation and its equivalents to the west, and deposition of these Upper Ordovician and Lower Silurian siliciclastic strata is generally linked to tectonic uplift associated with the Taconian orogeny (Swezey, 2002). The appearance of fine-grained siliciclastic strata (Martinsburg Formation and Reedsville Shale) is interpreted as corresponding with sediment accumulation in a distal foredeep, and the appearance of coarse-grained siliciclastic strata (e.g., Tuscarora Sandstone) as corresponding with sediment accumulation in a proximal foredeep (Chapman and DeCelles, 2015). Regardless of the true cause and effect behind sediment-tectonic correlations, Ordovician carbonate sedimentation ultimately ended as the influx of siliciclastic sediments, in tandem with the deepening of the water column, overwhelmed the carbonate depositional system. Along the eastern margin of the foredeep in Virginia, turbidites associated with submarine fan development were deposited as the Martinsburg Formation (McBride, 1962; Rader and Henika, 1978) above the deep ramp and basin margin carbonates of the Edinburg Formation. To the west, the depth of the basin was never as great as in the east and, instead of turbidites, the sediments of the Reedsville Shale accumulated in mixed carbonate and siliciclastic shelf settings that were disrupted by storms, leading to the development of tempestites (Kreisa, 1981; Kreisa and Bambach, 1982; Lehman and Pope, 1989).

During this time, one or more magmatic arcs developed in the Iapetan Ocean along a subduction zone located along the edge of the approaching Taconic landmass and between that landmass and the Laurentian margin. Tephras that erupted from volcanoes along the arc are now altered to potassium bentonites (K-bentonites; Haynes, 1994; Haynes et al., 1998). As convergence continued, subduction evolved into collision between the Laurentian continental crust and the continental crust of the Taconic terrane or microcontinent, and volcanic activity along the magmatic arc ended. This was followed by acceleration of the weathering and erosion of the arc and of the Taconic highlands (Haynes et al., 1998), which began to produce voluminous amounts of siliciclastic sediments. These sediments were subsequently transported into the foredeep where they buried the older Ordovician platform carbonates (Rader and Henika, 1978; Diecchio, 1985b, 1986). **Stop 1-2** shows the vertical transition from peritidal carbonates deposited in shallow water to basin margin turbidites deposited in deep water, and some of the interbedded K-bentonites.

The coarse siliciclastic sediments of the Upper Ordovician Taconic clastic wedge accumulated to varying thicknesses in this region, where they now comprise the lithic and sublithic arenites of the Oswego Sandstone and the Juniata Formation (Drake et al., 1989). Those units are succeeded by the cleaner and generally finer grained mature silica-cemented quartz arenites of the Tuscarora Sandstone, the oldest Silurian unit in this region. Although a few trace fossils can be found in the Tuscarora Sandstone, the first identifiable body fossils of Silurian age are in the overlying Rose Hill Formation (Woodward, 1941), a sequence of marine shales and interbedded hematite-cemented quartz arenites, part of the widespread Silurian “Clinton” ironstone facies (Van Houten, 1990).

Owing to the lack of biostratigraphic control, the Ordovician-Silurian boundary in this region is uncertain. Thus it has been placed at the contact between the Juniata Formation and the overlying Tuscarora Sandstone (Diecchio, 1985b), or at the unconformity within the Tuscarora Sandstone at the contact of the “lower” Tuscarora and “upper” Tuscarora (Dennison et al., 1992; Dorsch et al., 1994; Dorsch and Driese, 1995). The Tuscarora Sandstone is overlain by the Rose Hill Formation, and in turn overlain by the Keefer Sandstone, with the Keefer being essentially the youngest siliciclastic unit of the package of upper Ordovician-lower Silurian strata. Harris et al. (1994) placed the lower Silurian-upper Silurian boundary (possibly correlative with the Wenlock-Ludlow boundary) at the contact between the Keefer Sandstone and the overlying McKenzie Formation.

Silurian-Devonian Inter-Orogenic Calm: Return to a Carbonate Depositional System

As Taconian tectonism ended, the supply of siliciclastic sediments diminished, and deposition evolved toward a mosaic of shallow marine environments characterized by quartz sand, siliciclastic mud, and some carbonate sediments (Woodward, 1941, 1943; Patchen, 1974; Patchen and Smosna, 1975; Smosna and Patchen, 1978). There are carbonate sediments of diverse types in the McKenzie Formation including quartzose oolitic grainstones, ostracode grainstones and packstones, and laminated lime mudstones (Woodward, 1941; Haynes et al., 2014, 2015a) and also in the Wills Creek Formation farther upsection where laminated lime mudstones and intraclast grainstones and packstones are present. Between the McKenzie and Wills Creek Formations in this region are the mature quartz arenites and interbedded ostracode packstones and grainstones of the Williamsport Sandstone (Woodward, 1941).

The first predominantly carbonate unit of Silurian age along the field trip route is the regionally widespread Tonoloway Limestone (Smosna et al., 1977; Bell and Smosna, 1999). Sedimentary structures in some of the carbonate beds in the Wills Creek Formation and in the lower and upper parts of the Tonoloway Limestone are associated with a restricted semi-arid to arid sabkha environment (Smosna et al., 1977; Smosna and Patchen, 1978). The thick lower and upper parts of the Tonoloway Limestone in this region (seen at **Stop 2-2**), in particular, are characterized by evaporite breccias and vugs, pseudomorphed crystals of evaporite minerals, laminated and thin-bedded lime mudstone with a sparse and restricted fauna of gastropods and ostracodes, and minor intraclastic grainstone and packstone (Woodward, 1941; Bell and Smosna, 1999; Haynes, 2014; Haynes et al., 2014). By contrast, the carbonate strata of the middle part of the Tonoloway Limestone are mostly grainstones and packstones characterized by a diverse and abundant fauna of corals, stromatoporoids, bryozoans, brachiopods, crinoids, and trilobites (Woodward, 1941; Haynes, 2014; Haynes et al., 2014; Swezey et al., 2015). This middle part, which accumulated in a higher energy and more open marine shelf setting, probably developed in response to a sea-level rise that can reasonably be considered as a prelude to the mostly open marine carbonate platform that developed during deposition of the overlying Keyser

Limestone and succeeding units of the Helderberg Group (Dorobek and Read, 1986; Dorobek, 1987). The accumulation of appreciable thicknesses of evaporite sediments elsewhere in the Appalachian Basin (Smosna et al., 1977) and Michigan Basin (Swezey, 2008) during the late Silurian, when the Tonoloway Limestone was being deposited is consistent with a paleogeographic reconstruction that includes the intermittent development of extensive sabkha environments during this time.

Overlying the Tonoloway Limestone are the carbonate strata of the Silurian-Devonian Helderberg Group, which is visible in essentially its entirety at **Stop 2-1** and **Stop 2-3**. The oldest formation of the Helderberg Group, the Keyser Limestone, is a thick sequence of primarily bioclastic grainstones, packstones, and lesser wackestones characterized by a diverse assemblage of open marine fauna including some biohermal and biostromal coral-stromatoporoid boundstone (Woodward, 1943; Smosna and Warshauer, 1979; Dorobek and Read, 1986; Stock and Holmes, 1986; Cole et al., 2015). In this region, the Silurian–Devonian boundary occurs within the uppermost part of the Keyser Limestone (Denkler and Harris, 1988a,b; Harris et al., 1994).

Overlying the Keyser Limestone is the thin New Creek Limestone with its crinoidal grainstones, which in turn is overlain by cherty brachiopod packstones and wackestones of the thin Corriganville Limestone. The distinctive bedded cherts of the Corriganville Limestone are typically light to medium gray, and on weathered surfaces the chert commonly looks almost white. The New Creek and Corriganville Limestones together comprise minor gas reservoirs in eastern West Virginia (Baez et al., 2004). Overlying the Corriganville Limestone is the Mandata Shale, a thin black shale unit limited in areal extent to southern Pennsylvania, Maryland, and northeastern West Virginia (Dorobek and Read, 1986). Above the Mandata Shale is the Licking Creek Limestone, the uppermost formation of the Helderberg Group that has two members (Head, 1974). The lower member is the Cherry Run Member, a sequence of cherty packstone and wackestone, with lesser lime mudstone, some with prominent pink shale partings. The chert of the Cherry Run Member is black, is commonly irregularly lenticular to nodular bedded, and up to several centimeters thick, all of which contrast with the markedly thinner light gray chert of the Corriganville Limestone which tends to be more regularly bedded and somewhat laterally continuous.

Above the Cherry Run Member is the Little Cove Member of the Licking Creek Limestone, a generally chert-poor and typically arenaceous sequence of lime mudstone and wackestone. As discussed by Haynes et al. (2014), the name Little Cove Member was applied by Head (1974) to the sandy and chert-free beds of the upper part of the Licking Creek Limestone, specifically to replace the earlier but stratigraphically invalid name "Warren Point Member" that Head (1969, 1972) had applied incorrectly in his studies of the Helderberg Group.

The Devonian-Early Mississippian Acadian Orogeny

Much as the older Upper Ordovician and Lower Silurian siliciclastic strata are linked to tectonic uplift associated with the Taconian orogeny, the Devonian siliciclastic strata are generally linked to tectonic activity associated with the Acadian orogeny (Woodrow and Sevon, 1985; Swezey, 2002), with eustatic sea-level change also hypothesized to have played a role in governing the changes in depositional environments observed (Dennison and Head, 1975). The carbonate strata of the Licking Creek Limestone are overlain by the Oriskany Sandstone, a calcarenaceous quartz arenite with numerous large brachiopods, including *Spirifer arenosus* (Woodward, 1943). Because of the apparently conformable nature of this contact over a wide area (as will be seen at **Stop 2-1**), there is some debate as to whether the onset of the Acadian orogeny is denoted by the arrival of siliciclastic sand on top of the Helderberg carbonates (i.e., the basal Oriskany Sandstone), or by the abrupt contact between the Oriskany Sandstone and the overlying mudrocks of the Needmore Shale, a stratigraphic contact that has been the subject of much debate as to its significance. This abrupt stratigraphic contact is complex; it is interpreted as initially recording a eustatic sea-level drop known as the Wallbridge discontinuity (Dennison and Head, 1975; Dennison et al., 1992), and then recording a subsequent sea-level rise that in this region is probably partly tectonic in origin in that it is related to tectonism associated with the Acadian orogeny, but which in any event produced the stratigraphic progression from Oriskany to Needmore to Marcellus Shale. This sequence occurred relatively rapidly but conformably in response to the gradual deepening of the foreland basin as a response to the onset of the Acadian orogeny. This eustatic influence on the change in depositional regime is represented by the Oriskany Sandstone and the Needmore Shale, along with the influence on sea-level of the tectonic activity associated with the development and evolution of the Acadian foreland basin, is also evident regionally. The Acadian foredeep resulted from the collision of a microplate or island arc with the southeastern margin of Laurentia, a convergence that ultimately produced the Acadian orogeny and the ensuing Catskill clastic wedge (Woodrow and Sevon, 1985).

At **Stop 2-1**, the Oriskany Sandstone conformably overlies the Little Cove Member of the Licking Creek Limestone, as evidenced by the very gradual transition from arenaceous limestones to calcareous quartz arenites that occurs over a meter or more of section not only here, but in many exposures throughout this region. On weathered surfaces the brachiopods of the Oriskany Sandstone are commonly present only as biomoldic pores; here, by contrast, we see unweathered beds of the Oriskany in which the brachiopod fragments are still extant as calcareous shelly debris, as well as some weathered blocks from higher up on the exposure in which the typical development of biomoldic porosity can be observed. The biomoldic porosity, along with interparticle porosity developed from the dissolution of calcite cement and secondary fracture porosity have collectively allowed the Oriskany Sandstone to be a prolific oil and gas producer in many areas of the Appalachian Basin (Diecchio, 1985a; Milici et al., 2003).

The Needmore Shale in this region is typically a greenish-gray mudrock that is commonly calcareous in many intervals and which commonly weather to various shades of light gray to olive gray or greenish gray, as seen at **Stop 2-1**; however, the lowermost beds of the Needmore Shale can also present as a black shale of variable thickness. Discrete beds of argillaceous limestone are present in most exposures of the Needmore Shale, and in many exposures the Needmore Shale contains a diverse and moderately abundant marine fauna of whole and fragmental corals, brachiopods, trilobites (notably *Phacops* sp.; Woodward, 1943), bryozoans, crinoids, and ostracodes. At most exposures in this region there is dark-gray to black shale at the base of the Needmore Shale that is normally only 1-2 m (3 to 6 ft) thick; this is the Beaver Dam Shale Member of Willard (1939). The Needmore Shale spans the Early to Middle Devonian boundary (Rossbach and Dennison, 1994; Harris et al., 1994).

Overlying the Needmore Shale is the Marcellus Shale (seen at optional **Stop 2-1a**), a sequence of dark-gray to black, fissile, pyritic shale deposited in quiet anoxic waters of the Acadian foredeep (Enomoto et al., 2012). The actual water depth is a subject of some debate, and may have been less than 100 m (300 ft) (Schieber, 2016). Some exposures and drill cores in this region show that thin interbedded layers of dark-gray argillaceous limestone or calcareous shale are present, but most of the Marcellus Shale is not calcareous, in contrast to the underlying Needmore Shale. The Marcellus Shale is a major petroleum source rock and also a reservoir unit that, since about 2008-2009, has been targeted for gas production using hydraulic fracturing ("fracking") from northern Pennsylvania southward into West Virginia (Zagorski et al., 2012; Milici and Swezey, 2014).

The Mahantango Formation (seen at **Stop 1-4a**) overlies the Marcellus Shale in this region, and it consists of thin-bedded to laminated gray shale, greenish-gray siltstone, and fine-grained, greenish-gray sandstone, some of which are sparsely to abundantly fossiliferous. The Mahantango Formation represents deposition in suboxic, generally quiet water. The presence of still-articulated fossils of sessile organisms including brachiopods and corals suggests that dissolved oxygen levels were occasionally high enough to allow colonization of the seafloor by benthic organisms.

Along the route of this field trip, the Mahantango Formation is overlain by the Harrell Shale and the Brallier Formation (seen at **Stop 1-4**). The Harrell Shale is a dark gray to black, fissile, silty shale that can be seen in outcrop at **Stop 1-4**, with approximately 15 m (45 ft) exposed. The Brallier Formation is comprised of interbedded shale, sandstone, and siltstone generally ranging in thickness from 1200 to 1800 m (365 to 550 ft), interpreted to be sedimentation from turbidity flows onto a low-angle, broad ramp into a depositional basin, likely representing a gradual steepening of the slope onto which the Mahantango Formation and Harrell Shale were previously deposited. The overlying Foreknobs Formation consists of marginal marine deposits associated with a subsequent drop in sea level. The change in sediment character from the fossiliferous greenish-gray and dark gray shale, siltstone, and micaceous sandstone of the Mahantango Formation to the dark gray to black, sparsely fossiliferous and fissile Harrell Shale is recognizable throughout this region. Atop the Harrell Shale is a sequence of thinly interbedded siltstone and silty shale of the Brallier

Formation, with abundant tool marks and flute casts indicative of turbidity flows (Lundegard et al., 1980). The trace fossil *Pteridichnites biseriatus* is most abundant in the lower-middle portion of the Brallier Formation (McDowell et al., 2007). The upper portion of the Brallier Formation is distinguished by gradual increasing proportion of sand content up section, and, at least in this region, an occasional interval of transported fossil hash, often located at the base of sandstone beds. The sedimentology, petrology, and gas potential of the Brallier Formation were studied by Lundegard et al. (1980), Donaldson et al. (1996), Milici and Swezey (2006), and Milici and Swezey (2014).

Above the Brallier Formation is the Foreknobs Formation, the type section of which was defined and measured by Dennison (1970) along West Virginia Highway 42, about 0.5 km (1600 ft) northwest of Scherr in Grant County. Dennison's (1970) original definition included two formations comprising the Greenland Gap Group: the Scherr Formation, and the overlying the Foreknobs Formation. In the area covered by this field guide, we do not recognize the Scherr Formation as a lithologically distinct, mappable unit. Therefore, we are including any strata considered by Dennison (1970) to be the Scherr Formation to be within the upper part of the Brallier Formation, and recognize the Foreknobs Formation as the overlying unit above the Brallier (see discussion in **Stop 1-4**).

The Foreknobs Formation was named for the geographic expression of the prominent dissected ridge immediately east of the Allegheny Front, called the Fore Knobs (although much of this ridge is actually held up by the overlying Hampshire Formation and younger units). In this region, the Foreknobs Formation is equivalent to the unit formerly called the Chemung Formation (named for the type locality at Chemung Narrows in New York State), and it is composed of interbedded sandstone, siltstone, and shale that is highly fossiliferous. The unit represents the gradual marine regression and shoreline advance out onto a gently sloping marine shelf that records multiple short term, low amplitude sea level oscillations. Notably, two 3^{rd}-order cycles are manifested in two widespread sandstone packages, named the Briery Gap and Pound Sandstone Members (Dennison, 1970). Individual sandstone beds within these packages often have erosional basal contacts with quartz pebble conglomerates, shale rip-up clasts, and fossil plant material indicating a marginal marine to non-marine depositional environment. The deeper-water facies of the formation can be highly fossiliferous, with abundant brachiopods and crinoids. The upper part of the Foreknobs Formation represents a transition from a nearshore/shoreline marginal marine environment into the terrestrial facies of the Hampshire Formation, across multiple transgressive-regressive cycles.

The Hampshire Formation (seen at **Stop 1-4**, **Stop 1-5**, and **Stop 2-4**) is a thick unit of gray, tan and red sandstone and maroon mudrock. These deposits are mostly red beds interpreted to represent fluvial to deltaic sediments. The red beds and associated strata of the Hampshire are typically medium-bedded to finely laminated mudstones to cross-stratified sandstones with plant fossils including *Elkinsia polymorpha*, a Late Devonian gymnosperm that is among the older and better known of all primitive gymnosperms (Rothwell et al., 1989), and occasional rootlet trace fossils. Rare thin coal beds also occur. This lithologic association is interpreted as the upper portions of the “Catskill delta” complex that prograded westward into northern Pennsylvania, Maryland, West Virginia, and Virginia during the Late Devonian (Woodrow, 1985). More specifically, the Hampshire Formation is interpreted as a combination of fluvial and deltaic deposits that may include emergent delta top-set beds or inter-distributary splays, as well as nearshore marine sediments that exhibit field evidence of storm-wave action and rare marine elements.

The Hampshire Formation is capped by a regional unconformity that forms the boundary between the Kaskaskia I sequence and the overlying Kaskaskia II sequence, and that is present in many places throughout the Appalachian Basin (Sloss, 1963). To the north in Maryland and within the region of the field trip route, Brezinski (1989) did not recognize a great unconformity at the Devonian-Mississippian boundary; however, a notable glaciogenic facies is present in our study area that has been linked to a global cooling event near the end of the Devonian and beginning of the Mississippian (Brezinski et al., 2008; Brezinski et al., 2010; Brezinski and Cecil, 2015). The facies is characterized by a diamictite containing “exotic” clasts of various igneous, metamorphic, and sedimentary lithologies, many of which are faceted and striated. The evidence for glaciogenic origin as well as the widespread character of the deposit—spanning more than 40 km (25 mi) wide and 400 km (250 mi) long — indicates these deposits were sourced from localized mass wasting (Brezinski et al., 2010). This diamictite is present within the Spechty Kopf Formation of

Pennsylvania, the lower part of the Rockwell Formation of Maryland (Brezinski et al., 2008, 2010), and the Spechty Kopf formation (herein) of West Virginia. In northeastern West Virginia, the Rockwell Formation is assigned to the units overlying the Hampshire Formation by Lessing et al. (1992). In most of West Virginia, the Price Formation overlies the Hampshire Formation, where that formation is present, and includes the generally non-red rocks above the non-marine red beds of the Hampshire Formation (or above the Foreknobs Formation where the Hampshire is absent) and below the Greenbrier Limestone (Bjerstedt and Kammer, 1988). Nomenclatural differences notwithstanding, the base of the unit overlying the Hampshire Formation at **Stop 2-4** on this field trip is marked by the occurrence of the aforementioned diamictite.

Along the western edge of the Valley and Ridge at the base of the Allegheny Front in the immediate area of this field trip, the deltaic sediments of the Price Formation prograded westward into a foreland basin. However, the Price Formation is thin or even absent in some of this area, due to erosion or lack of deposition onto the West Virginia dome or Beverly uplift (Yielding and Dennison, 1986; Bjerstedt and Kammer, 1988). This feature is interpreted as a syndepositional basement protuberance that influenced depositional architecture in north-central West Virginia during the Mississippian, but its origin is not clearly understood.

Mississippian Inter-Orogenic Calm: The Final Paleozoic Carbonate Depositional System

As Acadian tectonism waned during the Late Devonian and into the Early Mississippian, turbidity levels in the sea decreased as the supply of siliciclastic sediments from the Acadian orogenic highlands diminished, much as the influx of siliciclastic sediments from the Taconic highlands decreased during the early Silurian with waning and ultimately cessation of Taconian tectonic activity. Above the Price Formation in this region is a sequence of limestone and thin beds of red mudrock that in West Virginia is collectively referred to as the Greenbrier Limestone. These carbonates include oolitic, bioclastic, and peloidal grainstones and packstones deposited in higher energy shelf settings, and lower energy lagoonal lime mudstones, wackestones, and packstones with bedded and nodular chert common in some of the carbonate units (Wynn and Read, 2007, 2008). Interbedded quartz sands and red mudrocks, some with minor dolomite, are interpreted as evidence of eolian activity in a semi-arid climate. Collectively these strata of the Greenbrier Limestone record deposition in marine shelf and peritidal environments that developed and evolved during the interorogenic calm between the end of the Acadian orogeny and the onset of the Alleghanian orogeny. In central and western West Virginia, oil and natural gas are produced from some wells developed in the Greenbrier Limestone (Smosna, 1996; Milici and Swezey, 2006). Above the Greenbrier Limestone is the Mauch Chunk Formation, a thick sequence of red mudrocks and lesser green and gray mudrocks, some with abundant plant fossils (Beuthin and Blake, 2002, 2004). Although the Mauch Chunk is assigned a Group rank in southern West Virginia and Virginia, the defining units are absent in the northern part of the basin and thus Formation rank is preferred in the region covered by this guidebook. The Mauch Chunk Formation is capped by a regional unconformity that forms the boundary between the Kaskaskia sequence and the overlying Absaroka sequence, a boundary that is present throughout the Appalachian Basin and adjacent Michigan and Illinois Basins (Swezey, 2002, 2008). This unconformity forms an abrupt break from underlying red mudrock to overlying siliciclastic sandstone and conglomerate, and in the central Appalachians, it is widely interpreted as marking the onset of the Alleghanian orogeny (Chapman and DeCelles, 2015).

The Pennsylvanian-Permian Alleghanian Orogeny

Strata of Late Mississippian to Permian age are primarily siliciclastic mudrocks and sandstones, many of them coal-bearing, associated with deposition in a complex mosaic of fluvial, deltaic, estuarine, and alluvial depositional systems (Cecil et al., 1985; Blake and Beuthin, 2008; Grimm et al., 2013). The transition from the Mississippian carbonate depositional system to the siliciclastic-dominated system of the Alleghanian orogeny is not linked to development of a foredeep that was initially filled with distal turbidites and mud, which contrasts with the earlier transitions as discussed above (i.e., Cambrian-Ordovician carbonates to siliciclastics of the Taconian orogeny, and Silurian-Devonian carbonates to the siliciclastics of the Acadian orogeny, both of which were characterized by down-warping of Laurentian crust and the development of a foreland basin). Instead, the Late Mississippian and Early Pennsylvanian in this region was a time characterized by deposition of extensive redbeds with many paleosols. These in turn are overlain by coal-bearing sublithic arenites interbedded with fine to very coarse siliciclastic sediments, all deposited in fluvial to deltaic settings. This contrast could record sedimentation rates keeping pace with development of accommodation space, and so even though the total thickness of siliciclastic sediments generated by the Alleghanian orogeny is appreciable – and clearly required the presence of a basin that could then be filled with this sediment – the development of this basin did not outpace the production of sediment in the Alleghanian orogenic highlands (Rast, 1984, 1988).

During latest Mississippian and Pennsylvanian time glaciation affected sedimentation patterns globally, including in the Appalachian Basin (Smith and Read, 2000). Upper Mississippian and Pennsylvanian sandstones, mudrocks, and coal of predominantly terrestrial character were deposited in a variably subsiding and generally overfilled foreland basin punctuated periodically with glacioeustatic marine transgressions (Cecil, 2003; Cecil and Dulong, 2003).

The deformation associated with the Alleghanian orogeny is responsible for the structure that we see at nearly all of the stops on this field trip route. Collision of the northwestern coast of Gondwana (present-day Africa) with the eastern coast of Laurentia (present-day North America) during the assembly of Pangea is widely accepted as the tectonic event that produced Alleghanian deformation along the length of Appalachian orogen. The folded strata seen in nearly all of the exposures along US 48/Corridor H east of the Alleghany Front are evidence of this deformation, the surface expression of which extends for hundreds of kilometers in eastern North America, from Newfoundland to Alabama.

DESCRIPTION OF FIELD TRIP STOPS

Day 1

Day 1 Itinerary		
Stop #	**Location**	**Time**
	Leave Baltimore, Maryland	8:00 AM
1-1	Neoproterozoic and Cambrian Blue Ridge rift sequence at Middleburg, Virginia	10:00 AM
1-2	Ordovician carbonates at Tumbling Run, Virginia	11:30 AM
1-3	Silurian Tuscarora Sandstone at Baker, West Virginia	1:15 PM
1-4	Devonian Mahantango Formation to Hampshire Formation at Baker	2:00 PM
1-5	Devonian Hampshire Formation at Baker	3:10 PM
1-6 (optional)	Devonian Foreknobs Formation at the Whip Cove anticline, West Virginia	
1-7 (optional)	Devonian Hampshire Formation at the Town Hill syncline, West Virginia	
	Arrive at hotel in Moorefield, West Virginia	5:30-6:00pm

Day 1 of the field trip begins in Baltimore, Maryland and proceeds through eastern Maryland and into Virginia to the first stop. At **Stop 1**, exposures of the Mesoproterozoic to Neoproterozoic Blue Ridge basement complex at the base of the stratigraphic succession will be seen. Subsequent field trip stops this day continue upsection to the top of the Devonian strata. Day 1 consists of 5 stops and ends at Moorefield, West Virginia.

Stop 1-1: Neoproterozoic Iapetan Rifting

At **Stop 1** we will see three units; the younger unit (Catoctin Formation) at **Stop 1-1a**, and the older units (Marshall Metagranite and Fauquier Group) at **Stop 1-1b** (**Figure 4**). The bedrock geology of this area is based on mapping by Kline et al. (1990), and Southworth et al. (2006).

Stop 1-1a: Rift basalts; Neoproterozoic Catoctin Formation, Middleburg, Loudoun County, Virginia (38°56'42"N, 77°40'26"W)

The Catoctin Formation is a dark-green to bluish-gray, fine-grained to aphanitic metabasalt that varies texturally from massive, locally amygdaloidal greenstone to well-foliated greenschist (Southworth et al., 2006). It derives its green to blue-green colors from chlorite, actinolite, and epidote minerals formed during metamorphism.

The Catoctin Formation is a significant unit in the central Appalachian Basin that crops out from southern Pennsylvania to south-central Virginia. It represents the continental basalts associated with the rifting of Rodinia during the late Neoproterozoic (Fichter and Diecchio, 1986a). In this area the Catoctin Formation lies above the Fauquier Group (**Stop 1-1b**) and below the Cambrian Weverton Formation.

Stop 1-1b: Proterozoic basement nonconformity, Marshall Metagranite and Fauquier Group, Middleburg, Loudoun County, Virginia (38°56'54"N, 77°42'36"W)

This stop proceeds from the Grenville basement to the overlying sedimentary strata. The basement here is biotite granite gneiss that was initially mapped as the Marshall Metagranite, but which has more recently been identified as a different unit on the basis of isotopic age (Southworth et al., 2006). Note the high-grade metamorphic foliation formed during the Grenvillian orogeny associated with the assembly of the supercontinent of Rodinia.

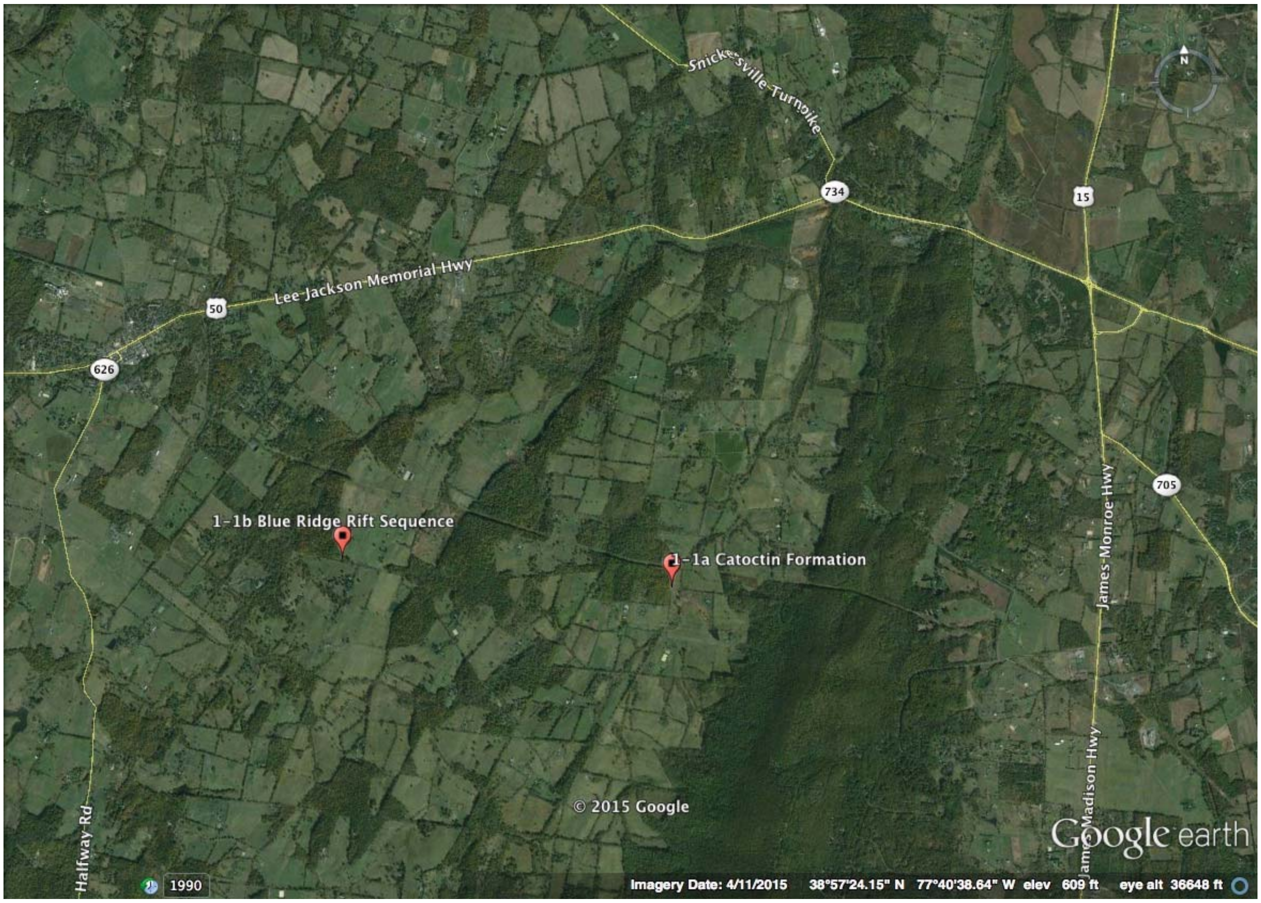


Figure 4: Google Earth image showing the locations of Stop 1-1a and 1-1b.

Upslope, there are boulders of diabase, probably from a Mesozoic dike that is not exposed in outcrop. This locality is approximately 5 miles (8 km) west of the Culpeper Basin, a Mesozoic rift basin associated with the rifting of Pangea. Dikes and sills of similar composition to these boulders are common in the Culpeper Basin as well as surrounding areas in the vicinity.

At the top of the hill, beds of weakly foliated meta-arkose and pebbly arkosic conglomerate of the Fauquier Group are exposed. These strata constitute the basal sedimentary unit in this area, and here they were deposited directly on Grenville basement. The lack of a strong metamorphic foliation indicates that the Fauquier Group was deposited after the Grenvillian orogeny. The weak foliation developed during one or more of the succeeding Taconian, Acadian, or Alleghanian orogenies.

Stop 1-2: Ordovician carbonate-to-siliciclastic transition from passive margin to Taconian orogeny

As one walks up the section at **Stop 1-2** (**Figure 5**), it is possible to view the strata in ascending order through the upper part of the Beekmantown Group, New Market Limestone, Lincolnshire Limestone, and Edinburg Formation, to the lower part of the Martinsburg Formation. Information for this stop is taken in part from Fichter and Diecchio (1986b). **Figure 6** is a diagram of a subsidence model that applies to **Stop 1-2**.

Stop 1-2a: Passive margin platform carbonate to deep ramp transition; Ordovician Beekmantown Group, New Market Limestone, Lincolnshire Limestone, and Edinburg Formation exposed along Tumbling Run, Strasburg, Shenandoah County, Virginia (38°58'53"N, 78°23'34"W)

The Tumbling Run section is an important reference section for the Middle and Upper Ordovician of the Appalachian Basin, and a classic location in Appalachian stratigraphy. The upper part of the Beekmantown Group at this locality consists of limestone and dolostone of the Rockdale Run Formation and Pinesburg Station Dolomite. The contact between the Pinesburg Station Dolomite and the overlying New Market Limestone is present in the streambed. In southwestern Virginia the top of the Beekmantown Group represents the Knox unconformity, the boundary between the Sauk and Tippecanoe major stratigraphic sequences (Sloss, 1963). Many authors also place the Lower Ordovician-Middle Ordovician boundary at the Knox unconformity, and at most locations in the Appalachian Basin the unconformity occurs at the top of the Beekmantown Group and its equivalent, the Knox Group (Mussman and Read, 1986). At this locality, however, a pronounced disconformity is lacking. Lowry (1957) hypothesized that the carbonate platform in this area may have been more actively subsiding than elsewhere, resulting in water depths great enough to allow sedimentation to continue with little or no interruption across the Early Ordovician-Middle Ordovician boundary.

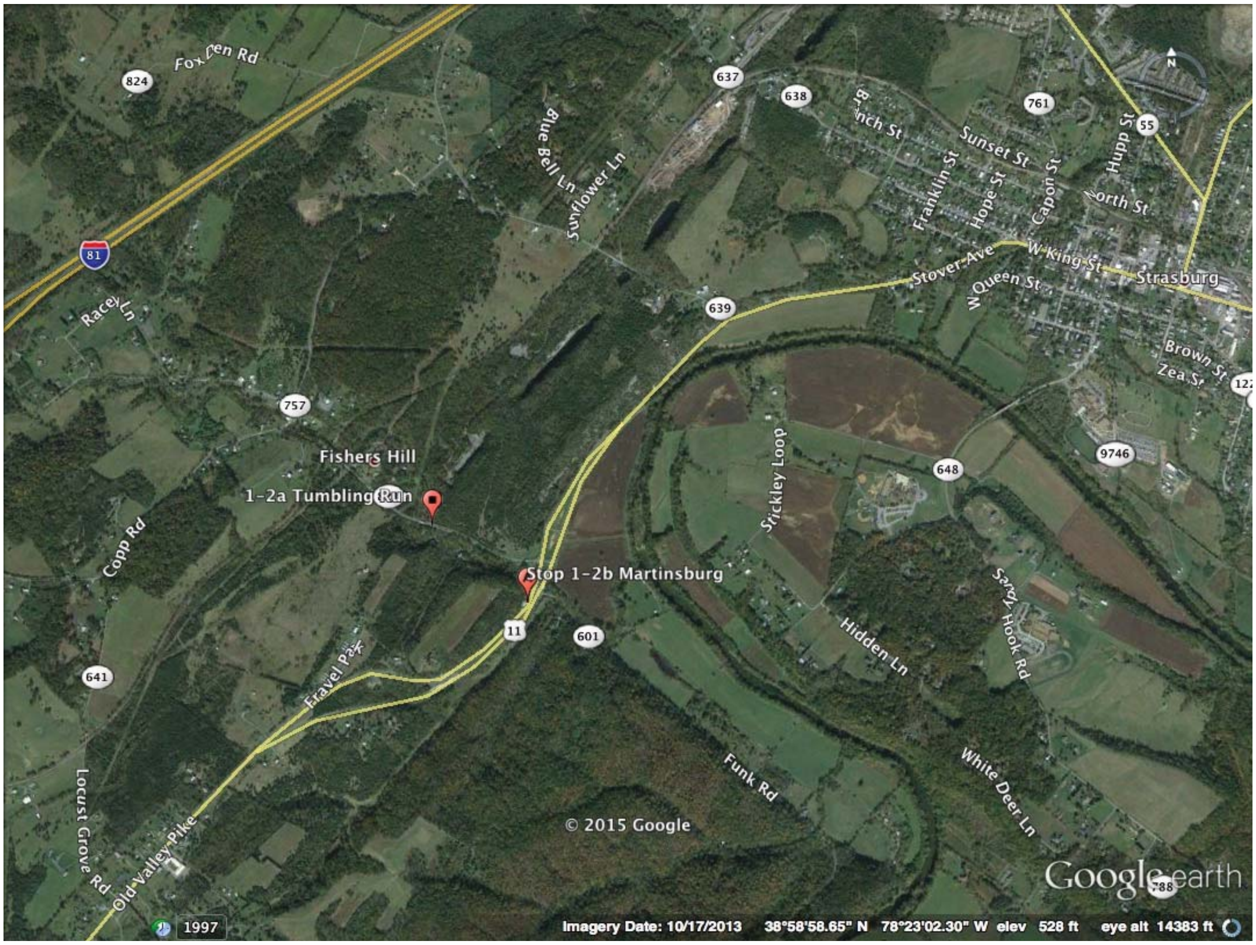


Figure 5: Google Earth image showing the location of Stop 1-2.

According to Chapman and DeCelles (2015), the Knox unconformity denotes the initial formation of a tectonic forebulge followed by accumulation of Ordovician carbonate strata on a platform margin. The subsequent appearance of fine-grained siliciclastic strata (e.g., Martinsburg Formation/Reedsville Shale) corresponds with sediment accumulation in a distal foredeep, and the overlying succession of coarser-grained siliciclastic strata (Oswego Sandstone, Juniata Formation, and Tuscarora/Massanutten Sandstone) corresponds with sediment accumulation in a proximal foredeep setting **(Figure 6)**.

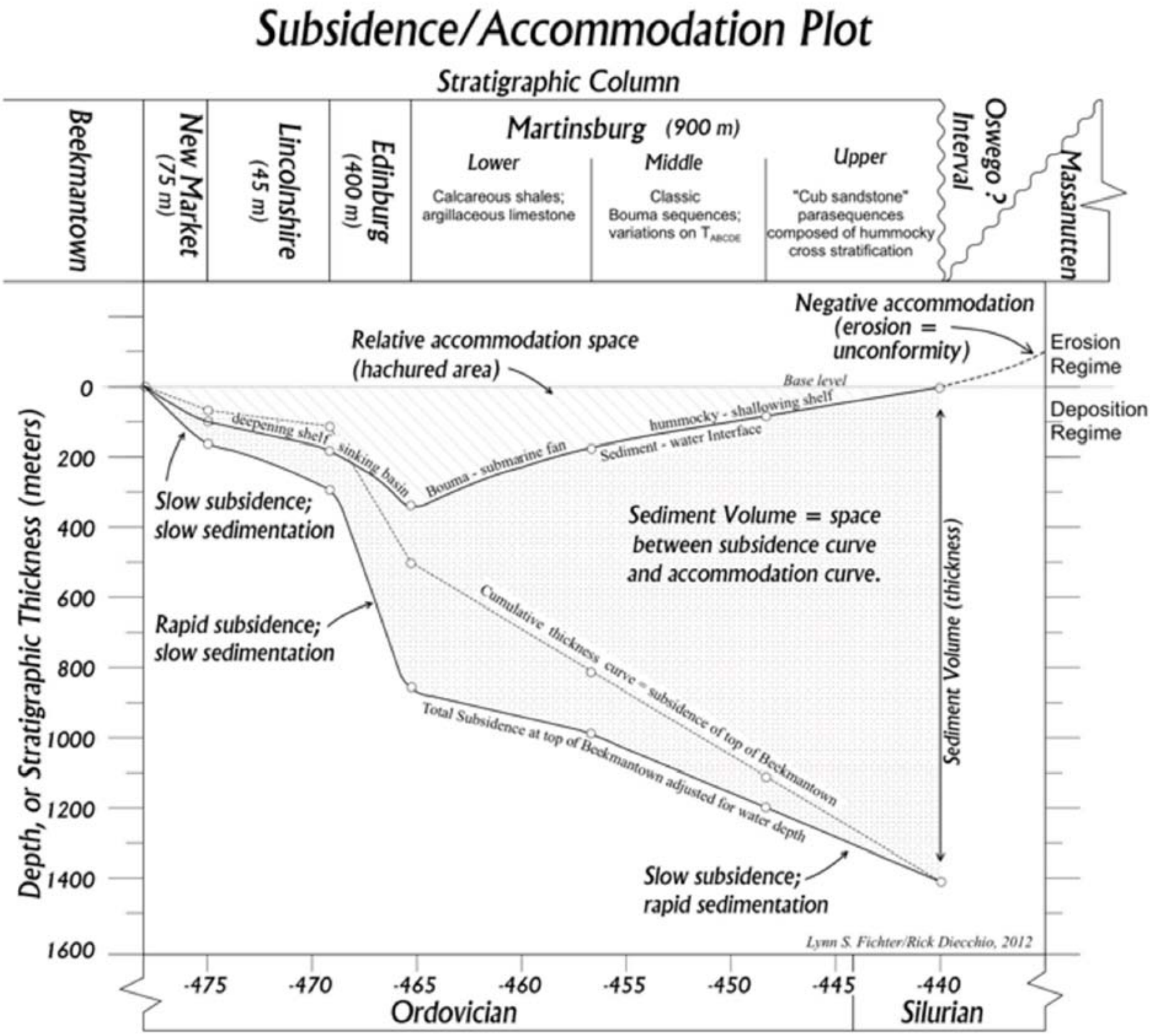


Figure 6: Subsidence/accommodation plot for the later Ordovician of the northern Shenandoah Valley (from Whitmeyer et al., 2015)

The New Market Limestone, which overlies the Beekmantown Group, is a light to medium gray sparsely fossiliferous lime mudstone with a distinctive conchoidal fracture with numerous “birds-eyes” of sparry calcite. The depositional environment was probably an intertidal/subtidal carbonate flat. The New Market Limestone is an important source of high-calcium lime that is quarried regionally. The contact between the New Market Limestone and overlying Lincolnshire Limestone in much of this region is an unconformity that is characterized by an irregular and scalloped surface with flame structures (Read and Grover, 1977). This surface is visible at Tumbling Run as the scalloped contact located high on the exposure just east of the bridge. The Lincolnshire Limestone is a sequence of bioclastic grainstones and packstones with black chert occurring as beds, lenses, and nodules. The Lincolnshire Limestone is characterized by a diverse assemblage of whole to comminuted Ordovician open marine fauna, which typically includes trilobites, crinoids, brachiopods, bryozoans, and cephalopods. The Lincolnshire Limestone is overlain conformably by the Edinburg Formation. At the base of the Edinburg Formation are several K-bentonites, with the thickest one overlying a thin but continuous bed of black chert. The Edinburg Formation is notable for its diverse lithologies, including nodular-bedded black lime mudstone, wackestone, and packstone, planar-bedded black lime mudstone (some with prominent laminations), and interbedded black calcareous shale that can include a cryptic volcanic component (Haynes et al., 1998). The Edinburg Formation was deposited in a shallow to deep ramp environment (Read, 1980). The upward increase in shale, the change from light gray to dark gray to black color, and the upward change in bedding from massive fenestral lime mudstones to nodular bedded packstone and wackestone has been interpreted to record continual deepening of the Laurentian shelf margin and foundering of the carbonate platform (Rader and Henika, 1978; Read, 1980).

Stop 1-2b: Onset of turbidite deposition during the Taconian Orogeny; Ordovician Stickley Run Member of the Martinsburg Formation along U.S. 11 near Strasburg, Shenandoah County, Virginia (38°58'43"N, 78°23'20"W)

The base of the Martinsburg Formation at this locality is distinct, composed of very calcareous bluish dark-gray to black shale to shaly black lime mudstone. Epstein et al. (1995) revised the stratigraphy of this part of the Ordovician sequence. They assigned the lower part of the Martinsburg Formation to the Stickley Run Member, and placed the immediately underlying fossiliferous nodular limestones, gray calcareous shales, and K-bentonites that were formerly assigned to the thin Oranda Formation within the older Edinburg Formation. Thus, the Oranda Formation was abandoned as a stratigraphic name. At this location, the beds in the Stickley Run Member of the Martinsburg Formation range in thickness from 0.4 in to 4 in (1 to 10 cm) and are graded. These strata were deposited as distal turbidites in a deep foreland basin that developed on top of the foundered carbonate platform (**Figure 6**).

Here in northern Virginia, the Martinsburg Formation is restricted in occurrence to the Massanutten Synclinorium (Diecchio, 1993). Time-equivalent strata farther west are different in character, and are referred to as the Dolly Ridge Formation (older) and Reedsville Shale (younger) (Perry, 1972; Haynes et al., 2015b). The strata here at the Edinburg-Martinsburg contact are interpreted to represent the deepest facies in the Ordovician of the Shenandoah Valley (**Figure 6**), and this deep-water facies does not occur in the Reedsville Shale farther west.

Stop 1-3: Waning of Taconian Orogeny; Silurian Tuscarora Sandstone and contact with the overlying Silurian Rose Hill Formation, Hanging Rock anticline, Baker, Hardy County, West Virginia (39°02'36"N, 78°42'58"W)

The Tuscarora Sandstone principally consists of thick- to massive-bedded, white to grayish-white to pale-yellow to pale-pink silica-cemented supermature sandstone (quartz arenite) and orthoquartzite with locally prominent cross-bedding. Because of its extreme erosional resistance, the Tuscarora Sandstone is one of the dominant ridge-forming stratigraphic units of the central Appalachian Basin. Thin beds of quartz-pebble conglomerate occur in the lower half of the Tuscarora Sandstone at many exposures. The trace fossils *Skolithos*, *Arenicolites* (vertical burrows), and *Arthrophycus* (horizontal and single to compound elongate burrows) can be found in some beds and on bedding planes.

Stop 1-3 is an extensive exposure of folded Tuscarora Sandstone forming the Hanging Rock anticline (**Cover photo**, and **Figure 7**). Channels and high-angle cross stratification can be seen in the medium to thick-bedded grayish white quartz arenites. Siliciclastic mudrock of the overlying Rose Hill Formation is visible at the western side of this exposure, and the contact with the underlying Tuscarora is placed at the transition from mature light yellow to white quartz arenites to dusky-red and dark maroon hematite-cemented quartz arenites. The most recognizable lithologies in the Rose Hill Formation are the distinctive dusky-red to blackish red to dark-maroon hematite-cemented quartz and sublithic sandstones known regionally as the Cacapon Sandstone Member of the Rose Hill Formation and the Cresaptown Member of the Rose Hill Formation. These distinctive facies of

Figure 7: (Upper) Google Earth image showing the location of Stop 1-3. (Lower) GigaPan image of outcrop by Callan Bentley.

hematite-cemented sandstone, ferruginous sandstone, and true ironstone are an important but stratigraphically variable part of the Rose Hill Formation (Hunter, 1960), rather than as a distinct stratigraphic unit. The two members occupy different stratigraphic positions in the formation. Slabs of these hematite-cemented sandstones commonly accumulate in abundance on the dip slopes of ridges throughout this region where the Rose Hill Formation crops out upsection from—and also downhill from—the resistant sandstone ledges of Tuscarora Sandstone. In addition to these maroon colored ferruginous sandstone beds, the Rose Hill Formation also includes appreciable thin-bedded olive to gray mudrock interbedded with reddish shale and siltstone, some beds of which are sparsely to moderately fossiliferous with ostracodes, brachiopods, and trilobites.

Stop 1-4: Acadian orogeny; Devonian Mahantango Formation through Hampshire Formation at Baker, Hardy County, West Virginia (39˚02'49"N, 78˚44'35"W)

This stop (**Figure 8**) provides an exceptional exposure of the Middle to Upper Devonian strata of the Catskill siliciclastic sedimentary wedge.

Figure 8: Google Earth image showing the location of Stop 1-4.

The exposure is notable for its relative completeness, lack of structural deformation, and ease of access along a reasonably safe roadcut. The exposed section begins at the top of the Mahantango Formation, and it includes the Harrell Shale, the entire Brallier Formation, the entire Foreknobs Formation (with upper and lower contacts well exposed), and the lower to middle portion of the Hampshire Formation.

Moving up through the entire exposed section, one passes through a sequence of rocks that represent a first order transgressive-regressive cycle across the Acadian orogeny. The depositional environment of these units at **Stop 1-4** is one of a broad marine ramp sloping to the west into a foreland basin that formed as a result of the onset of the orogeny, and then was progressively filled over a time span of about 30 My (McClung et al., 2013). Although not exposed here, the rather abrupt transition from the shoreline facies of the Oriskany Sandstone into the fine-grained black shales of the Needmore Shale and Marcellus Shale marked the onset of the Acadian orogeny (exposed at **Stop 2-1**). The exposure here begins with fossiliferous shale, siltstone, and sandstone of the Mahantango Formation that overlie the black shales. Maximum marine deepening is reflected in the deposition of the Harrell Shale and distal beds of the Brallier Formation that accumulated under conditions of broad, relatively low-energy turbidity flows across a shelf platform. The transition from the lower Brallier into the upper Brallier represents a shift from deep to shallow depositional conditions. The marginal marine deposits of the Foreknobs Formation indicate continued shallowing and record a number of rapid transgressive-regressive sea level changes.

The exposure at **Stop 1-4** begins within the informal Clearville siltstone in the uppermost Mahantango Formation (Cate, 1963) that crops out along the exit ramp for State Highway 259 at Baker heading off of eastbound US 48/Corridor H. Here approximately 48 m (160 ft) of the Clearville siltstone and the overlying Harrell Shale is exposed (**Figures 8, 9, 10, 11**). The traverse begins with the Clearville siltstone, a dark gray, massive-bedded, fossiliferous siltstone. White and light gray fossil rugose corals (**Figure 9A**), bryozoans (**Figure 9B**), and brachiopods (**Figure 9C, D**) are readily found weathering in contrast against the dark siltstone.

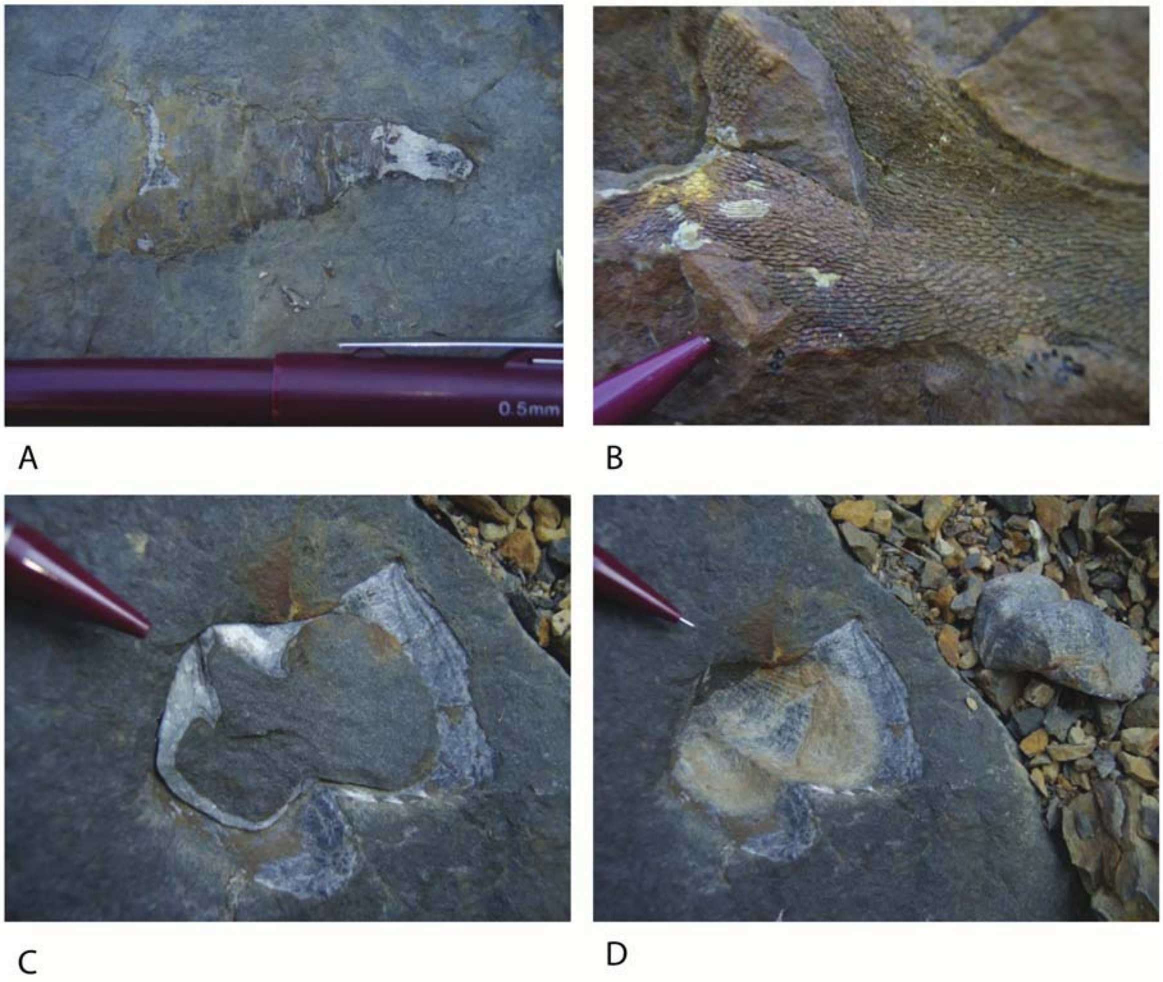


Figure 9. Fossils found within the Devonian Clearville siltstone at the top of the Mahantango Formation. A) Solitary rugose coral. B) Fenestrate bryozoan. C) Brachiopod mold filled with siltstone. D) Same brachiopod as C, *Spinocyrtia granulosa*?

North and west of Winchester, Virginia, the Clearville siltstone is much coarser making it a definitive ridge-forming unit that is mappable from Pennsylvania into Virginia (Jolley, 1983; Doctor et al., 2010). At this locality, the Harrell Shale exists between the Clearville siltstone and the overlying Brallier Formation (Hasson and Dennison, 1988), and the upper and lower contacts are exposed along this same outcrop. The Harrell Shale is at least 15 m (45 ft) thick here, and grades upward from fissile shale into a greater abundance of thinly interbedded siltstone and shale with minor amounts of fine sandstone.

Figure 10. Typical interbedded siltstone, shale, and minor sandstone lithology of the Devonian Brallier Formation. Note the offset beds resulting from minor reverse faulting during the Alleghanian orogeny.

The overlying Brallier Formation is primarily characterized by interbedded shales and siltstones that often exhibit hummocky cross-stratification and graded bedding of partial Bouma sequences (**Figure 10**). The Brallier Formation also contains beds of sandstone that range in thickness from 5 cm to 2 m (2 inches to 6 ft), and that become more prevalent toward the top of the formation.

The shale and siltstone of the Brallier Formation become increasingly micaceous moving up section, and occasional planar-bedded sandstone beds begin to appear. In this area, some of these sandstone beds have fossil hash beds composed primarily of brachiopods and crinoids at their base (**Figure 11**). These occasional thin fossil hashes and sandstone beds may represent a shift toward shallowing sea level conditions, as their frequency and thickness increase upward through the section and into the base of the Foreknobs Formation. This rather subtle change in lithologic character prompted Dennison (1970) to break out several stratigraphic divisions, defining this interval as the Scherr Formation based upon observations of the stratigraphy as reflected in well logs along the Allegheny Front. Dennison (1970) thus formalized the Scherr Formation and the overlying Foreknobs Formation as the Greenland Gap Group. However, discerning the contact between the Scherr Formation (lower formation of the Greenland Gap Group) and the Brallier Formation based on the criteria proposed by Dennison (1970) is not suitable for mapping purposes (Raymond et al., 2012). In describing this lithologic boundary, Dennison (1970, p. 54) wrote, “The Scherr Formation is dominated by turbidite strata with significant sandstone; southwestward [of Greenland Gap] the Scherr Formation becomes finer by facies change and passes into the upper portion of the Brallier Formation.”

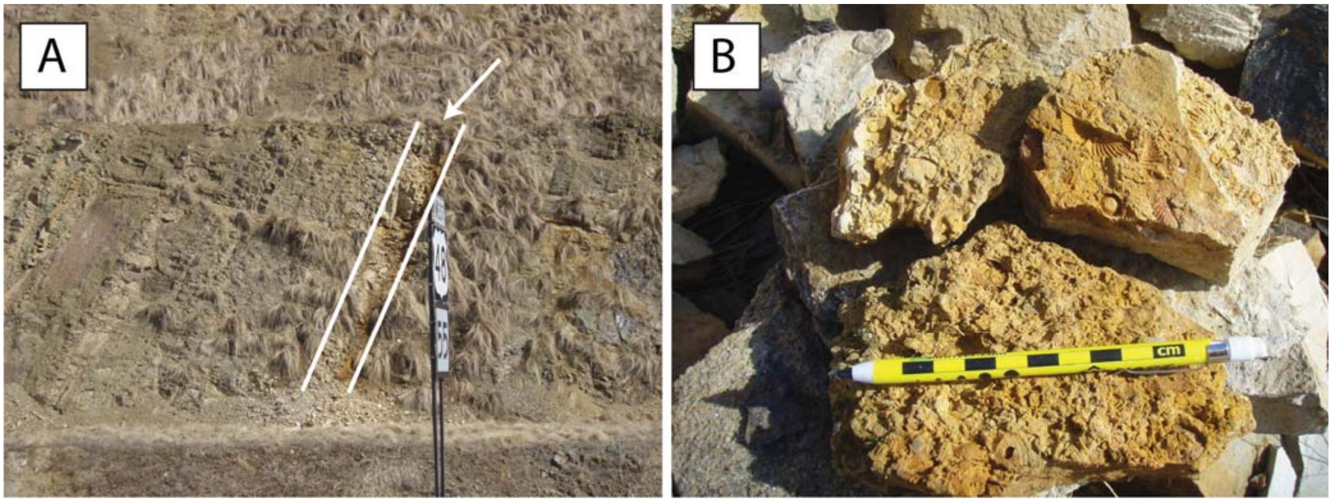


Figure 11. A) A light colored, fine grained sandstone bed in the Brallier Formation is located directly across from the West 48/55 road sign on the westbound lane at Baker (indicated by the arrow). B) This sandstone contains abundant fossil impressions of primarily crinoids and brachiopods at its base.

It is the opinion of the authors that it is of greater utility for mapping to abandon the ill-defined boundary between the Scherr and Brallier Formations (McDowell et al., 2007), and instead include the Scherr interval within the Brallier, possibly as an upper member. In fact, Dennison et al. (1988, p. 22) stated, “The similarity in lithologies and sedimentary structures of the Brallier and Scherr Formations leads to a similar depositional environment for both”, and “There is less sandstone in the Scherr of Randolph County [West Virginia] than in equivalent beds farther east...; the upper Brallier at Kelley Mountain is equivalent to the Scherr along the Allegheny Front.” Similarly, the lowermost Mallow Member of the

Foreknobs Formation as initially defined by Dennison (1970) is impractical for mapping (e.g., Brezinski and Conkwright, 2013), and may also be advantageously included as part of the upper Brallier in order to better define mappable formational boundaries based upon distinctive lithologic variation within typical exposures.

Schultz (1997, p. 4), described the contact between the Brallier and Foreknobs Formations within the Broadtop synclinorium (the area crossed by this field trip) in this way:

> The upper contact of the Brallier Formation is placed beneath the first occurrence of ridge-forming, thin to thick-bedded conglomeratic sandstone of the Foreknobs Formation… Because the upper part of the Brallier Formation is rarely exposed and because there is much folding and faulting within the formation, the placement of the boundary based solely on the first appearance of a one foot thick sandstone is not possible in the area of this report. Also, Rossbach (1992) has pointed out that in places, the boundary between the Brallier and Greenland Gap Group is so transitional that it is difficult to define a contact. For this study [Geology of the Broadtop synclinorium], both topography and lithology were used to differentiate the Brallier from the overlying Chemung or Foreknobs Formation.

Following the approach of Schultz (1997), the contact between the Brallier and Foreknobs Formations at the Baker section is placed at the base of the lowest bed of conglomeratic sandstone containing rounded pebbles within the continuous section. At this stop, the contact is exposed along the westbound lanes of US 48/Corridor H just west of the intersection with State Highway 29 (**Figures 12, 13**).

Defined in this manner, the thickness of the Brallier Formation is approximately 768 m (2,520 ft) at this location. The coarse conglomeratic sandstone at the base of the Foreknobs Formation may be equivalent to the Briery Gap Member of the Foreknobs Formation as defined by Dennison (1970), but owing to the inability to correlate these sandstone beds across depositional strike (McClung et al., 2013), abandonment of this and the other member names within the Foreknobs Formation may also be warranted in favor of informal upper and lower sandstone packages. Recent mapping has shown that this approach is more workable, as these upper and lower sandstone packages can be mapped on the basis of topography as well as lithology (Doctor et al., 2010; Doctor and Parker, *in press*).

Figure 12. Bed of conglomeratic sandstone within the Baker section. The base of this bed provides a readily identifiable horizon at which to place the base of the Devonian Foreknobs Formation.

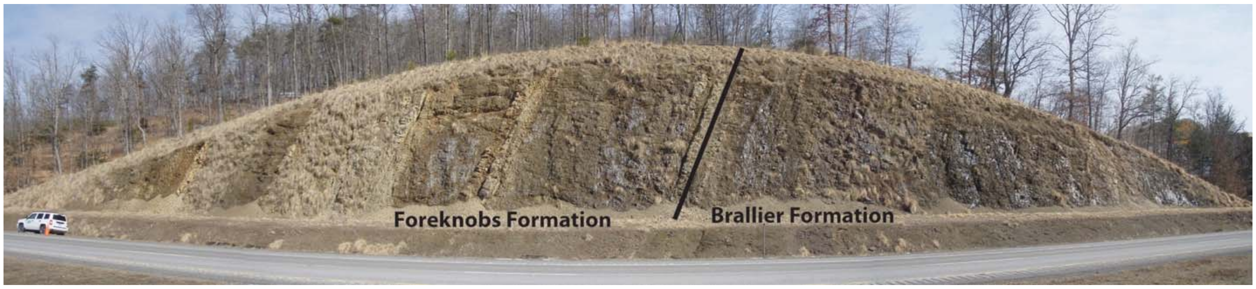


Figure 13. Location of the mappable contact between the Devonian Brallier and Foreknobs Formations at Baker, West Virginia.

The Foreknobs Formation represents a complex marginal shoreline setting that experienced multiple rapid marine transgressive-regressive cycles, with as many as perhaps 70 individual 5th-order cycles (McClung et al., 2013), and it records the transition from a marine environment into the fluvial-deltaic environment that characterizes the overlying Hampshire Formation. McClung et al. (2013) presented a measured section of this exposure of the Foreknobs Formation (**Figure 14**), placing the contact with the Brallier Formation immediately above the covered interval on the north (westbound) side of the highway located about 1 km (0.6 mi) west of the intersection between US 48/Corridor H and Route 29. According to the criteria outlined above, the contact is now placed farther upsection by approximately 58 m (190 ft), at the base of the lowest bed of conglomeratic sandstone (**Figures 13, 14**).

At Baker, the upper contact of the Foreknobs Formation is placed at the top of a unit of greenish-grey planar-bedded well-sorted sandstone, just below an 8 m (26 ft) thick bed of massive maroon, tan-weathering sandstone that is mapped as the Devonian Hampshire Formation. The greenish-gray sandstone that is mapped as the Foreknobs Formation contains the last occurrence of marine fossils (crinoids and brachiopods), whereas the overlying maroon bed of the Hampshire Formation contains abundant black plant fragments that may be part of a paleosol (**Figure 15**).

The transition between the shoreline marginal marine facies of the upper part of the Foreknobs Formation to the terrestrial fluvial-deltaic facies of the Hampshire Formation occurs across multiple transgressive-regressive cycles; therefore, consistent placement of the contact is extremely challenging, even with full exposure of the units above and below the contact.

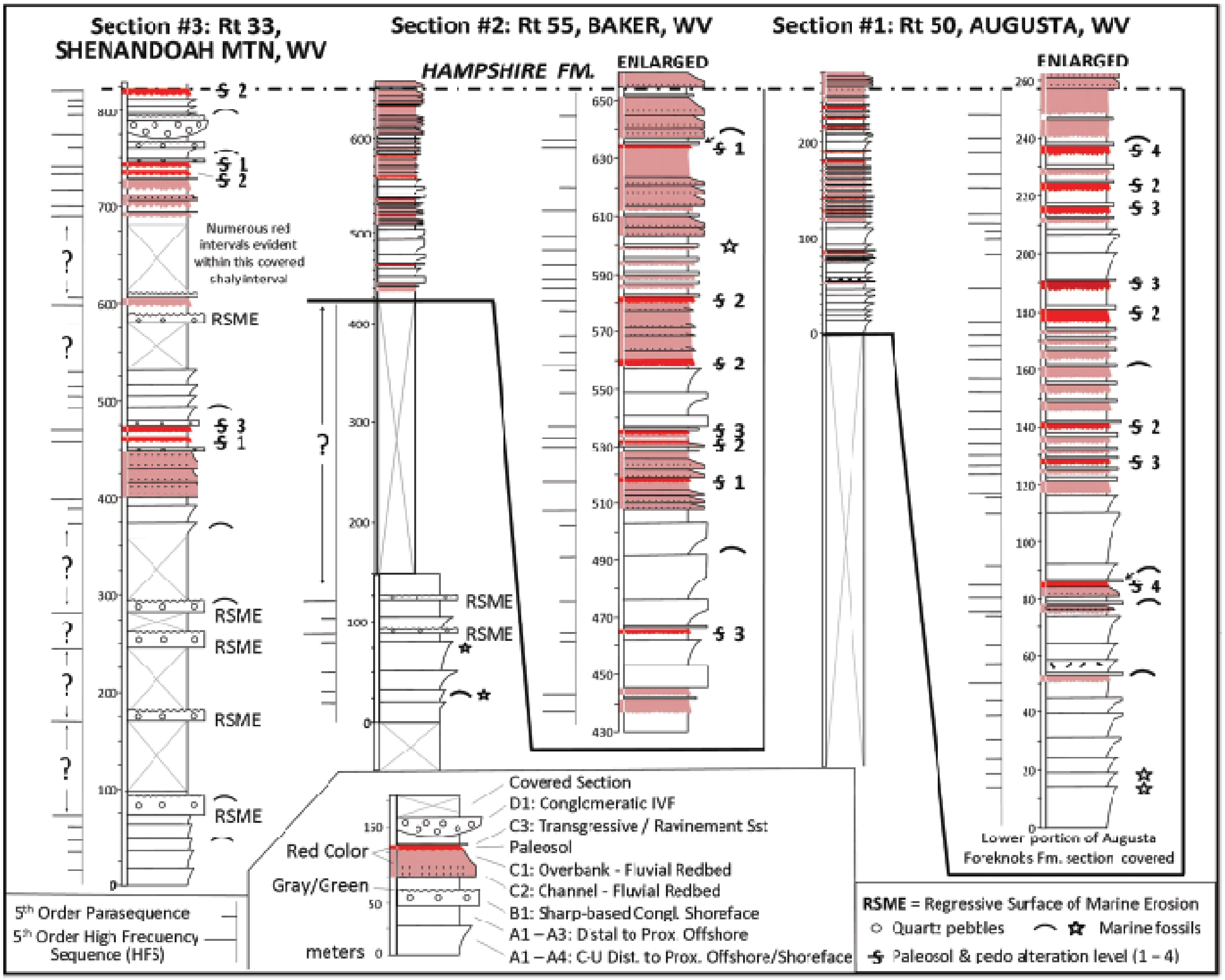


Figure 14. Measured sections of the Foreknobs Formation at three localities (McClung et al., 2013). The revised basal contact for the Baker section is herein placed at the base of the first conglomeratic sandstone shown in Section #2, what McClung et al. (2013) show as the lower "Regressive Surface of Marine Erosion (RSME)."

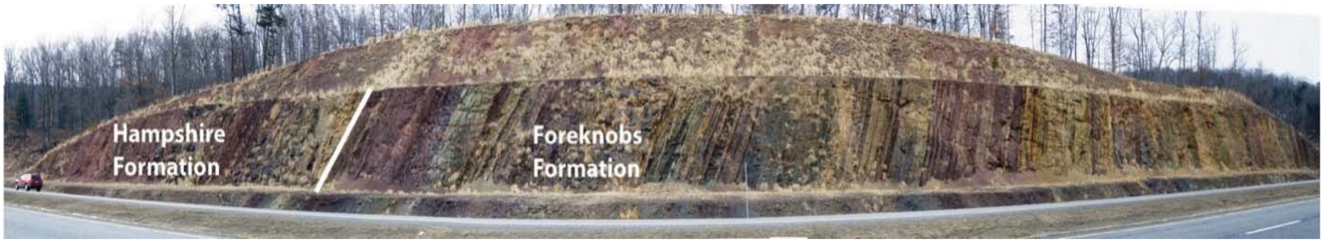


Figure 15. Location of the mappable contact between the Devonian Foreknobs and Hampshire Formations at Baker, West Virginia.

Based on the measured section #2 in **Figure 14** (McClung et al., 2013), it is difficult to discern exactly where the contact between the Foreknobs and Hampshire Formations was placed, but by distance it would approximately coincide with the location shown in **Figure 15**. The upper contact of the Foreknobs Formation occurs 479 m (1,570 ft) of linear distance west of the lower contact, and with beds consistently dipping about 65° degrees to the west-northwest, the total thickness of the Foreknobs Formation at this exposure is 432 m (1,420 ft).

Here at **Stop 1-4**, the exceptionally continuous and nearly undeformed exposure of this interval of Devonian stratigraphic succession serves as a reference section for future geologic studies.

Stop 1-5: Acadian orogeny: Top of the siliciclastic wedge, Devonian Hampshire Formation (39°03'06"N, 78°46'12"W)

This stop along Diamond in the Rough Road (**Figure 16**) is another exposure of the Hampshire Formation. Sandstone beds with sharp erosional contacts into the typical red mudrock of the Hampshire Formation are present. The erosional contacts beneath the sandstone beds possibly indicate fluvial incision into floodplain muds. An abundance of plant fragments can be seen with blocks of sandstone at the base of the outcrop. There are also several examples of vertical cylindrical structures in the mudrock (**Figure 17**) that have been interpreted as lungfish burrows (Benison et al., 2013).

Figure 16. Google Earth image showing the location of Stop 1-5.

Figure 17. Vertical, cylindrical structures interpreted as lungfish burrows in mudrock of the Devonian Hampshire Formation at Stop 1-5.

Day 2

Day 2 Itinerary		
Stop #	**Location**	**Time**
	Hotel, Moorefield, West Virginia	7:45
2-1	Silurian-Devonian Helderberg Group, Devonian Oriskany Sandstone, Needmore Shale, and Marcellus Shale at Timber Ridge, West Virginia	8:00 AM
2-2	Silurian Tonoloway Limestone at Patterson Creek Mountain Anticline, West Virginia	9:05 AM
2-3	Silurian-Devonian Helderberg Group at Forman, West Virginia	10:00 AM
2-4	Devonian Hampshire Formation, diamictite facies, mass transport deposit, and Mississippian Price Formation at the Allegheny Front, West Virginia	11:30 AM
2-5 (optional)	Mississippian Mauch Chunk Formation at the Allegheny Front, West Virginia	
2-6 (optional)	Mississippian–Pennsylvanian unconformity at State Hwy. 42, West Virginia	
2-7	Pennsylvanian Conemaugh Group at Mt. Storm, West Virginia	12:40 PM
	Arrive in Baltimore, Maryland	5:00 - 5:30 PM

Day 2 of this trip begins in Moorefield where the field trip continues upsection through the stratigraphic column. Stops will include Silurian-Devonian carbonates of the Tonoloway Limestone and Helderberg Group; Devonian Oriskany Sandstone, Needmore Shale, and Marcellus Shale; Devonian-Mississippian siliciclastic strata that filled the Acadian foreland basin; and Pennsylvanian coal-bearing sandstone. On this day, the field trip makes 5 stops, and there is an optional stop if time permits. Day 2 ends in Baltimore, Maryland.

Stop 2-1: Devonian carbonate-to-siliciclastic transition from passive margin to Acadian orogeny

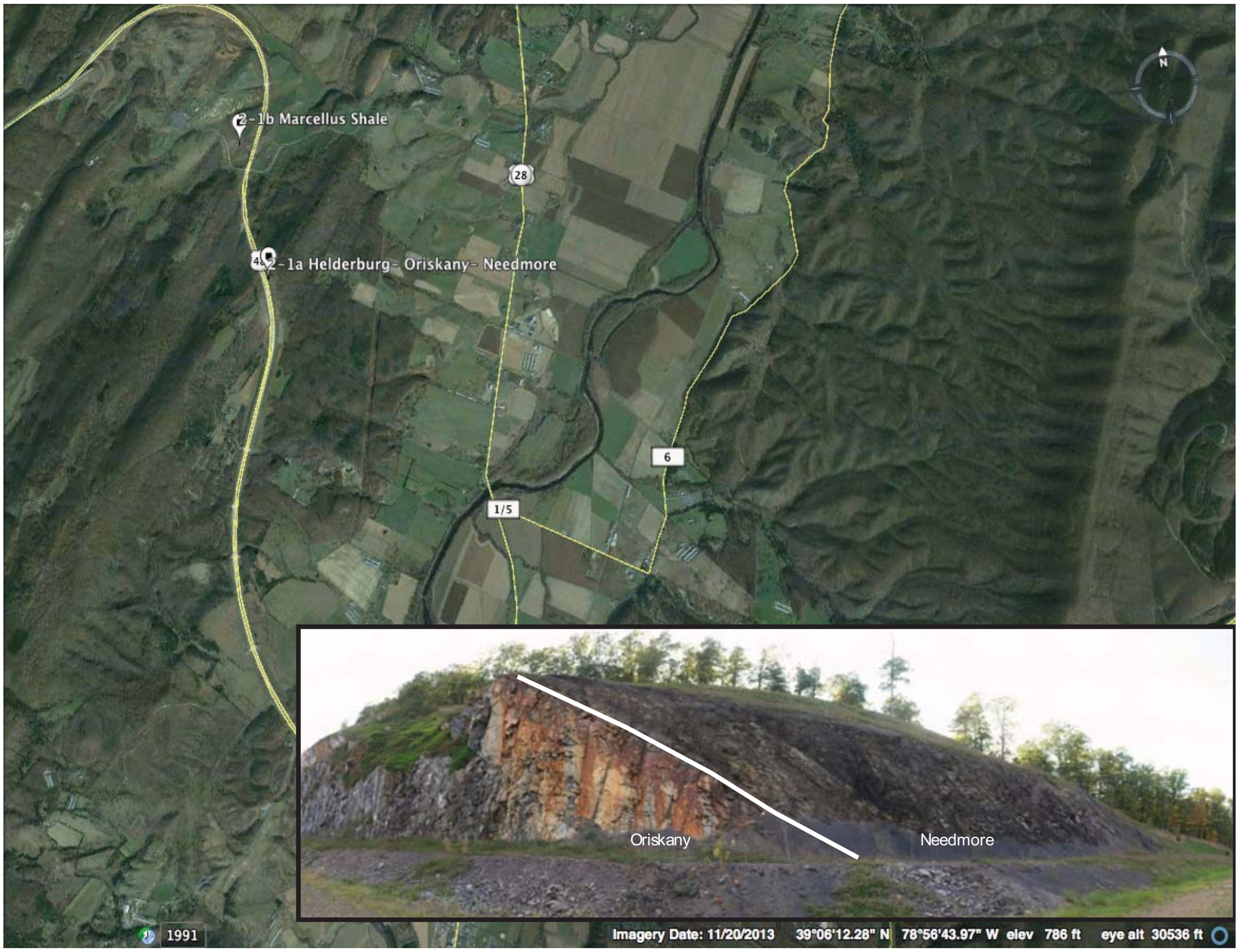


Figure 18. Google Earth image showing the location of Stop 2-1, with inset outcrop photo (GigaPan image by Alan Pitts) showing the contact between the Devonian Oriskany Sandstone and the Needmore Shale at Stop 2-1a.

Stop 2-1a: Transition from Devonian passive margin to Acadian orogeny - Licking Creek Limestone, Oriskany Sandstone, Needmore Shale, and Wallbridge discontinuity (39°07'21"N, 78°58'50"W)

The first stop on Day 2 (**Figure 18**) visits an outcrop that provides excellent exposures of 1) the stratigraphic transition from the Licking Creek Limestone of the Helderberg Group to the overlying Oriskany Sandstone, and 2) the stratigraphic transition from the Oriskany Sandstone to the overlying Needmore Shale. The Licking Creek-Oriskany contact is gradational over several meters, in stark contrast to the Oriskany-Needmore contact that is more abrupt. The sharp Oriskany-Needmore contact is interpreted to result from the relatively rapid deepening of the Acadian foreland basin.

The Oriskany-Needmore contact is an abrupt change of lithologies that occurs over just a few centimeters that may correspond to the regionally extensive Wallbridge discontinuity, which may or may not also be an unconformity. At some localities in southwestern Virginia an unconformity is present both beneath and above the Oriskany Sandstone (Dennison et al., 1992). One of these unconformities is correlated with the Wallbridge discontinuity, the boundary between the Tippecanoe sequence and the overlying Kaskaskia sequence (Sloss, 1963; Swezey, 2002). The Oriskany Sandstone here is calcareous to calcarenaceous quartz arenite, with some pebbly beds. At this stop the Oriskany Sandstone also contains abundant and prominent spiriferid brachiopods and brachiopod moldic pores characteristic of this stratigraphic unit throughout the central Appalachian Basin (**Figure 19**). At this stop, the Oriskany Sandstone is darker than at many other locations, evidently due to the lack of weathering within the fresh exposures. Where weathered, the sandstone turns to rusty light brown upon loss of the calcareous cement.

The Needmore Shale records deposition following the initial foundering of the shallow marine sediments of the Helderberg Group and Oriskany Sandstone. Shales of the Needmore represent progressively deeper ramp to basin margin depositional settings, and the accompanying extensive deposition of siliciclastic muds into the developing foredeep. The Needmore is often fossiliferous and calcareous.

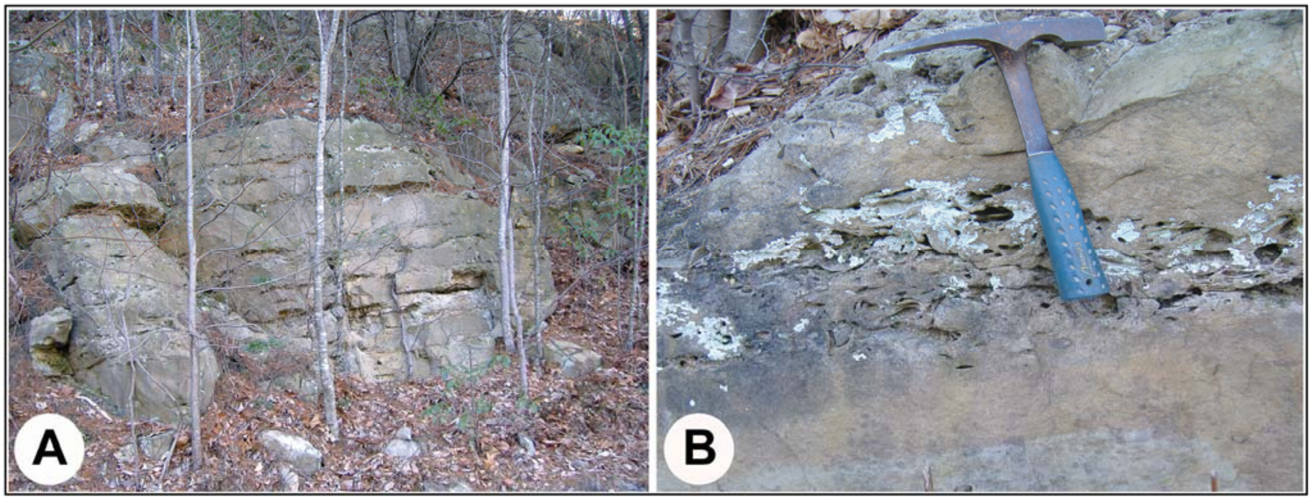


Figure 19. Devonian Oriskany Sandstone along the field trip route. A) Ledges of sandstone along old State Highway 55 near Wardensville, West Virginia. B) Biomoldic pores of spiriferid brachiopods in the Oriskany Sandstone, which are very common in the Oriskany Sandstone throughout this region. Location same as A).

Stop 2-1b: Acadian orogeny: Devonian Marcellus Shale (39˚08'04"N, 78˚59'02"W)

At this stop, the Marcellus Shale is exposed in a small roadside excavation. Good exposures of the Marcellus Shale are difficult to find because of its high susceptibility to physical weathering (being fissile mudrock) generally resulting from pervasive frost wedging and shattering along the numerous fractures and joints, as well as along the bedding planes. Here, the Marcellus Shale is predominantly a gray-black to black thinly laminated pyritic shale. Although calcareous concretions and occasional limestone beds are often observed within the Marcellus in the surrounding region (Dennison and Hasson, 1976), they have not been observed at this exposure. With recent development of horizontal drilling and hydraulic fracturing (“fracking”) methods to extract gas from tight shale, the Marcellus Shale has become a major target across much of the central Appalachian Basin, from southern New York State through Pennsylvania and Maryland and into central West Virginia (Zagorski et al., 2012).

Stop 2-2: Silurian passive margin: Tonoloway Limestone, Grant County, West Virginia (39°07'49"N, 79°02'19"W)

This stop shows a section of the Tonoloway Limestone exposed in the core of the Patterson Creek Mountain anticline. Also exposed are excellent examples of Alleghanian deformation in the form of two broad anticlines, each located on either side of a more tightly folded syncline (**Figure 20**).

Figure 20. (Lower) Google Earth image shows the location of Stop 2-2. (Upper) outcrop photo (GigaPan image by Alan Pitts) showing the anticlines and syncline in the thin-bedded Silurian Tonoloway Limestone exposed along the axis of the Patterson Creek Mountain anticline.

Throughout this region, the Tonoloway Limestone consists of three unnamed but laterally persistent members (Woodward, 1941; Bell and Smosna, 1999). The lower member consists primarily of thin-bedded and laminated gray to black lime mudstone, commonly peloidal and usually cut by many prominent orthogonal fractures. In some beds, pink to red to reddish-brown argillaceous and dolomitic partings are prominent, and a few thin beds of ostracode and gastropod packstone and grainstone along with thin oolitic grainstone are present. The middle member consists of thick- to massive-bedded bioclastic grainstone in which abundant crinoid fragments and lesser sponge, brachiopod, coral, and bryozoan debris are common, along with sparse boundstone and coral-stromatoporoid framestone.

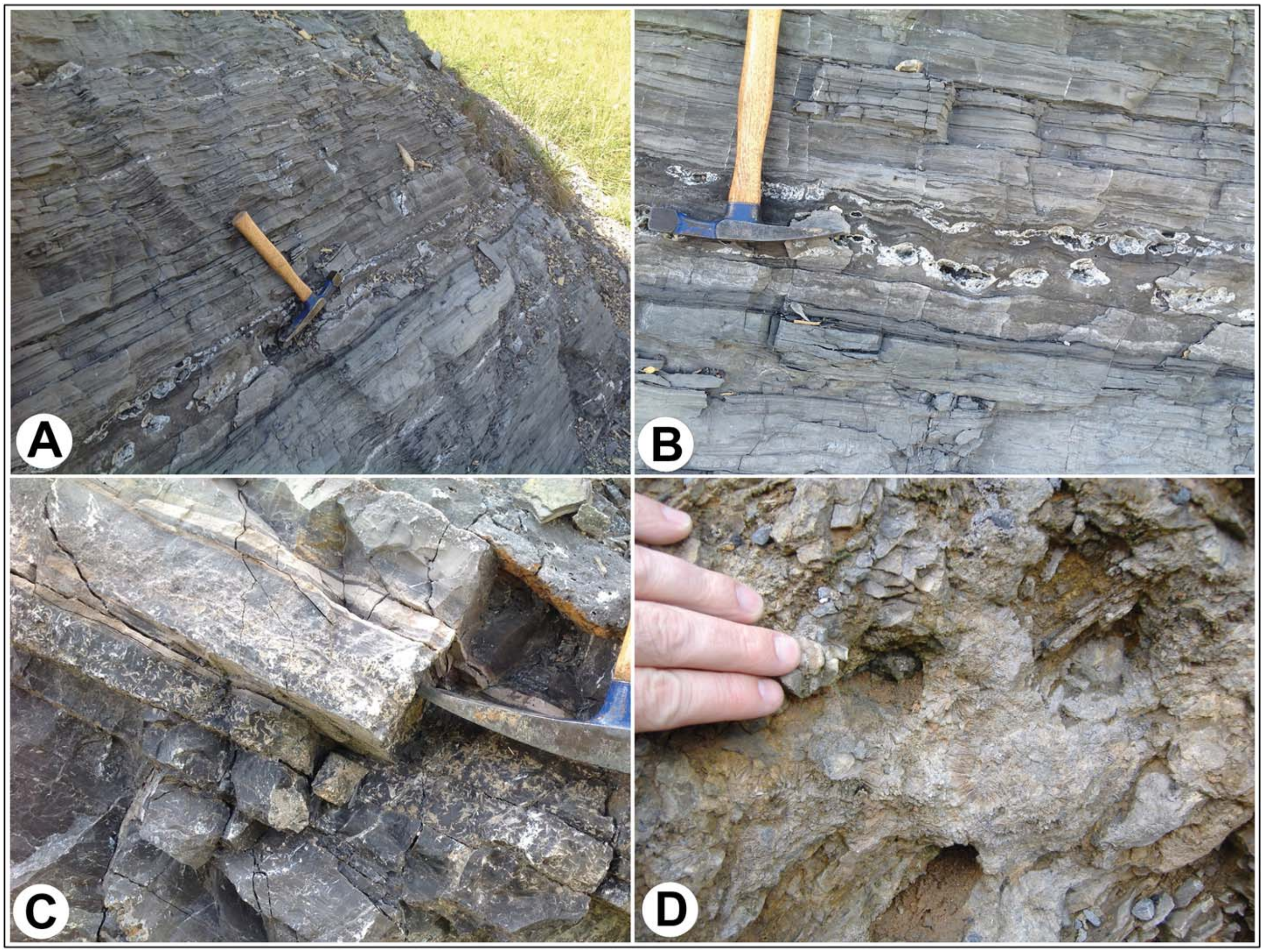


Figure 21. Sedimentary structures in the upper member of the Silurian Tonoloway Limestone. A) Characteristic thin-bedded and laminated lime mudstone cut by numerous joints and fractures along US 48/Corridor H. B) Calcite crystals in vugs that are pseudomorphs after nodular anhydrite along US 48/Corridor H. C) Densely packed gypsum crystals replaced by calcite, in several beds along US 48/Corridor H. D) Gypsum “daisies,” replaced by pseudomorphic calcite, in an evaporite breccia within the Tonoloway Limestone along US 33 near Oak Flat, West Virginia.

The upper member, exposed at this stop, typically consists of thin-bedded and laminated gray lime mudstone that has orthogonal fractures that cut individual beds (**Figure 21**). Thin sections have revealed that many of the lime mudstone beds are in fact composed of peloidal packstone to grainstone. Within the upper member of the Tonoloway Limestone, and to some extent the lower member as well, mud cracks, algal laminates (some with well-developed domal stromatolites), and a few thin beds of intraclast grainstone and packstone are commonly present. To the south of the field trip area in Virginia, the lower member also contains three to four thin beds of calcite-cemented sandstone (quartz arenite) up to 4 m (12 ft) thick (Haynes, 2014). Relict evaporite textures include 1) vugs lined with drusy calcite interpreted as evaporite (probably anhydrite) nodules now replaced by calcite (**Figure 21A, B**), 2) lenticular and well-formed gypsum crystals now pseudomorphed by calcite (**Figure 21C**), and 3) evaporite breccias including one located to the south in Pendleton County, West Virginia that has gypsum “daisies” replaced by pseudomorphic calcite (**Figure 21D**). These textures record the development of thin and discontinuous evaporite depositional environments considered to be correlative with the much thicker evaporites of the Silurian Salina Group in the subsurface of the Appalachian Basin farther north and west (Smosna et al., 1977; Ryder et al., 2007).

Stop 2-3: Silurian-Devonian passive margin; Helderberg Group on the West Flank of the Patterson Creek Mountain anticline, Grant County, West Virginia (39˚ 07'46"N, 79˚03'08"W)

The Helderberg Group is interpreted as a third-order sequence deposited over an 8-10 My period that consists of three transgressive-regressive sequences, each deposited over 2-3 My (Dorobek and Read, 1986). At this exposure nearly the entire Helderberg Group is visible, from oldest to youngest as follows: the Keyser Limestone, the New Creek Limestone, the Corriganville Limestone, the Mandata Shale, and the Licking Creek Limestone (**Figure 22**). It is possible to identify the Jersey Shore Member and likely the LaVale Member of the Keyser Limestone, and the Cherry Run Member of the Licking Creek Limestone, on the basis of their respective distinguishing features: large corals and other reef-formers in the Jersey Shore Member, anastomosing arenaceous laminae in the LaVale Member, and black chert nodules and lenses with pinkish partings in the Cherry Run Member.

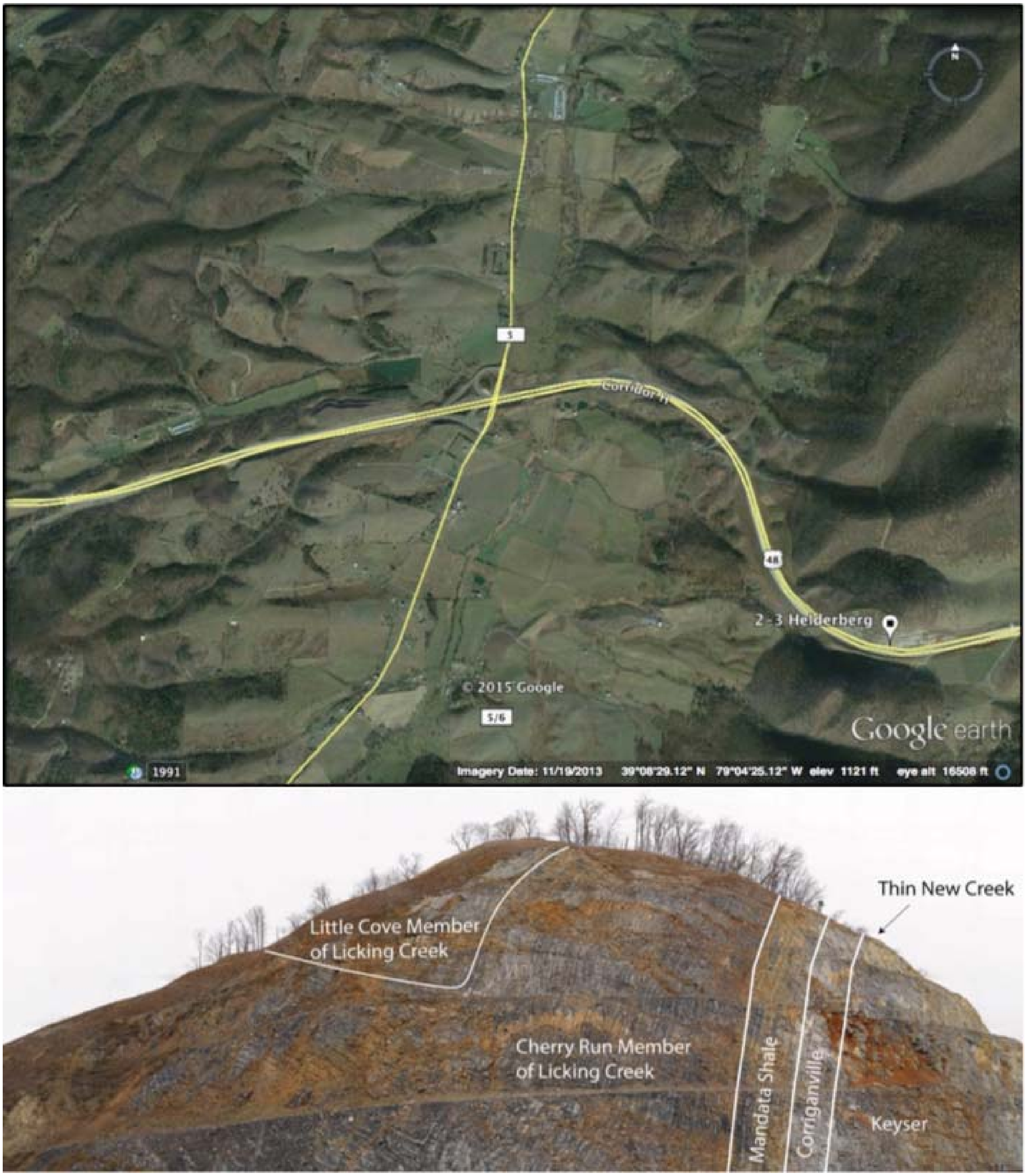


Figure 22. (Upper) Google Earth image showing the location of Stop 2-3. (Lower) outcrop photo showing thicknesses of and contacts between the stratigraphic units of the Silurian-Devonian Helderberg Group exposed at Stop 2-3 (GigaPan image by Alan Pitts).

Strata of the Helderberg Group are of particular interest to the ongoing search for a Silurian and Lower Devonian petroleum system in the Appalachian Basin (Swezey, 2002; Ryder et al., 2007). The carbonates of the Silurian Tonoloway Limestone and overlying Silurian-Devonian Helderberg Group in this region of the central Appalachian Basin have been buried to sufficient depth for petroleum to have been generated, as determined by regional studies of burial history and thermal maturation (Repetski et al., 2008). Evidence that hydrocarbons and hydrothermal fluids have moved through these strata includes analyses of fluid inclusions, cements, and diagenetic replacement minerals (Dorobek, 1987), and the presence of saddle (baroque) dolomite throughout the Tonoloway Limestone and the overlying Helderberg Group (Dorobek and Read, 1986; Dorobek, 1987; Haynes et al., 2010; Cole et al., 2015). The existence of saddle dolomite in these strata is important evidence that there has been significant rock-brine interaction at temperatures that coincide with the oil window and the dry gas window (Spötl and Pitman, 1998). Natural gas has been produced from the Devonian New Creek and Corriganville Limestones of the Helderberg Group (Baez et al., 2004), but the source of those hydrocarbons has not yet been identified, nor has a detailed investigation of porosity and permeability in those units been conducted.

It is hypothesized that the Mandata Shale may have been the source of these hydrocarbons in the Helderberg Group, as the work by Baez et al. (2004) shows that the area of gas production from the Helderberg Group also corresponds with the area where the Mandata Shale is present. At this exposure, the Mandata Shale is a fissile, dark gray to black, calcareous shale.

The cherty Cherry Run Member of the Licking Creek Limestone may also be a candidate as a hydrocarbon source in the Helderberg Group. The chert in the Corriganville Limestone is typically light gray to white, but going upsection into the Cherry Run Member of the Licking Creek Limestone, the chert becomes darker gray to black over a relatively short stratigraphic interval. This change in color may reflect an increase in total organic carbon (TOC) from the Corriganville Limestone into the Licking Creek Limestone (Dorobek and

Read, 1986). Thin sections of Corriganville and Licking Creek cherts show that siliceous sponge spicules were a major source of silica for the chert, although Cecil (2004) hypothesized that many of the extensive Paleozoic chert beds in the Appalachians may have had an eolian origin. It is conceivable that both marine and eolian processes may have contributed to the development of the chert of the Corriganville Limestone and the Licking Creek Limestone. The pink partings in the Cherry Run Member, which are particularly prominent at this stop, may have an eolian origin related to windblown silt. Thin sections of similar pink partings in the lower member of the Tonoloway Limestone show that the color is from a coating of hematite on quartz silt grains (Swezey et al., 2015).

Stop 2-4: Acadian orogeny; glaciogenic deposits(?) and the contacts for the Devonian Hampshire Formation, Spechty Kopf, and Devonian-Mississippian Price Formation (39°13'58"N, 79°10'36"W)

The long outcrop of strata at **Stop 2-4** includes the transition from redbeds of the Hampshire Formation into diamictite of the overlying Spechty Kopf formation of West Virginia (herein) (Spechty Kopf Formation of Pennsylvania, Rockwell Formation of Maryland, Brezinksi et al., 2008 and 2010) (**Figure 23**). This unit extends laterally over 400 km (250 mi) across eastern Pennsylvania, western Maryland, and eastern West Virginia (Lessing et al., 1992; Brezinski et al., 2008 and 2010; Brezinski and Cecil, 2015).

Deposits in these equivalent stratigraphic units have been interpreted as being of glaciogenic origin based on textures and sedimentary structures typically associated with glacial environments, including faceted and lightly striated clasts and poorly sorted to unsorted diamictites (Brezinksi et al., 2008). At **Stop 2-4**, a bed with similar characteristics occupies the same stratigraphic interval observed at several other locations in this region, including a large roadcut on Interstate 68 at Sideling Hill in western Maryland (Kammer and Bjerstedt, 1986; Brezinski et al., 2008, 2010 and Brezinski and Cecil, 2015).

Figure 23. Google Earth image showing the locations of Stop 2-4 and optional Stop 2-5.

The Spechty Kopf (Rockwell of Maryland) at **Stop 2-4** contains pebble- to cobble-sized clasts of various lithologies, including igneous and metamorphic rocks. Some clasts show faceting and faint striations (**Figure 24**), textures interpreted to be consistent with deposition in a glaciogenic environment as described by Brezinski et al. (2008, 2010) and Brezinski and Cecil (2015). The diamictite is overlain by red mudrock that grades upward into shale and fine to medium-grained sandstone that has prominent convoluted bedding and large-scale soft-sediment deformation structures (see inside back cover photo), and which varies in thickness along the extent of this outcrop. This succession of convolutely-bedded clasts and matrix is interpreted as a marine slump or mass-transport complex. It was likely deposited on a slope along the margin of the Acadian foredeep that, in this region, was almost completely filled across most of its lateral extent. This complex bed of clasts and deformed matrix contains a large number of completely recumbently folded sandstone "flow-rolls." At other locations, similar soft-sediment deformation features have been interpreted to be the result of seismic activity (Mills, 1983; Roep and Everts,

1992) or rapid pulses of floodwater input and turbidity flows (Mills, 1983). The link between the origin of this bed and the glaciation that was occurring along the Laurentian margin or a nearby region, if any, is not yet clear.

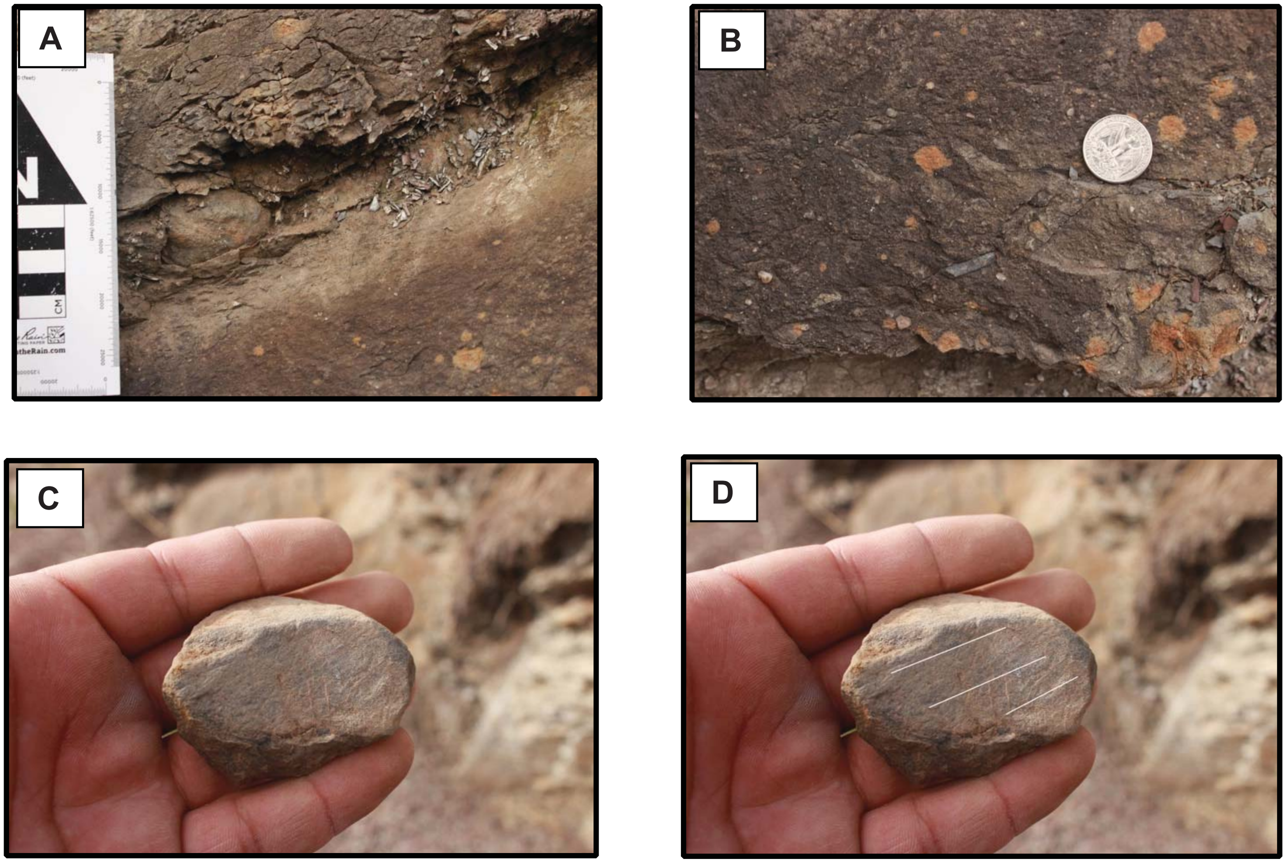


Figure 24. Exposure of diamictite within the Devonian Spechty Kopf Formation (Rockwell Formation of Maryland). A) Cobble size clast in massive mudstone. B) Poorly sorted matrix-supported diamictite. C) Faceted clast removed from outcrop. D) Annotated photo highlighting faint striations.

After leaving **Stop 2-4**, the field trip route ascends the line of low hills known as the Fore Knobs. The route continues upsection and crosses the belts of the Greenbrier Limestone (not exposed along US 48/Corridor H), the red mudrocks of the Mauch Chunk Formation, and the coal-bearing sandstones and mudrocks of the Pottsville Formation (note: the Mauch Chunk Group and Pottsville Group are not sub-divisable in the northern Appalachian region, so Formation rank is preferred). Although not exposed in the roadcuts along this highway, the Greenbrier Limestone is a prominent carbonate unit within this part of the stratigraphy, marking a regional sequence stratigraphic boundary. The extensive exposures of red mudrocks exposed in the road cuts on the north side of the highway just west of **Stop 2-4** are assigned to the Mauch Chunk Formation. A 7 m (23 ft) thick limestone crops out stratigraphically near the base of the Mauch Chunk Formation. This limestone is tentatively correlated herein with the Reynolds Limestone Member of the Bluefield Formation, the basal formation of the greatly expanded Mauch Chunk Group in southern West Virginia and Virginia (Cole, 2005). Alternatively, it possibly may be correlated with the Glenray limestone of the Bluefield Formation, also farther south, or it may not be possible at all to correlate this limestone with a named member in the south.

Near the top of the long ascent, the field-trip route passes over the unconformable Mississippian-Pennsylvanian boundary, which is overlain by sandstone and conglomerate of the Lower and Middle Pennsylvanian Pottsville Formation (equivalent to the New River and Kanawha formations to the south). There is an optional **Stop 2-5** to investigate a typical paleovertisol of the Mauch Chunk Formation, and the Mississippian-Pennsylvanian unconformity and the transition that takes place from Mississippian red mudrocks with little organic matter into the overlying organic-rich Pennsylvanian siliciclastic strata.

Optional Stop 2-5 and Optional Stop 2-6: Changing climate during the late Paleozoic

Stop 2-5: Mississippian passive margin: redbeds of the Mauch Chunk Formation, (39°13'02"N, 79°12'01"W)

The Mauch Chunk Formation is well exposed in the roadcuts along the field trip route as beds of conspicuously red mudrock and sandstone along the Alleghany Front (**Figure 23**). These beds have been interpreted as terrestrial sediments deposited in upper delta/alluvial flood plain environments in an arid or semiarid climate (Edmunds and Eggleston, 1993; Cecil et al., 2004; Beuthin and Blake, 2002, 2004; Blake, 2009).

Late Mississippian paleogeographic reconstructions place the central Appalachian Basin approximately 10 degrees south of the paleoequator, in the region where, like today, the boundary between the Hadley and Ferrel cells is the subtropical high pressure area where descending warming and dry air results in aridity (Scotese and McKerrow, 1990). The Upper Mississippian and Pennsylvanian strata thicken southward into a rapidly subsiding portion of the Appalachian Basin where the Upper Mississippian Mauch Chunk Group exceeds 2000 m (3,500 ft) in thickness and is subdivided, in ascending order, into the Bluefield Formation, Hinton Formation, Princeton Sandstone, and Bluestone Formations (Reger and Price, 1926; Barlow, 1996). This dominantly redbed succession includes numerous paleovertisols (**Figure 25**) and paleocalcisols (**Figure 25D, E**), common calcareous globules that locally coalesce into calcrete (caliche), common mud cracks, rare salt crystal casts, possible gypsum films coating vertic structures, and gypsiferous nodules within at least one calcic vertisol (Cecil et al., 2004; Blake et al., 2009 and references therein).

Where present, coal beds are discontinuous, thin, and of low quality, characteristics that suggest ground water control on peat accumulation (Beuthin and Blake, 2002, 2004). Collectively, these climatic proxies suggest that the Late Mississippian paleoclimate of the central Appalachian region varied between semi-arid and subhumid, in response to Milankovitch-forced changes in southern hemisphere ice volumes (Cecil et al., 1985; Cecil, 2003; Cecil and Dulong, 2003; Cecil et al., 2004; Blake et al., 2009). Marine-influenced strata intercalated with the non-marine strata were deposited during periodic glacioeustatic transgressions, and these marine strata are used to subdivide the monotonously stacked sequences of Mauch Chunk Group redbeds into various formations (Beuthin and Blake, 2004). The basal contact of the Mauch Chunk Group is conformable with the underlying Greenbrier Limestone, but this contact is not exposed along the route of this field trip. A basin-wide unconformity of varying extent exists between the top of the Mauch Chunk Group and the overlying lower Pennsylvanian Pottsville Group (Blake and Beuthin, 2008). In the northern part of the basin, fossiliferous horizons interpreted as marine zones and other marker beds may be absent, and as a result the individual formations of the Mauch Chunk Group can be difficult to distinguish, such as here along US 48/Corridor H. As a result, the term Mauch Chunk Group is typically used in southern West Virginia, whereas the term Mauch Chunk Formation is typically used in northern West Virginia and adjacent parts of Maryland and Pennsylvania. It is the absence of marker beds that necessitates this stratigraphic “lumping” (as it does along US 48/Corridor H), so that the Mauch Chunk unit may be afforded formational rather than group rank.

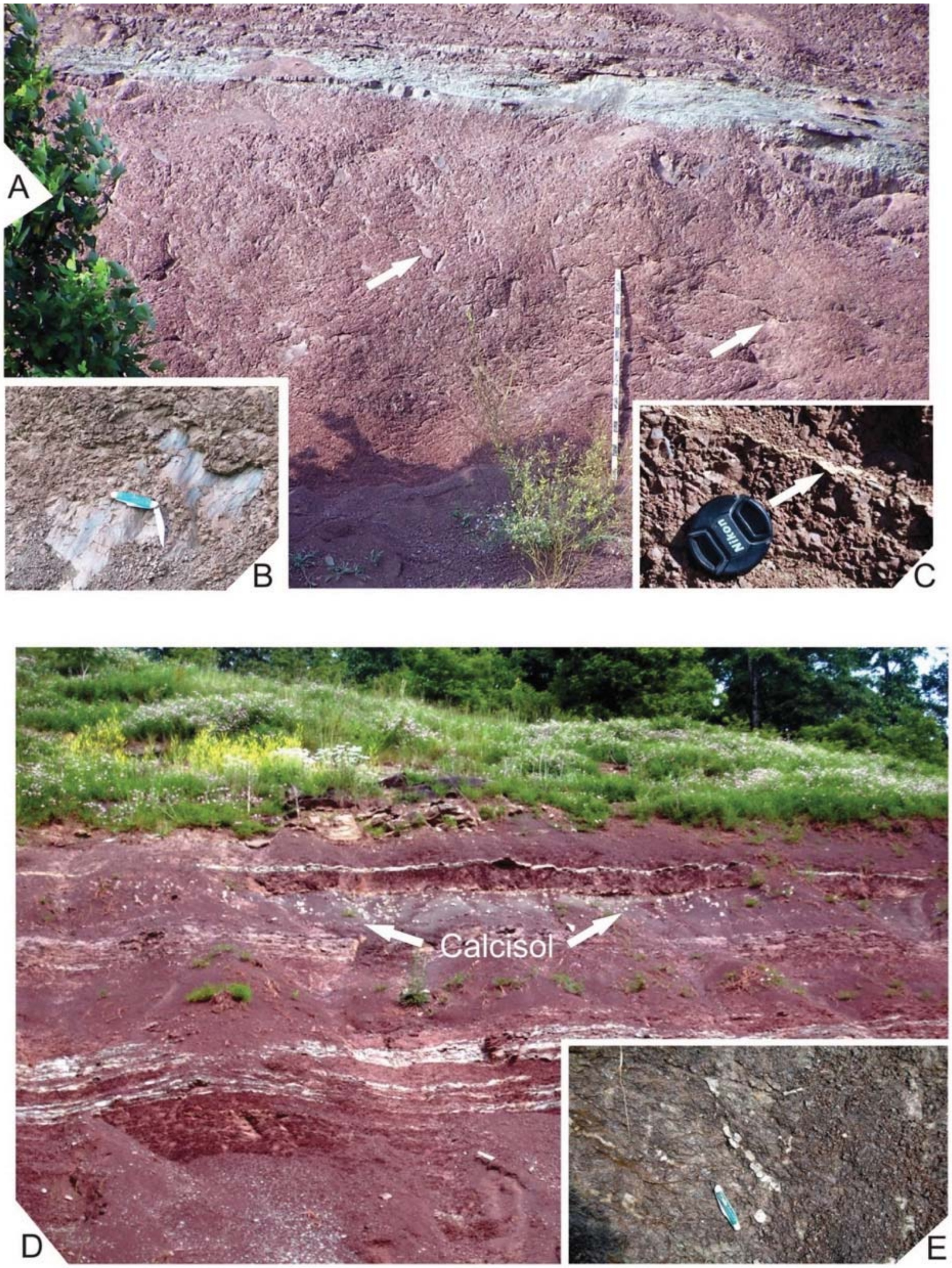


Figure 25. Paleosols from the Mississippian Hinton and Bluestone Formations (Mauch Chunk Group). A) Paleovertisol from the Hinton Formation located on the south side of US 460, near Possum Hollow, approximately 5 km east of Princeton, West Virginia. B) Close up of slickenside surface from paleovertisol in A) above, formed from repeated shrink-swell cycles as expanding clays react to the seasonal availability of moisture. Knife handle is 7.5 cm long. C) Calcite films coating slickenside surfaces in paleovertisol from the Hinton Formation, along Laurel Creek Road near Athens, West Virginia; this bed is in the same stratigraphic interval as the one shown in A) and B). Lens cover for scale is 63 mm in diameter. D) Calcisol from the red member of the Bluestone Formation on the north side of US 460 near Green Valley, West Virginia. E) Close-up of calcisol showing calcareous nodules and possible rhizoconcretions. Knife handle is 7.5 cm long. Figures taken from Blake et al. (2009).

Optional Stop 2-6: Onset of the Alleghanian orogeny; The Mississippian-Pennsylvanian unconformity, and the Pennsylvanian Pottsville Formation (39°12'54"N, 79°12'22"W)

The contact between the Mauch Chunk Formation and the Pottsville Formation is well exposed in road cuts along both sides of West Virginia State Highway 42 beneath the U.S. 48 overpass, but especially along the west-southwest side of WV 42 (**Figure 26**).

Figure 26. Google Earth image showing the location of optional Stop 2-6 and Stop 2-7.

At this locality, the uppermost part of the Mauch Chunk, the Mississippian-Pennsylvanian unconformity, and the lower part of the Pottsville are visible. A quartz-pebble lag with abundant organic material at the base of the Pottsville Formation is in erosive contact with underlying beds of fine sandstone (many of which are slightly greenish) assigned to the Mauch Chunk Formation. This seemingly unimpressive surface is the Mississippian-Pennsylvanian unconformity, also known as the "Miss-Penn Boundary." At this location the unconformity spans the middle and upper Namurian (Upper Mississippian) and the lower part of the Langsettian Stage (Lower Pennsylvanian), as discussed in Blake et al. (2002, 2009), representing a duration exceeding 3 million years (Blake and Beuthin, 2008). In other areas of the central Appalachian Basin, well-developed paleosols are preserved along this unconformity at the top of the Mauch Chunk Formation (below the Pottsville Formation), but such features likely represent interfluve soil development that survived erosion (Blake and Beuthin, 2008, and references therein).

Owing to variable dip and minor faulting along the route of the field trip, the true thickness of the Mauch Chunk Formation is not available at this location, but subsurface data indicate the thickness of the Mauch Chunk in Grant County can range from approximately 120-175 m (400 to 900 ft) (Ryder et al., 2008). On the other hand, a maximum total thickness of 250 m (800 ft) is a reasonable estimate here for the overlying Lower-Middle Pennsylvanian Pottsville Formation. In areas of its maximum development in West Virginia, to the south of this field trip area, the Pottsville Group attains a maximum thickness of approximately 1250 m (4000 ft) where it is subdivided into the Lower Pennsylvanian Pocahontas and New River Formations and the Lower-Middle Pennsylvanian Kanawha Formation (Blake et al., 1994) (**Figure 27**). Within the Kanawha Formation (upper part of the Pottsville Group), glacioeustatic marine zones are intercalated throughout the otherwise primarily terrestrial coal-bearing sandstone and mudstone (**Figure 27**).

Regionally, the Pottsville Group thins northward to approximately 110 m (350 ft) thick in northernmost West Virginia. As this thinning occurs, the unit crosses from the Northern to the Southern Coal Field of West Virginia (**Figure 28**). In the Northern Coal Field, regional correlations are highly dependent on paleobotany (Blake, 1997; Blake et al., 2002). The Mississippian-Pennsylvanian unconformity occurs between the underlying Mauch Chunk and the Pottsville Group. This unconformity is present across the entire paleoequatorial belt and is generally attributed to a glacial eustatic sea level drop associated with onset of widespread Gondwanan glaciation (e.g., Blake et al., 2002; Blake and Beuthin, 2008; and references within both).

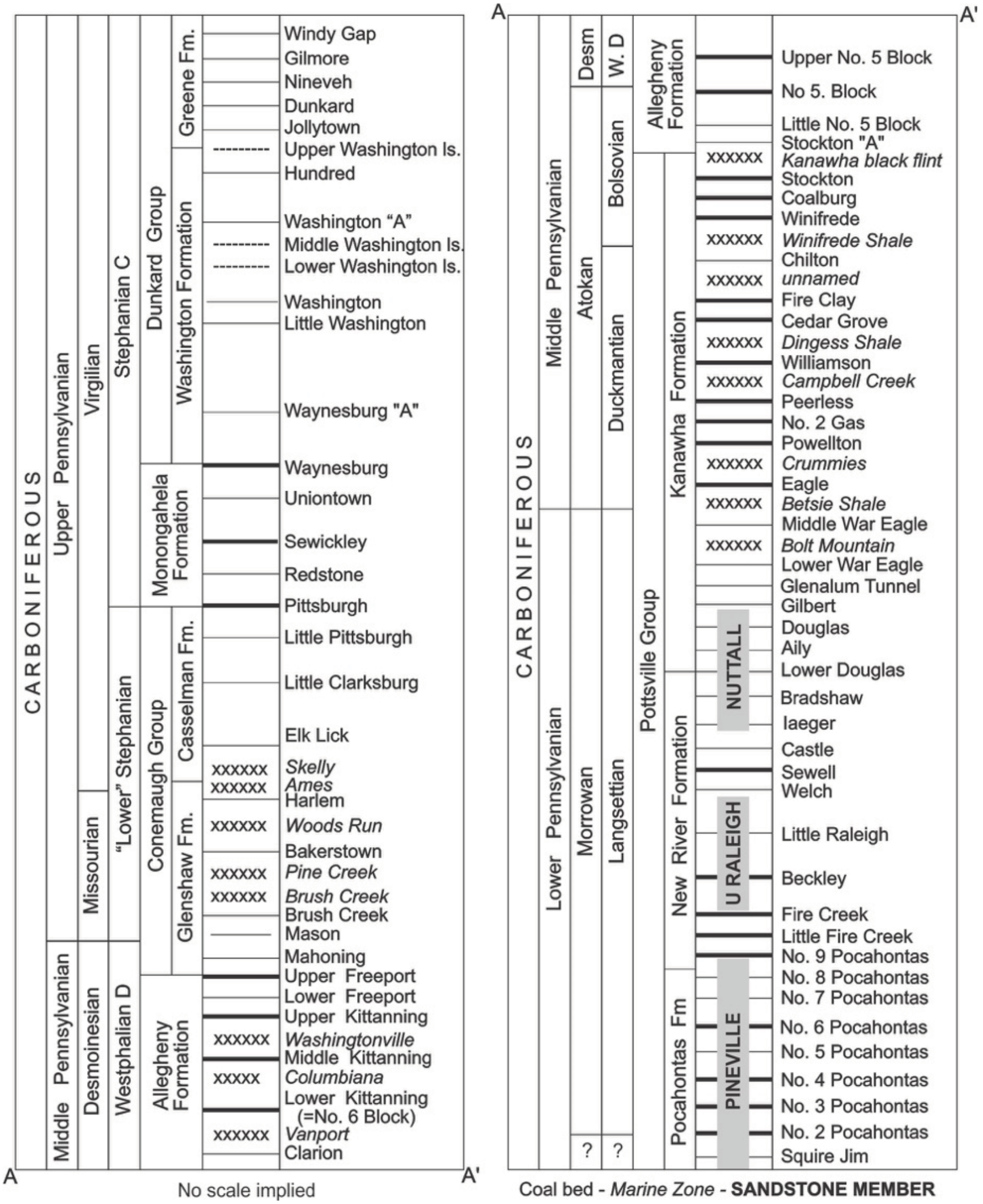


Figure 27. Chronostratigraphic chart showing Pennsylvanian stratigraphy of West Virginia. Italics denote fossiliferous marine zones (Blake et al., 2002).

In addition, the scale of the unconformity increases generally northward from southern West Virginia, likely because accommodation space was limited as a result of slow subsidence to the north.

In contrast to the semi-arid paleoclimate that existed during deposition of the Mauch Chunk, the Pottsville was deposited under tropical wet to ever-wet conditions (Cecil et al., 1985; Cecil, 2003; Cecil and Dulong, 2003). Paleogeographic reconstructions for the early Pennsylvanian suggest that North America had drifted northward closer to the paleoequator, out of the desert belt into the tropics (Scotese and McKerrow, 1990).

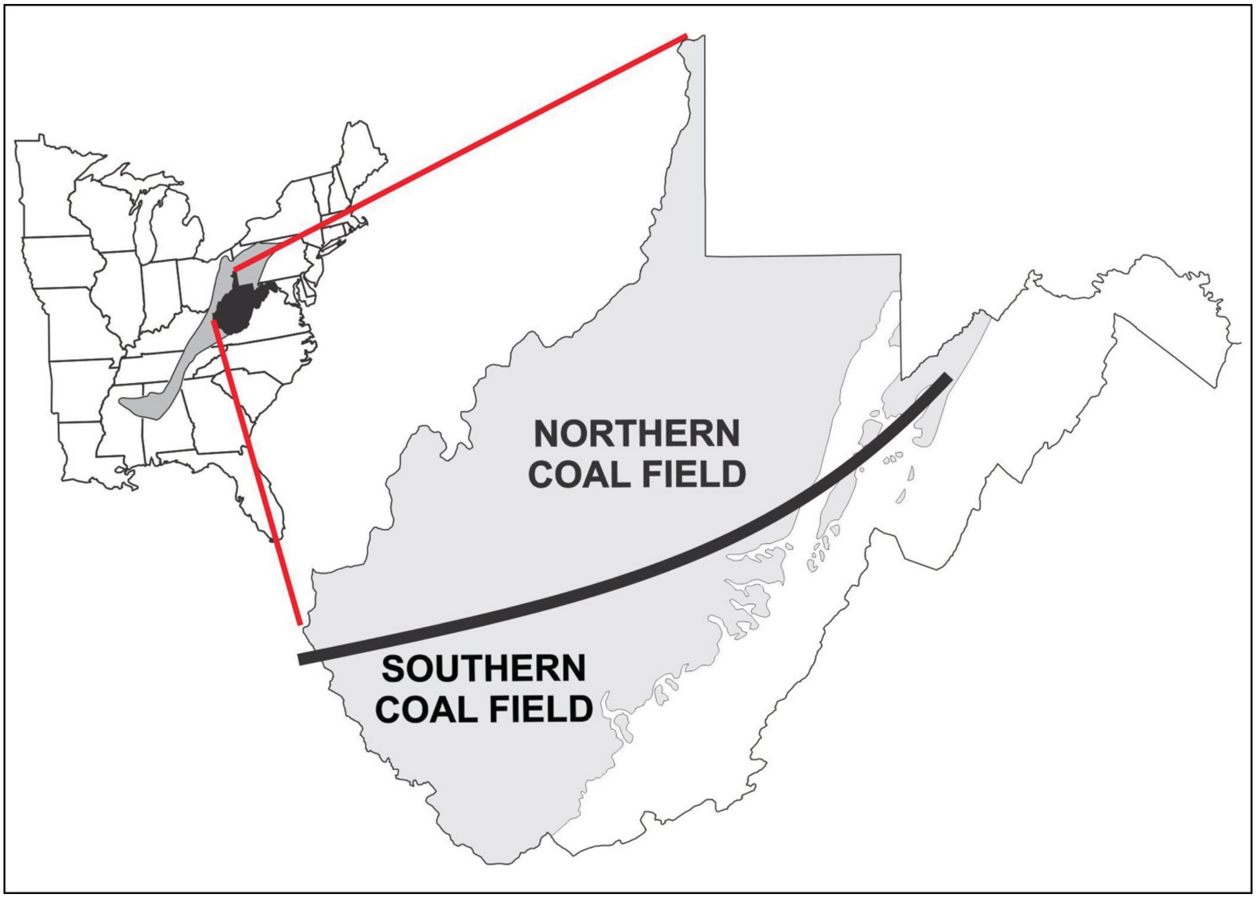


Figure 28. Pennsylvanian coal fields of the West Virginia portion of the Appalachian Basin, and the hinge line between the major coal fields that also marks a zone of change in the thickness of the Pennsylvanian Pottsville (Blake et al., 2002).

Raised peat beds fed by rainwater formed under the tropical humid climate, and terrestrial organic productivity was high. In contrast to the pervasive red coloration of the Mauch Chunk, rocks of the Pottsville are commonly shades of gray with no greenish or reddish tints, and they generally contain abundant plant-derived organic material. In contrast to the thick coal beds that developed throughout the rapidly subsiding foreland to the south, economically minable coal beds are generally absent in the Pottsville north of the hinge line. Several marine zones have been identified in mudrocks of the Pottsville north of the hinge line, but exposures are limited, and correlations remain tentative. Therefore, in some areas the Pottsville is reduced to formation rank in the northern areas of the Appalachian Basin in West Virginia and in the states farther north.

At **Stop 2-6**, several red paleovertisols of the Mauch Chunk Formation like those shown in **Figure 25** are exposed in the road cuts below the unconformity. Here vertic structures with slickensides like those in **Figure 25A** are well exposed, and calcite films are preserved (**Figure 25C**). Vertic structures are pedogenic features that form under a semi-arid or monsoonal climate with distinct wet and dry periods. Calcareous glaebules within the paleovertisols also support soil formation under arid conditions. In contrast to the red mudrock of the Mauch Chunk, the siliciclastic strata of the Pottsville above the unconformity are markedly gray from the appreciable organic matter preserved in them.

A small paleomacroflora at this locality is present approximately 20 m (65 ft) above the base of the Pottsville Formation. Overall this flora, especially *Neuralethopteris pocahontas*, suggests a biozone that is identified in the middle of the New River Formation, near the Sewell coal bed (**Figure 27**), in southern West Virginia (Blake et al., 1994). Still higher in the Pottsville Formation, another small collection of flora is suggestive of a biozone in the lower part of the Kanawha Formation (see charts in Blake et al., 2002), but detailed comparative work has not been published as of this time. A marine zone with articulate brachiopods is present in mudrocks 100 m (328 ft) above the base of the Pottsville, and this zone is tentatively correlated with the Betsie Shale Member of the Kanawha Formation (**Figure 27**). The Betsie Shale Member is a basin-wide unit within the Kanawha Formation (Blake et al., 1994; Blake et al., 2002), assigned as the Lower-Middle Pennsylvanian Stage boundary in North America (Blake, 1997; Blake et al., 2002) and is correlative with the Langsettian-Duckmantian Stage boundary of western European basins (Blake, 1997; Blake et al., 2002). The great lateral extent of these correlations is supportive of a glacioeustatic origin (Riley and Turner, 1995; see discussions in Blake et al., 1994 and Blake et al., 2002), and the specific biostratigraphical correlations are supported by paleobotanical work on megafloras (Blake et al., 1994 and references therein) and spores (Peppers, 1996).

Stop 2-7: Alleghanian orogeny; The Pennsylvanian Bakerstown coal zone and paleoslumps in the upper Pennsylvanian Conemaugh Group (39°12'48"N, 79°15'43"W)

At this, the final stop of the field trip (**Figure 26**), the exposed strata are assigned to the Upper Pennsylvanian Conemaugh Group. The apparent multiple beds of coal at this stop, including those in an area informally named “the dragon’s tongue” (**Figure 29**), are assigned to the Bakerstown coal zone, a bituminous coal within the Glenshaw Formation of the Conemaugh Group (**Figure 27**). Upper Pennsylvanian coal beds, such as the Bakerstown coal zone, are generally higher in sulfur content and ash yield as compared to older coal beds of the Pottsville Group. The Conemaugh Group extends from the top of the Upper Freeport coal bed to the base of the Pittsburgh coal bed. Although it is formally subdivided into the Glenshaw and Casselman Formations, regionally the name “Conemaugh” is generally more widely recognized and used (**Figure 27**). These contacts follow long-established tradition in North America of placing formation contacts at a geographically widespread, economically important coal bed. Unfortunately, these contacts tend to be difficult to locate in exposures where the coal bed is absent. Across the Appalachian Basin, numerous marine zones in mudrocks and carbonates of continent-wide – if not global – extent have been recognized and mapped (**Figure 27**). These marine zones are commonly identified as being part of the classic cyclothems as originally described in Upper Carboniferous strata around the world, where coal-bearing strata alternate with other sedimentary strata in repetitive vertical sequences (Heckel, 1990, 1994).

Across much of the region, Conemaugh Group strata strongly resemble the Mauch Chunk Formation strata. The non-marine mudrocks of the Conemaugh Group are dominated by abundant, well-developed red paleovertisols and paleocalcisols with features indicating development under seasonally-dry (monsoonal) climatic conditions. Such features include calcareous glaebules that locally coalesce into calcrete (caliche), common mud cracks, and calcite and possible gypsum films coating vertic structures (Joeckel 1995; Blake et al., 2004). Gypsum has been found in subsurface drill tests of the Conemaugh Group (M. Blake, unpublished data).

Coal beds in the Conemaugh Group are thin, impure, and areally restricted, suggesting that water table position was the primary factor controlling peat formation and accumulation, in stark contrast to the importance of a perennially wet climate that governed peat formation in the lower strata (Cecil et al., 1985, Cecil, 2003; Cecil and Dulong, 2003). Intercalated marine zones in mudrocks are important for stratigraphic correlation, as they demonstrate a biotic connection with the North American Interior basins that were characterized by marine incursions more frequently than here in the Appalachian Basin (Busch and Rollins, 1984; Heckel 1990, 1994). In addition, they help to define the lesser developed Appalachian Basin cyclothems, which are not as easily recognized because the siliciclastic sediments shed from the rising Alleghenian orogeny overwhelmed the classic cyclothem pattern or “signal” of the midcontinent (Heckel, 1994). The Glenshaw Formation is overlain by the Casselman Formation (**Figure 27**), a lithologically similar unit that does not contain intercalated marine zones.

Stop 2-7 is informally named “the dragon’s tongue” for the resemblance that an interesting tear structure in one of the coal beds has to the forked tongue of a dragon (**Figure 29**), inasmuch as such features are commonly portrayed in works of fiction. This tear structure, and others like it, most likely formed when the floating tattered remnants of the eroded margin of the Bakerstown peat were entombed in sediment (M. Blake, unpublished data). Overall, the Bakerstown peat developed on a calcic paleosol with abundant calcareous glaebules that have since locally coalesced into continuous beds of limestone (caliche). Overlying the Bakerstown is a heterolithic siliciclastic unit dominated by shale. The pteridosperms *Macroneuropteris scheuchzeri* and *Neuropteris ovata* are the common plant fossils found in the roof shale above the Bakerstown coal zone, and these plants probably grew in dense thickets of 7-10 m (20-30 ft) high “trees.” Reconstructions of pteridosperms envision a tree similar to extant tree ferns with adventitious roots forming a mantle to support a thin stele (Blake et al., 1994). Foliage consisted of several meter-long fronds bearing fern-like pinnules "leaves." The now extinct pteridosperms were seed-bearing plants, and as such were not related to the tree ferns that they resemble.

Figure 29. The "dragon's tongue", a tear structure in one of the coal beds of the Pennsylvanian Bakerstown coal zone at Stop 2-7.

Possible incised paleovalley fill and slumps

The exposure at **Stop 2-7** is a superb example of a paleoslump complex that exhibits multiple rotated blocks within the Glenshaw Formation (**Figures 30, 31, 32**). This series of rotated slump blocks involves the Bakerstown coal zone and immediately overlying strata (Glenshaw Formation). The entombed terminal stringers of Bakerstown coal, seen at the western end of the exposure, are common features in the Appalachian Basin. They are interpreted to have formed where paleochannels eroded through peat bodies and the tattered peat mat stringers floated in the stream. If totally detached from the peat body, such peat mats may float downstream and eventually be deposited with stream sediment, generally sand. The allochthonous nature of these floated peat mats is demonstrated by the lack of an underlying “seat earth.” A series of rotated slump blocks occur to the east of the entombed peat margin (**Figure 30**). Evidence from observations suggests that these slump blocks are part of the same sedimentary sequence, including the Bakerstown coal zone. The leading edges of the slump blocks show evidence of compression during slumping and rotation, which deformed the unconsolidated underlying sediments.

Figure 30. The Upper Pennsylvanian Conemaugh Group exposed at Stop 2-7. Part of a series of slump blocks interpreted as rotated paleovalley wall slumps formed after formation of an incised valley. Slumping may have been initiated by seismic activity in the tectonically active Alleghany orogen to the east. Stratigraphic and structural relationships between slump blocks are complicated.

The Bakerstown coal zone clearly shows evidence of movement such as 1) differential rotation within coherent peat masses, 2) great variation in bed thickness within individual slump blocks, and 3) abrupt termination of peat beds into stringers entombed in sediment. On the upper bench of the cut, the Bakerstown coal zone and overlying shale were deformed into a "U"-shape over a distance of a few meters. The relations among the various coal stringers in the vicinity of the "dragon's tongue" are much more complex than would appear upon casual examination. Excavation on the upper bench demonstrates that the stringers exposed on the lower bench do not physically connect with any stringers on the upper bench, greatly complicating interpretations.

Figure 31. The Upper Pennsylvanian Conemaugh Group exposed at Stop 2-7. Sedimentary sequence above the continuous erosional surface overlying the slump block complex. Notice the shale beds draping what appears to be a rotated slump block.

The top of the 5-7 m (15-20 ft) thick slump block is capped by an unconformity, above which lie thin beds of sandstone of variable thickness. At one place, this sandstone bed fills a channel incised several meters into the underlying slump block complex and is filled with a quartz pebble conglomerate lag. This sandstone bed is present along the entire exposure. Locally towards the eastern end of the exposure, laminated sandstone and siltstone drape a several meter-thick rotated block that is not clearly related to the underlying slump block complex (**Figure 31**). The entire interval is capped by a thin coal bed and associated seat earth. Deeply weathered dark gray shale overlies the coal bed and contains poorly preserved plant fossils.

Greb and Weisenfluh (1996) described paleoslump features within coal-bearing strata of the Pennsylvanian Breathitt Group in eastern Kentucky. They stated, “Slumps are inferred to have been triggered by a wide range of mechanisms, such as loading of water-saturated sediment on rigid substrates, synsedimentary faulting, and over-pressurization of channel margin and bar slopes”, and identified four types of paleoslumps based on the relation to the deformed beds to the bounding geologic units:

> Type-1 describes slumps of coal-bearing strata above undeformed carbonates. Type-2 paleoslumps are associated with synsedimentary normal faults and occur without regard to stratigraphic position. Type-3 paleoslumps occur without evidence of faulting, along relatively narrow, linear to curvilinear paleochannel margins. Type-4 paleoslumps are similar to type-3 paleoslumps, but occur within laterally juxtaposed cosets of point bars
>
> - Greb and Weisenfluh, 1996, p. 118

Guided in part by the general descriptions provided from Greb and Weisenfluh (1996), the trip participants are invited to make critical observations and to consider various hypotheses for the formation of the structures seen in the outcrop. To facilitate discussion, an interpreted annotated sketch is provided of the outcrop in **Figure 32**.

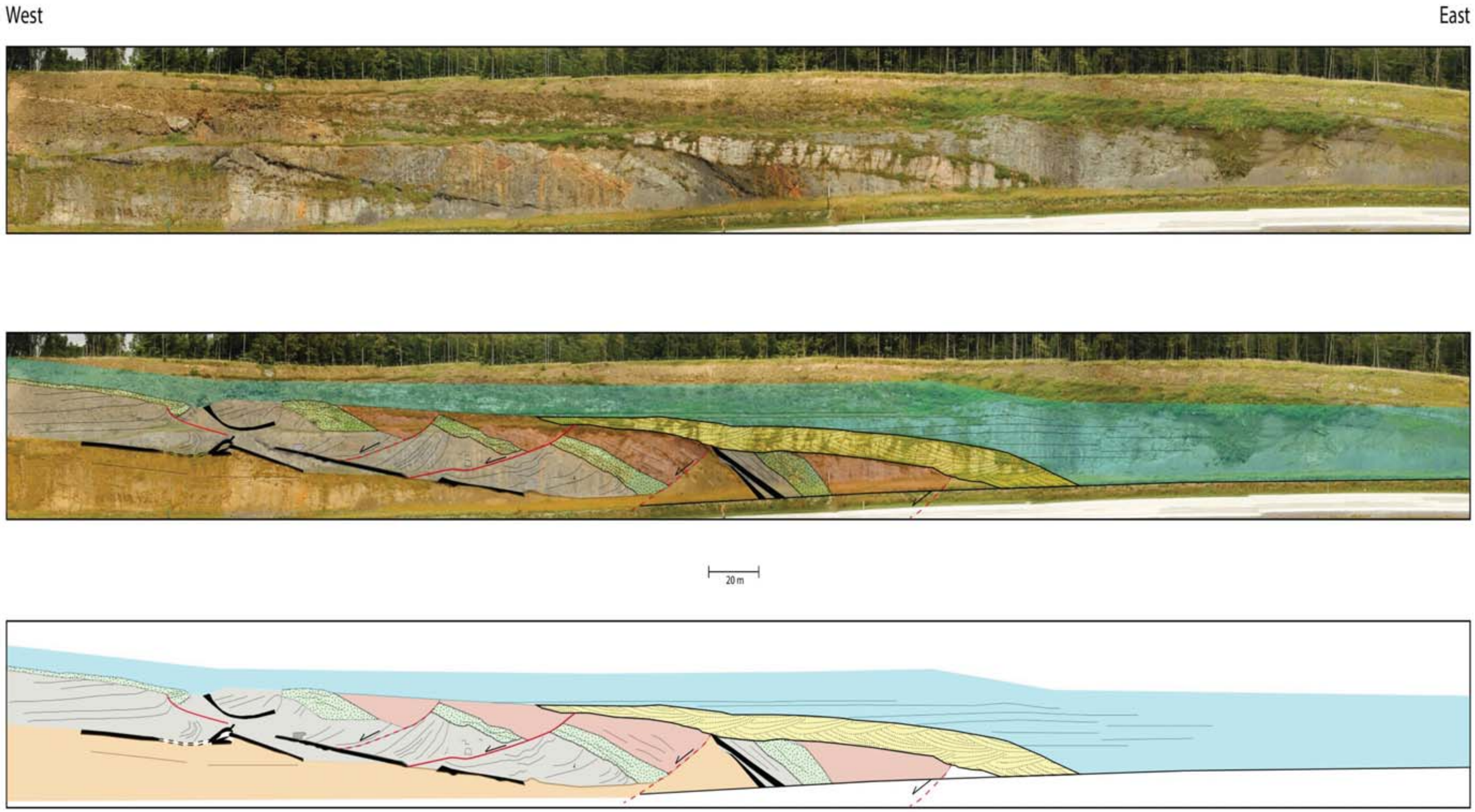


Figure 32. Preliminary outcrop sketch for Stop 2-7 highlighting interpreted slump blocks and associated surfaces of rotation along which slumping occurred. The Upper Pennsylvanian Conemaugh Group exposed at Stop 2-7.#

As a discussion topic, the following possible mechanisms may explain the origin of the slump structures:

1. **Penecontemporaneous Alleghanian faulting**. This mechanism seems unlikely. Peat forms on low-lying coastal plains under tropical humid climates. Decades of work on the Carboniferous strata of the Appalachian Basin have produced no credible evidence that penecontemporaneous tectonics had any control on sedimentation beyond providing accommodation space in the subsiding Appalachian Basin.

2. **Compaction of peat or other subjacent sediment.** Compaction of the Bakerstown peat clearly occurred, and a general rule of thumb for bituminous coal beds like the Bakerstown coal zone is a compaction rate of somewhere around 10:1. Although this compaction rate would seem to lend itself to disrupting overlying sediment during burial, slump features such as these are very uncommon and coal beds are not. If peat compaction can generate slump features, then why are slump features seen only at a few, widely separated locations? Likewise with the involved non-peat sediment. Currently, this mechanism is not deemed to be credible.

3. **The slumps resulted from a lack of accommodation space**. Again, this is the same argument discussed above.

4. **The “dragon’s tongue” represents a paleoseismite.** This is a viable hypothesis, although the lack of injectites (Neptunian dikes; sand volcanoes, etc.) formed from overpressured water-filled sediments (these features commonly occur in unconsolidated sediments during earthquakes) is a concern. Again, as discussed in number 2 above, these structures and features are not common across the basin.

5. **Paleovalley wall slump blocks.** This interpretation is currently preferred. Evidence supporting the presence of an incised paleovalley includes the rotated slump blocks from the valley wall, and paleovalley wall material entrained down the thalweg. There are a series of rotated blocks that overlie adjacent blocks comprised of discordant strata (**Figure 31, 32**). In addition, the Bakerstown coal zone, which is located beneath distinct and separate blocks, shows clear evidence of dislocation, including termination into peat stringers, rotation of part of the original peat, and disruption of coal bed thickness.

This preceding list is not meant to be inclusive. However, because this site is an isolated outcrop within the Stoney River syncline, it is unlikely that additional supporting data will become available. Nevertheless, the exposure is very interesting, and it makes for a fitting conclusion to this field trip.

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INSIDE BACK COVER: Mass transport deposit consisting of gray siltstone clasts that show convolute bedded along with the matrix that consists of gray mudrock. This bed is interpreted as part of the Upper Devonian-Lower Mississippian Price Formation (hammer for scale). This exposure is **Stop 2-4** of the field trip.