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Geologic Maps of the Stephenson and Winchester Quadrangles, Frederick and Clarke Counties, Virginia, and Inwood and White Hall Quadrangles, Berkeley and Jefferson Counties, West Virginia

Pamphlet to accompany

Scientific Investigations Map 3487

U.S. Department of the Interior
U.S. Geological Survey

Geologic Maps of the Stephenson and Winchester Quadrangles, Frederick and Clarke Counties, Virginia, and Inwood and White Hall Quadrangles, Berkeley and Jefferson Counties, West Virginia

By David J. Weary, Daniel H. Doctor, and Randall C. Orndorff

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

AMT	audio-magnetotelluric
CAI	color alteration index
cm	centimeter
DEM	digital elevation model
EM	electromagnetic
ESRI	Environmental Systems Research Institute
ft	foot
ft^2	square foot
Hz	hertz
in.	inch
km	kilometer
m	meter
m^2	square meter
Ma	million years before present
mi	mile
^{207}Pb	lead-207
^{235}U	uranium-235
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Geologic Maps of the Stephenson and Winchester Quadrangles, Frederick and Clarke Counties, Virginia, and Inwood and White Hall Quadrangles, Berkeley and Jefferson Counties, West Virginia

By David J. Weary, Daniel H. Doctor, and Randall C. Orndorff

Introduction

The study area consists of four contiguous 7.5-minute quadrangles, and is located in Frederick and Clarke Counties, Virginia, and Berkeley and Jefferson Counties, West Virginia. The individual quadrangles are Stephenson (sheet 1), Winchester (sheet 2), Inwood (sheet 3), and White Hall (sheet 4). The study area lies within the Great Valley subprovince of the Valley and Ridge physiographic province (fig. 1) where about 23,000 feet (ft) (7,000 meters [m]) of Middle Cambrian to Upper Devonian sedimentary rocks are exposed and are overlain by Holocene and older surficial deposits. The area of the four maps is divided into three geologic regions based on the following primary lithologies: (1) Cambrian and Ordovician carbonate rocks of the Great Valley southeast of the North Mountain fault zone and east and west of the core of the Massanutten synclinorium; (2) shale, graywacke, and calcareous shale of the Ordovician Martinsburg Formation of the Great Valley and Massanutten synclinorium; and (3) Ordovician through Devonian clastic rocks and minor limestone and dolostone northwest of and within the North Mountain fault zone (fig. 2). Rocks of all three regions were folded and faulted during the late Paleozoic Alleghanian orogeny (roughly 320 to 250 million years before present [Ma]). The terrain of this portion of the Great Valley generally is gently to moderately rolling with low local relief with elevations in the study area ranging from about 425 ft (130 m) where Opequon Creek flows out of the eastern edge of the Inwood quadrangle, to about 950 ft (290 m) adjacent to Round Hill in the western part of the Winchester quadrangle. Sinkholes and other karst features are common in the carbonate rocks of the Great Valley. The area west of the North Mountain fault zone is underlain by middle Paleozoic strata and consists of a series of ridges and valleys with higher local relief, with elevations ranging from about 785 ft (240 m) in the vicinity of Green Spring in the central part of the White Hall quadrangle, to about 1,435 ft (437 m) at the summit of North Mountain in the northeastern part of the White Hall quadrangle.

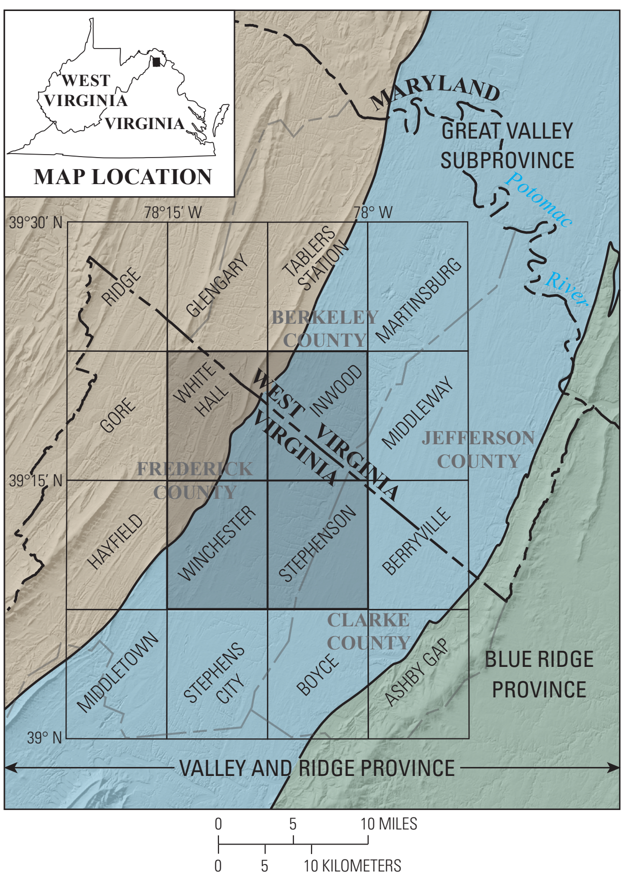


Figure 1. Map showing the location of the study area in northern Virginia and eastern West Virginia. The study area consists of the Stephenson, Winchester, Inwood, and White Hall 7.5-minute quadrangles located in Frederick and Clarke Counties, Virginia, and Berkeley and Jefferson Counties, West Virginia. Surrounding 7.5-minute quadrangles are also shown. County names are in gray type. County boundaries are dashed gray.

Previous Work

The study area included in this report has been previously mapped at various scales. In Virginia, previously published large scale maps including all or significant parts of the study area are the following: (1) a map of Frederick County, at 1:62,500 scale (Butts and Edmundson,1966); (2) geologic and hydrogeologic unit maps of Clarke County at 1:50,000 scale (Hubbard,1990a, b); (3) a preliminary map of the Winchester 30- x 60-minute quadrangle at 1:100,000 scale (McDowell, 1991); (4) a map of Clarke, Frederick, Page, Shenandoah, and Warren Counties at 1:100,000 scale (Rader and others, 1996); (5) a map of the Virginia portion of the Winchester 30- x

60-minute quadrangle at 1:100,000 scale (Rader and others, 2001, 2003); and (6) a study of the geology and conodont biostratigraphic and thermal maturity data within the Winchester 30- x 60-minute quadrangle (Harris and others, 1994). Southworth and others (2007) published a map of the Frederick 30- x 60-minute quadrangle at 1:100,000 scale, which adjoins the study area to the east.

In Virginia, more detailed adjoining or overlapping preliminary geologic maps at 1:24,000 scale include the following: (1) maps of the Berryville, Stephenson, and Boyce quadrangles (Edmundson and Nunan, 1973); (2) the Middletown quadrangle (Orndorff and others, 1999); and (3) digital U.S. Geological Survey (USGS) Open-File Report maps of the Winchester 7.5-minute quadrangle (Orndorff and others, 2003) and the White Hall 7.5-minute quadrangle (Doctor and others, 2010).

The West Virginia Geological and Economic Survey produced 1:24,000-scale Open-File maps of the West Virginia parts of the Inwood and Stephenson quadrangles (Dean and others, 1994).

Burgeoning development and expanding construction, both commercial and residential, in the Winchester, Virginia, and adjacent areas of the Shenandoah Valley in Virginia and West Virginia has created a need for detailed geologic map data that extend over a large area. Except for Orndorff and others (2003), Rader and others, (2003), and Doctor and others (2010) none of the previous mapping in the study area was available as digital data that could be utilized within a geographic information system (GIS). High resolution base topography, compiled from newly acquired lidar (light detection and ranging) elevation data (Burke and Doctor, 2021), allows visualization of geologic details and geomorphic features that were not available to previous researchers, therefore the entire study area was substantially remapped as part of this project.

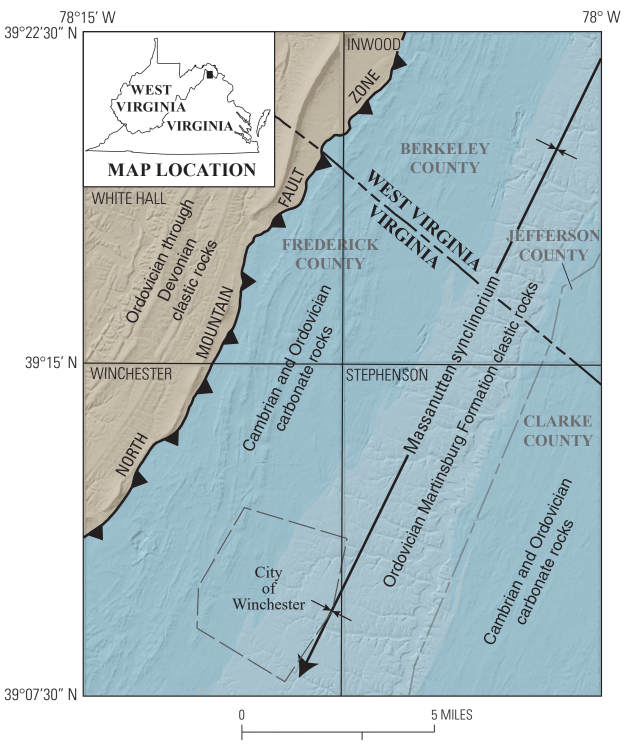


Figure 2. Map showing geologic regions and major structures in the study area. The study area consists of the Stephenson, Winchester, Inwood, and White Hall 7.5-minute quadrangles located in Frederick and Clarke Counties, Virginia, and Berkeley and Jefferson Counties, West Virginia. Sawteeth on the North Mountain fault zone are on the upper plate. Large arrow on the Massanutten synclinorium indicates the southwest direction of plunge; small arrows indicate the dip direction of limbs.

Description of Map Units and Stratigraphic Notes

Rocks exposed in the Stephenson, Winchester, Inwood, and White Hall quadrangles range from Middle Cambrian to Late Devonian in age and consist of a variety of carbonate and clastic rocks (fig. 3). Rocks from the Middle and Upper Cambrian Elbrook Formation through the Upper Ordovician Edinburg Formation, are composed of predominantly limestone and dolostone, whereas rocks from the Upper Ordovician Martinsburg Formation through the Upper Devonian Hampshire Formation are predominantly siltstone, sandstone, and shale with a few carbonate intervals.

Elbrook Formation and Conococheague Limestone

The oldest stratigraphic unit exposed in the study area is the Elbrook Formation (Middle and Upper Cambrian; map unit Ꞓe). The Elbrook is interbedded limestone, dolostone, dolomitic siltstone and calcareous shale. The limestone is medium gray to bluish gray, fine to medium grained, thin to medium bedded, and contains ribbon rock (fig. 4), algal bioherms, intraformational conglomerates, and mottled beds. The dolostone is light to medium gray, fine grained, laminated, medium bedded, and weathers to a yellowish-gray buff color. The dolomitic siltstone and calcareous shale is often stripped of its carbonate content and weathers to a distinctive yellow-orange color. The limestone contains algal bioherms, intraformational conglomerates, and dolomitic burrow mottles. The lowest beds exposed are bluish-gray, medium- to thick-bedded limestone with dolostone ribbons and mottles; and medium-gray, thick-bedded dolostone of the middle part of the formation. Cycles of bluish-gray algal limestone, grainstone, and light-gray argillaceous dolostone occur in the upper part of the Elbrook Formation. A distinctive lithology is yellowish weathering, thin-bedded dololaminite that appears shaly in weathered outcrops. Thickness is at least 2,500 ft; the apparent thickness is increased in some areas by intraformational folding.

The Elbrook Formation is exposed within the western limb of the Massanutten synclinorium in the Winchester, White Hall, and Inwood quadrangles. This unit, as well as the overlying Conococheague Limestone (O€c), contains repetitive limestone and dolostone beds of shallowing-upward subtidal, peritidal, and supratidal cycles in restricted shallow-marine environments. Cycles generally include from the base upwards: intraformational conglomerate, grainstone, calcareous siltstone, algal bioherm, ribbon rock (interlaminated tan dolostone and gray limestone), and mudcracked dolostone. Dololaminite in the Elbrook Formation, and sandstone and (or) dololaminite in the Conococheague Limestone cap these cycles. The Elbrook ranges from Middle to Late Cambrian age, with about the lower two-thirds of the formation being Middle Cambrian (Ryder, 1992). In nearby parts of Maryland, the Elbrook has been divided into the following three informal members: (1) a cyclic, lower shaley dolostone and lime mudstone unit; (2) a middle noncyclic lime mudstone; and (3) an upper unit characterized by meter-scale peritidal cycles each comprising limestone, ribbon rock, and laminated dolostone (Brezinski, 1996). The middle and upper members have been recognized during mapping in the study area but are not broken out separately due to incomplete exposures generally truncated by faulting.

The Conococheague Limestone (Lower Ordovician and Upper Cambrian; map unit O€c) comprises interbedded limestone, dolostone, and sandstone. The Conococheague is extensively exposed within the Massanutten synclinorium, cropping out on the western limb of the synclinorium in the Winchester, White Hall, and Inwood quadrangles, and on the eastern limb in a small area of the southeastern corner of the Stephenson quadrangle. The quartz sandstone-bearing basal Big Spring Station Member was used as a key interval in mapping the contact with the underlying Elbrook Formation but was not mapped as a separate unit in this study. The lower contact is placed at the base of the first sandstone or sandy dolostone at the base of the Big Spring Member. The Conococheague Limestone, particularly the sandstone-rich intervals, tends to weather into linear ridges that are often planted with apple orchards in the study area.

The limestone in the Conococheague is medium gray to bluish gray, fine to coarse grained, thin to medium bedded, and contains intraformational conglomerate (fig. 5), algal bioherms (fig. 6), intertidal limestone and dolomitic stringers (“ribbon rock”), and oolite. The dolostone and dololaminite are light gray, fine grained, and medium bedded. The formation contains distinct beds of medium to coarse grained calcareous sandstone that are light gray to tan, and weather to a reddish-orange color. The lower 200 ft (61 m) consist of the Big Spring Station Member of Wilson (1952), containing (1) gray to tan, reddish-weathering, coarse-grained, calcareous sandstone; (2) medium-gray (*N* 5), fine-grained limestone with intraformational conglomerate; and (3) light-gray (*N* 7), fine-grained dolostone. Sandstone beds occur at the base of the formation and in two ridge-forming packages in the upper part of the formation. The thickness of the Conococheague Limestone in the study area is approximately 2,800 ft.

The Cambrian-Ordovician boundary is located within the upper part of the Conococheague Limestone (Orndorff, 1988; Brezinski and others, 2012; Read and Repetski, 2012).

Stonehenge Limestone, Rockdale Run Formation, and Pinesburg Station Dolomite of the Beekmantown Group

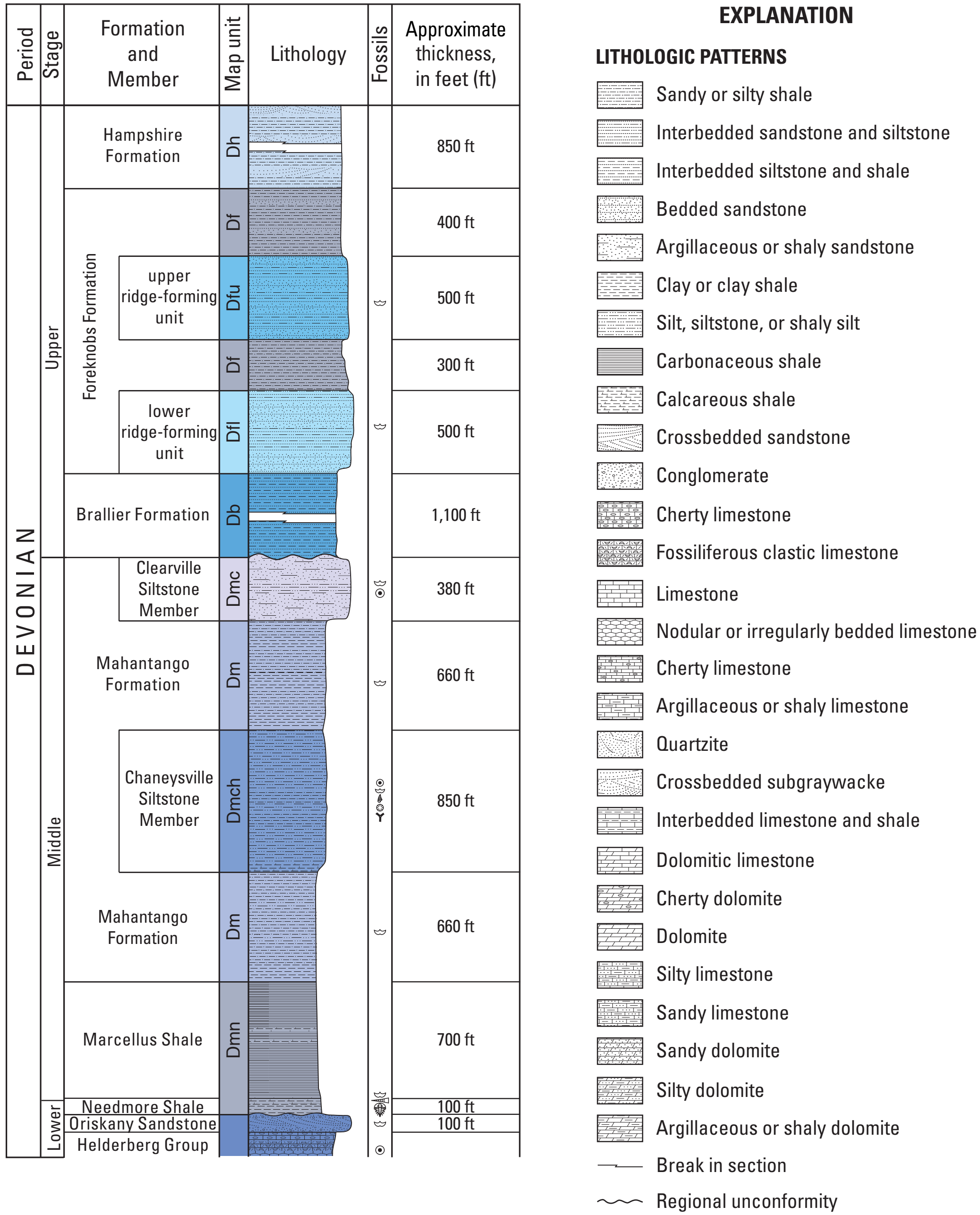
The Beekmantown Group in northern Virginia is divided into (1) a lower limestone unit, the Stonehenge Limestone (Lower Ordovician) (map unit Os); (2) a medial, cyclic carbonate unit of limestone and dolostone, the Rockdale Run Formation (Middle and Lower Ordovician) (map unit Or); and (3) an upper dolostone unit, the Pinesburg Station Dolomite (Middle Ordovician) (map unit Op). Exposures of Beekmantown Group units occur on both limbs of the Massanutten synclinorium and in each of the four quadrangles in the study area.

The peritidal cycles of the underlying Conococheague Limestone grade upwards into the predominantly subtidal cycles of the Stonehenge Limestone. The basal Stoufferstown Member of the Stonehenge (Sando, 1958), is not mapped as a separate unit in the study, but weathers to a topographic ridge that is a useful marker for mapping purposes (fig. 7).

The Stonehenge Limestone is predominantly dark-gray, fine- to medium-grained, thick-bedded to massive, fossiliferous limestone, with crinkly laminations and minor black chert. It also contains algal bioherms, intraformational conglomerates, bioclastic beds, and minor dolostone. The gastropod *Lecanospira* is common in middle part of the formation. The massive limestone is locally mottled with dolomitic burrows. The contact with the underlying Conococheague Limestone is gradational; the base is placed at first dark-gray limestone with crinkly siliceous laminations (Stoufferstown Member) and above the uppermost dolostone that caps Conococheague carbonate cycles. The Stonehenge reaches a thickness in the study area of approximately 770 ft.

Channeled algal bioherms and siliceous laminated limestone are characteristic of the Stonehenge Limestone. Taylor and others (1992) suggested that the Stonehenge represents a third-order transgressive-regressive cycle in which the lowermost and uppermost thin-bedded units were deposited in lagoons behind barrier islands, and the main algal body of the formation represents the transgression of an offshore stromatolitic barrier complex.

Overlying the Stonehenge Limestone, peritidal carbonate cycles reappear in the Rockdale Run Formation (Or). The Rockdale Run comprises interbedded limestone and dolostone. The limestone is bluish gray, medium gray, and dark gray, fine to medium grained, thin to medium bedded, and fossiliferous. The dolostone is medium gray, fine to medium grained, medium bedded, and crystalline. Lithologies occur as fining upward carbonate cycles capped by dololaminite beds as much


Period
Stage
Formation and Member
Map unit
Lithology
Fossils
Approximate thickness, in feet (ft)
DEVONIAN
Upper
Middle
Lower
Hampshire Formation
Dh
850 ft
Foreknobs Formation
Df
400 ft
upper ridge-forming unit
Dfu
500 ft
Df
300 ft
lower ridge-forming unit
Dfl
500 ft
Brallier Formation
Db
1,100 ft
Clearville Siltstone Member
Dmc
380 ft
Mahantango Formation
Dm
660 ft
Chaneysville Siltstone Member
Dmch
850 ft
Mahantango Formation
Dm
660 ft
Marcellus Shale
Dmn
700 ft
Needmore Shale
100 ft
Oriskany Sandstone
100 ft
Helderberg Group
EXPLANATION
LITHOLOGIC PATTERNS
Sandy or silty shale
Interbedded sandstone and siltstone
Interbedded siltstone and shale
Bedded sandstone
Argillaceous or shaly sandstone
Clay or clay shale
Silt, siltstone, or shaly silt
Carbonaceous shale
Calcareous shale
Crossbedded sandstone
Conglomerate
Cherty limestone
Fossiliferous clastic limestone
Limestone
Nodular or irregularly bedded limestone
Cherty limestone
Argillaceous or shaly limestone
Quartzite
Crossbedded subgraywacke
Interbedded limestone and shale
Dolomitic limestone
Cherty dolomite
Dolomite
Silty limestone
Sandy limestone
Sandy dolomite
Silty dolomite
Argillaceous or shaly dolomite
Break in section
Regional unconformity

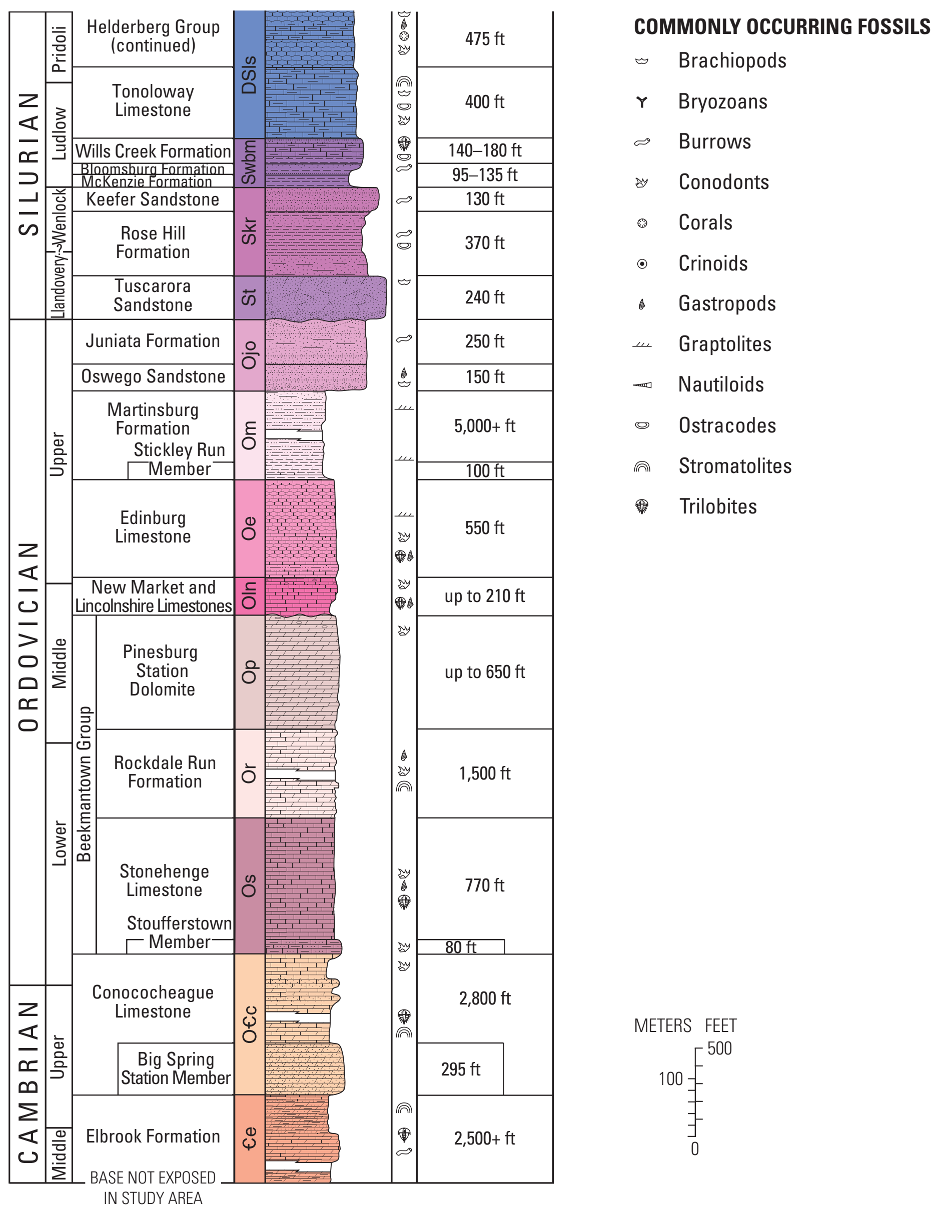


Figure 3. Stratigraphic and lithologic column of bedrock map units exposed in the study area. The Hampshire Formation and units that are thicker than 1,000 ft (300 m) are condensed, with a "break in section" to save space in the column.

as 2 ft thick. Limestone beds also contain intraformational conglomerates, algal bioherms, bioclastic zones, and burrow mottling. The gastropod *Lecanospira* is common in the lower and middle parts of the formation. The lower contact is placed at the base of the lowermost crystalline dolostone or dololaminite bed overlying dark-gray, thick-bedded limestone of the Stonehenge Limestone. The exposed thickness of the Rockdale Run in the study area is approximately 1,500 ft; the actual thickness is uncertain due to faulting and folding.

The carbonate cycles in the Rockdale Run Formation indicate a return to depositional environments like those of the underlying Conococheague Limestone. The ground surface topography expressed in the Rockdale Run Formation often consists of alternating ledges of exposed dolostone of the depositional cycle tops and covered swales above the intervening limestone. On the eastern side of the Massanutten synclinorium, the combination of pervasive axial planar cleavage, which obscures bedding planes, and relative scarcity of thick dolostone beds in the Rockdale Run Formation can make discriminating its contact with the underlying Stonehenge Limestone difficult.

Based on conodont studies, the boundary of the Lower-Middle Ordovician is located in the upper part of the Rockdale Run Formation in the study area (Harris and Harris, 1978; Harris and others, 1994).

An area of pervasively dolomitized rocks within the lower part of the Rockdale Run Formation, occurs just west of the hamlet of Rest in the Inwood quadrangle. The outcrops in this area resemble those of the overlying Pinesburg Station Dolomite. A similar area of nonstratigraphically controlled dolomitization in the Rockdale Run Formation was reported southwest of the study area in the southwest corner of the Middletown quadrangle (Orndorff and others, 1999) and in the adjoining southeastern corner of the Mountain Falls quadrangle (McDowell, 1995). An area of silicified breccia, apparently replacing dolomite, occurs in the White Hall quadrangle near Green Spring and is also assigned to the Rockdale Run Formation (Doctor and others, 2010). In addition, an area of dark-gray, light-gray weathering, brecciated limestone along the Apple Pie Ridge fault, in the north-central part of the Winchester quadrangle, was mapped as the Rockdale Run Formation. This assignment was based, in part, on conodonts recovered from it (USGS catalogue sample number 12121-CO) although the age is equivocal and is compatible with both the upper part of the Stonehenge Limestone and the lower Rockdale Run.

Interbedded limestone and dolostone of the Rockdale Run Formation transition upward in the section to dolostone of the Pinesburg Station Dolomite (Op). The Pinesburg Station is composed of dolostone and dololaminite, medium- to light-gray, buff to light weathering, fine-grained, medium- to thick-bedded with minor white and light-gray chert nodules. Weathered surfaces exhibit “butcher-block” (cross-hatched joints) texture. The unit also contains a few thin, medium-gray, fine-grained limestone beds in its lower part. The lower contact is placed at the base of first light-gray, thick-bedded dolostone overlying dominantly limestone cycles of the Rockdale Run Formation (Or). The thickness of the Pinesburg Station Dolomite ranges up to about 650 ft in the study area.

The dolostone was deposited in a restricted shallow-marine environment that was at times subaerially exposed. The Pinesburg Station Dolomite is thinner in the eastern limb of the Massanutten synclinorium and is discontinuously present along strike in some outcrop belts in the eastern part of the map area. The contact between the Pinesburg Station Dolomite and the underlying Rockdale Run Formation was not mapped

Figure 4. Photograph of ribbon rock within the middle limestone member of the Elbrook Formation (Ꞓe), White Hall quadrangle, about 1 mile (1.6 kilometers) north of the hamlet of White Hall. Photograph coordinates and datum: Universal Transverse Mercator (UTM) zone 17N; 746,059e, 4,354,559n; North American Datum of 1983.

Figure 5. Photograph of rip-up clasts in intraformational conglomerate in the Conococheague Limestone, White Hall quadrangle, about 1 mile (1.6 kilometers) east of the hamlet of White Hall. Photograph coordinates and datum: Universal Transverse Mercator (UTM) zone 17N; 746745e, 4351592n; North American Datum of 1983.

in detail on the ground, rather it was delineated in many places based on interpretation of the apparent roughness of the lidar-derived topography; therefore, this contact is symbolized on the geologic maps as inferred. In the topography, linear ledges that were produced by differential weathering of cyclic limestone and dolostone (characteristic of the upper part of the Rockdale Run Formation) are distinctive from the relatively smooth topography underlain by the more massive and chemically uniform Pinesburg Station Dolomite.

New Market and Lincolnshire Limestones

The New Market Limestone and overlying Lincolnshire Limestone, undivided (Middle and Upper Ordovician) (map unit Oln), are mapped as one unit in this study since both, particularly the Lincolnshire, are thin.

The New Market represents the change from passive margin to active margin deposition (Rader and Read, 1989) in response to the Taconian orogeny. The remainder of the Middle and Upper Ordovician section, from the Lincolnshire Limestone to the Martinsburg Formation, represents the transition from continental shelf, to ramp, to foreland-basin deposition (Brezinski and others, 2012).

The New Market Limestone (Middle Ordovician) is composed predominantly of limestone that is medium to light gray, weathers light and very light gray, thick bedded, micritic, and fenestral. The lower 10 ft is medium- to light-gray, thin-bedded dolomitic limestone interbedded with light-gray dololaminite. The base of the formation is placed at the top of uppermost medium-gray, thick-bedded dolostone of the Pinesburg Station Dolomite (Op) and below the dolomitic limestone of the New Market Limestone. Thickness of the New Market Limestone in the study area is as much as 200 ft (60 m).

Figure 6. Photograph of stromatolites (algal bioherms) within the Conococheague Limestone, White Hall quadrangle, about 1.4 miles (2.3 kilometers) east of the hamlet of White Hall. Photograph coordinates and datum: Universal Transverse Mercator (UTM) zone 17N; 748110e, 4352934n; North American Datum of 1983.

The Lincolnshire Limestone (Upper Ordovician) consists of medium-dark-gray and medium-gray limestone, locally containing red clay partings. The limestone is medium to thin bedded, medium grained, bioclastic, and contains irregular black chert nodules in places. This unit thins to the northeast where other workers have mapped it as part of the Chambersburg Limestone in West Virginia. Thickness of the Lincolnshire Limestone in the study area ranges from only a few feet, up to about 50 ft (15 m).

In the study area, these limestones are exposed in belts along both limbs of the Massanutten synclinorium and in a few fault slices in the North Mountain fault zone in the Inwood and White Hall quadrangles. Regionally, the New Market Limestone unconformably overlies the Pinesburg Station Dolomite but locally, the contact may be conformable. At some locations in the study area, the lower 10 ft (3 m) of the New Market Limestone appears to be a transitional interval of interbedded dolomitic limestone wackestone, grainstone, and dololaminite that may be equivalent to the Row Park Limestone in Maryland (Neuman, 1951). The New Market Limestone was probably deposited in a tidal flat or lagoon environment (Walker and others, 1989).

The Lincolnshire Limestone, which conformably overlies the New Market is thinner than in areas to the southwest of the study area such as at Tumbling Run, Shenandoah County, Virginia, where it is 132 ft (40 m) thick (Butts and Edmundson, 1966). Also, compared to Lincolnshire Limestone sections to the south, the irregular black chert nodules that are characteristic of the formation become scarce to absent, making the formation impractical to map as a separate unit in the study area. The Lincolnshire thins substantially to the north, and equivalent rocks are traditionally mapped, along with rocks of the overlying Edinburg Limestone, as the Chambersburg Limestone in the eastern Panhandle of West Virginia. The Middle Ordovician-Upper Ordovician boundary is probably located near the base of the Lincolnshire Limestone (Brezinski and others, 2012).

Edinburg Limestone

The Edinburg Limestone (Upper Ordovician) (map unit Oe) is exposed along both limbs of the Massanutten synclinorium and in a few fault slices in the North Mountain fault zone in the Inwood and White Hall quadrangles.

The Edinburg Limestone consists of interbedded limestone, calcareous shale, and siltstone. The limestone is medium gray to medium dark gray, fine to medium grained, and thin to thick bedded; bedding is often irregular with knobbly weathering. The calcareous shale is medium dark gray to very dark gray. The Edinburg locally contains an olive-brown siltstone interval in its lower part. Locally, the lower contact is placed above the top of medium- to coarse-grained, locally chert-bearing Lincolnshire Limestone. The Edinburg is locally fossiliferous with small brachiopods and contains the index fossil *Cyclocrinities pyriformis* (Basler) (previously known as

Nidulites or *Mastipora pyriformis*; see Beadle, 1991, p. 116, fig. 2a–d). The unit is equivalent to most of the Chambersburg Limestone, which is nomenclature commonly used north of Virginia in the eastern panhandle of West Virginia and in Maryland. The Edinburg Limestone reaches a thickness in the study area of as much as 550 ft (168 m).

Butts and Edmundson (1966) described an olive-brown siltstone, about 3 ft thick, near the base of the Edinburg Limestone in the section at Tumbling Run, Virginia, about 17 mi (27 km) southwest of Winchester. They informally named this the Tumbling Run siltstone and noted its presence on the western limb of the Massanutten synclinorium, in the vicinity of Stephens City and Winchester. This siltstone was observed by us in the study area as far north as downtown Inwood, West Virginia, where it is exposed in a road cut on the south side of Middleway Pike (State Route 51).

The fine-grained and dark-colored limestone and shale of the Edinburg Limestone indicate depositional environments transitional from the earlier, shallow water carbonates of the New Market and Lincolnshire Limestones to deep water deposition increasingly affected by increased clastic sedimentation associated with the onset of the Taconic Orogeny (Rader and Henika, 1978; Fichter and Diecchio, 1986).

The Edinburg Limestone contains numerous faults and outcrop-scale folds, complicating true thickness determinations in many locations. In places, the Edinburg weathers along subhorizontal joints forming low, flat, pavement-like outcrops. These natural stone pavements are often visible in aerial imagery. Axial planar cleavage is particularly well developed locally in the Edinburg and may obscure bedding planes.

Martinsburg Formation

The Edinburg Limestone grades upward into the dominantly siliciclastic Martinsburg Formation (Upper Ordovician) (map unit Om). The Martinsburg Formation consists of interbedded shale and lesser graywacke-siltstone and graywacke-sandstone. The shale is medium gray to dark gray and light olive gray, weathers grayish orange and dark yellowish orange, is commonly silty, and generally noncalcareous, although calcareous intervals occur in the lower part of formation (Stickley Run Member). The siltstone and sandstone (immature, generally lithic graywacke) are medium gray, weather grayish orange, are very fine to fine grained, commonly graded (fining upward), lenticular, and slightly calcareous to noncalcareous; contains many small cross beds. The graywacke is more abundant and more thickly bedded higher in section where it forms conspicuous ribs in creek beds and may constitute as much as 30 percent of some intervals that are several hundred feet thick. Thicker sandstone beds are generally graded, characteristic of complete Bouma cycles. The rocks of the Martinsburg Formation are prone to development of axial planar cleavage, which may locally obscure bedding. Regional thickness of the Martinsburg Formation may be more than 5,000 feet.

The basal Stickley Run Member of the Martinsburg Formation (Epstein and others, 1995) is a silty limestone, calcareous shale, and siltstone, but was not mapped as a separate unit in this study. The Martinsburg crops-out within a large area flanking both sides of the axis of the Massanutten synclinorium, as well as within discontinuous north-northeast trending fold belts on the east limb of the Massanutten synclinorium and in the footwall of the North Mountain fault zone. The lower contact with the Edinburg Limestone, often obscured by soil and vegetation, can be approximately placed based on the topographic expression that is visible in the lidar-derived topographic imagery. The contact zone is marked by a transition from subdued, simple sinuous surface drainages in areas underlain by the Edinburg to well-formed dendritic surface drainages in areas underlain by the Martinsburg Formation.

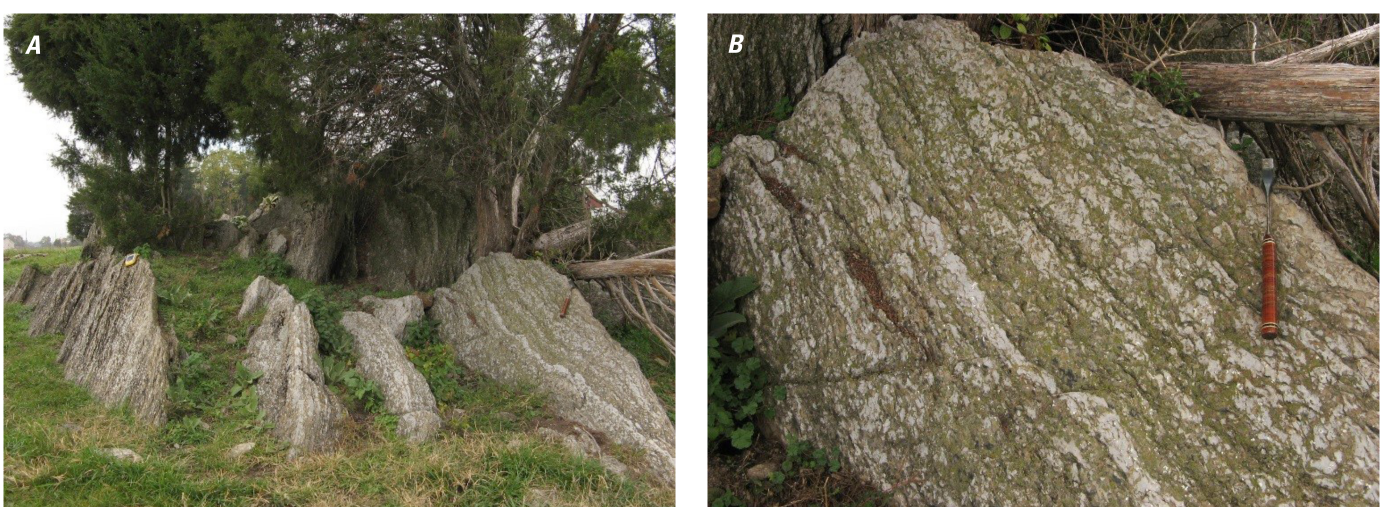


Figure 7. Photographs (*A* and *B*) of the Stoufferstown Member of the lower Stonehenge Limestone, White Hall quadrangle, exposed along Welltown Road, about 0.9 miles (1.5 kilometers) north of Welltown. Photograph coordinates and datum: Universal Transverse Mercator (UTM) zone 17N; 747,445e, 4,350,251n, North American Datum of 1983.

Oswego Sandstone and Juniata Formation

The Oswego Sandstone and the Juniata Formation, undivided (Upper Ordovician) (map unit Ojo), is exposed in a narrow, discontinuous, north northeast-trending outcrop belt just to the west of the North Mountain fault zone in the northwestern part of the Winchester quadrangle, the central part of the White Hall quadrangle, and northwestern corner of the Inwood quadrangle.

The Oswego Sandstone, which conformably overlies the Martinsburg Formation, consists of sandstone and conglomerate of marine origin. Some of the conglomerate beds include intraformational mudstone rip-up clasts. The gray Oswego Sandstone beds characteristically weather to an olive-brownish color with the grains taking on a salt and pepper appearance due to the oxidation of lithic fragments and pyrite. The sandstone is friable where its locally calcareous. The Oswego Sandstone is sparsely fossiliferous with rare, poorly preserved brachiopods, usually occurring low in the formation.

The Juniata Formation conformably overlies the Oswego Sandstone and consists of arkosic quartz sandstone and reddish shale and mudrock. Some of the mudrock beds may be paleosols developed during times of subaerial exposure (Driese and Foreman, 1992). The Juniata, Bloomsburg, upper part of the Foreknobs, and Hampshire Formations are stratigraphic units with a dominantly reddish color.

The Oswego Sandstone and Juniata Formation are probably facies of the same depositional system (Diecchio, 1985). The Oswego Sandstone may be partly correlative with the informally named "Cub sandstone" (Thornton, 1953; Fichter and Diecchio, 1986), which occurs above the Martinsburg Formation in the lower slopes of Massanutten Mountain about 15 mi (24 km) south-southwest from the city of Winchester. The depositional environment for the Juniata Formation has been variously interpreted as fluvial, fluvio-deltaic, marginal marine, and shallow marine. See Blue (2011) for a discussion on the depositional environment for the Juniata Formation and a comprehensive list of references.

This map unit (Ojo) is faulted and tectonically thinned over most of its extent in the study area. In the northeastern part of White Hall and the northwest corner of the Inwood quadrangles, where the upper and lower contacts of this unit appear to be conformable, its stratigraphic thickness is about 400 ft (122 m). This compares closely with thickness estimates of 100 to 200 ft (30–60 m) for the Oswego Sandstone and as much as 200 ft for the Juniata Formation in Great North Mountain in Frederick County, Virginia, by Butts and Edmundson (1966). Woodward (1951) reported thicknesses of 300 to 500 ft (91–152 m) for the Oswego Sandstone and 200 to 400 ft (60–122 m) for the Juniata Formation in the eastern panhandle of West Virginia.

Tuscarora Quartzite

The Tuscarora Quartzite (Llandovery [lower Silurian]) (map unit St) occurs as a relatively thin discontinuous outcrop belt just to the west of the North Mountain fault zone in the Winchester, White Hall, and Inwood quadrangles.

The Tuscarora is a white to pinkish-gray, medium- to coarse-grained, medium- to thick-bedded, sandstone to orthoquartzite that is locally conglomeratic with quartz pebbles as much as 2 cm in diameter. The base is placed at the bottom of white orthoquartzite ledges. The thickness of the Tuscarora Quartzite in the study area is about 240 ft (73 m).

Although often interfingering or gradational with the underlying Juniata Formation at localities to the southwest (Diecchio, 1985), the contact between the basal Tuscarora Sandstone and Juniata Formation is marked by an unconformity in the study area (Read and Repetski, 2012). A lack of body fossils in these units precludes precise biostratigraphic correlation, but the Ordovician-Silurian boundary is traditionally placed at the base of the Tuscarora. Although the Tuscarora is thin relative to other map units in the area, due to its mechanical and chemical resistance to weathering, it is significant to the geomorphology of the Valley and Ridge province of the central Appalachians as a prominent ridge-forming unit. Within the study area, it holds up the ridge of Little North Mountain; further west in West Virginia, it holds up many of the higher ridges of the Potomac Highlands.

Rose Hill Formation and Keefer Sandstone

The Rose Hill Formation and Keefer Sandstone, undivided (Wenlock and Llandovery [lower Silurian]) (map unit Skr), is in a relatively thin discontinuous outcrop belt just to the west of the North Mountain fault zone in the Winchester, White Hall, and extreme northwestern corner of the Inwood quadrangle.

The Rose Hill Formation is composed of grayish-red sandstone (some of it hematite-cemented), brownish-gray to maroon shale, and interbedded olive-gray sandstone. The shale generally weathers to a black patina. The Rose Hill in the study area is considerably thinned in partial exposures within the horse block that holds up Little North Mountain along the North Mountain fault zone. The Rose Hill Formation ranges up to about 350 ft (107 m) thick in the study area.

The Keefer Sandstone is a medium-gray to white, cross-bedded, sandstone and orthoquartzite in the upper part; and it contains fine-grained, thin-bedded sandstone and sandy shale intervals in the lower part. The Keefer only occurs in the study area as considerably thinned partial exposures within the horse block that holds up Little North Mountain along the North Mountain fault zone. The thickness of the Keefer Sandstone in the study area is about 30 to 50 ft (9–15 m) but is considerably thinned due to faulting. Both the Keefer Sandstone and Rose Hill Formation are sparsely fossiliferous in the study area with the Keefer containing invertebrate trace fossils and the Rose Hill locally containing ostracodes.

McKenzie, Bloomsburg, and Wills Creek Formations

The McKenzie, Bloomsburg, and Wills Creek Formations, undivided (Ludlow [lower and upper Silurian]) (map unit Swbm), occurs in a relatively thin, discontinuous outcrop belt to the west of the North Mountain fault zone in the Winchester and White Hall quadrangles.

The McKenzie Formation consists of shale and siltstone. The shale is olive gray and light olive gray to yellow tan with silky luster, fissile, and fossiliferous. The siltstone is yellow gray and can be calcareous. The McKenzie Formation is generally poorly exposed in the study area due to weathering and by burial beneath Keefer Sandstone-derived detritus. It was only observed in the study area as considerably thinned partial exposures within the horse block that holds up Little North Mountain along the North Mountain fault zone. Conodonts recovered from the upper part of the McKenzie Formation indicate an early Ludlow age (Harris and others, 1994); the Wenlock-Ludlow Series boundary is placed arbitrarily at the base of the formation.

The Bloomsburg Formation is composed of interbedded reddish sandstone, siltstone, mudstone, and shale that lies conformably above the McKenzie Formation. It contains interbedded sandstone, siltstone, mudstone, and shale. The sandstone is reddish brown to grayish red, or gray, fine to medium grained, and thin to thick bedded. The siltstone is grayish red, reddish brown, grayish purple, medium gray, light olive gray, or greenish gray, thin to medium bedded, and shows prominent cleavage. The mudstone is maroon red, weathers dusky pale red, and exhibits separate yet internally cohesive lumps in outcrop. The shale is gray, greenish gray, or reddish brown. Locally, the Bloomsburg Formation contains *Skolithos* burrows, and it occurs as considerably thinned partial exposures within the horse block that holds up Little North Mountain along the North Mountain fault zone.

The Wills Creek Formation consists of interbedded shale, siltstone, limestone, and sandstone. The shale is medium dark gray and greenish gray to light olive gray, weathers yellowish gray to reddish gray, crinkly laminated, and calcareous. The siltstone is greenish gray to gray, weathers dark brownish gray or grayish yellow. The limestone is medium dark gray to olive gray, very fine grained, with local intraclastic flat-pebble conglomerate. A 15 to 20 ft (4.5–6 m) thick, massive crossbedded sandstone occurs near the top of the unit and was informally named the “Tavenner sandstone member” by Butts and Edmundson (1966). The total thickness of the formation is approximately 140 to 180 ft; but is considerably thinned in the study area due to faulting within the North Mountain fault zone.

The Wills Creek Formation grades upwards from dominantly siliciclastic to carbonate sedimentation. The Wills Creek interbedded laminated limestones and shales were likely deposited in restricted carbonate mudflat environments (Denkler and others, 1983), and evaporite mineral casts have been reported from these rocks (Smosna and others, 1977; Cecil and others, 2004).

Tonoloway Limestone, Helderberg Group, and Oriskany Sandstone

The DSls map unit (Ludlow [upper Silurian] to Lower Devonian) consists of (1) the Ludlow and Pridoli Tonoloway Limestone, (2) the Silurian (Pridoli [upper Silurian]) and Devonian Keyser Limestone (and other units of the Helderberg Group), and (3) the overlying Lower Devonian Oriskany Sandstone. This unit is poorly exposed in a single outcrop belt west of the North Mountain fault zone in the Winchester and White Hall quadrangles. This belt can only be traced by the occurrence of residual chert float from weathering of the Helderberg Group limestones. This unit is as much as 875 ft (265 m) thick in the study area. The descriptions below are based upon previous mapping from areas adjacent to the study area (for example, Butts and Edmundson, 1966; McDowell, 1991; Harris and others, 1994; Rader and others, 1996; Orndorff and others, 1999; Rader and others, 2001, 2003).

The basal formation in this unit, the Tonoloway Limestone, is lithologically similar to the underlying Wills Creek Limestone, but has more limestone beds and less clastic material. The Tonoloway is predominantly limestone and shale. The limestone is medium gray to medium dark gray, and crinkly laminated to thin bedded. The shale is medium gray to dark gray and calcareous. Locally, beds contain ripple marks and mud cracks. The Tonoloway Limestone is about 300 ft (90 m) thick in the adjoining Hayfield quadrangle to the west (Doctor and Parker, 2018), but is considerably thinned in the study area due to faulting within the North Mountain fault zone.

The Tonoloway Limestone was deposited in an intertidal to supratidal, restricted marine environment, and casts of evaporite minerals have been reported (Smosna and others, 1977; Cecil and others, 2004). In the subsurface, strata correlative to the Tonoloway Limestone to the northwest of the study area, contain evaporite minerals including halite (Smosna and others, 1977).

The Tonoloway Limestone is overlain by limestones of the Helderberg Group. Subdivision of the Helderberg Group into its constituent formations is impractical in the study area due to their thinness and a lack of exposures. Based on mapping in nearby areas, mainly to the west (Harris and others, 1994; Doctor and Parker, 2018), the Helderberg Group consists of, in ascending stratigraphic order, the Keyser, New Creek, Corriganville, and Licking Creek Limestones. The Corriganville Limestone is a chert-rich limestone that contributes much material to the residuum that occurs above the DSls map unit. The Silurian-Devonian boundary, as determined by conodont biostratigraphy, occurs about 3 m (6 ft) below the top of the Keyser Limestone in the study area (Denkler and Harris, 1988).

Helderberg Group rocks include medium- to dark-gray, fine-grained, irregularly bedded, fossiliferous limestone containing black or light-gray to white chert nodules, lenses, and beds as much as 1.5-ft thick near the top. Some of the limestone is medium gray, coarse grained, and crinoidal. The Helderberg Group is about 100 to 140 ft (30–42 m) thick in the general region of Frederick County, and good exposures occur in the adjoining Hayfield quadrangle (Doctor and Parker, 2018). The only observed outcrops in the study area occur in the White Hall quadrangle on the northeast flank of Little North Mountain, and in a faulted structural block at Green Spring.

The Oriskany Sandstone conformably overlies the Helderberg Group. The Oriskany consists of light-gray, yellowish-gray, or yellowish-brown weathering; and medium- to coarse-grained, medium- to thick-bedded, locally crossbedded, calcareous sandstone. It is locally conglomeratic with quartz pebbles as much as 0.5 inches (in.) long; friable when weathered; and contains molds of brachiopod shells. The base of the formation is placed at top of cherty limestone of the Licking Creek Limestone of Helderberg Group.

Conodont collections from just west of the study area confirm an Early Devonian age for the Oriskany Sandstone, but also include reworked specimens of Ordovician species (Harris and others, 1994). These indicate that Ordovician rocks to the east and southeast were exposed to erosion during the Devonian and quartzitic sediments derived from them, along with sparse conodonts, were redeposited in the Oriskany Sandstone (Harris and others, 1994).

Needmore Shale and Marcellus Shale

The Needmore Shale and Marcellus Shale, undivided (Middle and Lower Devonian) (map unit Dmn), lies unconformably above the Oriskany Sandstone. This unit is poorly exposed in the study area and occurs in a single outcrop belt west of the North Mountain fault zone in the Winchester and White Hall quadrangles.

The Needmore Shale is composed of calcareous shale; dark-greenish-gray to olive-gray, and dark-gray, fissile silty shale; and is locally fossiliferous. The Needmore Shale grades up into the Marcellus Shale through a series of thin, fossiliferous limestone beds. The base of the Needmore Shale is placed at the top of coarse, quartz-rich calcareous sandstone of the underlying Oriskany Sandstone. The contact is at the regional Wallbridge discontinuity (Dennison and Head, 1975; Haynes and others, 2018). The thickness of the Needmore Shale in the study area is about 100 ft.

The Marcellus Shale consists of fissile, black to dark-gray shale, with localized beds or concretions of dark-gray, argillaceous limestone or calcareous shale. The Marcellus Shale forms thin, platy chips and weathers dusky yellowish gray. The Tioga ash bed, a regional stratigraphic marker, occurs at the base of the Marcellus Shale. Monazite crystals from the type locality of the ash bed in Union County, Pennsylvania, have $^{207}Pb/^{235}U$ ages of 390.0±0.5 Ma (Roden and others, 1990). The thickness of the Marcellus Shale is as much as 700 ft in the study area.

Conodont biostratigraphy in northern Virginia and eastern West Virginia, indicates that the age of the Needmore Shale is Early and earliest Middle Devonian and the age of the Marcellus Shale is Middle Devonian (Eifelian) (Harris and others, 1994; Doctor and Parker, 2018); therefore, the Early-Middle Devonian boundary has been placed just below the top of the Needmore Shale (fig. 3).

Mahantango Formation

Exposures of the Mahantango Formation (Middle Devonian) (map unit Dm) occur northwest of the North Mountain fault zone in the northwestern part of the Winchester and White Hall quadrangles. Two subunits of the Mahantango Formation have distinctive rocks with sufficient thickness and topographic expressions to have utility in mapping and are delineated as separate map units. These are equivalent to the following formally named members: the Clearville Siltstone Member of Cate (1963) and Jolley (1982) (map unit Dmc in this report), and the Chaneysville Siltstone Member of Willard (1935) (map unit Dmch in this report). Along the North Mountain fault zone, the undifferentiated Mahantango Formation is mapped where the Clearville and Chaneysville Siltstone Members are thinned or are entirely missing due to faulting.

The basal part of the Mahantango Formation is about 660 ft (200 m) thick and consists of dark-gray and olive-gray interbedded mudstone, siltstone, and shale.

Above the basal Mahantango Formation is the dark-gray, fossiliferous, and generally massively bedded Chaneysville Siltstone Member (Dmch) (Bradford, 1935). The Chaneysville unit occurs at a consistent stratigraphic level and is topographically traceable over much of the study area as a series of subtle ridges. On the southeastern limb of the Mount Pleasant syncline, the Chaneysville unit is discontinuous along strike and is tentatively mapped based on its topographic expression south of the White Hall-Winchester quadrangle boundary.

Above the Chaneysville Siltstone Member, is another interval of dark-gray and olive-gray interbedded mudstone, siltstone, and shale mapped as undifferentiated Mahantango Formation (Dm) that is about 660 ft (200 m) thick in the study area.

At the top of the Mahantango Formation, is another ridge-forming unit, the Clearville Siltstone Member (Dmc) (Cate, 1963; Jolley, 1982). The Clearville unit is composed of fossiliferous, medium- to fine-grained sandstone, siltstone, and shale, and is about 380 ft (116 m) thick in the study area.

The Mahantango is one of the most fossiliferous formations in the map area, with locally abundant brachiopods, corals, crinoids, gastropods, and trilobites. Conodont biostratigraphy indicates that the age of the Mahantango Formation is Middle Devonian (Givetian) (Harris and others, 1994; Weary and Harris, 1994).

Brallier Formation

The Brallier Formation (Upper Devonian) (map unit Db), a thick sequence of interbedded shale, siltstone, and sandstone beds, is the basal unit of a generally east to west progradational clastic wedge associated with uplift of the Acadian orogeny to the east of the study area. The Brallier Formation is exposed west of the North Mountain fault zone in the northwestern part of the Winchester quadrangle and western part of the White Hall quadrangle.

The Brallier Formation consists of interbedded shale, siltstone, and sandstone that is dark gray to greenish gray, weathers light brownish gray, and sparsely fossiliferous. Grain size increases irregularly upward in section; sandstone beds that are 2 to 6 in. (5–15 cm) thick, become more abundant near the top of the formation. Shale, that is thickly laminated with scattered siltstone beds up to 3 in. thick, makes up the bulk of the formation. The thickness of the Brallier Formation in the study area is approximately 1,100 ft.

The planar bedded siltstone and sandstone of the Brallier Formation have been interpreted as marine turbidite deposits, on the eastern slope of the Appalachian basin (Van Tassell, 1987). Based on conodont biostratigraphy, there is an unconformity between the top of the Mahantango Formation and the base of the Brallier Formation (Weary and Harris, 1994). The age of the Brallier Formation is Late Devonian (Frasnian) (Brame, 2001). To the west of the map area, the Harrell Shale occurs between the Mahantango and the Brallier Formations. The Harrell Shale is probably a deep, quiet water facies equivalent to the basal part of the Brallier Formation within the study area (Weary and Harris, 1994).

Foreknobs Formation

The Foreknobs Formation (Upper Devonian) (map unit Df) consists of rocks that were called the Chemung Formation prior to redefinition by Dennison (1970). The Foreknobs Formation consists of sequences of (1) fossiliferous, marine sandstones, siltstones, and shales composed mainly of yellowish-gray, brownish-gray to light-olive-gray, greenish-gray, and grayish-red, yellowish-gray to light-olive-gray weathering; (2) thin- to medium-bedded, thick-bedded to massive, interbedded sandstone, siltstone, and shale; and (3) some thin beds of conglomerate. Two coherent packages of thick-bedded to massive sandstones occur as topographic ridge-forming units (map units Dfl and Dfu) that are mappable throughout the study area. These packages consist of 3- to 10-ft (1- to 3-m)-thick, massive sandstone interbedded with siltstone and shale and hold up two ridges that are mappable units throughout the Winchester and White Hall quadrangles. The thicknesses and number of sandstone beds within each ridge-forming unit are variable.

The basal contact was placed at the first occurrence of a medium- to coarse-grained, quartz-rich sandstone bed, generally containing rounded quartz pebbles, at the base of the lower ridge-forming unit (Dfl) (Doctor and others, 2010; Doctor and Parker, 2018; Haynes and others, 2018).

The lower ridge-forming unit (Dfl) consists of three to four thick-bedded, resistant sandstones, interbedded with siltstone and shale that form a prominent ridge at the base of the formation. The strata between the two ridge-forming units consists of thin- to medium-bedded sandstone, siltstone, and shale that generally occupies the drainage area between the two ridges and is commonly not well exposed. This unit is about 500 ft (150 m) thick in the study area.

The intervals of unit Df (both between and above the two ridge-forming units) consists of thin- to medium-bedded sandstone, siltstone, and shale and typically occupies the valley between the two ridges; rocks of these units are commonly not well exposed.

The upper ridge-forming unit (Dfu) consists of five to six beds of resistant sandstone that form a prominent ridge in the upper part of the formation; locally two or more masses form distinct ridges. This unit is also about 500 ft (150 m) thick in the study area.

The Foreknobs Formation is sparsely to moderately fossiliferous, although concentrations of marine fossils occur as lag deposits at the bases of some of the sandstone beds. The most common invertebrate fossils are brachiopods and crinoids, and plant fragments are also found in the upper portion of the formation. Molds of spiriferid brachiopods are the most notable fossil type.

Hampshire Formation

The Hampshire Formation (Upper Devonian) (map unit Dh) is exposed west of the Little North Mountain fault zone in the northwestern part of the Winchester quadrangle and western part of the White Hall quadrangle.

The Hampshire Formation consists of sandstone, mudstone, siltstone, and minor shale. The sandstone is reddish gray to brownish gray, medium to thick bedded, in part micaceous and (or) arkosic, commonly crossbedded and unfossiliferous. The mudstone is maroon red and typically weathers into small crumbly lumps. The siltstone and shale are reddish brown to gray. The exposed thickness of the unit as much as 850 ft (260 m). The upper part of the formation is not exposed in map area. The lower contact is placed at the base of red-beds and at the top of the highest gray, fossiliferous sandstone and shale of the underlying Foreknobs Formation.

These rocks are part of the Catskill magnafacies (Caster, 1934) of continental deposits that are characterized by fluvial facies (river channel, overbank, and floodplain deposits as well as paleosols) associated with progradation of the Devonian clastic wedge deposited during the Acadian orogeny.

Conodont Biostratigraphy

Several samples of limestone and dolostone were collected for conodont biostratigraphy from various stratigraphic units to help resolve unit identifications in structurally complex areas via conodont biostratigraphy (table 1). Conodont species identifications and age determinations were made by John Repetksi (USGS Emeritus). These sample localities are shown on the geologic maps and are labeled with USGS collection numbers. The locations of other USGS conodont samples, collected and analyzed during a previous study of the region (Harris and others, 1994) are also shown on the maps. These conodont collections yield information on the biostratigraphic position of the rocks they were recovered from as well as the thermal maturity of the rocks as indicated by the conodont color alteration index (CAI) (Epstein and others, 1977; Rejebian and others, 1987).

Conodont CAI values for all USGS samples collected at the surface in the study area generally range from 3.5 to 5, indicating thermal maturity above the oil generation window, but within the possibility for dry gas production, which has an upper thermal limit near an index of 4 to 4.5 (Epstein and others, 1977).

One conodont collection (10927-CO) recovered from the Conococheague Limestone in the southwestern part of the Winchester quadrangle, contains elements with CAI values of 4.5, 5.5, 6, and 7 (Harris and others, 1994). The lowest value of 4.5 probably reflects the regional thermal maturity due to burial depth. The anomalous higher values suggest localized contact with hydrothermal fluids (Epstein and others, 1977; Rejebian and others, 1987).

Surficial Deposits

The bedrock of the Stephenson, Winchester, Inwood, and White Hall quadrangles is overlain by a variety of younger surficial and residual, as well as artificial fill. These are predominantly Pleistocene or Holocene in age, but it is possible that there may be some deposits as old as Cretaceous in age (Doctor, 2016).

Fluvial Deposits

Fluvial deposits are common in and adjacent to stream channels, particularly along perennial streams in areas above the clastic bedrock units. These deposits are mapped as either alluvium (Qa), or as terrace deposits (Qt). The alluvium deposits include channel fill, bars, and overbank and floodplain sediments that extend beyond the regular annual flood zones.

Terrace deposits were only mapped as a separate unit in one area within the west-central part of the White Hall quadrangle (Doctor and others, 2010). These deposits consist of rounded to subrounded, highly weathered cobbles, sand, silt, and clay that can be examined along State Route 681 near the confluence of Isaacs Creek and Back Creek. The cobbles are predominantly quartz sandstone and chert. Although only mapped in one area, there are probably similar, smaller deposits in other parts of the study area. The cobbles may be remnants of terrace deposits that were more aerially extensive and may indicate that large streams in the ancestral Shenandoah Valley meandered over great distances. Similar terrace deposits were mapped flanking Cedar Creek in the Middletown quadrangle about 10 mi (16 km) south-southwest of the city of Winchester (Orndorff and others, 1999).

Tufa and Marl

Many of the stream valleys are underlain by deposits of tufa and marl (map unit Qtm). Faults that provide pathways to the surface for carbonate saturated water to rise from deep in the aquifer are often associated with travertine-depositing springs and streams (Hubbard and others, 1985; Herman and Hubbard, 1990). These tufa and marl deposits originate in areas overlying carbonate rocks but can extend for long distances downstream from their carbonate sources and occur over silicilastic units such as the Martinsburg Formation. Several of these deposits were mapped directly in the field, and other areas were extracted and modified from Natural Resources Conservation Service online soils map databases (Natural Resources Conservation Service, 2013a, b, 2014, 2016) based on their described calcite-bearing characteristics. These limey soils include the Fairplay silt loam, Hollywood clay loam, Lappans silt loam, Massanetta loam, and Wever silt loam.

Historically, marl soils were mined in various locations within the study area as sources of agricultural lime, such as along Redbud Run in the Winchester Quadrangle (Hubbard and others, 1985).

Artificial Fill

Although extensive areas of artificial fill occur within the map area, they were not mapped as part of this study. These areas include road fills, bridge abutments, and building sites. In some areas, particularly industrial parks in the Winchester metropolitan area, large building pads and landscaped areas are constructed of transported rock and soil that obscure the underlying bedrock. Much of this material is overburden and spoil transported from local limestone quarries. Therefore, it is not uncommon to encounter displaced soils derived from the Martinsburg Formation and large exotic blocks of stone from the Rockdale Run Formation, Pinesburg Station Dolomite, and the New Market, Lincolnshire, and Edinburg Limestones. Areas underlain by artificial fill are easy to identify by visual analysis of the high resolution lidar topography for the area.

Structural Geology

Most of the tectonic deformation of the bedrock in the study area took place during the Alleghanian orogeny of the late Paleozoic Era when the North American continent collided with the continents of Africa and Europe, forming the supercontinent Pangaea. Most geologic structures in the study area verge to the northwest indicating latest compression from the southeast. See map sheets 1 to 4 and cross sections *A–A′*, *B–B′*, *C–C′*, *D–D′*, *E–E′*, and *F–F′*.

Bedding

Typical of rocks in this part of the Valley and Ridge province most bedding in the study area strikes to the north-northeast, except near fold noses (fig. 8). The trend of measured bedding attitudes clusters around a strike of about 27° NE and a dip of about 45° NW (fig. 8).

Cleavage

Axial planar cleavage is pervasive throughout the rocks of the study area but is particularly pronounced in certain

Table 1. Data describing conodont sample collections made in the study area during this study (in bold) and in a previous study by Harris and others (1994).

[Conodont identification and interpretation was carried out by John Repetksi, U.S. Geological Survey (USGS) Emeritus. CAI, color alteration index]

USGS collection number	Field number	Quadrangle	Conodont age	Conodont CAI	Formation
10881-CO	IN-1a	Inwood	early Early Ordovician (probably *Cordylodus angulatus* zone)	4.5–5	Stonehenge Limestone
10882-CO	IN-1b	Inwood	early Early Ordovician (*Rossodus manitouensis* zone)	4.5–5	Stonehenge Limestone
10883-CO	IN-2	Inwood	Middle Ordovician (*Cahabagnathus friendsvillensis*-*C. sweeti* zone)	4	Lincolnshire Limestone
10884-CO	IN-3	Inwood	Middle Ordovician (probably Rocklandian)	4	Lincolnshire Limestone
10885-CO	IN-4	Inwood	Late Ordovician (probably Rocklandian)	4	Edinburg Limestone
10886-CO	IN-5a	Inwood	Late Ordovician (Llanvirnian-early Caradocian)	4	Edinburg Limestone
10887-CO	IN-5b	Inwood	Late Ordovician (*Baltoniodus gerdae* subzone of *Amorphognathus tvaerensis* zone)	4	Edinburg Limestone
10888-CO	IN-5c	Inwood	Late Ordovician (*Baltoniodus gerdae* subzone of *Amorphognathus tvaerensis* zone)	4	Edinburg Limestone
10889-CO	IN-5d	Inwood	Late Ordovician (*Baltoniodus gerdae* subzone of *Amorphognathus tvaerensis* zone)	4	Edinburg Limestone
10890-CO	IN-5e	Inwood	Late Ordovician (*Baltoniodus gerdae* subzone of *Amorphognathus tvaerensis* zone)	4	Edinburg Limestone
10891-CO	IN-5f	Inwood	Late Ordovician (*Baltoniodus gerdae* subzone of *Amorphognathus tvaerensis* zone)	4	Edinburg Limestone
10892-CO	IN-5g	Inwood	Late Ordovician (*Baltoniodus gerdae* subzone of *Amorphognathus tvaerensis* zone)	4	Edinburg Limestone
12124-CO	**WIN-354a**	**Inwood**	**late Early Ordovician (Floian)**	**4–4+**	**Rockdale Run Formation**
10910-CO	SS-1	Stephenson	early Early Ordovican (*Rossodus manitouensis* zone)	4.5–5	Stonehenge Limestone
10911-CO	SS-2a	Stephenson	early Middle Ordovician (Middle Whiterockian, upper *Histiodella sinuosa* zone to lower *Cahabagnathus friendsvillensis* zone)	4	Rockdale Run Formation
10192-CO	SS-2b	Stephenson	Middle Ordovician (middle Whiterockian, uppermost *Histiodella holodentata* zone to lowermost *Cahabagnathus friendsvillensis* zone)	4	New Market Limestone
9489-CO	SS-3	Stephenson	middle Middle Ordovician (late Whiterockian)	4–4.5	New Market Limestone
10913-CO	SS-4	Stephenson	Late Ordovician	4–4.5	Edinburg Limestone

Table 1. Data describing conodont sample collections made in the study area during this study (in bold) and in a previous study by Harris and others (1994).—Continued

[Conodont identification and interpretation was carried out by John Repetksi, U.S. Geological Survey (USGS) Emeritus. CAI, color alteration index]

USGS collection number	Field number	Quadrangle	Conodont age	Conodont CAI	Formation
12123-CO	**WST-23a**	**Stephenson**	**middle Early Ordovician (late Tremadocian to early Floian)**	**4–4+**	**Rockdale Run Formation**
10931-CO	WH-1a	White Hall	latest Cambrian (*P. muelleri* or *Eoconodontus* zone)	4.5	Conococheague Limestone
10932-CO	WH-1b	White Hall	latest Cambrian (*Eocon-odontus* zone)	4.5	Conococheague Limestone
10925-CO	WH-2	White Hall	Early Ordovician (lower *Oepikodus communis* zone)	4.5	Rockdale Run Formation
10926-CO	WH-3	White Hall	Middle Ordovician (probably middle to late Whiterockian)	3.5–4	Lincolnshire Limestone
12191-SD	WH-4	White Hall	Early Devonian (Lochovian to Pragian, probably Pragian)	3.5–4	Oriskany Sandstone
12102-CO	**DrWH-025**	**White Hall**	**Early Ordovician (*Cordylodus angulatus* zone)**	**4.5**	**Conococheague Limestone**
12104-CO	**DrWH-035**	**White Hall**	**Early Ordovician (*Rossodus manitouensis* zone)**	**4.5**	**Stonehenge Limestone**
12106-CO	**DrWH-275**	**White Hall**	**Early Ordovician (*Rossodus manitouensis* zone)**	**4.5**	**Stonehenge Limestone**
12107-CO	**DrWH-276**	**White Hall**	**Early Ordovician (*Rossodus manitouensis* zone)**	**4.5**	**Stonehenge Limestone**
12108-CO	**DrWH-280**	**White Hall**	**Early Ordovician (*Cordylodus angulatus* zone)**	**4.5**	**Stonehenge Limestone**
12105-CO	**DrWin-036**	**White Hall**	**Early Ordovician (*Rossodus manitouensis* zone)**	**4.5**	**Stonehenge Limestone**
12115-CO	**DrWIN-182**	**Winchester**	**Late Cambrian**	**4–4.5**	**Conococheague Limestone**
10927-CO	WI-1	Winchester	latest Late Cambrian (*Clavo-hamulus elongatus* subzone of *Cordylodus proavus* Zone)	4.5–7	Conococheague Limestone
10928-CO	WI-2	Winchester	earliest Early Ordovician (*Cordylodus lindstromi* zone)	4.5–5	Conococheague Limestone
4715-CO	WI-3	Winchester	Early Ordovician (Ibexian)	4	Stonehenge Limestone
10929-CO	WI-4a	Winchester	Early Ordovician (North Ameri-can Midcontinent Province fauna D)	4.5	Rockdale Run Formation
10930-CO	WI-4b	Winchester	Early Ordovician (North Ameri-can Midcontinent Province fauna D)	4–4.5	Rockdale Run Formation
12121-CO	**WW-81**	**Winchester**	**Early Ordovician (Tremadocian)**	**4.5**	**Lowermost parts of the Rockdale Run Forma-tion, or upper part of the Stonehenge Limestone.**
12122-CO	**WW-230**	**Winchester**	**Ordovician (Tremadocian)**	**4–4.5**	**Most likely the Stonehenge Limestone. Possibly the lower part of the Rock-dale Run Formation.**

fine-grained rocks and tends to be more strongly developed on the eastern limb of the Massanutten synclinorium. Where cleavage was recognized, the planar attitude was recorded in the database and is shown on the maps. Most of the cleavage measurements are from rocks in the Massanutten synclinorium, particularly from silty/shaley units like the Elbrook Formation, Stonehenge and Edinburg Limestones, and the Martinsburg Formation.

The majority of structural measurements carried out in the study area indicate cleavage planes striking to the northeast (average about 30°), recording compression of these rocks from the southeast (fig. 9). A large percentage of the cleavage planes dip steeply towards the southeast (clustered around 72°), supporting the regional model of vergence of compressional geologic structures towards the northwest.

In some places, particularly near the noses of large folds, linear ledges are visible in the lidar topographic models that appear to be nearly parallel to regional bedrock strike but are actually a weathering expression of well-developed axial planar cleavage. An area of small north-northwest to north-northeast trending ridges in the Conococheague and Stonehenge Limestones near the nose of the Pumpkin Ridge anticline, in the northeastern corner of the Winchester quadrangle, is a good example.

Joints

Tectonically induced jointing is pervasive throughout rocks in the study area. Most joints are systematically related to the bedding and most may be characterized as strike (joints that parallel bedding strike and are normal to the bedding dip), dip (joints that are oriented approximately perpendicular to the bedding), and diagonal joints (fig. 10). Joint attitudes were measured and recorded because these fractures are important potential pathways for local lateral groundwater flow across the trend of the bedding and cleavage. In terms of frequency, the observed data are skewed towards measurement of dip joints, then strike joints and diagonal joints in descending numbers. This bias occurs because most outcrops in the map area are ledges with relatively obvious dip joints exposed on the rock faces created by breakage along the strike joints. Most of the joints measured are vertical to steeply-dipping with the strike trend of the cross joints clustering at about N 70° W (fig. 11). The orientation of these joint sets supports the regional model of compression of geologic structures towards the northwest and with the dip joints developed perpendicular to the minimum principal stress vector.

Patterns of Faulting and Folding

Fold axes and faults in the eastern part of the Massanutten synclinorium tend to be oriented north-northeast and the folds verge to the west-northwest, indicating compression towards the northwest. A few reverse faults, with fault planes dipping steeply to the southeast, are antithetic to this trend. Some of the mesoscale folds and faults in the western part of the synclinorium, southeast of the North Mountain fault zone are oriented almost north-south, suggesting rotation of the direction of compression from the southeast to the east-southeast later in the Alleghanian orogeny. West of the North Mountain fault zone, structures are oriented in the predominant north-northeastern trend. These trends suggest a counterclockwise (probably transpressional) left-lateral rotation of structures in the relatively stiff carbonate sequence of rocks in the western part of the Massanutten synclinorium. An earlier study of cross faults and shear zones, on the eastern limb of the Massanutten synclinorium in West Virginia to the north of the map area (Orndorff, 1992), concluded that rotation of the stress field in that area was clockwise.

Previously Mapped Structures

Many of the folds and faults in the study area were documented in previous mapping at various scales. Where these structures are substantially coincident with those mapped in this study, the previously assigned names were retained and the sources cited. Exact geographic positions and structural relationships of some previously mapped faults have been reinterpreted by the authors of this study, in large part due to the recent availability of high-resolution base topography. Previously unnamed structures discussed in this text are assigned names for convenience in identifying and locating them on the maps (sheets 1 to 4).

Folds

The bedrock in the study area is pervasively folded, from gentle, open symmetrical, to asymmetrical and overturned folds. Most folds are open and slightly asymmetrical with a vergence towards the northwest. Many folds in the study area are overturned, with the southeastern limbs of synclines overturned and the northwestern limbs upright. Overturning is most prevalent in rocks of the eastern limb of the Massanutten synclinorium. Overturned beds are common along the Stonehenge Limestone-Rockdale Run Formation contact in the southeastern part of the Stephenson quadrangle. Overturning also occurs locally in tightly folded carbonate rocks and in the clastic rocks of the Martinsburg Formation trending along both flanks of the main Martinsburg Formation outcrop belt in the Inwood and Stephenson quadrangles. Overturned beds are also common in rocks of all ages in areas to the northwest of the Little North Mountain fault as the result of footwall deformation associated with the thrust faulting.

Particularly on the eastern limb of the Massanutten synclinorium, there are numerous small tight folds in the Edinburg Limestone at scales too small to delineate on the maps. Delineation of small folds within the main belt of the Martinsburg Formation is difficult due to lack of outcrops over broad areas, except within streams flowing on bedrock.

Some folds in rocks of the Massanutten synclinorium area show attenuation in the thickness of their limbs, particularly anticlinal forelimbs. The relatively pure New Market, Lincolnshire, and Edinburg Limestones are most affected by this phenomenon (presumably affected by shearing and pressure solution of the carbonates). The morphology of these folds appears to fall within the precursor continuum of forelimb stretch thrust-fault formation (Heim, 1919; Mitra, 2002).

In this report, we have eschewed the practice of previous mappers (for example, Edmundson and Nunan, 1973) who delineated and named long, continuous, linear fold axes often with extents of several miles. Most of these folds terminate in shorter lengths and tend to plunge out and step over to adjoining folds in a tight *en echelon* pattern. Previously published names for prominent folds coinciding with those identified in this study are labeled with the historical name; previously unnamed folds that are remarked upon herein are assigned new names for discussion purposes; other folds are left unnamed.

The Massanutten Synclinorium

The most prominent fold in the study area is the Massanutten synclinorium (fig. 2; cross sections *B–B′*, *D–D′* and *F–F′*). The axis of the synclinorium crosses parts of the Winchester, Stephenson, and Inwood quadrangles. The trace of the axial zone is inferred, as outcrop data are too sparse to precisely locate it. Structurally disturbed zones, comprising tightly folded and faulted rocks, occur along the axis of the Massanutten synclinorium and are probably associated with space accommodation in the core of the syncline. To the west of the synclinorium axis, bedding is usually right-side up and folds are more open and have a longer wavelength. Larger subsidiary folds on the eastern limb of the Massanutten synclinorium tend to plunge towards the northeast; those on the western limb tend to plunge to the southwest. This rotation suggests large scale left-lateral shear parallel to the axis of the synclinorium, and normal to the direction of compression.

Folds on the Eastern Side of the Massanutten Synclinorium

One of the curiosities of the study area is the presence of several narrow overturned and faulted synclines located on the eastern limb of the Massanutten synclinorium, located in the southeastern part of the Stephenson quadrangle and trending to the southwest into the Boyce quadrangle. These synclines are usually bounded on their southeastern flanks by southeast dipping reverse faults that bring older rocks of the Rockdale Run Formation up into contact with the Martinsburg Formation. They may also be bounded on their western margins by splays off of the reverse faults (cross section *F–F′*). These folds are appressed and usually contain cores of Martinsburg Formation shale and siltstone that, being more chemically resistant to weathering than the surrounding carbonate rocks, produce, after weathering, distinctive low topographic ridges.

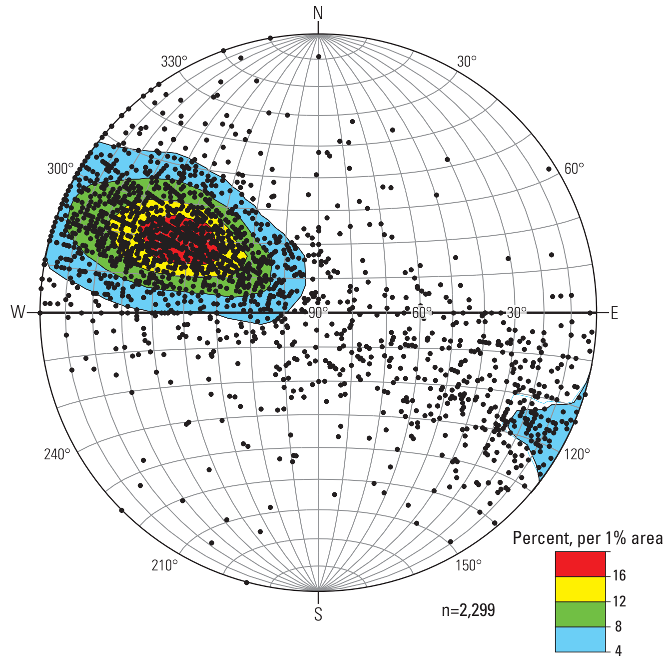


Figure 8. Contoured equal-area stereonet projection of measured poles to bedding (black dots) for rocks in the study area (n=2,299). The trend of measured bedding attitudes clusters around a strike of about 27° NE and a dip of about 45° NW. Contoured intervals represent percent, per 1 percent area on stereonet.

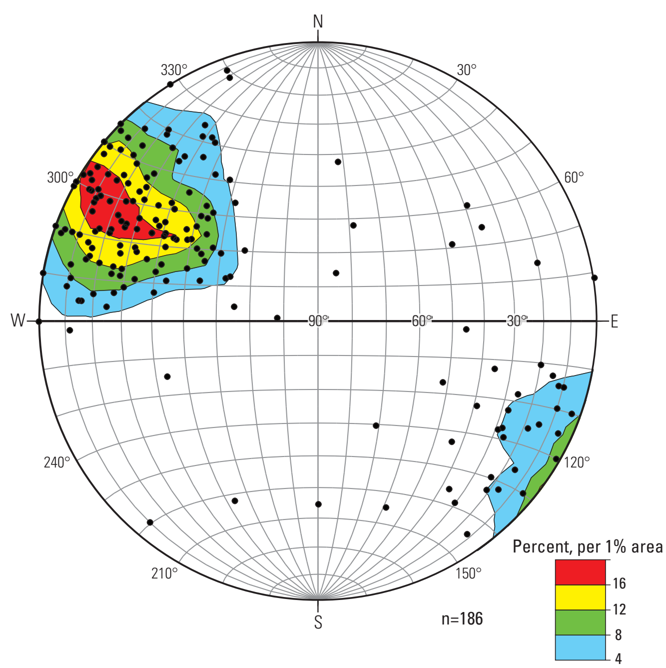


Figure 9. Contoured equal-area stereonet projection of measured poles to planes of cleavage (black dots) for rocks in the study area (n=186). Clustering of poles illustrates the dominant northeast-striking (average about 30°) and southeast-dipping (clustered around 72°) regional trend of cleavage in the study area. Contoured intervals represent percent, per 1 percent area on stereonet.

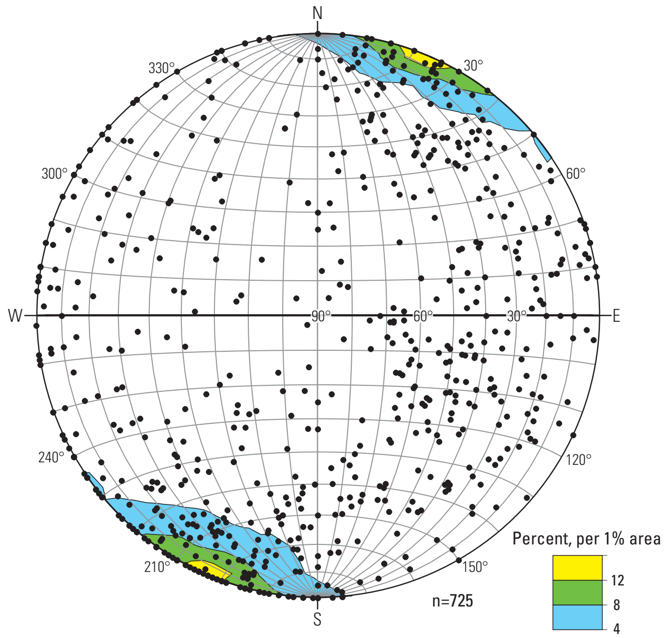


Figure 10. Contoured equal-area stereogram summarizing poles to planes (black dots) of measured joints in the study area (n=725). Clustering of poles illustrates sampling biased towards cross joints oriented around N 70° W and approximately perpendicular to the regional bedding strike direction of about N 30° E (fig. 9). Contoured intervals represent percent, per 1 percent area on stereonet.

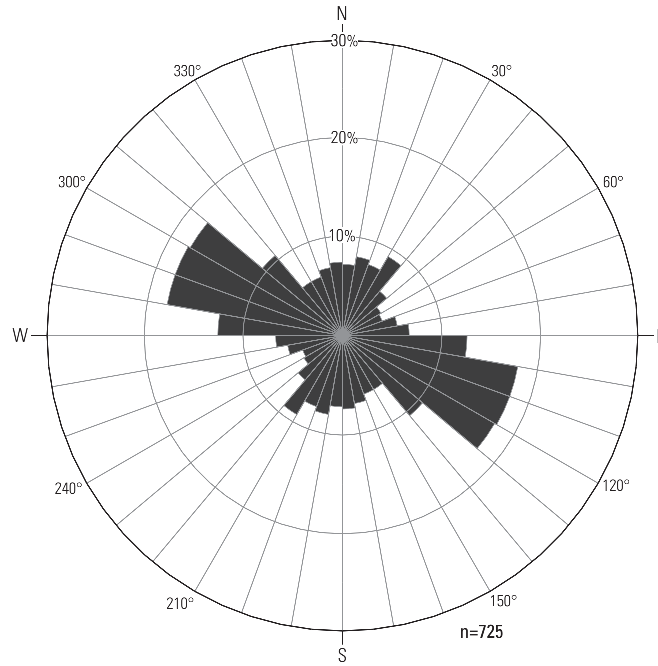


Figure 11. Rose diagram showing strike trends of all measured joint planes in the study area. Most joints are vertical or steeply dipping, and sampling shows bias towards joints that are perpendicular to the predominantly northeast-striking bedding. Petals are grouped within 10-degree classes, and petal length is a function of the percent (%) of the total number of measurements (n=725).

Strata of Ordovician limestones (for example, the New Market, Lincolnshire and Edinburg Limestones) in the limbs of these synclines are attenuated so that the outcrop expression of unit thicknesses is much thinner locally than typically found elsewhere. The morphology of these attenuated folds appears to fall within the continuum of examples of forelimb stretch thrust-fault formation (Heim, 1919; Mitra, 2002).

Erosion of the Wadesville anticline (Edmundson and Nunan, 1973), a north-northeastern trending, doubly plunging fold in the north-central part of the Stephenson quadrangle, exposes rocks of the Rockdale Run Formation. Mapping by Edmundson and Nunan (1973) showed a southern continuation of this anticline, offset to the west by a rotational fault. We interpret that this anticline is not a continuation of the same fold, but rather, a separate *en echelon* fold separated from the Wadesville anticline by an antithetic reverse fault on its eastern limb. The Wadesville anticline itself simply plunges out to the south. We have named this separate fold, the axis of which is upright north of U.S. Highway 50 and overturned to the west (south of the highway), the Wrights Mill anticline.

The doubly plunging Opequon anticline (Dean and others, 1994) is the most noticeable fold in the map pattern of the southeastern part of the Inwood quadrangle. Our mapping shows the axis of this fold to be located slightly to the east of that previously traced by Dean and others (1994). We have mapped a southeast dipping reverse fault that is probably an into-anticline thrust fault (Mitra, 2002) that offsets bedding just to the northwest of the anticlinal axis (cross section *B–B′*).

Folds on the Western Side of the Massanutten Synclinorium

The axis of the Ridings Hill anticline trends out of the northeastern corner of the Middletown quadrangle (Orndorff and others, 1999) and into the southwestern corner of the Winchester quadrangle where it ends just to the southwest of the southern terminus of the Abrams Creek fault.

The axial trace of the south-plunging Apple Pie Ridge anticline extends along a north-northeast trend in the central part of the Winchester quadrangle from about 1 mile (1.6 km) south of Kernstown to about 1 mi (1.6 km) north-northwest of the intersection of U.S. Routes 37 and 522, north of the city of Winchester. There are numerous tight subsidiary folds particularly along the west limb of this large fold. The Apple Pie Ridge anticline is bounded along its western edge by the Apple Pie Ridge fault.

The axis of the south-plunging Welltown syncline (Doctor and others, 2010) trends to the northeast from the northeastern part of the Winchester quadrangle, across the southeastern corner of the White Hall quadrangle and into the west-central part of the Inwood quadrangle. The axis of the syncline is offset by a cross fault in the southeastern part of the White Hall quadrangle and bounded in part on its eastern flank by the Welltown fault (Doctor and others, 2010) that is developed in the shared limb with the Pumpkin Ridge anticline adjacent to the east.

The Gordondale syncline (newly named) is named for the hamlet of Gordondale, located in the southwestern part of the Inwood quadrangle, just south of the Virginia-West Virginia State line, near the intersection of Virginia State Route 670 (Reubuck Road) and Grandview Lane. The eastern limb and northern part of the axis of this large fold is overthrust from the east by older rocks along the Mill Creek fault.

The Mount Pleasant syncline, located in the central part of the White Hall quadrangle and the northwestern part of the Winchester quadrangle, is a large doubly plunging reclined syncline that has steeply dipping overturned beds in its east limb, which is also in the footwall of the North Mountain fault zone. This is the northernmost extent of a regional syncline that spans all of Frederick County, Virginia (Butts and Edmundson, 1966).

In the north-central part of the White Hall quadrangle, the southernmost extent of the Bailey Ford anticlinorium plunges southwestward into a complex series of synclines and anticlines lying parallel to the Mount Pleasant syncline.

The south-plunging Ridgeway syncline (newly named) in the south-central part of the Inwood quadrangle is an open fold and cored by rocks of the Martinsburg Formation in areas south of the hamlet of Ridgeway, West Virginia (cross section *B–B′*). To the north of Ridgeway, the fold is interrupted by a northwest trending normal fault, and the continuation of the fold to the north of the fault has overturned limbs.

The south-plunging Specks Run anticline (newly named) is adjacent to the east of the Ridgeway syncline (cross section *B–B′*). The fold pair is separated along their shared limb by the Bunker Hill fault. Like the Ridgeway syncline, the Specks Run anticline is also broken by the same northwest-trending normal fault so that after erosion the trace of the fold axis to the north of the fault is offset to the west.

The Freyco anticline (newly named) crosses the northwestern Stephenson quadrangle boundary into the southwestern Inwood quadrangle. Large parts of this fold have been excavated in quarries operated by Carmeuse Lime and Stone-Winchester Operation, which extracts the New Market Limestone for chemical grade limestone and the Edinburg Limestone for aggregate. The Freyco anticline appears to be a break-thrust fold (Willis, 1893) overturned on the northwest limb and bounded by a southeast-dipping thrust/reverse fault just to the west.

Faults

Several of the approximately north-trending, west-verging faults in the study area appear to be forelimb shear thrusts produced as fold-accommodation faults (Mitra, 2002). In other words, folding began before faulting, with the west limbs of the anticlines attenuating and eventually failing, allowing westward thrusting of each anticline over its adjacent syncline to the west. These deformed anticlines have been referred to as break-thrust folds (Willis, 1893; Fischer and others, 1992) or stretch thrust faults (Heim, 1919). We have symbolized these faults as reverse faults, since they have higher angle fault planes and much more limited longitudinal extent than thrust faults.

North Mountain Fault Zone

The North Mountain fault zone is a regional structure that trends from southwest to northeast from central Virginia into south-central Pennsylvania. The fault zone in Virginia may be as wide as 1 mi (Orndorff, 2012). The North Mountain fault zone cuts through the northwestern part of the Winchester, eastern part of the White Hall, and northwest part of the Inwood quadrangles. It is a series of thrust faults generally oriented northeast-southwest that separate the Silurian and Devonian shales, siltstones and sandstones to the northwest from the Cambrian and Ordovician carbonate rocks and shales to the southeast of the fault zone. Several fault-bounded horses occur within the fault zone. See Orndorff (2012) for a discussion of the kinematics of the fault zone.

The North Mountain fault zone is demarked on the east by the Apple Pie Ridge fault in the White Hall and Inwood quadrangles (Doctor and others, 2010). To the southwest, in the northern part of the Winchester quadrangle, the Apple Pie Ridge fault splays away from the main fault zone in a more southward trend.

The western edge of the North Mountain fault zone is bounded by the Little North Mountain fault in the Winchester quadrangle and the south-central part of the White Hall quadrangle (Doctor and others, 2010). To the northeast of the Little North Mountain fault, the fault zone is bounded on its northwest side by unnamed fault segments that are probably continuations and splays of the North Mountain fault zone.

Dean and others (1994) named the thrust splay along the west side of North Mountain (beginning at Green Spring in the east central part of the Whitehall quadrangle) the Back Creek fault; this is probably the northern extension of the Little North Mountain fault. The Back Creek fault has been traced approximately 24 mi northward from Green Spring into Maryland and converges with the North Mountain fault zone at McCoy's Ferry, Maryland; thus, the ridge of North Mountain in the northern part of the Whitehall quadrangle and areas to the north, is a large horse (Dean and others 1994).

There is evidence in the map pattern and cross section (*E–E′*) in the Winchester quadrangle that the North Mountain fault zone involves ramping of thrust movement from the Waynesboro detachment along the Apple Pie Ridge fault on the southeastern side hanging wall, up to the higher Martinsburg detachment on the west side of the hanging wall at Little North Mountain.

The large-scale structure to the southeast of the fault zone appears to be a large, overturned anticline or anticlinorium as suggested by Orndorff (2012) (cross section *E–E′*) that overrides an overturned synclinorium in the footwall rocks northwest of the fault zone.

Other Northwest and West Verging Faults in the Map Area

The Horsepen Spring fault (Edmundson and Nunan, 1973) in the southeastern part of the Stephenson quadrangle is interpreted to be a southeast-dipping high-angle reverse fault. This fault was previously interpreted as a left-lateral strike-slip feature and the trace was extended much farther to the north-northeast (Edmundson and Nunan, 1973). Compression on the footwall northwest of the fault has resulted in tight, overturned folding in the Conococheague Formation, Stonehenge Limestone, and the Rockdale Run Formation (cross section *F–F′*).

The Rouss Spring fault (newly named) in the vicinity of Rouss and Shawnee Springs in the east-central part of the Winchester quadrangle, is interpreted to be a break-thrust fault juxtaposing the eastern limb of a south-plunging anticlinal structure with the west limb of a south-plunging syncline. The shared limb of both folds has been removed by erosion.

The Abrams Creek fault is a northeast trending, southeast dipping thrust fault in the west-central part of the Winchester quadrangle. A segment of the trace of this fault was shown on earlier maps, but was unnamed (Butts and Edmundson, 1966; Rader and others, 1996, 2001; Orndorff and others, 2003). Movement of this fault has juxtaposed older rocks of the Elbrook Formation and Conococheague Limestone in the eastern hanging wall with younger rocks of the Conococheague and Stonehenge Limestones that lie in a footwall syncline on the western side. The northern terminus of the Abrams Creek fault abuts the Babbs Run fault, an antithetic reverse fault.

The Welltown fault trends north-south along the northeast edge of the Winchester quadrangle and extends to the north well into the White Hall quadrangle (Doctor and others, 2010). Along its southern extent, this fault offsets rocks of the Martinsburg Formation and older rocks in the west limb of the Massanutten synclinorium. In its northern extent, the fault offsets Cambrian and Ordovician rocks in the shared limb of the Pumpkin Ridge anticline and the Welltown syncline.

The Apple Pie Ridge fault (Orndorff and others, 2003; Doctor and others, 2010) trends from the north-northeast to south-southwest across the northwestern part of the Inwood quadrangle, southeastern part of the White Hall quadrangle, and across the central part of the Winchester quadrangle. Relatively older rocks, mainly the Cambrian Elbrook Formation exposed in the south plunging Apple Pie Ridge anticline, are displaced over relatively younger rocks in the footwall on the west-northwest side of the fault.

The Mill Creek fault, located in the north-central part of the Inwood quadrangle, was first identified by Dean and others (1994). This fault is a break thrust fault, with rocks of the Mill Creek anticline thrust to the west over rocks in the adjacent Gordondale syncline.

The Bunker Hill fault in the central part of the Inwood quadrangle was mapped by Dean and others (1994). This is another break thrust fault and offsets rocks of the Specks Run anticline over younger rocks of the Ridgeway syncline.

The Turkey Run fault, located in the southeastern part of the Inwood quadrangle, was mapped by Dean and others (1994). Where they deflected the trace of the northeastward trending fault trace to the northwest and then north along Turkey Run, we have chosen instead to break and offset the Turkey Run fault with a separate northwest trending, unnamed normal fault, down thrown to the southwest.

Cross Faults

Cross-strike faults and faults that are oblique to the structural trend, occur in the Massanutten synclinorium in the study area. These are typically normal or reverse faults with little or no lateral offset. This type of faulting becomes more common to the north of the map area, where it was interpreted by Orndorff (1992) to be associated with an oroclinal bend in the Appalachian orogen. We speculate that more unobserved cross faults occur in the study area, but lack of exposures of marker beds make them difficult to identify.

The southwest to northeast-trending Swimley fault, crosses the southeastern corner of the Inwood quadrangle and continues into the north-central part of the Stephenson quadrangle. This fault, named for the nearby hamlet of Swimley, Virginia, is interpreted to be a normal fault, downthrown to the northwest side. The western extent of the fault trace in the main Martinsburg Formation belt is poorly constrained by outcrop data and is drawn to coincide with a topographic lineament. The Swimely fault cuts the southern terminus of the Turkey Run fault and after erosion the vertical offset moved the trace of the southern unnamed extension of that fault to the west.

The Town Run fault (newly named) in the east-central part of the Winchester quadrangle is an east-west trending normal fault that swings to the north in its western extent to abut the Rouss Spring fault. Rocks on the south side of the Town Run fault are dropped down in relation to those on the north side.

Two south-southeast- to north-northwest-trending normal faults along the northeastern edge of the Winchester quadrangle offset rocks of the Rockdale Run through Martinsburg Formation sequence. Vertical offset along both faults is downthrown to the north-northeast. The southernmost of the two faults appears to be associated with the locations of both Sempeles and Faye Springs, two of the largest springs in the study area.

The two unnamed short faults that offset the Middle Ordovician limestone belt in the central part of the Inwood quadrangle, were originally mapped by Dean and others (1994) as right-lateral strike-slip faults. We interpret them to be primarily dip-slip normal faults and both down on the south side.

An oblique fault that trends north off the northern edge of the Inwood quadrangle (about 1 mi west of Darkesville), was symbolized as an east-dipping antithetic thrust fault by Dean and others (1994). Our interpretation is that this is a normal fault downthrown to the northeast.

We have extended an unnamed cross fault at Ridgeway further to the east that was originally mapped by Dean and others (1994) so that it offsets rocks in the Specks Run anticline as well as those in the Ridgeway syncline. This is a normal fault that is downthrown to the south.

Antithetic Reverse Faults

While most faults identified in the study area are synthetic and verge towards the northwest, there are a few antithetic reverse faults. In the northeastern part of the Winchester quadrangle, cross section *E–E′* crosses a reverse fault that is antithetic to the regional trend (dipping to the west). This fault, probably an out-of-syncline back thrust, bounds the east side of an anticline that exposes rocks of the Elbrook Formation.

In the north-central part of the Winchester quadrangle, the antithetic Babbs Creek fault borders horses containing rocks of the Stonehenge Limestone and Rockdale Run Formation caught between the Apple Pie Ridge fault to the east and the Abrams Creek fault and North Mountain fault zone to the west (cross section *E–E′*).

Audio-Magnetotelluric Survey and Section

Data from audio-magnetotelluric (AMT) soundings were collected and processed along a section traversing the central Martinsburg Formation outcrop belt in the Stephenson quadrangle in 2005 to characterize and better understand the properties of the materials in the subsurface and to image the gross structure at depth of the axial Massanutten synclinorium. AMT soundings are made to determine variations in the electrical resistivity of the Earth with depth (Cagniard, 1953). The AMT method uses natural-source multi-frequency electromagnetic signals from lightning or atmospheric disturbances as an energy source. These natural signals diffuse into the Earth and the diffusion governs the electromagnetic induction.

These AMT soundings consist of electric and magnetic field measurements over a range of frequencies from 10- to 100,000-hertz (Hz) with fixed receiver and transmitter locations. The distribution of currents induced in the Earth depends on the Earth's electrical resistivity, Earth's magnetic permeability, and frequency measured. Since low-frequency signals penetrate to greater depths than high-frequency signals, measurements of the electromagnetic (EM) response at several frequencies contain information on the variation of resistivity at depth. These soundings are inverted and stitched together to form pseudo-sections at various angles to the geologic structures.

The AMT tensor soundings were recorded using a Strata-Gem Geometrics EH-4 system. No vertical magnetic field data were recorded because the system is limited to four channels (Ex, Ey, Hx, and Hy). Initially, about 2,000 frequencies were collected and then reduced to approximately 40 frequencies (10 per decade) for the two directions (X and Y) from 10 to 100,000 Hz. The magnetic field sensors, electric field sensors, buffers, and pre-amplifiers for both systems, including a 60-Hz notch filter to reduce interference from electric power lines, were manufactured by Electromagnetic Instruments, Inc. (EMI), now Schlumerger EMI Technology Center.

In our AMT survey, the Geometrics EH-4 receiver employed a two-stage coefficient-of-coherence cutoff filter that first removed any signals having a coefficient of coherence less than 0.3, then removed any signals having coefficients of coherence less than 0.5 in the second stage. Signal amplitudes were monitored and any that saturated the receiver amplifiers were rejected. Time series that had more than seven sensor or instrument saturations were also rejected. Assessments were made of the sounding locations before and after data collection. Sites were chosen so that stations were more than 100 m away from power lines. Background electric and magnetic fields were monitored prior to recordings, and stations were moved if the static fields were above 200 millivolts on the electric lines or above 150 nanoteslas on the magnetic coils. Two-dimensional invariant inversions of the collected data were completed using a uniform half-space starting with 100 ohm-meters. Calculated values of phase-sensitive skew indicate that two-dimensionality is a good assumption for most frequencies. Generally, all frequency decades, 10 Hz to 100,000 Hz, have skews less than 0.25.

These AMT tensor soundings were collected by Herbert. A. Pierce (USGS) who also processed the data to produce a 2-D apparent resistivity section. A total of 10 soundings (MBERG1 to MBERG10) were made across the axis of the anticlinorium and projected to a linear transect of 6.063 km (3.8 mi) giving an average spacing of about 0.6 km (0.4 mi) between stations. This transect coincides with a large part of cross section *D–D′*. The effective depth of exploration in this survey varies from station to station reaching a maximum at station MBERG3 of about 600 m (2,000 ft) below the ground surface and reaching an elevation of about 410 m (1,350 ft) below mean sea level.

The AMT section shows low-resistivity anomalies, indicated by blue colors, in three locations within the Massanuttten synclinorium (see cross-section *D–D′*). These may be interpreted to represent groundwater saturated zones of higher flow or bodies of more conductive groundwater that are probably oriented parallel to the axis of the synclinorium and all three are underlain by the clastic rocks of the Martinsburg Formation. Anomaly 1, located between stations MBERG1 and MBERG2, is associated with faulting and overturned beds near the margin between the clastic rocks of the Martinsburg Formation and the carbonate rocks of the Middle and Upper Ordovician limestones. Along with enhanced fracturing in this area, permeability may be enhanced by solution occurring along the interface of soluble/insoluble rocks near the Martinsburg Formation-Edinburg Limestone contact. Opequon Creek, the major surface stream in the Stephenson quadrangle, flows at the west margin of this anomaly and locally represents the top of the phreatic zone.

Anomaly 2, located between stations MBERG3 and MBERG8, appears to be associated with the Martinsburg Formation in the axis of the synclinorium. Lower resistivity in this volume may be related to groundwater flow in the more intense fracturing along the syncline axis and (or) to the trough-like geometry of the bedding in this synclinal area. Both conditions will tend to concentrate flow and channel it to the north-northeast along strike and down the regional hydraulic gradient.

Anomaly 3, the least distinctive of the three, located between stations MBERG8 and MBERG5, is associated with faulting on the west side of the Freyco anticline and the occurrence of a trough-shaped body of Martinsburg Formation rocks in the unnamed syncline adjacent to the west.

Karst

Previous Studies

Karst features, including sinkholes, caves, springs, and travertine deposits, were reported from the Shenandoah Valley part of the Winchester 30' x 60' quadrangle by Orndorff and Goggin (1994). Identification and location of these features were derived from examination of U.S. Geological Survey 7.5-minute quadrangle maps, field reconnaissance, and reference to earlier reports. Many of the sinkhole locations shown in this report were compiled from the work of Hubbard (1983, 1990b). Hubbard's sinkhole delineations were achieved by examination of topographic maps and high-resolution aerial photography as well as extensive field checking. For a comprehensive regional discussion of karst in the northern Virginia and the eastern West Virginia panhandle, including the study area, see Doctor and others (2015). Deposits of marl and travertine, which are related to karst processes, are discussed in the "Surficial Deposits" section of this report.

Sinkholes in This Study

A database of sinkhole locations and extents was generated for the study area using a combination of sources and techniques. These included the following: (1) examination of previously published sinkhole locations (Hubbard, 1983; Orndorff and Goggin, 1994); (2) sinkholes encountered and mapped on the ground during fieldwork for this mapping project; and (3) closed depressions identified by application of elevation tools and semi-automated analysis of digital elevation models (DEMs) derived from lidar topographic elevation data (Doctor and Young, 2013; Wall and others, 2015).

A digital elevation model with a horizontal resolution of 1 m that was derived from publicly available lidar data through the USGS National Map website (https://viewer.nationalmap.gov/basic/) was acquired for the study area. This DEM was processed with a semi-automated tool (the HydroCutter tool for ArcGIS) developed by Wall and others (2015) that utilizes the Environmental Systems Research Institute (ESRI) ArcGIS Spatial Analyst Extension to identify areas of closed depressions. This tool was used to reduce the number of artificial depressions by filtering out many that had been artifacts of drainage areas that abutted culverts beneath roads and other transportation features. To reduce additional spurious data, any machine-identified closed depressions less than 10 square meters (m^2) in area and less than 30 centimeters (cm) in depth were deleted from the database.

Even after automated filtering, the majority of the DEM-derived closed depressions are not karst sinkholes. Many are artifacts of filtering of the raw lidar data to remove trees, buildings, machinery, and other above ground features to produce a bare-earth topographic model. Therefore, each remaining apparent sinkhole was examined manually to verify the nature of the depression in the DEM. All sinkholes were examined using an overlay of aerial imagery, both current and historical, available in Google Earth to visually verify machine-identified closed depressions as natural karst features. Each polygon was examined in the context of the DEM and overlain on aerial imagery. Many sinkholes were inspected and verified during the course of fieldwork.

Sinkholes between 10 m^2 (108 square feet [ft^2]) and 1,000 m^2 (10,760 ft^2) in area are portrayed on the geologic maps as simple point symbols. Sinkholes greater than or equal to 1,000 m^2 (10,760 ft^2) in area are shown as outlined polygons.

Caves

The field area contains numerous, generally small, solution caves developed in the limestone and dolostone bedrock units, but data were not collected on cave locations in this study. There are no show caves in the field area. For a general discussion of Virginia caves, see Douglas (1964) and Holsinger (1975). For further information on caves in Virginia, see the Virginia Speleological Survey at http://www.virginiacaves.org/. For general information on West Virginia Caves, see Davies (1958, 1965). For more specific information on West Virginia caves see the West Virginia Speleological Survey at https://www.wvass.org/.

Springs

There are numerous karst springs within the study, many of which served as water supplies for historic homesteads, manors, and Civil War field hospitals. Historically known springs, and those shown on USGS topographic maps, have been shown on the geologic maps of the study area. Also shown on the geologic maps of the study area are several previously unmapped springs observed during fieldwork. For information on the Virginia part of the study area see reports on groundwater studies for Frederick County (Harlow and others, 2005) and Clarke County (Nelms and Moberg, 2010). For information on the West Virginia part of the field area, see reports on Berkeley County (Shultz and others, 1995; McCoy and others, 2005a) and Jefferson County (McCoy and others, 2005b). Doctor and others (2015), includes descriptions of several large springs located in the study area.

Economic Geology and Mineral Resources

The main unit of current economic interest is the high-calcium New Market Limestone. Excluding the lowermost beds of the New Market Limestone, which contain some magnesian limestone, the unit is as much as 98 percent calcium carbonate (Edmundson, 1945) and is used in the manufacture of portland cement, steel, aluminum, glass, and paper, as well as for an acid waste stream neutralizer and agricultural lime.

Two quarries in the New Market Limestone are currently active in the study area, both located on the west limb of the Massanutten synclinorium. One is the Carmeuse Lime & Stone Winchester quarry, located just east of the town of Clearbrook, in the Stephenson quadrangle. This quarry supplies Chemical grade limestone sized for steel making, flue gas treatment, and cement manufacturing. They also produce engineered limestone with consistent chemical and physical properties for roofing shingles, animal feed, flue gas treatment, glass making, carpet manufacturing, and coal-mine rock dust abatement. The other quarry is that operated by DL Morgan Jr. Inc., located about 1 mi (1.6 km) south of the town of Inwood, West Virginia, in the Inwood quadrangle. This quarry supplies limestone aggregate for various uses including concrete production. Several abandoned quarries, typically flooded by groundwater, exist along the outcrop belt of the New Market Limestone.

The Stewart M. Perry company operates a large quarry complex about 3 mi (4.8 km) west of the city of Winchester in the Winchester quadrangle. There, rocks of the Conococheague Formation are quarried for decorative stone, aggregate, manufactured sand, lime, and clay.

Subeconomic quantities of manganese and iron mineralization are known to occur locally in association with the Helderberg Group limestones and the overlying Oriskany Sandstone. Some of these deposits were mined in the past in parts of Frederick County, Virginia, about 20 mi (32 km) southwest of the city of Winchester (Butts and Edmundson, 1966). Since these strata are relatively thin and poorly exposed in the study area, there are unlikely to be economically viable deposits.

The Martinsburg Formation contains large reserves of shale suitable for clay production used for brick making. The only manufacturer in the region currently utilizing this resource is the Continental Brick Company in Martinsburg, West Virginia, about 20 mi (32 km) north-northwest of the city of Winchester.

The Oriskany Sandstone is a potential source of silica-glass sand but is not mined in the study area. Nearby operations include a quarry at Gore, Virginia, about 10 mi (16 km) west-northwest of the city of Winchester operated by the Covia Corporation, and quarries near Berkeley Springs, West Virginia, about 30 mi (48 km) north-northwest of Winchester.

Description of Map Units

Dh **Hampshire Formation (Upper Devonian)**—Sandstone, mudstone, siltstone, and minor shale. Sandstone, reddish-gray to brownish-gray, medium- to thick-bedded, in part micaceous and (or) arkosic, commonly crossbedded, and unfossiliferous. Mudstone, maroon red and typically weathers into small crumbly lumps. Siltstone and shale, reddish-brown to gray. Exposed thickness of the unit as much as 850 ft. Upper part of the formation is not exposed in map area. The lower contact is placed at the base of the redbeds and at the top of highest gray, fossiliferous sandstone and shale of the underlying Foreknobs Formation. The unit is exposed west of the North Mountain fault zone in the northwestern part of the Winchester quadrangle and western part of the White Hall quadrangle

Df **Foreknobs Formation (Upper Devonian)**—Predominantly yellowish-gray, brownish-gray to light-olive-gray, greenish-gray, grayish-red, yellowish-gray to light-olive-gray weathering, thin- to medium-bedded, thick-bedded to massive, interbedded sandstone, siltstone, and shale, and some thin beds of conglomerate; locally fossiliferous. Two coherent packages of thick-bedded to massive sandstones occur as two ridge-forming units that are mappable throughout the study area. The upper ridge-forming unit (Dfu) consists of 5 to 6 intervals of thick, resistant, interbedded sandstone, siltstone, and shale that form a prominent ridge in the upper part of the formation; locally two or more masses form distinct ridges. This unit is about 500 ft (150 m) thick. The lower ridge-forming unit (Dfl) consists of 3 to 4 intervals of thick-bedded to massive, resistant interbedded sandstone, siltstone, and shale, which form a prominent ridge at the base of the formation. This unit is also about 500 ft (150 m) thick. The intervals (Df) between the two ridge-forming units and above the upper ridge-forming unit consists of thin- to medium-bedded sandstone, siltstone, and shale and typically occupies the drainage area between the two ridges; commonly not well exposed. The lower contact with the Brallier Formation is placed at the first occurrence of massive sandstone greater than 6 ft (2 m) thick, with quartz pebble conglomerate or centimeter (cm)-size clasts of sandstone, siltstone, and shale observed within the sandstone. Overall thickness of the Foreknobs Formation is about 1,700 ft (520 m). The unit is exposed west of the North Mountain fault zone in the northwestern part of the Winchester quadrangle and western part of the White Hall quadrangle

Db **Brallier Formation (Upper Devonian)**—Interbedded shale, siltstone, and sandstone that is dark gray to greenish gray, weathers light brownish gray, and sparsely fossiliferous. Grain size increases irregularly upward in section; sandstone beds, 2 to 6 in. thick, become more abundant near the top of the formation. Thickly laminated shale with scattered siltstone beds up to 3 in. thick makes up the bulk of the formation. The lower contact with the underlying Mahantango Formation is a disconformity above a massive sandstone unit (Dmc) at the top of the Mahantango Formation. Thickness is approximately 1,100 ft (305 m). The unit is exposed west of the North Mountain fault zone in the northwestern part of the Winchester quadrangle and western part of the White Hall quadrangle

Dm **Mahantango Formation (Middle Devonian)**—Mudstone, shale, siltstone, and minor sandstone. Mudstone, dark-gray to olive-gray, hackly weathering, locally very fossiliferous; bedding is obscure, with anastomosing cleavage that results in spheroidal weathering common within massive siltstone and mudstone. Sandstone (Dmc), equivalent to the informal Clearville member of Cate (1963) and Jolley (1982), medium-gray, fine-grained, medium- to thick-bedded, generally massive, locally fossiliferous; occurs as two well-indurated sandy siltstone intervals near the top of the formation separated by mudstone; total thickness is as much as 380 ft. The Chaneysville Siltstone Member (Dmch) is predominantly massive, dark-gray siltstone and black mudstone occurring in the lower part of the formation, locally fossiliferous, up to 850 ft thick, that grades into calcareous shale at the base. Thickness of Mahantango Formation (Dm), both above and below the Chaneysville Siltstone Member, is about 660 ft (200 m). Total thickness of entire formation ranges from 1,600 to 1,800 ft. The lower contact between the Mahantango Formation and the Marcellus Shale is marked by an unnamed ridge-forming siltstone bed approximately 20 ft (6 m) thick at the base of the Mahantango; this bed is well exposed along the creek that parallels the southwest side of Highway 50, about 1,500 ft southeast of the intersection of Highway 50 and Route 600 at Hayfield, 2.5 miles west of the study area (Doctor and Parker, 2018). Where this lower siltstone bed is not present, the contact is gradational, and placed at the base of the olive-gray mudstone and siltstone that is above the underlying black Marcellus Shale. The Mahantango Formation is exposed west of the North Mountain fault zone in the northwestern part of the Winchester quadrangle and western part of the White Hall quadrangle

Dmn **Marcellus Shale and Needmore Shale, undivided (Middle and Lower Devonian)**—Shale, silty shale, calcareous shale, and minor limestone. Thickness is as much as 800 ft; however, units are not well exposed in the map area due to faulting and colluvial cover. Exposure occurs in a narrow belt just northwest of the North Mountain fault zone in the Winchester and White Hall quadrangles. The descriptions below are based upon mapping conducted in adjacent quadrangles

Marcellus Shale (Middle Devonian)—Shale, black to dark-gray, highly fissile, with localized beds or concretions of dark-gray, argillaceous limestone or calcareous shale. Forms thin, platy chips and weathers dusky yellowish gray in exposed outcrops. Base of Marcellus is marked regionally by the Tioga Ash Bed, which is difficult to recognize in outcrops. Thickness up to 700 ft

Needmore Shale (Middle and Lower Devonian)—Calcareous shale, dark-greenish-gray to olive-gray, and dark-gray fissile silty shale; locally fossiliferous. Thickness is about 100 ft. Grades upward into the Marcellus Shale through a series of thin, fossiliferous limestone beds. The base is placed at the top of coarse, quartz-rich, calcareous sandstone of the underlying Oriskany Sandstone. The contact is correlative to the regional Wallbridge discontinuity (Dennison and Head, 1975; Haynes and others, 2018)

DSls **Oriskany Sandstone, Helderberg Group, and Tonoloway Limestone, undivided (Lower Devonian to Ludlow [upper Silurian])**—Sandstone, limestone, and shale. Thickness is as much as 875 ft (265 m); however, the units are not well exposed in the quadrangle due to faulting and colluvial cover. The descriptions below are based upon mapping conducted in adjacent quadrangles (Butts and Edmundson, 1966; McDowell, 1991; Harris and others, 1994; Rader and others, 1996; Orndorff and others, 1999; Rader and others, 2001, 2003)

Oriskany Sandstone (Lower Devonian)—Sandstone, light-gray, yellowish-gray- or yellowish-brown-weathering, medium- to coarse-grained, medium- to thick-bedded, locally crossbedded, and calcareous; locally conglomeratic with quartz pebbles as much as 0.5 in. long; friable when weathered; contains molds of brachiopod shells. The base is placed at the top of cherty limestone of the Licking Creek Limestone of the Helderberg Group

Helderberg Group, undivided (Lower Devonian and Pridoli [upper Silurian])—Limestone, medium- to dark-gray, fine-grained, irregularly bedded, and fossiliferous; contains black or light- gray to white chert nodules, lenses, and beds as much as 1.5 ft thick near the top; some limestone is medium gray, coarse grained, and crinoidal. The Helderberg Group is about 100–140 ft (30 to 42 m) thick in Frederick County, and good exposures occur in the adjoining Hayfield quadrangle (Doctor and Parker, 2018); however, individual units cannot be distinguished in the study area due to faulting and colluvial cover. The only observed outcrops in the study area occur in the White Hall quadrangle on the northeast flank of Little North Mountain, and in a faulted structural block at Green Spring

Tonoloway Limestone (Pridoli and Ludlow [upper Silurian])—Limestone and shale. Limestone, medium-gray to medium-dark-gray, and crinkly laminated to thin-bedded. Shale, medium-gray to dark-gray, and calcareous. Locally, contains ripple marks and mud cracks. The Tonoloway Limestone is about 300 ft (90 m) thick in the adjoining Hayfield quadrangle to the west (Doctor and Parker, 2018), but is considerably thinned in the study area due to faulting within the North Mountain fault zone

Swbm **Wills Creek Formation, Bloomsburg Formation, and McKenzie Formation, undivided (Ludlow [upper and lower Silurian])—**Shale, sandstone, siltstone, and limestone. Total thickness is as much 275 ft (84 m)

Wills Creek Formation (Ludlow [upper Silurian])—Interbedded shale, siltstone, limestone, and sandstone. Shale, medium-dark-gray and greenish-gray to light-olive-gray, weathers yellowish-gray to reddish-gray, crinkly laminated, and calcareous. Siltstone, greenish-gray to gray, and weathers dark-brownish-gray or grayish-yellow. Limestone, medium-dark-gray to olive-gray, very fine grained with local flat-pebble conglomerate. Sandstone, primarily near the top of the unit, exhibits massive weathering, is crossbedded, and is 15 to 20 ft thick; informally named the Tavenner sandstone member by Butts and Edmundson (1966). Total thickness of the formation is approximately 140 to 180 ft (43 to 55 m) but is considerably thinned in the study area due to faulting within the North Mountain fault zone

Bloomsburg Formation (Ludlow [upper Silurian])—Interbedded sandstone, siltstone, mudstone, and shale. Sandstone, gray and reddish-brown to grayish-red, fine- to medium-grained, and thin- to thick-bedded. Siltstone, grayish-red, reddish-brown, grayish-purple, medium-gray, light-olive-gray, and greenish-gray, thin- to medium-bedded, and shows prominent cleavage. Mudstone, maroon-red, weathers to crumbly lumps that are dusky pale red. Shale, gray, greenish-gray, and reddish-brown. Locally contains Skolithos burrows. Only observed as considerably thinned partial exposures within the horse block that holds up Little North Mountain along the North Mountain fault zone

McKenzie Formation (Ludlow [upper Silurian])—Shale and siltstone. Shale, yellow-tan with silky luster, olive-gray and light-olive-gray, fissile, and fossiliferous. Siltstone, yellow-gray and calcareous. Only observed in the study area as considerably thinned partial exposures within the horse block that holds up Little North Mountain along the North Mountain fault zone

Skr **Keefer Sandstone and Rose Hill Formation, undivided (Wenlock and Llandovery [middle to lower Silurian])**—Quartzite, sandstone, and shale. Thickness at most is approximately 400 ft (122 m)

Keefer Sandstone—Quartz sandstone and orthoquartzite, medium-light-gray, coarse-grained to pebbly, massive, and vitreous at base; grading up to medium-gray, medium-grained, olive-gray, fine-grained sandstone. Only observed as considerably thinned partial exposures within the horse block that holds up Little North Mountain along the North Mountain fault zone. Thickness is about 30 to 50 ft (9 to 15 m) at most but is considerably thinned due to faulting

Rose Hill Formation—Sandstone and shale. Sandstone, reddish-brown, grayish-red, grayish-purple, gray, medium- to coarse-grained, medium- to thick-bedded, and locally hematite cemented. Shale, gray, greenish-gray, reddish-brown, locally silty, and hackly weathering; locally fossiliferous. The lower contact is placed at the base of red sandstone overlying massive quartzite ledges of Tuscarora Sandstone. Only observed in the study area as considerably thinned partial exposures within the horse block that holds up Little North Mountain along the North Mountain fault zone. Thickness is as much as 350 ft (107 m) at most but is considerably thinned due to faulting

St **Tuscarora Quartzite (Llandovery [lower Silurian])**—Quartz sandstone and orthoquartzite, light- to medium-gray, medium- to coarse-grained, and thick-bedded; some beds are conglomeratic. The base is placed at the bottom of orthoquartzite beds. Thickness is about 240 ft (73 m)

Ojo **Juniata Formation and Oswego Sandstone, undivided (Upper Ordovician)**—Sandstone, shale, and conglomerate. Thinned by faulting in much of the study area; thickness is about 400 ft (122 m)

Juniata Formation—Sandstone and shale. Arkosic sandstone, grayish-red to brown, fine- to coarse-grained, thin- to medium-bedded, locally thick-bedded, and crossbedded. Shale or mudrock, grayish-red; occurs as thin beds and partings, mostly near the top of the formation

Oswego Sandstone—Lithic sandstone and conglomerate. Sandstone, greenish-gray, coarse-grained, thick-bedded, and conglomeratic. Conglomerate, interbedded with sandstone, composed of rounded clasts of chert and sandstone. Sandstone is friable where locally calcareous and fossiliferous

Om **Martinsburg Formation (Upper Ordovician)**—Interbedded shale and lesser graywacke-siltstone and graywacke-sandstone. Shale, medium-gray to dark-gray and light-olive-gray, weathers grayish-orange and dark-yellowish-orange, commonly silty, and generally noncalcareous, although calcareous intervals occur in the lower part of the formation (Stickley Run Member). Siltstone and sandstone (immature, generally lithic graywacke), medium-gray, grayish-orange weathering, very fine to fine-grained, commonly graded (fining upward), lenticular, and slightly calcareous to noncalcareous; contains many small crossbeds. Graywacke is more abundant and more thickly bedded higher in section where it forms conspicuous ribs in creek beds and may constitute as much as 30 percent of some intervals that are several hundred feet thick. Thicker beds are generally graded and display characteristics of complete Bouma cycles. The unit is prone to development of axial planar cleavage, which may locally obscure bedding. Regional thickness may be more than 5,000 feet (1,500 m)

Oe **Edinburg Limestone (Upper Ordovician)**—Interbedded limestone, calcareous shale, and siltstone. Limestone, medium-gray to medium-dark-gray, fine- to medium-grained, thin- to thick-bedded, irregularly bedded, and knobbly weathering. Calcareous shale, medium-dark-gray to very dark-gray. May locally contain a 3-ft-thick olive-brown siltstone interval in the lower part. Locally the lower contact is placed above the top of the medium- to course-grained, locally chert-bearing Lincolnshire Limestone. Locally fossiliferous with small brachiopods and the index fossil *Cyclocrinities pyriformis* (Basler) (previously known as *Nidulites* or *Mastipora pyriformis*; see Beadle, 1991, p. 116, fig. 2a–d). The unit is commonly mapped in previous studies as the Chambersburg Limestone in West Virginia. Thickness is as much as 550 ft (168 m)

Oln **Lincolnshire and New Market Limestones, undivided (Upper and Middle Ordovician)**—Limestone and minor amounts of black chert

Lincolnshire Limestone (Upper Ordovician)—Limestone, medium-dark-gray and medium-gray, locally containing red clay partings, medium- to thin-bedded, typically medium-grained, medium- to thick-bedded bioclastic, and containing irregular black chert nodules in places. The unit thins to the northeast in West Virginia where other workers have mapped it as part of the Chambersburg Limestone (for example, Dean and others, 1994). Thickness ranges from about 10 to 30 ft

New Market Limestone (Middle Ordovician)—Limestone, medium-gray and dove gray, weathers light- and very light-gray, thick-bedded, micritic, and fenestral. The lower 10 ft (3 m) is medium-gray to light-gray, thin-bedded dolomitic limestone that is interbedded with light-gray dololaminite. The base is placed at the top of uppermost medium-gray, thick-bedded dolostone of the Pinesburg Station Dolomite (Op) and below dolomitic limestone of the New Market Formation. Thickness is as much as about 200 ft (60 m)

Op **Pinesburg Station Dolomite of the Beekmantown Group (Middle Ordovician)**—Dolostone and dololaminite, medium- to light-gray, buff to light weathering, fine-grained, medium- to thick-bedded with minor white and light-gray chert nodules. Weathered surfaces commonly have "butcher-block" (cross-hatched joints) structure. Also contains a few thin, medium-gray, fine-grained limestone beds in the lower part. The lower contact is placed at the base of first light-gray, thick-bedded dolostone overlying dominantly limestone cycles of the Rockdale Run Formation (Or). Thickness ranges up to about 650 ft (198 m) and thins towards the southeast

Or **Rockdale Run Formation of the Beekmantown Group (Middle and Lower Ordovician)**—Interbedded limestone and dolostone. Limestone, bluish-gray, medium-gray, dark-gray, fine- to medium-grained, thin- to medium-bedded, and fossiliferous. Dolostone, medium-gray, fine- to medium-grained, medium-bedded, and crystalline. Strata occur in fining-upward carbonate cycles capped by dololaminite beds as much as 2 ft (6 m) thick. Limestone beds also contain intraformational conglomerates, algal bioherms, bioclastic zones, and burrow mottling. Gastropod *Lecanospira* is common in the lower and middle parts of the formation. The lower contact is placed at the base of the lowermost crystalline dolostone or dololaminite bed overlying dark-gray, thick-bedded limestone of the Stonehenge Limestone. Exposed thickness is approximately 1,500 ft (457 m); thickness is uncertain due to faulting and folding

Os **Stonehenge Limestone of the Beekmantown Group (Lower Ordovician)**—Limestone, dark-gray, fine- to medium-grained, thick-bedded to massive, fossiliferous, with crinkly laminations and minor black chert. Contains algal bioherms, intraformational conglomerates, bioclastic beds, and minor dolostone. Gastropod *Lecanospira* is common in the middle part of the formation. Massive limestone may have mottles derived from weathering of dolomitic burrows. The contact with the underlying Conococheague Limestone is gradational; the base is placed at the first dark-gray limestone with crinkly siliceous laminations (Stoufferstown Member) and above the uppermost dolostone that caps Conococheague Limestone carbonate cycles. Thickness is approximately 770 ft (235 m)

O€c **Conococheague Limestone (Lower Ordovician and Upper Cambrian)**—Interbedded limestone, dolostone, dololaminite and sandstone. Limestone, medium-gray, fine-grained, thin- to medium-bedded. Dolostone and dololaminite, light-gray, fine-grained, and medium-bedded. Sandstone, light-gray to buff, orange-reddish weathering, medium- to coarse-grained, and calcareous. Limestones occur in carbonate cycles and include intraformational conglomerates, algal bioherms, ribbon rock, and oolites. Lithologies occur as carbonate cycles; sandstone and (or) dololaminite cap these cycles. The lower 295 ft (90 m) consists of the Big Spring Station Member (not mapped separately) of Wilson (1952). The Big Spring Station Member consists of gray to buff, orange-reddish weathering, coarse-grained calcareous sandstone; medium-gray, fine-grained limestone with intraformational conglomerate; and light-gray, fine-grained dolostone. Sandstone beds also occur in the middle part of formation and form topographic ridges as much as 100 ft (30 m) high. The upper part of the formation contains very light-gray weathering, medium-gray limestone with thin siliceous laminae. The base is placed below the lowermost calcareous sandstone bed of the Big Spring Station Member. Thickness is approximately 2,800 ft (853 m)

Ꞓe **Elbrook Formation (Upper and Middle Cambrian)**—Interbedded limestone, dolostone, and shale. Limestone, medium-gray, fine- to medium-grained, and thin- to medium-bedded. Dolostone, light- to medium-gray, yellowish weathering, fine-grained, and medium-bedded. Shale, gray, yellowish weathering, and dolomitic. Limestone contains algal bioherms, intraformational conglomerate, and dolomitic burrow mottles. The lower part of the formation is not exposed. The exposed lowest beds are in the middle part of the formation and are bluish-gray, medium- to thick-bedded limestone with dolostone ribbons and mottles and medium-gray, thick-bedded dolostone. Cycles of bluish-gray algal limestone and grainstone, and light-gray argillaceous dolostone occur in the upper part of the Elbrook Formation. Dololaminite beds commonly cap these cycles. A distinctive lithology is yellowish weathering, thin-bedded dololaminite that appears shaly in weathered outcrops. Thickness is at least 2,500 ft (762 m); the apparent thickness is increased by intraformational folding

Ꞓw **Waynesboro Formation (Middle and Lower Cambrian)**—Shown in cross section *E–E′* only. Lithologies include interbedded sandstone, sandy dolomitic limestone, dolostone, maroon shale, and a few siltstone beds. Thickness is unknown in the study area due to lack of exposure but is reported (as the Rome Formation) to be 2,200-ft thick in Clarke County, Virginia, just to the east (Edmundson and Nunan, 1973)

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