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Prepared in cooperation with the Virginia Department of Energy, Geology and Mineral Resources Program

Geologic Map of the Buckner 7.5-Minute Quadrangle, Louisa County, Virginia

By Mark W. Carter, David B. Spears, Virginia M. Latane, E. Allen Crider, Benjamin R. Weinmann, Holly Mangum, Ryan J. McAleer, J. Wright Horton, Jr., Anjana K. Shah, and Sean P. Regan

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Cover. Photograph of an outcrop of Ordovician to Silurian granodiorite of Elk Creek (map unit SObg; see Description of Map Units). The hammer (approximately 38 centimeters long) is shown for scale. Photograph by Mark Carter, U.S. Geological Survey. For more information, see figure 5.

Acknowledgments

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
decimeter (dm)	0.3281	foot (ft)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Mass	
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
milligram (mg)	0.000002205	pound, avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datums

Horizontal coordinate information is referenced to the North American Datum of 1983.

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1988.

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

Abbreviations

Ar	argon
CA-TIMS	chemical abrasion thermal ionization mass spectrometry
ID-TIMS	isotope dilution thermal ionization mass spectrometry
lidar	light detection and ranging
Ma	mega-annum (million years ago)
Pb	lead
SHRIMP-RG	Sensitive High-Resolution Ion Microprobe with Reverse Geometry
Th	thorium
TIMS	thermal ionization mass spectrometry
U	uranium
USGS	U.S. Geological Survey

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By Mark W. Carter,[1] David B. Spears,[2] Virginia M. Latane,[3] E. Allen Crider,[1] Benjamin R. Weinmann,[1] Holly Mangum,[2] Ryan J. McAleer,[1] J. Wright Horton, Jr.,[4] Anjana K. Shah,[1] and Sean P. Regan[5]

Abstract

The Buckner 7.5-minute quadrangle straddles three terrane boundaries in the Piedmont Physiographic Province in central Virginia: the Chopawamsic terrane, the Elk Hill Complex, and the Goochland terrane. In much of the map area, the Elk Hill Complex separates the Chopawamsic and Goochland terranes. Rocks of the Chopawamsic terrane include Ordovician metavolcanic and metasedimentary rocks of the Chopawamsic Formation, Ordovician to Silurian granodiorite sheet intrusions, and Paleozoic mafic intrusions. Silurian to Devonian rocks of the Quantico Formation, mostly garnet-mica schist, crop out in the northwesternmost part of the map area, and are in unconformable contact with rocks of the Chopawamsic Formation on the southeastern limb of the Quantico synclinorium. The main map unit in the Elk Hill Complex is Neoproterozoic mica gneiss, which is in pre-metamorphic fault contact with rocks of the Chopawamsic Formation to the west. The main map unit of the Goochland terrane is the Maidens Gneiss. Except for Jurassic diabase dikes, all rocks on the Buckner 7.5-minute quadrangle were metamorphosed to amphibolite facies during the Alleghanian orogeny and preserve multiple compositional and phyllosilicate penetrative foliations. Evidence of amphibolite-facies metamorphism during the Taconic orogeny is preserved in rocks of the Elk Hill Complex. The entire width of the Maidens Gneiss on the Buckner 7.5-minute quadrangle is within the Spotsylvania high-strain zone and amphibolite-facies mylonitic textures are pervasive. Quartz veins and Jurassic diabase dikes crosscut all older rocks of the quadrangle.

Multiple levels of terrace deposits are present along and near the major streams of the quadrangle. The lower terrace deposits are likely remnants of former positions of the Little River on the landscape, whereas higher deposits may be remnants of former deposits of the Atlantic Coastal Plain that covered this portion of the Piedmont Province. A linear cluster of aftershocks from the magnitude 5.8 earthquake that occurred near Mineral, Virginia, in 2011 defines the Fredericks Hall fault, which is at depth on the Buckner quadrangle. Most of the aftershocks occurred in the core of the Elk Creek antiform and have no relation to faults mapped at the surface. Several abandoned crushed stone and building stone quarries, as well as a mica prospect, exist in the quadrangle.

Introduction

The Buckner 7.5-minute quadrangle is located in Louisa County in central Virginia. The Little River and its tributaries drain most of the quadrangle. Millpond Creek and Colmans Creek in the northeastern portion of the quadrangle are part of the North Anna River system, which is partially dammed to create Lake Anna. In the southwestern corner of the quadrangle, Turners Creek and its tributaries drain into the South Anna River. The major transportation routes are Fredericks Hall Road (State Route 618), Buckner Road (State Route 609), and U.S. Route 33. The Chesapeake and Ohio Railroad, now operated by Buckingham Branch Railroad, transects the northeastern corner of the quadrangle.

Purpose

Geologic mapping of the quadrangle was jointly funded by the U.S. Geological Survey (USGS) and Virginia Department of Energy (Geology and Mineral Resources Program) as part of the earthquake hazards response to the magnitude 5.8 (M5.8) earthquake that occurred west of the Buckner quadrangle near Mineral, Virginia, on August 23, 2011. As of 2015, at least 197 earthquake aftershocks up to about M2.6 have struck the quadrangle (Wu and others, 2015). Most of these occurred in a 6-kilometer-long diffuse zone that trends southwest to northeast in the north-central portion of the quadrangle. This zone defines the Fredericks Hall fault (at depth), one of several subsidiary faults that ruptured following the mainshock on August 23, 2011 (Horton and others, 2015).

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[2]Virginia Department of Energy, Geology and Mineral Resources Program.

[3]City of Charlottesville.

[4]U.S. Geological Survey, emeritus.

[5]University of Alaska Fairbanks.

Map Construction

Geologic mapping of the northwestern half of the quadrangle was conducted from October 2014 to January 2016 by the USGS; geologic mapping of the southeastern half was conducted from October 2016 to July 2018 by the Virginia Department of Energy, Geology and Mineral Resources Program. Field data including lithologic and structural information (foliations, lineations, and joints) were collected from outcrops encountered during overland traverses along creeks, roads, and railroads. Detailed ground-based geologic mapping was augmented with high-resolution airborne gravity, magnetic, and radiometric data that were collected over the epicentral area of the 2011 earthquake near Mineral, Va. (Shah, 2014; Shah and others, 2015). The USGS also procured high-resolution airborne light detection and ranging (lidar) data (quality level 1; pulse-spacing 0.33 meters [m]) that were used to generate shaded relief (hillshade), slope, and aspect raster datasets that were used for surficial geologic interpretation. Soil data from Carter (1976) were also used to augment interpretation of bedrock and surficial units where outcrops were sparse or absent; these soil data are available for download at https://websoilsurvey.nrcs.usda.gov/app/. Geologic data (Weinmann and others, 2025) as well as geochemical and geochronological data (Powell and others, 2024) are available in data releases associated with this scientific investigations map.

Previous Work

The best available reconnaissance geologic mapping coverage on the Buckner 7.5-minute quadrangle is at 1:100,000 scale (Marr, 2002). Similar smaller-scale maps adjacent to the north of the quadrangle include Pavlides (1990) and Mixon and others (2000). Bobyarchick and others (1981) mapped the northeast-adjacent Lake Anna East 7.5-minute quadrangle at 1:24,000 scale. Spears and others (2013) and Spears (2016) mapped the west-adjacent Pendleton 7.5-minute quadrangle and southwest-adjacent South Anna 7.5-minute quadrangle, respectively. Carter and others (2019) mapped the northwest- and north-adjacent Mineral and Lake Anna West 7.5-minute quadrangles. Carter and others (2020) reported Sensitive High-Resolution Ion Microprobe with Reverse Geometry (SHRIMP-RG) U-Pb zircon ages from the Stanford-USGS Micro Analytical Center for several rock units exposed on the quadrangle.

Geologic Setting

The Buckner 7.5-minute quadrangle lies in the Piedmont Physiographic Province, an amalgam of terranes that were deformed and accreted to the eastern edge of North America during a series of tectonic collisions in the Paleozoic Era (Horton and others, 1989; Hibbard and others, 2005). The quadrangle includes two terranes (Chopawamsic and Goochland) that are separated by a third terrane, the Elk Hill Complex, in much of the map area (fig. 1). The Lakeside fault separates the Chopawamsic terrane from the Elk Hill Complex in the southwestern part of the quadrangle, and the Spotsylvania fault (which roughly bisects the quadrangle from southwest to northeast) separates the Elk Hill Complex from the Goochland terrane in much of the map area. The Quantico Formation crops out in the Quantico synclinorium in the northwesternmost corner of the quadrangle. All bedrock units and terranes are defined based on differences in age, metamorphism, and character of the rocks. Surficial deposits of Neogene to Holocene age unconformably overlie bedrock of the Piedmont Province.

Lithology and Stratigraphy

Rocks of the Maidens Gneiss and Goochland Terrane (East of the Spotsylvania Fault)

The Maidens Gneiss, originally described by Poland (1976) and named by Poland and others (1979) for exposures along the James River near the village of Maidens, Goochland County, Va., is a heterogeneous unit consisting primarily of compositionally layered, quartzofeldspathic, garnetiferous biotite gneiss with lesser amphibolite and mica schist. The Maidens Gneiss composes most of the Goochland terrane on the Buckner 7.5-minute quadrangle and throughout the Piedmont Province of Virginia. On the Buckner 7.5-minute quadrangle, these rocks are subdivided into four map units: granofels (map unit Ymq), mica schist (map unit Yms), amphibolite (map unit ZYma), and biotite gneiss (map unit DYmm). Biotite gneiss may be both paragneissic and orthogneissic. Map-scale lenses of mica schist within biotite gneiss are most likely metasedimentary rocks but could also be lenses of recrystallized mylonite within the Spotsylvania high-strain zone. Variably mylonitic to gneissic textures in biotite gneiss and other map units of the Goochland terrane are ubiquitous (fig. 2*A*) and likely the product of multiple generations of Paleozoic ductile deformation. These rocks also contain outcrop- to map-scale bodies of metagranitoid (map unit Pzg) and abundant outcrop-scale pegmatite dikes that are generally deformed and oriented parallel to regional compositional layering and foliation (fig. 2*B*).

Pavlides (1980) described rocks of the Maidens Gneiss as the Po River Metamorphic Suite of the Fredericksburg Complex. Mixon and others (2000) followed the same naming convention in the north-adjacent Fredericksburg 30- × 60-minute quadrangle. However, the term “Maidens Gneiss” takes precedence over this term. Farrar (1984) interpreted relict granulite-facies assemblages in rocks of the Maidens Gneiss and Goochland terrane as evidence for a middle Proterozoic age and correlated the Maidens Gneiss with rocks associated with the Grenville orogeny that crop out in the Blue Ridge. Rankin (1994) noted continuity of the Po River Metamorphic Suite with the Maidens Gneiss and correlated the Maidens Gneiss with the Raleigh gneiss unit of Farrar (1985) in North Carolina.

Owens and others (2004) first reported Devonian U-Pb zircon crystallization ages (about 371 to 407 Ma) using traditional air abrasion techniques on three samples of garnetiferous quartzofeldspathic biotite gneiss of the Maidens Gneiss near Goochland, Va. Owens and others (2010) confirmed these initial results with chemical abrasion thermal ionization mass spectrometry (CA-TIMS) U-Pb zircon crystallization ages for three samples they interpreted to be meta-igneous. Martin and others (2019) interpret amphibolite assigned to the Sabot Amphibolite of the Goochland terrane to be Neoproterozoic in age (U-Pb zircon age of about 552±11 Ma from a felsic layer) and the metamorphosed equivalent of basalt extruded during continental extension and rifting of Laurentian crust. Despite continued systematic detailed mapping near type areas of these major units (for example, Evans and Farrar, 2015; Evans, 2019), detailed mapping of specific age-constrained lithologies and additional geochronologic studies over a broad area of the Goochland terrane are lacking, and many questions remain as to the precise age and stratigraphic succession of these units.

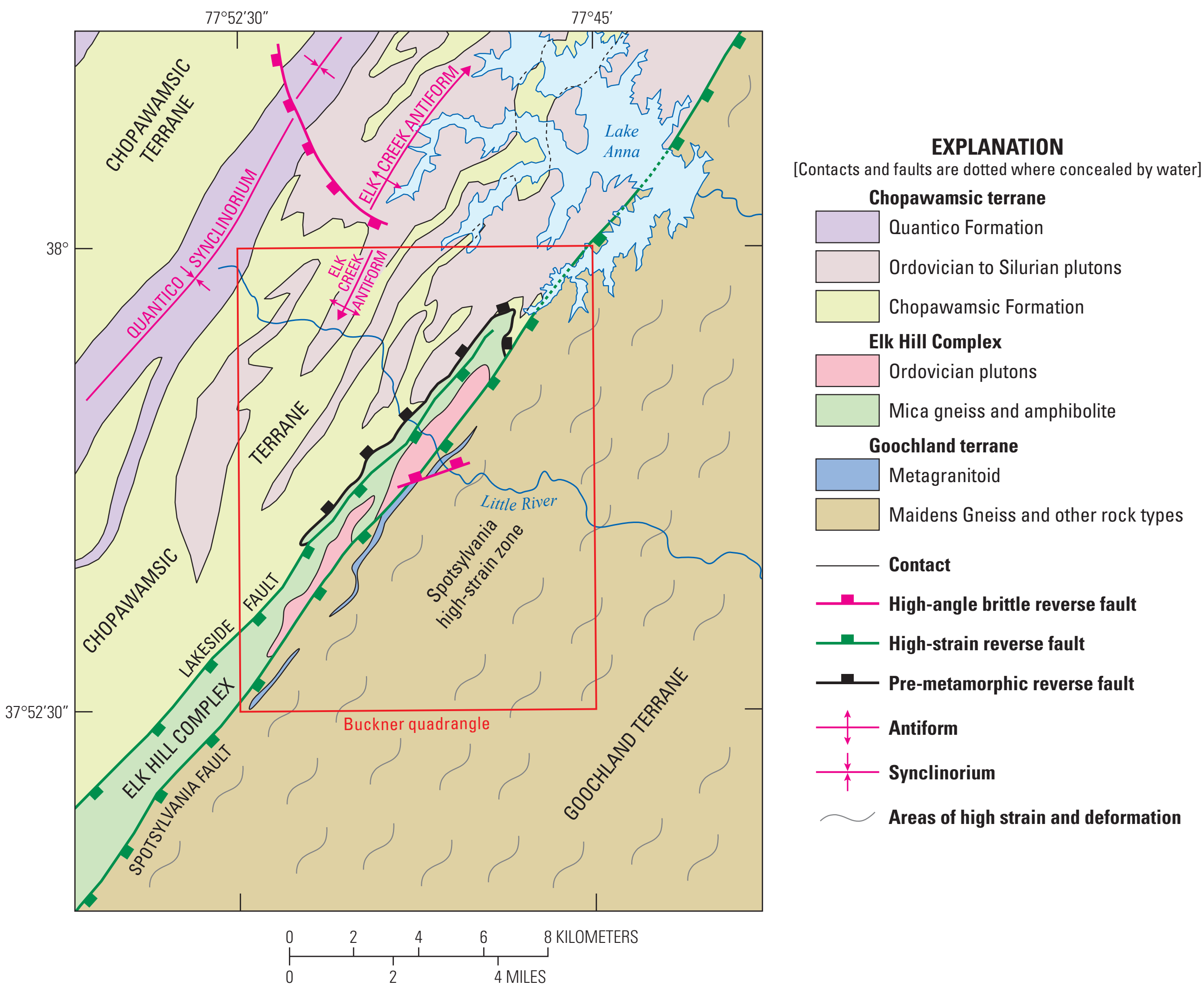


Figure 1. Simplified smaller-scale geologic map showing the location of the Buckner 7.5-minute quadrangle in relation to terranes and major geologic structures of the Piedmont Physiographic Province in central Virginia. Geology compiled from Virginia Division of Mineral Resources (1993), Spears and others (2013), Hughes and others (2015), Burton and others (2019), and Carter and others (2019).

Figure 2. Photographs of rocks of the Maidens Gneiss (map unit DYmm) and Goochland terrane. *A* (photograph locality 1 on the map), Saprolite exposure of mylonitic Maidens Gneiss in the high-strain region of the Spotsylvania high-strain zone. Light-colored feldspar porphyroclasts and discontinuous quartz-feldspar domains are separated by dark-colored biotite-rich domains. *B* (photograph locality 2 on the map), Outcrop of mylonitic, porphyroclastic Maidens Gneiss in the high-strain region of the Spotsylvania high-strain zone. Note the pegmatite (peg) boudins that are parallel to foliation. The view in both photographs is to the northeast with foliation dipping steeply southeast. The head of a hammer (18 centimeters wide) is shown for scale. Photographs by David Spears, Virginia Department of Energy (Geology and Mineral Resources Program).

Rocks of the Elk Hill Complex

The Elk Hill Complex is a northeast-trending belt of mica gneiss, amphibolite, and metagranitoids that was first defined by Taber (1913) along the James River in Goochland County, Va. On the Buckner 7.5-minute quadrangle, the Spotsylvania fault separates rocks assigned to the Elk Hill Complex from those of the Goochland terrane. Polydeformed mica gneiss (map unit Zmg; fig. 3*A*) of the Elk Hill Complex defines the western flank of the outcrop belt. These rocks are in unconformable contact or pre-metamorphic fault contact with overlying rocks of the Chopawamsic Formation in the northwestern part of the quadrangle, or are in fault contact with the Chopawamsic Formation along the Lakeside fault in the southwestern part of the quadrangle (fig. 1). Amphibolite (map unit Za), felsic gneiss (map unit Zfg), and hornblende-biotite tonalitic gneiss (map unit Obtg) also exist within the belt.

Carter and others (2020) sampled mica gneiss from the Elk Hill Complex and found that zircon grain cores were rounded in cathodoluminescence images. They analyzed 20 cores using the SHRIMP-RG technique, which yielded a multimodal age distribution (peak age populations from about 1,020 to 1,401 Ma) that indicated the rock is likely a paragneiss. The youngest peak age mode, which is interpreted to be the maximum depositional age for the mica gneiss, is about 926 Ma (youngest core analyzed).

Carter and others (2020) also sampled an intrusive hornblende-biotite tonalitic gneiss that contains xenoliths of foliated amphibolite (fig. 3*B*). This tonalitic gneiss yielded a SHRIMP-RG U-Pb zircon crystallization age of 452±6 Ma (19 zircon grains analyzed), which indicates that amphibolite of the Elk Hill Complex must be at least older than Ordovician (Carter and others, 2020). These results differ from those of Roig and others (2017), who reported an age of about 331±10 Ma using the isotope dilution thermal ionization mass spectrometry (ID-TIMS) method on 9 zircon grains from an intrusive granitoid collected at the type locality of Taber (1913).

Meter-scale blocks of very coarsely crystalline, massive pegmatite (consisting of alkali-feldspar crystals several decimeters in length and books of muscovite up to about a decimeter in length) are locally scattered within the outcrop belt of the Elk Hill Complex, but none have been found in place (fig. 3*C*). These blocks may be remnants of the Pegmatite Belt of Taber (1913), which is present west of the Lakeside fault along the James River to the southwest (Spears, 2011).

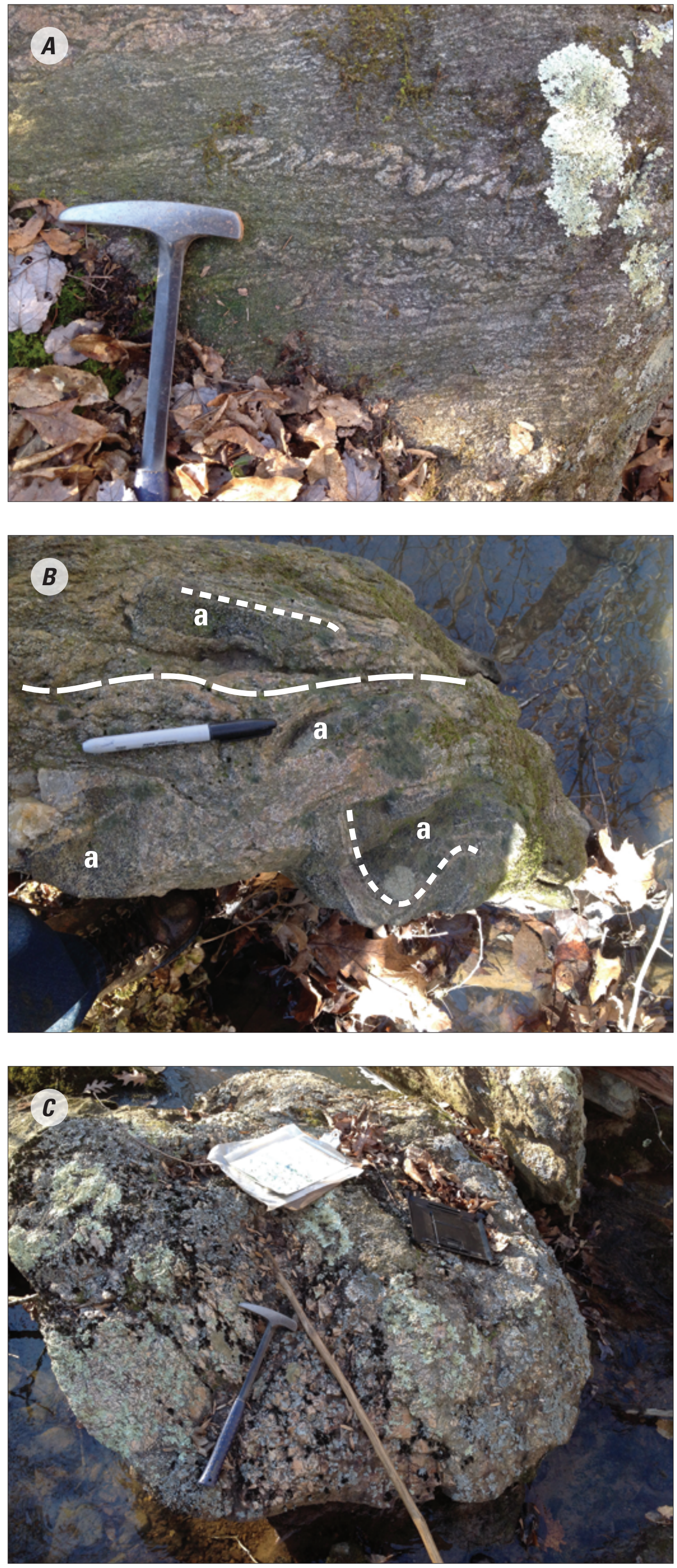


Figure 3. Photographs of rocks of the Elk Hill Complex. *A* (photograph locality 3 on the map), Mica gneiss (map unit Zmg) consisting of compositional layers of alternating quartzofeldspathic and muscovite + quartz-rich bands. The head of a hammer (17 centimeters wide) is shown for scale. *B* (photograph locality 4 on the map), Hornblende-biotite tonalitic gneiss (map unit Obtg) containing xenoliths of amphibolite (map unit Za; labeled as "a" on the photograph). Foliation in tonalitic gneiss (marked by a long-dashed white line) truncates compositional layering in amphibolite xenoliths (marked by short-dashed white lines in two xenoliths). The marker (13.6 centimeters long) is shown for scale. *C* (photograph locality 5 on the map), Large boulder of potassium-feldspar rich pegmatite. This rock was only observed as large float blocks; pegmatites were not observed crosscutting rocks of the Elk Hill Complex. These blocks may be remnants of the Pegmatite Belt of Taber (1913), which is present west of the Lakeside fault along the James River to the southwest (Spears, 2011). If so, those rocks must have been structurally above rocks of the Elk Hill Complex and have now been almost completely eroded away. The hammer (approximately 38 centimeters long) is shown for scale. Photographs by Mark Carter, U.S. Geological Survey.

Metasedimentary, Metavolcanic, and Meta-Igneous Rocks of the Chopawamsic Terrane

The Chopawamsic Formation is the major rock unit that composes the Chopawamsic terrane in the Piedmont Province of central Virginia (fig. 1). The Chopawamsic Formation is a lithologically heterogeneous assemblage of metasedimentary, metavolcaniclastic, metavolcanic, and hypabyssal meta-igneous rocks that are interpreted to be a volcanic island arc complex outboard of the Laurentian continental margin (Pavlides, 1981). On the Buckner 7.5-minute quadrangle, mafic rocks—mostly layered amphibolite (map unit Ocm; fig. 4*A*)—are the most common rock type of the Chopawamsic Formation. To the north, Pavlides (1980) assigned similar and abundant amphibolitic gneiss, along with biotite gneiss and schist east of the Quantico synclinorium, to the Ta River Metamorphic Suite. Pavlides and others (1994) cited a Cambrian age for the Ta River Metamorphic Suite, but noted its equivalence to the younger Ordovician Chopawamsic Formation west of the Quantico synclinorium. Coler and others (2000) confirmed a correlation between the Chopawamsic Formation west of the Quantico synclinorium and the Ta River Metamorphic Suite east of the structure with a thermal ionization mass spectrometry (TIMS) U-Pb zircon crystallization age of about 470 Ma from metabasalt of the Ta River Metamorphic Suite (although their sample came from the western belt of the Chopawamsic Formation). Map-scale bodies of altered ultramafic rocks (map unit Ocum) are also associated with layered amphibolite (map unit Ocm) on the Buckner 7.5-minute quadrangle.

Kyanite-muscovite-quartz schist (fig. 4*B*), quartzite, and felsic gneiss (which are grouped in map unit Ocf) are important rock types within the Chopawamsic Formation. Schist and quartzite on the Buckner 7.5-minute quadrangle may be sedimentary in origin, but kyanite quartzite and ferruginous quartzite elsewhere within the Chopawamsic Formation (outside of the Buckner quadrangle) have been interpreted to be metamorphosed hydrothermal deposits (Owens and Pasek, 2007; Owens and Peters, 2018). TIMS and SHRIMP-RG U-Pb zircon crystallization ages of about 460 to 474 Ma from volcanogenic felsic gneiss (Coler and others, 2000; Hughes and others, 2013; Carter and others, 2020) constrain the precise age of the formation and the volcanic island arc that defines the terrane infrastructure; however, a SHRIMP-RG U-Pb age of about 453 Ma reported by Horton and others (2010) from the Chopawamsic Formation in northern Virginia indicates that volcanism associated with the arc occurred well into the Late Ordovician.

Figure 4. Photographs of rocks of the Chopawamsic Formation. *A* (photograph locality 6 on the map), Thinly layered amphibolite (map unit Ocm) consisting of amphibole, biotite, plagioclase, and quartz ± garnet. Layering (marked by a short-dashed black line) consists of amphibole ± plagioclase and quartz layers alternating with mica-rich layers. The head of a hammer (17 centimeters wide) is shown for scale. *B* (photograph locality 7 on the map), Kyanite-muscovite-quartz schist containing porphyroblasts of kyanite (ky). This rock (part of map unit Ocf) may be a metamorphosed aluminous sediment, or a hydrothermally altered and metamorphosed volcanic rock as interpreted by Owens and Pasek (2007) and Owens and Peters (2018). The partial head of a hammer (approximately 4 centimeters wide) is shown for scale. *C* (photograph locality 8 on the map), Compositionally layered and foliated biotite gneiss (map unit Oci) consisting of quartz, feldspar, biotite, muscovite ± hornblende, and garnet. Layering consists of alternating quartzofeldspathic and mica-rich layers. This rock may be a metasedimentary paragneiss or a metamorphosed volcanic rock of intermediate composition. The hammer (approximately 38 centimeters long) is shown for scale. Photographs by Mark Carter, U.S. Geological Survey.

The older crystallization ages are consistent with detrital zircon ages of about 460 to 470 Ma from interlayered volcaniclastic and metasedimentary rocks (Hughes and others, 2014), indicating significant recycling of syndepositional volcanics as Hughes and others (2014) suggested. Biotite gneiss (map unit Oci; fig. 4*C*) may be sedimentary in origin (although evidence for volcaniclastic deposition is lacking) or the unit could represent metavolcanic rocks of intermediate (andesitic) composition.

At the top of the Chopawamsic Formation is a map-scale body of chlorite-garnet calc-silicate granofels (map unit Ocu), a unique rock type containing flattened nodules and lenses of garnet up to 3 centimeters in diameter. On the west-adjacent Pendleton 7.5-minute quadrangle (Spears and others, 2013), similar garnet-chlorite schist is mapped as lenticular sill-like bodies. Burton and others (2014, 2015a) speculate that these rocks may be a metamorphosed paleosol at the top of the Chopawamsic Formation that is present along the contact with rocks of the overlying Quantico Formation.

Meta-Igneous Intrusive Rocks

Igneous rocks intrusive into the Chopawamsic Formation in the Chopawamsic terrane (fig. 5) are map-scale sheet-like bodies of metamorphosed granodiorite (map unit SObg) and associated outcrop-scale dikes. These strongly foliated rocks (fig. 5*A*) are granodioritic, tonalitic, and trondhjemitic orthogneisses (fig. 6) that contain hornblende, biotite, and primary magmatic epidote (fig. 5*B*) and map-scale to outcrop-scale xenoliths of older rocks of the Chopawamsic Formation. On the north-adjacent Lake Anna West 7.5-minute quadrangle, Mixon and others (2000) interpreted these rocks to be equivalent to the Carboniferous Falmouth Intrusive Suite of Pavlides (1980) and equivalent to the Elk Creek pluton unit of Pavlides and others (1982). However, Carter and others (2020) reported SHRIMP-RG U-Pb zircon crystallization ages from two samples from the Buckner quadrangle that range from 442±6 Ma to 456±4 Ma. These data demonstrate that the rocks are not part of the Carboniferous Falmouth Intrusive Suite but are more closely associated in time to granodiorite of the Ellisville pluton (dated at about 437 to 444 Ma) that stitches the Ordovician Chopawamsic fault west of the Quantico synclinorium (Hughes and others, 2013). Carter and others (2019) renamed this unit granodiorite of Elk Creek.

Amphibolitic metadiorite and metagabbro (map unit Pzdg; fig. 5*C*) consists of metadiorite and metagabbro recrystallized to coarsely crystalline granoblastic amphibolite and exists as map-scale dike-like and sill-like bodies in the Chopawamsic terrane. These rocks are not precisely age constrained and relative crosscutting relations with other rocks of the terrane are not well constrained, as no map-scale dikes of this rock type were identified during mapping. Rocks of this unit are likely at least Ordovician in age and could be part of the volcanic arc infrastructure or the mafic component of bimodal Ordovician to Silurian plutonism.

Metasedimentary Rocks of the Quantico Synclinorium

The Quantico Formation (slate of Darton, 1894; Pavlides, 1980) is a narrow belt of metasedimentary and metavolcanic rocks that extends nearly 140 kilometers (km) from the Occoquan River (in Fairfax County, northern Virginia) to the James River (in Fluvanna County, central Virginia) and is present in the core of the Quantico synclinorium (fig. 1). Preserved faunal assemblages (Watson and Powell, 1911; Pavlides and others, 1980) and detrital zircons as young as about 390 Ma (Bailey and others, 2008) indicate that the Quantico Formation is a latest Ordovician and younger post-Taconic orogeny basin deposition (Pavlides, 1990; Hughes and others, 2015).

On the Buckner 7.5-minute quadrangle, garnet-mica schist (map unit DSqs) is the major rock type of the Quantico Formation, but lenses of quartzite (map unit Sq) that locally underlie schist are older and may be assigned to another unit (Carter and others, 2020). Geochronologic analysis of detrital zircon grains from an exposure of equivalent quartzite on the west-adjacent Pendleton 7.5-minute quadrangle yielded a maximum depositional age of 427±6 Ma (Carter and others, 2020). Carter and others (2020) also reported a SHRIMP-RG U-Pb zircon crystallization age of 448±2.2 Ma for felsic gneiss (interpreted as a metavolcanic rock) near the base of the Quantico Formation on the west-adjacent Pendleton 7.5-minute quadrangle. This age is statistically compatible with a U-Pb SHRIMP-RG zircon crystallization age of about 448 Ma from felsic tuff (Horton and others, 2010) in northern Virginia, which is also interpreted to be interlayered at the base of the Quantico Formation. On the northwest- and north-adjacent Mineral and Lake Anna 7.5-minute quadrangles, however, Carter and others (2019) assigned quartzite with graphitic schist, felsic schist, and mafic rocks (greenstone and amphibolite) to a variably thick but discontinuous Ordovician to Silurian unit of interlayered metasedimentary and metavolcanic rocks that exist unconformably between garnet-mica schist of the Quantico Formation and garnet-chlorite schist. Burton and others (2014, 2015a) interpreted garnet-chlorite schist to be a paleosol at the top of the Chopawamsic Formation (Spears and others, 2013). Only quartzite of this unit from Carter and others (2019) was identified on the Buckner 7.5-minute quadrangle. Evidence for an unconformity between garnet-mica schist and quartzite is discussed in Carter and others (2019).

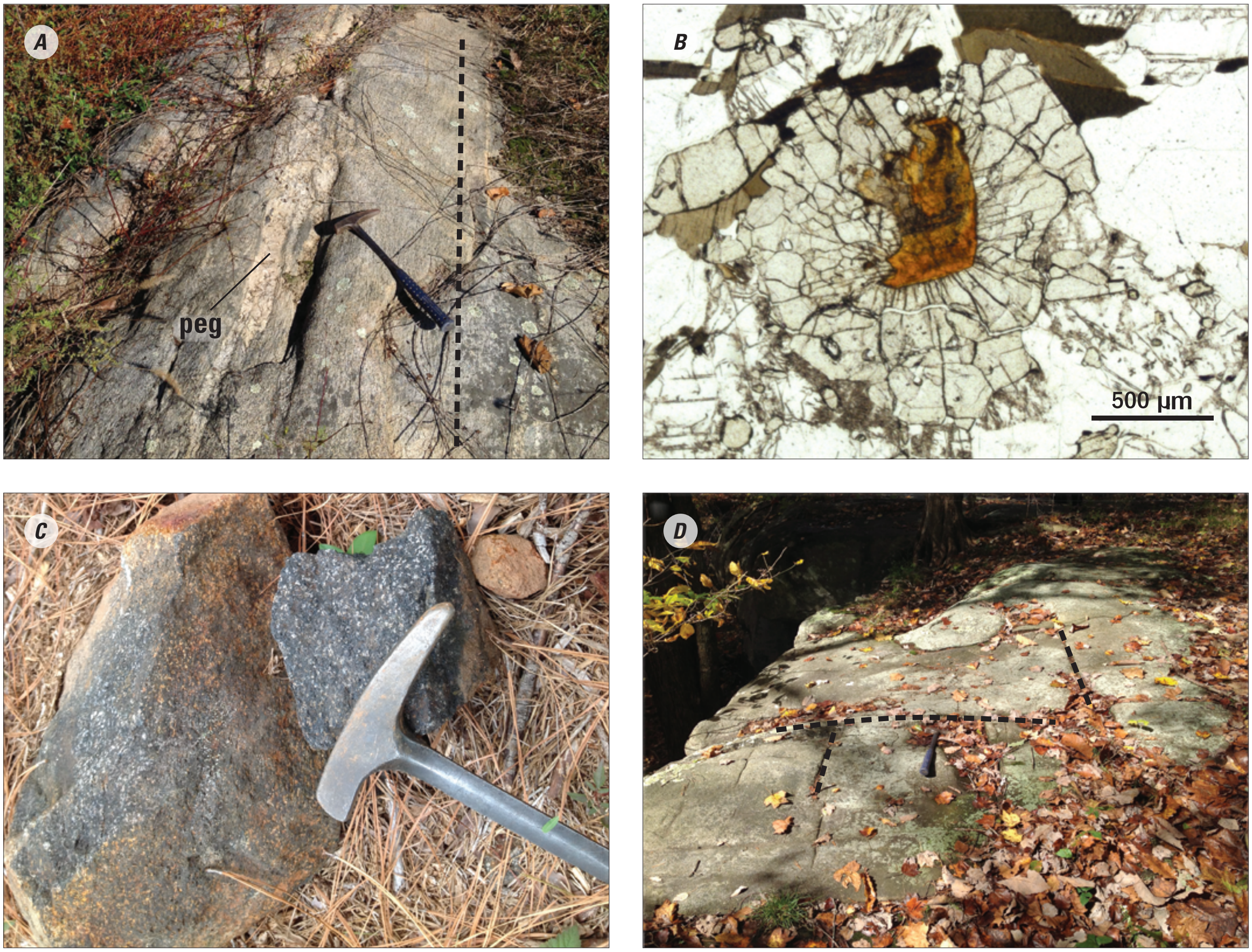


Figure 5. Photographs and photomicrograph of intrusive rocks of the Chopawamsic terrane. *A* (photograph locality 9 on the map), An outcrop of Ordovician to Silurian granodiorite of Elk Creek (map unit SObg). Note the strong foliation in this rock (marked by a dashed black line) and the pegmatite (peg) deformed within the foliation. The hammer (approximately 38 centimeters long) is shown for scale. *B* (photograph locality 10 on the map), Photomicrograph showing magmatic epidote in granodiorite of Elk Creek (dated at about 442 Ma [mega-annum]) in plane-polarized light at 500-micrometer (µm) scale. Hughes and others (2013) also noted magmatic epidote in nearby granodiorite of the Ellisville pluton (dated at about 444 Ma). *C* (photograph locality 11 on the map), Coarsely crystalline granoblastic amphibolite (map unit Pzdg) that is interpreted to be meta-igneous and consists of hornblende, plagioclase ± quartz, and garnet. Compare the texture of this amphibolite to layered amphibolite (map unit Ocm) in fig. 4*A*. The head of a hammer (17 centimeters wide) is shown for scale. *D* (photograph locality 12 on the map), Orthogonal joint sets (some marked by dashed black lines) in an outcrop of Ordovician to Silurian granodiorite of Elk Creek. The hammer (approximately 38 centimeters long) is shown for scale. Photographs by Mark Carter, U.S. Geological Survey.

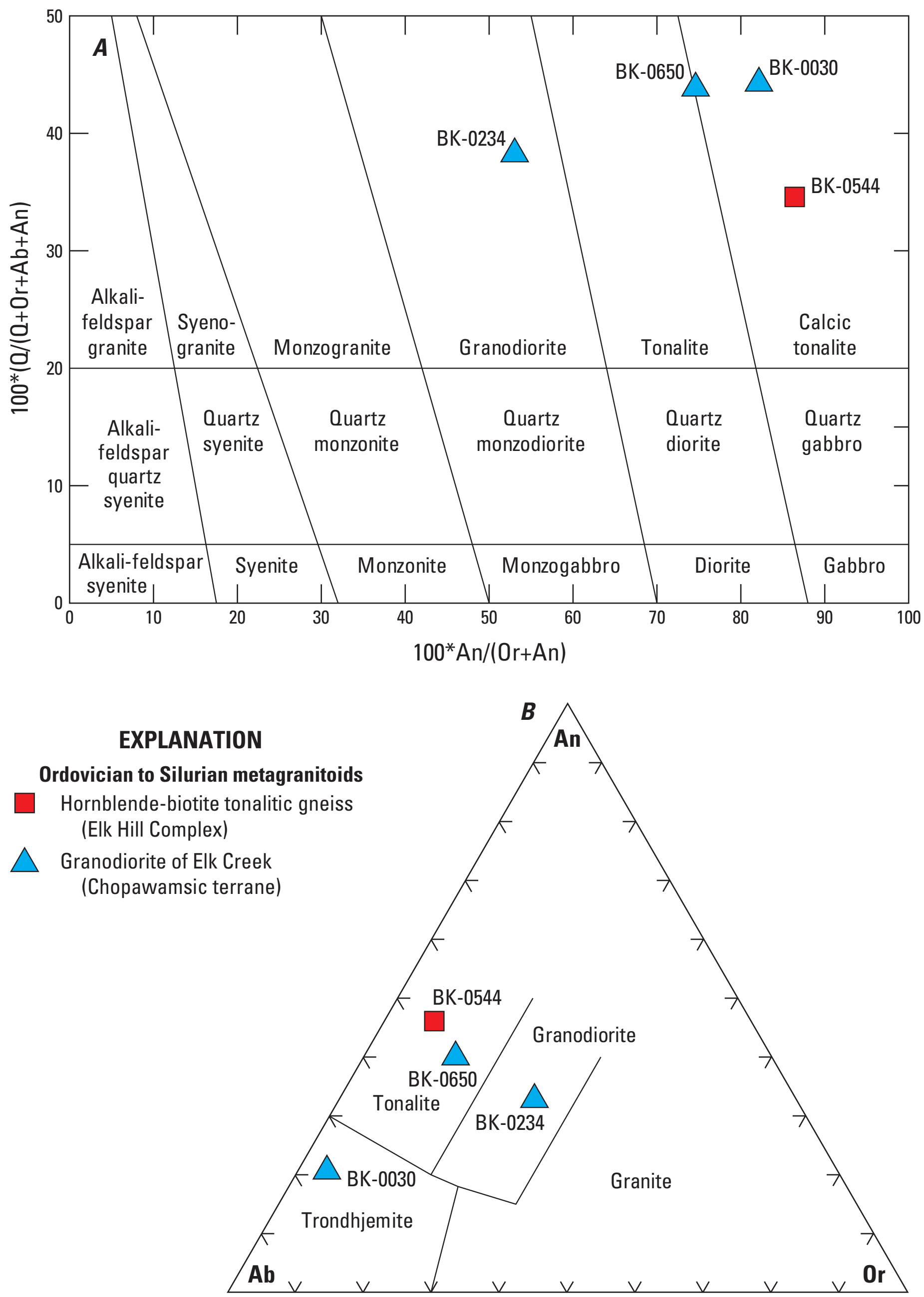


Figure 6. Geochemical rock classifications for granodiorite of Elk Creek (map unit SObg) in the Chopawamsic terrane and hornblende-biotite tonalitic gneiss (map unit Obtg) in the Elk Hill Complex depicted on a (*A*) classification diagram and (*B*) ternary diagram. Sample numbers correspond to those on the geologic map and those in the associated data releases (Powell and others, 2024; Weinmann and others, 2025). Mineral abundances were calculated as Cross, Iddings, Pirsson, and Washington (CIPW) norms from whole-rock chemical analyses. The diagrams were generated using Igpet for Windows. The open-access Igpet program was provided by Carr and Gazel (2017), and we used the version from January 12, 2020; for more information, see https://sites.google.com/site/tsigpetteaching/. The format of the classification diagram for part *A* is based on Whalen and Frost (2013) and the format of the ternary diagram for part *B* is based on Barker (1979). Abbreviations: Ab, albite; An, anorthite; Or, orthoclase; Q, quartz.

Rocks Associated with Faults, Veins, and Dikes

A narrow belt of phyllonite (map unit P̶zmy) marks the northernmost extent of the Lakeside fault, which was defined by Bourland (1976), Bourland and others (1979), and Brown (1986) south of the James River in Cumberland County, Va., approximately 45 km to the southwest. Muscovite from a slightly discordant but foliated pegmatite within the fault zone yielded an $^{40}Ar/^{39}Ar$ plateau age of about 294 Ma (fig. 7; Powell and others, 2024), indicating ductile deformation along the fault had ceased by earliest Permian time.

Quartz veins (map unit qtz) of variable thickness are present throughout the map area, but most are too small to accurately map at 1:24,000 scale. While the pegmatite dikes may be early to middle Paleozoic in age and related to emplacement of Ordovician to Devonian metagranitoids in the Chopawamsic terrane, Elk Hill Complex, and Goochland terrane, quartz veins are likely late Paleozoic in age.

Diabase (map unit Jd) is present as mostly southeast-northwest striking, nearly vertical dikes that intrude older rocks of the quadrangle. Dikes are most prevalent in the Maidens Gneiss and the Goochland terrane. Most dikes are up to about 10 meters thick and up to several hundred meters long, but one curved dike in the Maidens Gneiss is nearly 50 m wide and 6.3 km long. Some dikes are too small to accurately map at 1:24,000 scale. Aeromagnetic data show 80-m to 300-m wide linear magnetic anomaly highs (fig. 8) where the dikes are mapped, which is attributed to magnetite within the diabase dikes. In several areas, north- to northwest-trending anomalies with similar width and magnitude have been interpreted as dikes, although diabase was not observed at the surface. In areas with sparse outcrops, these aeromagnetic anomalies were used to delineate dikes on the map. In other areas, corresponding surface rocks were not observed, and the dikes may lie at shallow depths of up to several hundred meters beneath the surface (Shah and others, 2015). Diabase is early Jurassic in age (Kunk and others, 1992; Jourdan and others, 2009) and was emplaced throughout the Piedmont Province of Virginia during continental extension and the opening of the Atlantic Ocean in the Mesozoic Era (Manspeizer and others, 1989).

Terrace Deposits

Terrace deposits occupy five dominant elevations within the North Anna, Little, and South Anna River basins. Differences in elevation, clast roundness and composition, and matrix lithology define the map units. The two highest deposits (map units Nt_7 and QNt_6) are only mapped in the northwestern half of the quadrangle. These deposits are characterized by cobbles and boulders of iron- and manganese-cemented sand and angular quartz fragments, and (or) fluvially rounded pebbles and cobbles derived from that lithology, typically in a white to reddish-brown sandy matrix (fig. 9*A*, *B*). These two deposits, which are at least Pleistocene in age (Malenda, 2015) but may be as old as Miocene (Weems and Edwards, 2007), may be remnants of formerly extensive deposits of the Atlantic Coastal Plain that once covered the Piedmont Province in this area. Carter and others (2019) provided a thorough discussion of equivalent terrace deposits on the northwest- and north-adjacent Mineral and Lake Anna West 7.5-minute quadrangles. The three lower deposits (map units Qt_5, Qt_4, and Qt_3) are mapped separately on the northwestern half of the quadrangle but are undivided on the southeastern half (as Qtd). The lower terrace deposits are likely remnants of former positions of the Little River. These deposits consist of pebbles and cobbles of mostly vein quartz and rare quartzite in a clayey to sandy matrix (fig. 9*C*, *D*).

Alluvial Deposits

Quaternary alluvium consists mostly of fine-grained sediments (clay, silt, sand, and gravel) deposited in stream valleys. Alluvium thickness is variable but may be up to 6 m thick along most of the Little River system. In many tributary streams, alluvium deposits are much thinner, and some streams are floored by bedrock. In the northwestern half of the quadrangle, two distinct levels of alluvium (map units Qal_2 and Qal_1) were observed in the field and on the shaded relief imagery. The younger Qal_1 alluvial deposits are present on modern and well-defined floodplains; contacts between alluvium and bedrock valley walls are distinct. Older Qal_2 alluvial deposits along the margins of major streams are slightly topographically higher than younger Qal_1 alluvial deposits along the channelways. Younger Qal_1 alluvial deposits cut into the older Qal_2 alluvial deposits along an erosional scarp of a meter or more in height at the contact between the two units. The topographic surface of the older alluvial surfaces is hummocky, and contacts between alluvium and bedrock valley walls tend to be gently sloped and diffuse, indicating longer-term colluviation at the bedrock-alluvium interface. The presence of older Qal_2 alluvial deposits and subsequent stream incision and Qal_1 sediment deposition on the lower and modern floodplain indicate a regional drop in base level.

Artificial Fill and Colluvial-Alluvial Deposits

Holocene colluvial-alluvial material (map unit Hc) is present in distinct fan deposits that overlie modern floodplain alluvium at stream mouths. These fans are readily observed in the field and on shaded relief imagery and are interpreted to have been derived from extensive erosion of topsoil and saprolite since European settlement in the 1700s. Artificial fill (map unit af) is used locally for land modification and grading.

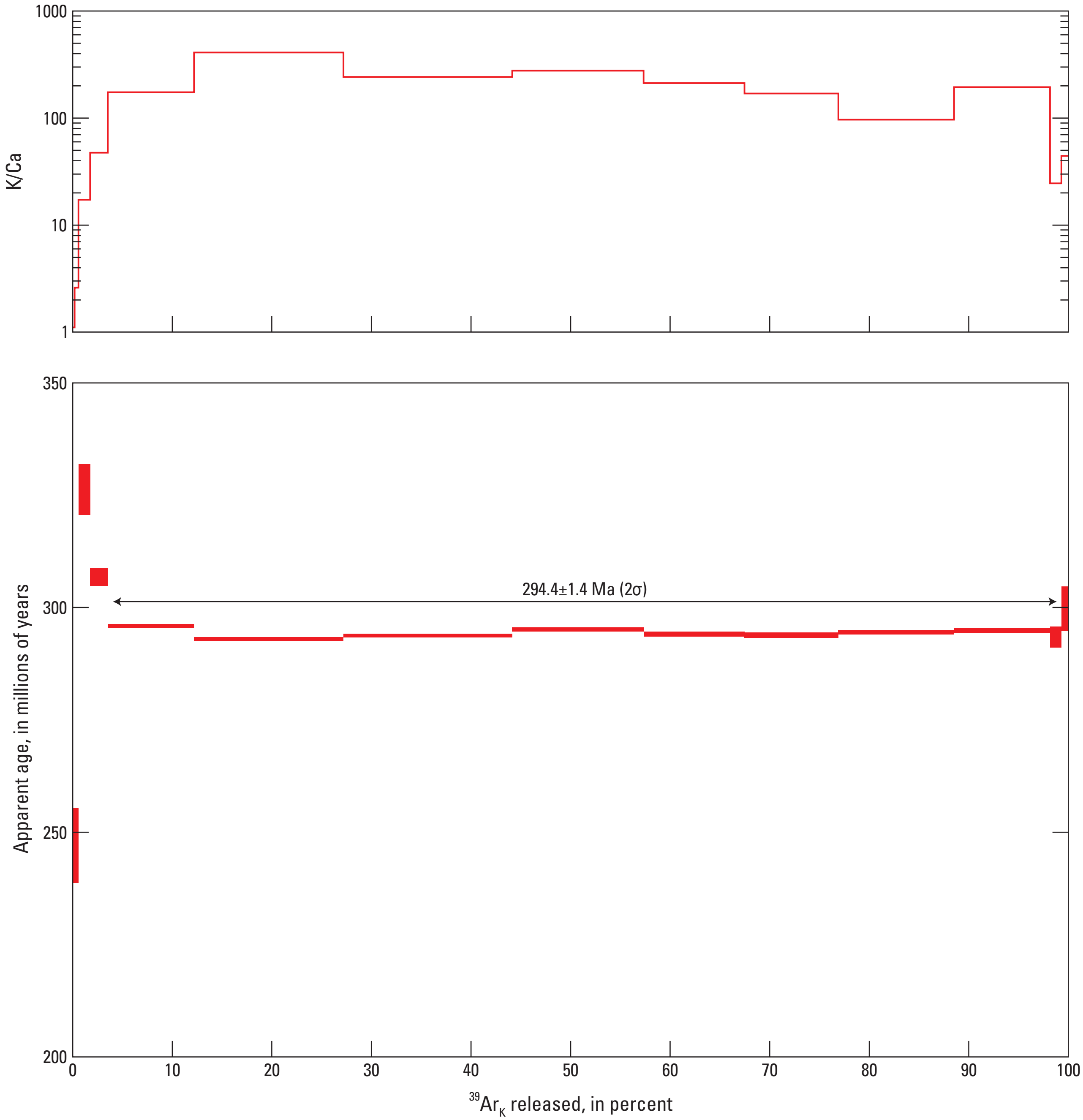


Figure 7. Plateau diagram showing a muscovite $^{40}Ar/^{39}Ar$ plateau age for a sample of foliated but slightly discordant pegmatite within biotite-muscovite phyllonite (map unit Pzmy) adjacent to the Lakeside fault (sample number BK-0556; see Powell and others [2024]). A single muscovite grain with mass of 0.768 milligrams was dated. Double headed arrows indicate the steps used in calculating the plateau age (294.4±1.4 Ma [2σ]). Abbreviations: σ, standard deviation; $^{39}Ar_K$, argon-39 (^{39}Ar) produced from reaction with potassium-39 (^{39}K) during irradiation; K/Ca, atomic ratio of potassium and calcium; Ma, mega-annum.

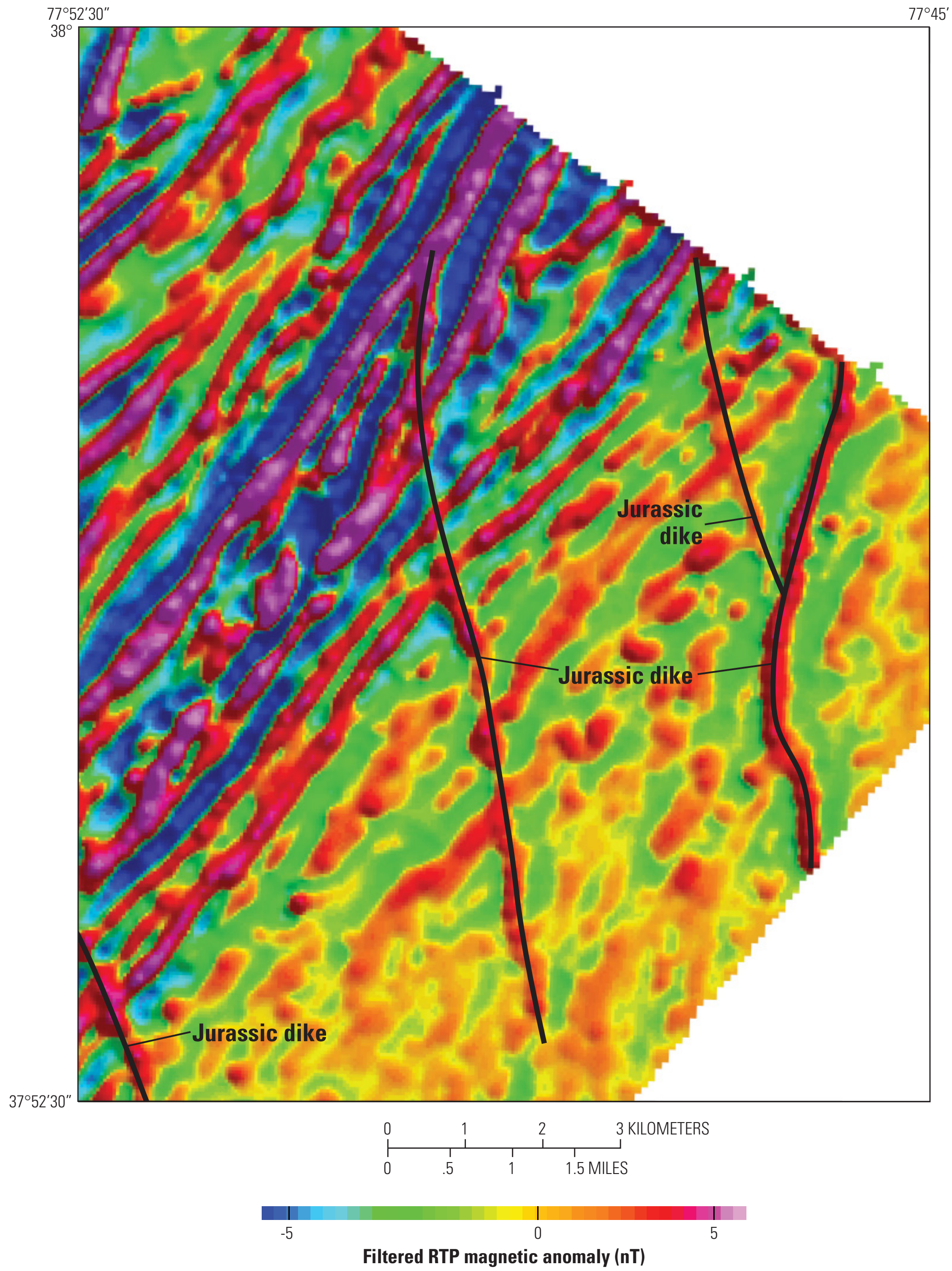


Figure 8. Filtered reduced-to-pole magnetic anomaly data map showing trends of multiple Jurassic diabase dikes (map unit Jd) for part of the Buckner 7.5-minute quadrangle. The dikes show as 80-meter- to 300-meter-wide linear magnetic anomaly highs, which are attributed to magnetite within the diabase. These data indicate that sparse outcrops at the surface are connected at shallow depths (up to several hundred meters) beneath the surface. Geophysical data are from Shah (2014) and Shah and others (2015). Abbreviations: nT, nanoteslas; RTP, reduced-to-pole.

Figure 9. Photographs showing characteristics of terrace gravels. *A* (photograph locality 13 on the map), A boulder of iron- and manganese-cemented ferricrete consisting of pebbles and cobbles of both angular vein quartz and subrounded quartzite clasts. This boulder is from the highest-level terrace deposits (Nt_7) and was found 450 feet above sea level in the west-central part of the Buckner 7.5-minute quadrangle on the interfluve between the Little and South Anna Rivers. Carter and others (2019) suggested that these ferricrete boulders may be the remnants of Neogene laterites of the Coastal Plain Province of Virginia. The exposed portion of a shovel handle (approximately 38 centimeters long) is shown for scale. *B* (photograph locality 14 on the map), Gravel of unit QNt_6 at 370 feet above sea level in the headwaters of North Fork Little River in the northwestern part of the quadrangle. Note the matrix of iron-stained quartz sand in this deposit. The head of a hammer (17 centimeters wide) is shown for scale. *C* (photograph locality 15 on the map), Gravel of unit Qt_5 at 350 feet above sea level west of Bearden Pond in the north-central part of the quadrangle. Note the yellowish-brown matrix of quartz sand in this deposit. The head of a hammer (17 centimeters wide) is shown for scale. *D* (photograph locality 16 on the map), Gravel of unit Qtd at 330 feet above sea level west of Hawkins Creek in the south-central part of the quadrangle. Gravel is a mixture of relatively fine, angular, locally derived vein quartz and larger, rounded, quartz sandstone cobbles likely remobilized from an older deposit. The head of a hammer (18 centimeters wide) is shown for scale. Photographs *A*, *B*, and *C* by Mark Carter, U.S. Geological Survey; photograph *D* by David Spears, Virginia Department of Energy (Geology and Mineral Resources Program).

Structure

Foliations

All metamorphic and igneous rocks of the Buckner 7.5-minute quadrangle that are older than Mesozoic are foliated, and some rocks preserve multiple foliations. Orientations of these structures are generally consistent across the quadrangle (fig. 10*A–H*). In rocks of the Chopawamsic Formation and Elk Hill Complex, S_0 compositional layering and S_1 penetrative foliation are coplanar and generally strike northeast to southwest and dip steeply to the northwest or southeast (fig. 10*A*, *B*); most variation occurs in the Maidens Gneiss where S_0 compositional layering (fig. 11*A*, *B*) roughly defines a northeast-plunging fold with axial-planar S_1 foliation (fig. 10*C*). In rocks west of the Spotsylvania fault, S_1 penetrative foliation is the dominant foliation in Ordovician to Silurian granodiorite of Elk Creek (map unit SObg; figs. 10*D*, 11*C*, 11*D*) and in Ordovician hornblende-biotite tonalitic gneiss (map unit Obtg; fig. 11*E*). Foliation preserved in amphibolite xenoliths within hornblende-biotite tonalitic gneiss (fig. 3*B*) must be older than about 452 Ma. Foliation in Silurian to Devonian garnet-mica schist (map unit DSqs) of the Quantico Formation is coplanar and concordant with S_1 foliation in adjacent rocks of the Ordovician Chopawamsic Formation and with granodiorite of Elk Creek; these relations indicate widespread penetrative foliation formation during late Paleozoic Alleghanian deformation. Note that S_0 compositional layering and S_1 penetrative foliation may not be equivalent across the Spotsylvania fault.

Most pegmatite dikes and quartz veins are oriented parallel to S_1 penetrative foliation in host rocks of the Chopawamsic Formation, Elk Hill Complex, Maidens Gneiss, and Ordovician to Silurian granodiorite of Elk Creek, but some are discordant and crosscutting (compare figures 10*A–D* and 12*A–D*). Quartz veins tend to crosscut the regional northeast to southwest grain in the Maidens Gneiss (compare figures 10*C* and 12*C*). Quartz veins are ubiquitous in most outcrops of mica schist of the Quantico Formation and are mostly parallel to foliation and the axial plane of the Quantico synclinorium, which formed by compression during the late Paleozoic Alleghanian orogeny.

S_2 high-strain (mylonitic) foliation overprints S_0 and S_1 foliations in all rocks, generally strikes northeast to southwest, dips steeply to the northwest and southeast, and increases in intensity from west to east across the quadrangle (fig. 10*E–H*). S_2 mylonitic overprint is sparse in rocks of the Chopawamsic Formation and in Ordovician to Silurian granodiorite of Elk Creek. In the Elk Hill Complex, S_2 foliation defines the Lakeside fault and overprints mica gneiss (map unit Zmg) and hornblende-biotite tonalitic gneiss away from the fault. S_2 mylonitic foliation is best developed in the Maidens Gneiss and defines the Spotsylvania high-strain zone that extends from the Spotsylvania fault to the southeastern corner of the quadrangle.

Folds

Outcrop-scale folds are common in all rocks of the quadrangle. In rocks of the Chopawamsic Formation, these folds deform S_0 compositional layering and S_1 penetrative phyllosilicate foliation with no axial planar secondary cleavage except very local crenulation cleavage in the most micaceous of rocks (fig. 13*A*). In Ordovician to Silurian granodiorite of Elk Creek (map unit SObg), several centimeter-thick quartz veins are tightly to isoclinally folded (fig. 13*B*) and S_1 foliation is axial planar. Mica gneiss of the Elk Hill Complex is polydeformed; isoclinal folds of S_0 compositional layering and S_1 foliation are refolded by tight to open folds (fig. 13*C*). Most of the shallow-plunging folds in the Chopawamsic Formation parallel the regional northeast to southwest trend of foliation, but some steeply plunging folds are oriented southeast to northwest (fig. 14*A*).

Regionally, these outcrop-scale folds generally mimic major map-scale folds of the Piedmont Province in central Virginia. Garnet-mica schist of the Quantico Formation forms the core of the Quantico synclinorium, which extends nearly 112 km from the Potomac River in northern Virginia to the James River in central Virginia (Mixon and others, 2000). Carter and others (2019) noted that the synclinorium must be the product of interference of multiple plunging fold axes to create a regional fold that trends for such a distance across the Piedmont Province in Virginia. Similarly, rocks of the Chopawamsic terrane east of the Quantico synclinorium are deformed into a broad, upright, northeast-plunging fold on the north-adjacent Lake Anna West 7.5-minute quadrangle, as first noted by Dames & Moore (1973); Carter and others (2019) termed this fold the Elk Creek antiform. On the Buckner 7.5-minute quadrangle, the limbs of the Elk Creek antiform are parallel and most outcrop-scale folds plunge gently to moderately northeast (figs. 10*A*, 14*A*). Carter and others (2019) interpret that the Quantico synclinorium and the Elk Creek antiform were constructed by rotation of minor folds within changing stress fields during dextral transpressional "zippering" along the Laurentian margin during Paleozoic amalgamation of Piedmont Province terranes (Hatcher, 2002). Rocks of the Goochland terrane and Maidens Gneiss comprise a northwest-verging, recumbent nappe (Glover and others, 1989) that Mixon and others (2000) termed the Matta nappe. On the Buckner quadrangle, outcrop-scale folds in the Maidens Gneiss either plunge very shallowly to the north or plunge steeply to the south (fig. 14*B*).

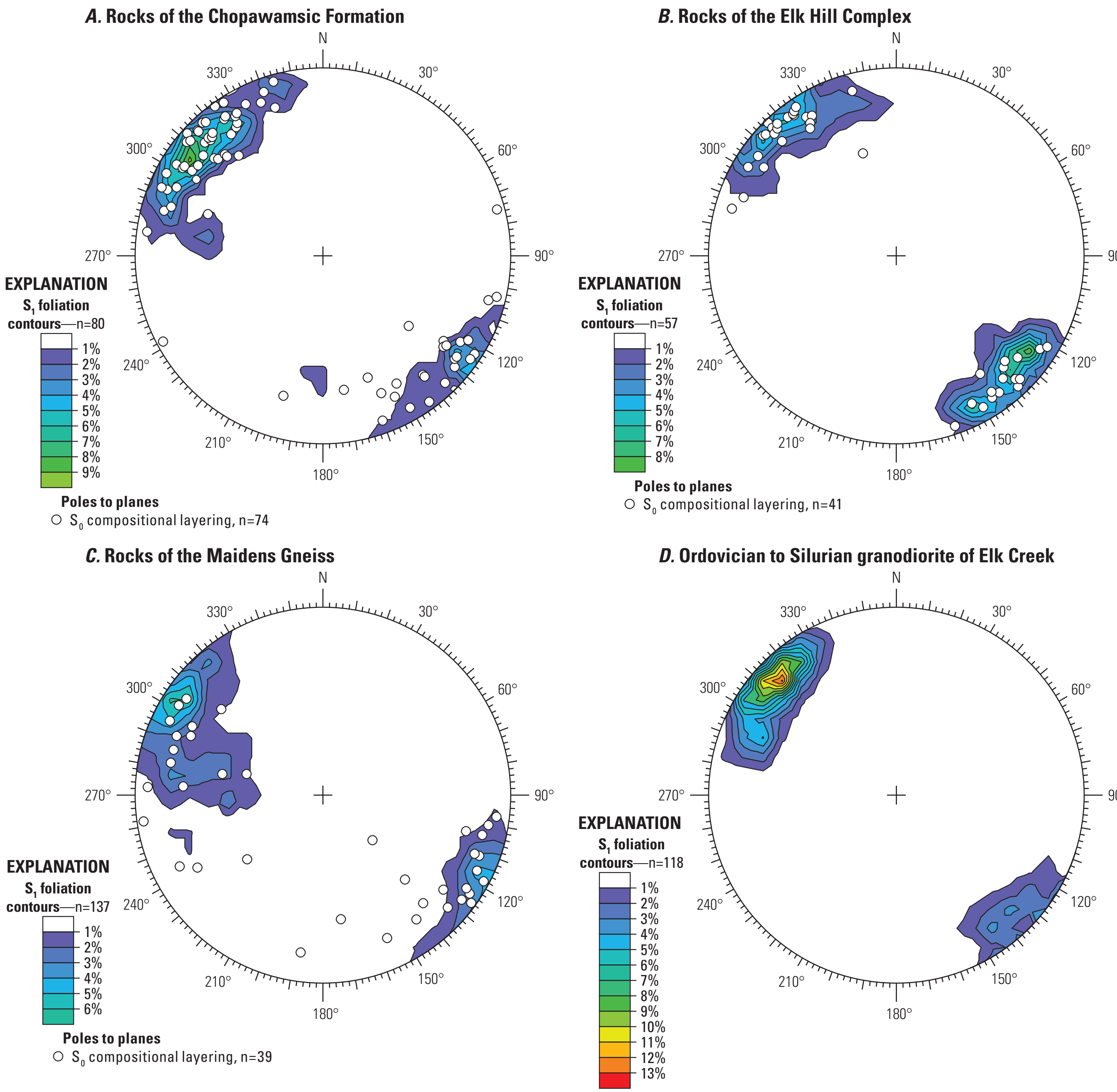
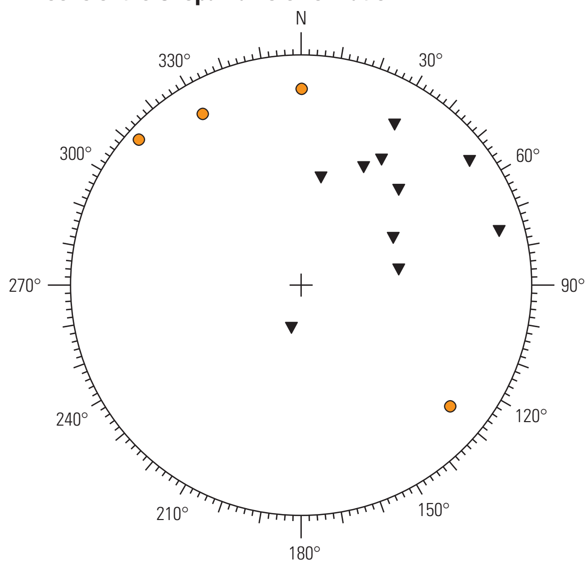


Figure 10. Lower-hemisphere equal-area stereograms that facilitated analysis of structural elements for rocks of the Chopawamsic Formation (map units Ocu, Ocf, Oci, Ocm, and Ocum), rocks of the Elk Hill Complex (map units Zmg, Za, Zf, and Obtg), rocks of the Maidens Gneiss (primarily map unit DYmm), and Ordovician to Silurian granodiorite of Elk Creek (map unit SObg). *A–D*, Comparison of orientations of S_0 compositional layering and S_1 penetrative foliation in the four rock categories. S_0 compositional layering and S_1 foliation are generally consistent across the quadrangle. S_1 penetrative foliation is coplanar to S_0 compositional layering in that both generally strike northeast to southwest and dip steeply to the northwest or southeast. Most variation occurs in rocks of the Maidens Gneiss (which compose most of the Goochland terrane on this quadrangle) where S_0 compositional layering roughly defines a northeast-plunging synform with axial-planar S_1 foliation. Note that S_0 and S_1 are likely not equivalent across the Spotsylvania fault. In each stereogram, S_1 penetrative foliation is contoured using the 2 percent per 1 percent area contouring method. *E–H*, Comparison of orientations of S_2 high-strain (mylonitic) foliation and mineral stretch lineations in the four rock categories. S_2 high-strain foliation increases in intensity from west to east across the quadrangle. S_2 foliation generally strikes northeast to southwest and dips steeply to the northwest and southeast. In rocks of the Maidens Gneiss, very shallow plunging lineations likely represent dextral transpressive deformation along the Spotsylvania fault. Stereograms were generated using Stereonet software (version 9.3.2) by Richard W. Allmendinger (Allmendinger and others, 2012; Cardozo and Allmendinger, 2013). Terms: %, percent; n, number of structural measurements.

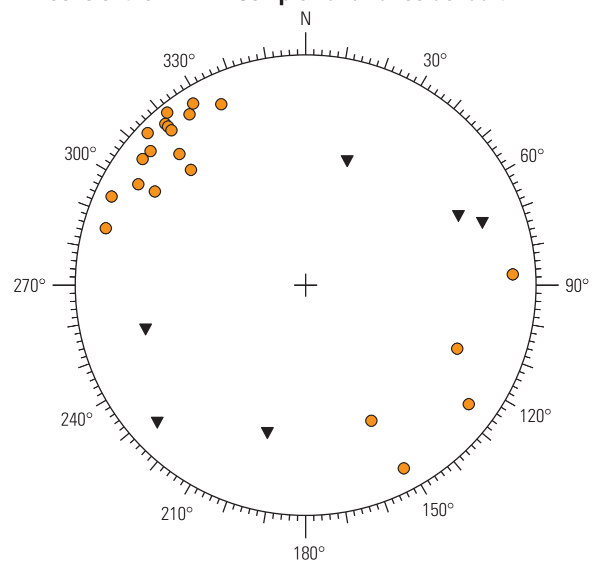
E. **Rocks of the Chopawamsic Formation**



EXPLANATION

- **S_2 high strain foliation poles to planes, n=4**
- **Mineral stretch lineations, n=10**

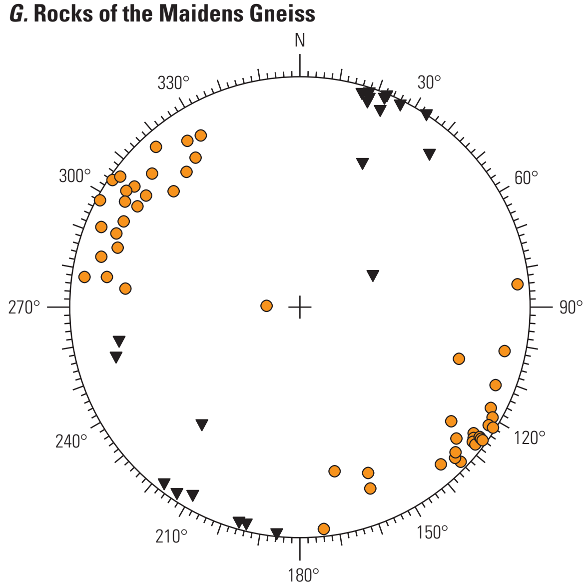
F. **Rocks of the Elk Hill Complex and Lakeside fault**



EXPLANATION

- **S_2 high strain foliation poles to planes, n=21**
- **Mineral stretch lineations, n=6**

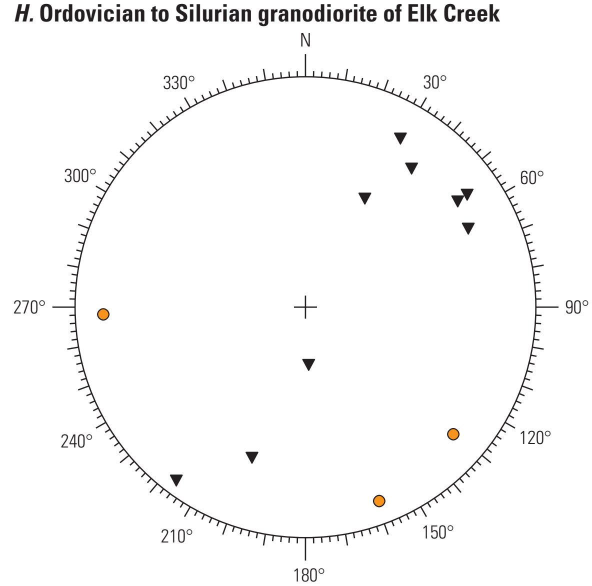
G. **Rocks of the Maidens Gneiss**



EXPLANATION

- **S_2 high strain foliation poles to planes, n=51**
- **Mineral stretch lineations, n=23**

H. **Ordovician to Silurian granodiorite of Elk Creek**



EXPLANATION

- **S_2 high strain foliation poles to planes, n=3**
- **Mineral stretch lineations, n=9**

Figure 10.—Continued

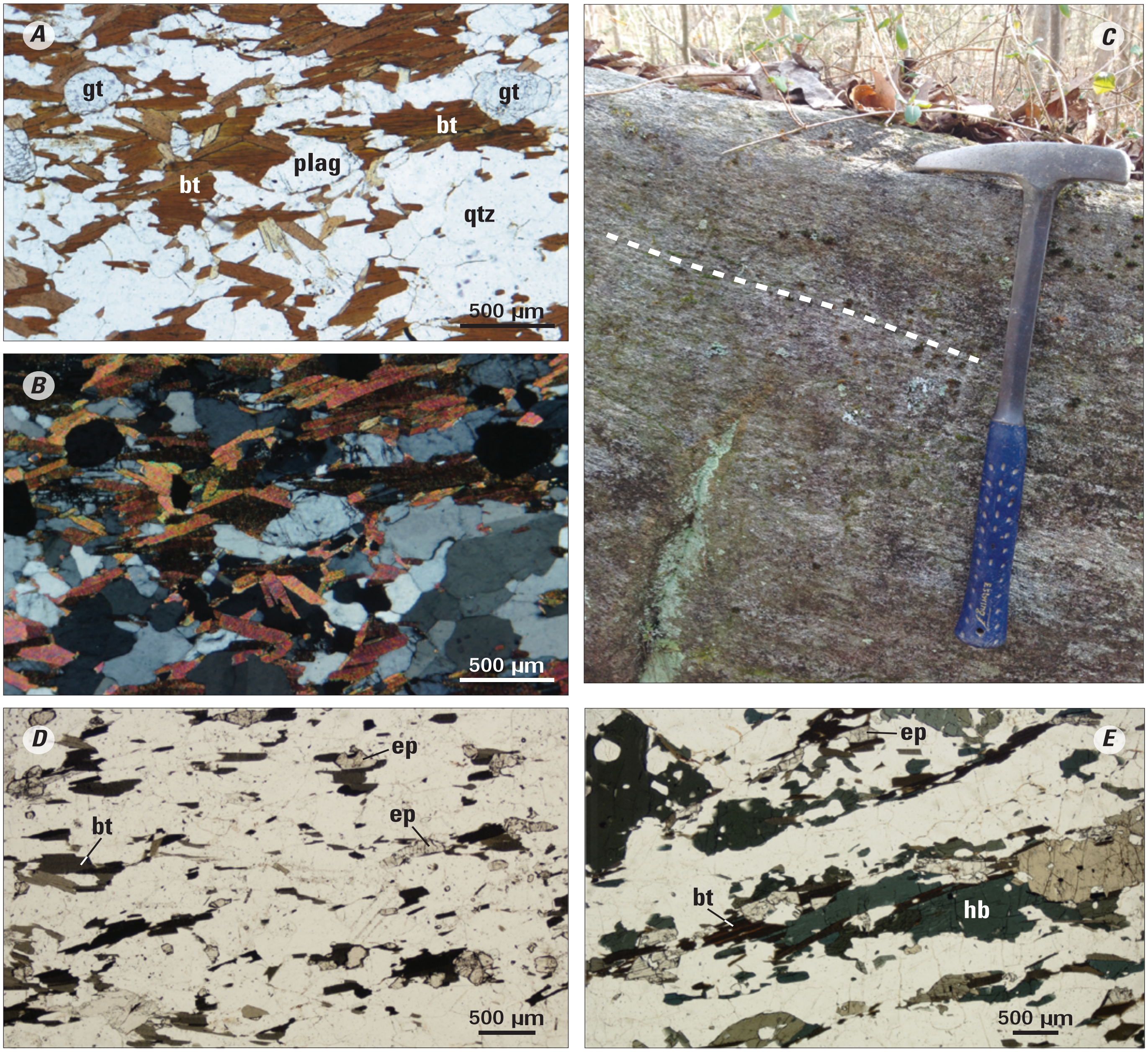


Figure 11. Photomicrographs and photograph showing foliation in rocks of the Goochland terrane, Elk Hill Complex, and Chopawamsic terrane. *A* (photograph locality 17 on the map), Gneissic character (compositional layering) defined by preferred orientation of biotite grains (bt) in biotite gneiss (map unit DYmm) of the Maidens Gneiss in the Goochland terrane. Other mineral constituents include porphyroblastic garnet (gt), quartz (qtz), and plagioclase feldspar (plag). Photomicrograph taken in plane-polarized light at 500-micrometer (µm) scale. *B*, Biotite gneiss of the Maidens Gneiss (same view as in part *A*) in cross-polarized light at 500-µm scale. *C* (photograph locality 18 on the map), Photograph showing foliation in intrusive granodiorite of Elk Creek (map unit SObg; dated at about 442 to 456 Ma [mega-annum]), marked by a dashed white line. The foliation is defined by the preferred orientation of hornblende, biotite, and epidote in these rocks, and must be younger than about 442 Ma (that is, it formed after the Ordovician Taconic orogeny). The hammer (approximately 38 centimeters long) is shown for scale. *D* (photograph locality 19 on the map), Photomicrograph of foliation in intrusive granodiorite of Elk Creek (dated at about 442 to 456 Ma) in the Chopawamsic terrane, defined in this sample by aligned biotite and metamorphic epidote (ep) grains. Photomicrograph taken in plane-polarized light at 500-µm scale. *E* (photograph locality 20 on the map), Foliation defined by aligned grains of hornblende (hb), biotite, and metamorphic epidote grains in hornblende-biotite tonalitic gneiss of the Elk Hill Complex (map unit Obtg; dated at about 452 Ma). Foliation in this rock must have also formed after the Ordovician Taconic orogeny, but discordant compositional layering preserved in amphibolite (map unit Za) xenoliths within this rock must be older than about 452 Ma. Photomicrograph taken in plane-polarized light at 500-µm scale. Photomicrographs *A* and *B* by Michael Smith, Virginia Department of Energy (Geology and Mineral Resources Program); photograph *C* and photomicrographs *D* and *E* by Mark Carter, U.S. Geological Survey.

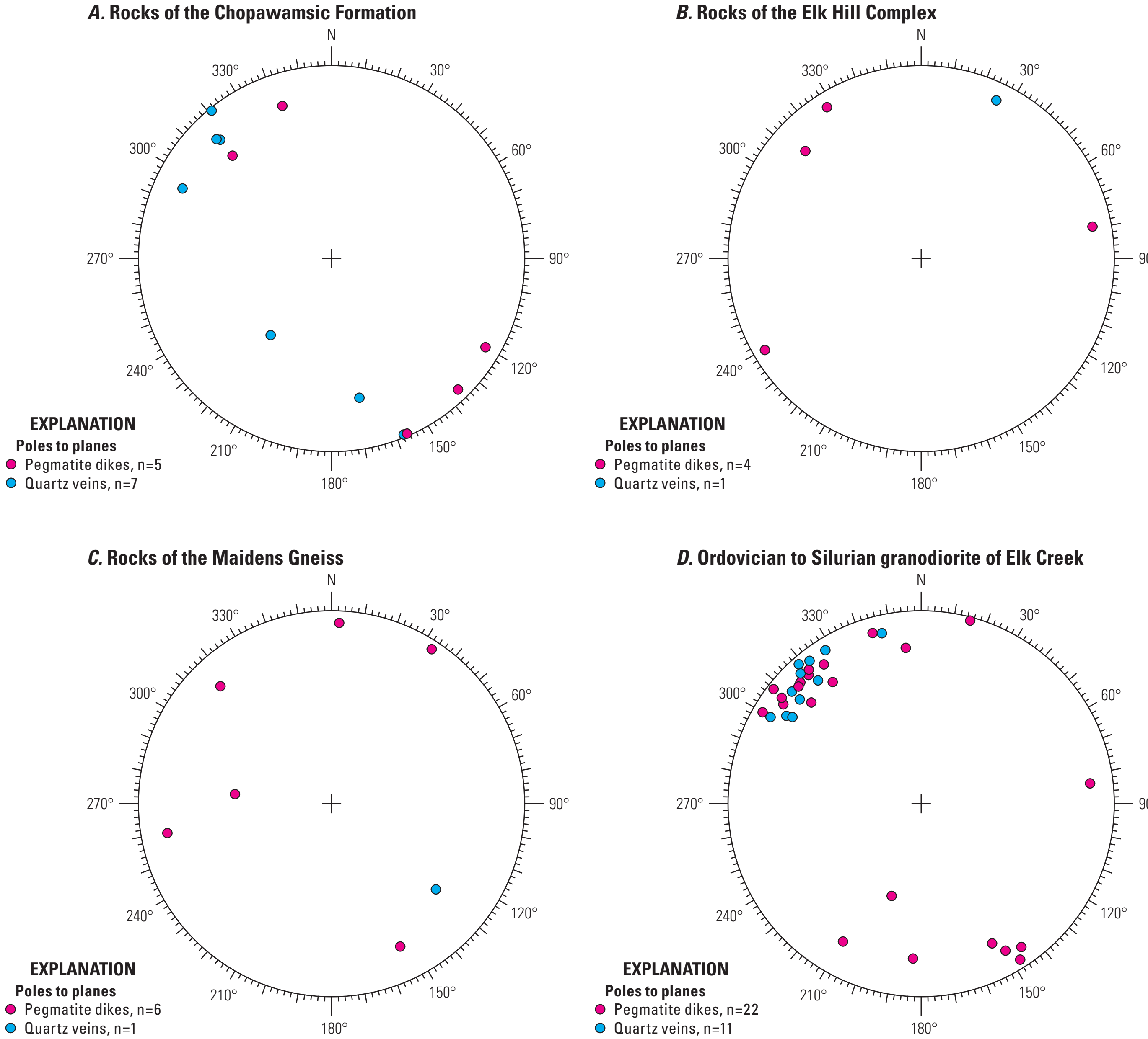


Figure 12. Lower-hemisphere equal-area stereograms comparing orientations of pegmatitic dikes and quartz veins for (*A*) rocks of the Chopawamsic Formation (map units Ocu, Ocf, Oci, Ocm, and Ocum), (*B*) rocks of the Elk Hill Complex (map units Zmg, Za, Zf, and Obtg), (*C*) rocks of the Maidens Gneiss (primarily map unit DYmm), and (*D*) Ordovician to Silurian granodiorite of Elk Creek (map unit SObg). Pegmatite dikes generally parallel compositional layering and foliations across the Buckner 7.5-minute quadrangle; quartz veins tend to crosscut the regional northeast to southwest grain. Stereograms were generated using Stereonet software (version 9.3.2) by Richard W. Allmendinger (Allmendinger and others, 2012; Cardozo and Allmendinger, 2013). Terms: %, percent; n, number of structural measurements.

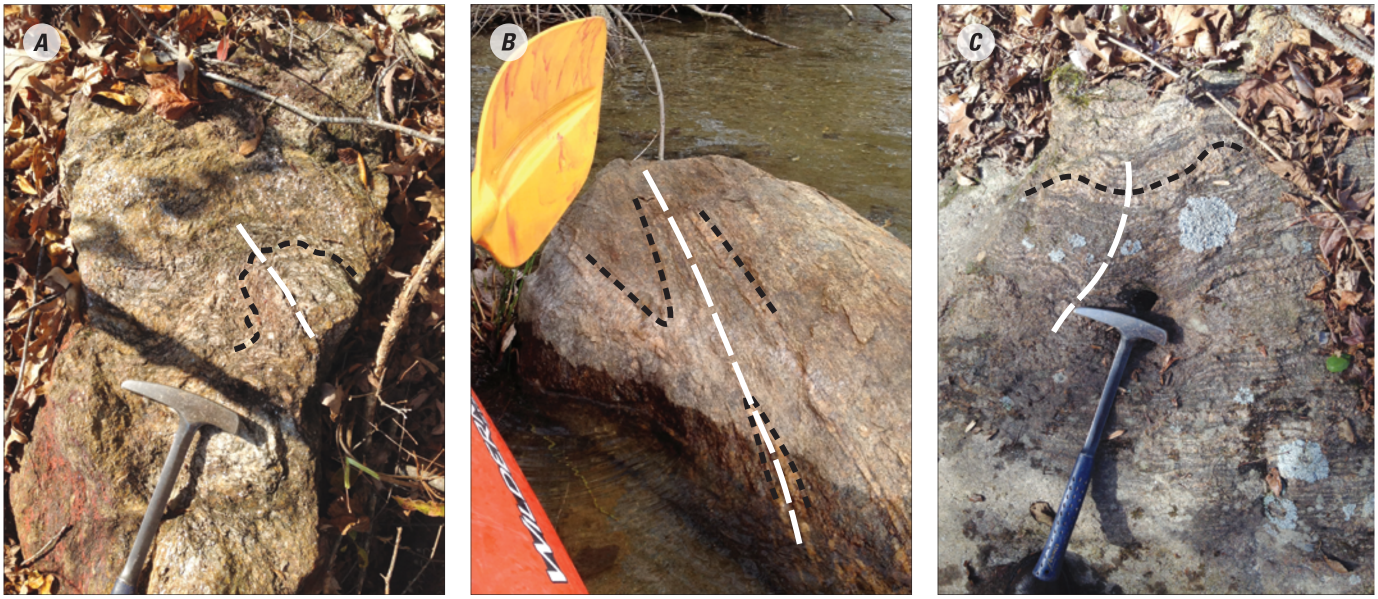


Figure 13. Photographs showing folds in rocks of the Chopawamsic terrane and Elk Hill Complex. *A* (photograph locality 21 on the map), Foliation (marked by a short-dashed black line) in kyanite-muscovite-quartz schist (part of map unit Ocf) of the Chopawamsic Formation is deformed into open folds. The muscovite-rich composition allowed for the formation of secondary axial planar crenulation cleavage (marked by a long-dashed white line). An $^{40}Ar/^{39}Ar$ muscovite plateau age of about 287 Ma (mega-annum) reflects cooling to less than 350 degrees Celsius by that time. The head of a hammer (17 centimeters wide) is shown for scale. *B* (photograph locality 22 on the map), Tight folds of quartz veins and pegmatite dikes in intrusive granodiorite of Elk Creek (map unit SObg; dated at about 442 to 456 Ma). Compositional layering (marked by short-dashed black lines) and the fold axis (marked by a long-dashed white line) are also shown. S_1 penetrative foliation in this rock is axial-planar to the folds, and both the folds and foliation must be younger than about 442 Ma. The kayak paddle head (approximately 40 centimeters long) is shown for scale. *C* (photograph locality 23 on the map), Polydeformed mica gneiss (map unit Zmg) of the Elk Hill Complex. Isoclinal folds of compositional layering (marked by a short-dashed black line) are refolded by gentle to open similar folds (one fold axis is marked by long-dashed white line). Sensitive High-Resolution Ion Microprobe with Reverse Geometry (SHRIMP-RG) analysis of detrital and metamorphic zircon from this Neoproterozoic rock shows metamorphic zircon growth (and likely concurrent with deformation) at about 439 Ma and during the Alleghanian orogeny from about 318 to 334 Ma. The hammer (approximately 38 centimeters long) is shown for scale. Photographs by Mark Carter, U.S. Geological Survey.

Faults

The Spotsylvania fault is a major tectonic boundary that separates the Goochland terrane (Farrar, 1984) to the southeast from the Chopawamsic terrane and Elk Hill Complex to the northwest (fig. 1). In the southeastern half of Buckner quadrangle, the Goochland terrane is composed almost entirely of the Maidens Gneiss (Poland, 1976). Here, the Maidens Gneiss is a garnetiferous, quartzofeldspathic two-mica gneiss with a strong mylonitic overprint (fig. 15*A*) with very shallow-plunging lineations. The mylonitic portion of the Maidens Gneiss has been termed the Spotsylvania high-strain zone, which records dextral transpression and tens to hundreds of kilometers of right-lateral offset (Bailey and others, 2004).

The Lakeside fault is a discrete zone of phyllonite that consistently shows dextral transpressive kinematics (fig. 15*B*). Mylonitic fabric overprints most of the rocks of the Elk Hill Complex away from the fault (fig. 15*C*). In the southwestern part of the quadrangle, the Lakeside fault is the boundary between the Elk Hill Complex and Chopawamsic terrane. Farther north where the Lakeside fault runs internal to the Elk Hill Complex, the boundary is the contact between mica gneiss (map unit Zmg) of the Elk Hill Complex and rocks of the Chopawamsic terrane. This contact is concordant and dips southeast for much of its length, with mica gneiss structurally above rocks of the Chopawamsic terrane. In the northeastern corner of the quadrangle, mica gneiss comprises the core of a reclined, west-vergent and north-plunging map-scale antiform (not depicted on the map); the Lakeside fault tips out in the core of the fold and the east limb of the fold is truncated by the Spotsylvania fault. These relations indicate that the contact between mica gneiss of the Elk Hill Complex and rocks of the Chopawamsic terrane is either an overturned unconformity, with mica gneiss underlying rocks of the Chopawamsic terrane, or a pre-metamorphic fault. Our preferred interpretation is that the contact is a pre-metamorphic fault, which implies that rocks of the Chopawamsic terrane were thrust over rocks of the Elk Hill Complex prior to amphibolite-facies metamorphism.

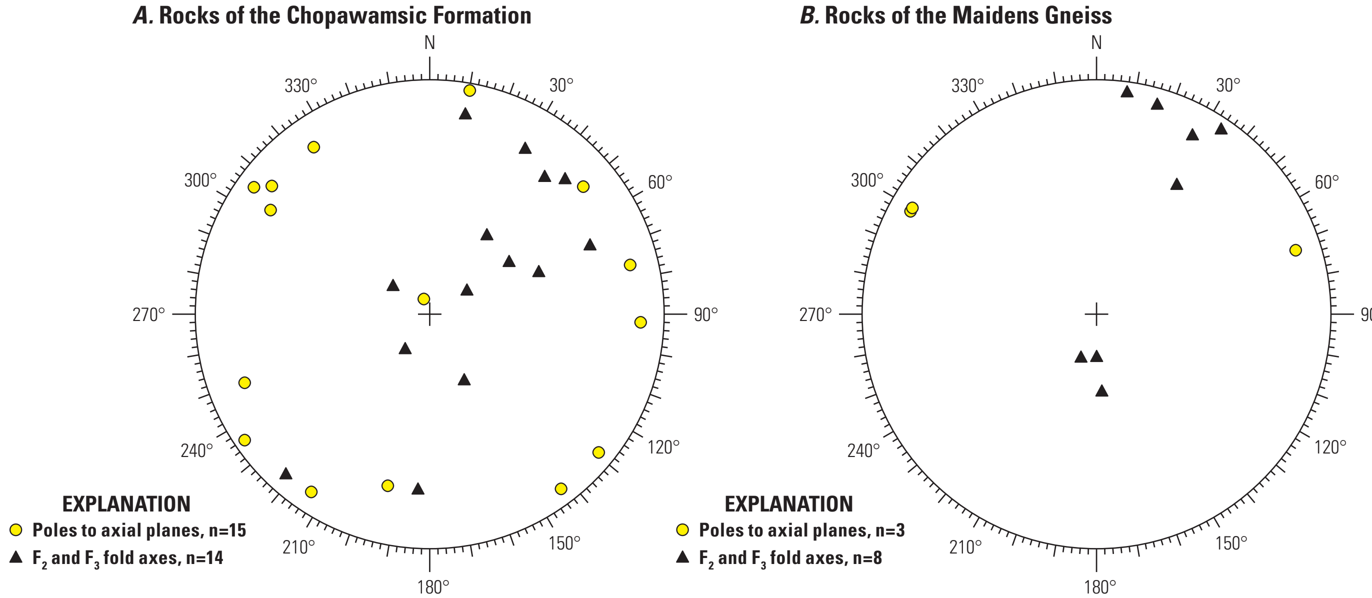


Figure 14. Lower-hemisphere equal-area stereograms comparing orientations of F_2 and F_3 fold axes and axial planes for (*A*) rocks of the Chopawamsic Formation (map units Ocu, Ocf, Oci, Ocm, and Ocum) and (*B*) rocks of the Maidens Gneiss (primarily map unit DYmm). F_2 folds deform S_0 compositional layering and S_1 penetrative foliation; F_3 folds deform F_2 fold hinges. Fold axes generally plunge shallow to steep to the northeast in the Chopawamsic terrane (rocks of the Chopawamsic Formation) and the Goochland terrane (Maidens Gneiss). Overprinting F_3 folds oriented north-northwest to south-southeast are most common in the Chopawamsic Formation of the Chopawamsic terrane. Note that there may not be a relation between F_2 folds and S_2 high-strain foliation. Stereograms were generated using Stereonet software (version 9.3.2) by Richard W. Allmendinger (Allmendinger and others, 2012; Cardozo and Allmendinger, 2013). Terms: %, percent; n, number of structural measurements.

A similar cryptic suture has recently been identified in the Goochland terrane, where rocks of the Maidens Gneiss form the hanging wall of a shallow thrust sheet that was emplaced over Mesoproterozoic rocks of the State Farm Gneiss and Montpelier Anorthosite after about 400 Ma but prior to amphibolite- to granulite-facies metamorphism related to the Acadian orogeny (Duke and others, 2019). North of the termination of the Elk Hill Complex in the northeastern part of the Buckner 7.5-minute quadrangle, the Spotsylvania fault is the boundary between the Goochland terrane and the Chopawamsic terrane, as it is in northern Virginia (Pavlides, 1980; Mixon and others, 2000).

Silicified cataclasite has not been found in the Buckner 7.5-minute quadrangle along the Lakeside fault (although it was reported along the fault trace to the southwest of the Buckner map area [Spears, 2011]) or along the Spotsylvania fault. However, outcrop-scale overprinting brittle faults with slickenlined manganese coatings or millimeter- to centimeter-thick clay seams that offset compositional layers and pegmatites are numerous in the best-exposed outcrop of phyllonite at Goodwin Lake (fig. 15*D*). The faults may be as old as Permian in age, as indicated by a nearby slightly discordant but foliated pegmatite that yielded an $^{40}Ar/^{39}Ar$ muscovite plateau age of about 294 Ma (fig. 7); this age demonstrates cooling to below about 350 degrees Celsius (°C) by that time. However, the brittle overprint could be much younger. All of these structures are in saprolite, but it is unclear if the rocks were deformed prior to or after saprolitization. Burton and others (2014, 2015a) provide evidence that similar brittle faults in the Piedmont Province in central Virginia are as young as Cenozoic. These faults on the Buckner quadrangle do not deform the A- or B-horizons of the soil profile; Carter (2015) also found no convincing proof of soil deformation along similar faults.

In the central part of the quadrangle, a northeast- to southwest-oriented brittle fault offsets the trace of the Spotsylvania fault and map units within the Maidens Gneiss. The precise ages of brittle faults in this region are unknown. Carter and others (2019) compiled evidence from many sources (for example, Dames & Moore, 1973; Bobyarchick, 2015; Burton and others, 2015a) to suggest that these faults may range from the Permian to the Cenozoic in age.

Figure 15. Photographs showing ductile and brittle faults in rocks of the Goochland terrane and Elk Hill Complex. *A* (photograph locality 24 on the map), Ductile-deformed porphyroclastic Maidens Gneiss (map unit DYmm) in the Spotsylvania high-strain zone. The view is to the southeast, looking down the plane of steeply dipping mylonitic foliation. In this outcrop, feldspar porphyroclasts (p) show no consistent asymmetry. The coin (2.5 centimeters in diameter) is shown for scale. *B* (photograph locality 25 on the map), Stair-step dextral shear bands (marked by the dashed white line) in biotite-muscovite phyllonite (map unit Pzmy) marking the Lakeside fault at Goodwin Lake. The head of a hammer (17 centimeters wide) is shown for scale. *C* (photograph locality 26 on the map), Dextral-sheared and stacked "books" of quartzofeldspathic layering (below the hammer) in mica gneiss (map unit Zmg) of the Elk Hill Complex. Also notice the asymmetric dextral isoclinal fold in layering above the hammer. The hammer (approximately 38 centimeters long) is shown for scale. *D* (also at photograph locality 25 on the map), Brittle faults (marked by dashed white lines) deform a saprolitized concordant pegmatite dike within biotite-muscovite phyllonite marking the Lakeside fault at Goodwin Lake. Brittle faults in the outcrop are defined by either slickenlined manganese (Mn) coatings or centimeter-thick seams of clay (cl). The brittle faults in this photograph are truncated by a manganese-coated fault that projects out of the outcrop, and the upper fault roots into (or is offset by) another fault marked by a clay seam. The faults may be as old as Permian but could be much younger. The marker at the bottom-center of the photograph (13.6 centimeters long) is shown for scale. Photograph *A* by David Spears, Virginia Department of Energy (Geology and Mineral Resources Program); photographs *B*, *C*, and *D* by Mark Carter, U.S. Geological Survey.

Seismogenic Faults in the Central Virginia Seismic Zone

The central Virginia seismic zone (Bollinger, 1969, 1973) is a region of intraplate seismicity located roughly between the cities of Fredericksburg, Farmville, Richmond, and Charlottesville. Prior to 2011, seismicity in the central Virginia seismic zone was characterized as diffuse (Stover and Coffman, 1993), with no correlation to faults exposed at the surface. The M5.8 earthquake that occurred near Mineral, Va., was among the largest to occur along the eastern seaboard in historic time; it was likely felt by more people than any other earthquake in U.S. history (nearly a third of the U.S. population; Horton and Williams, 2012) and caused widespread but light damage as far as Washington, D.C., and Baltimore, Maryland (Horton and Williams, 2012). Rapid deployment of portable seismographs by multiple institutions in the days and weeks following the earthquake produced the best-recorded aftershock sequence in the eastern U.S. (Carter and others, 2012). This sequence defines several active faults in the region, including the Fredericks Hall fault that is present on the Buckner 7.5-minute quadrangle (Horton and others, 2015) as well as the Quail fault (which is believed to be the causative fault for the M5.8 earthquake), the Cuckoo fault, and the Northwest fault (which are all on adjacent quadrangles).

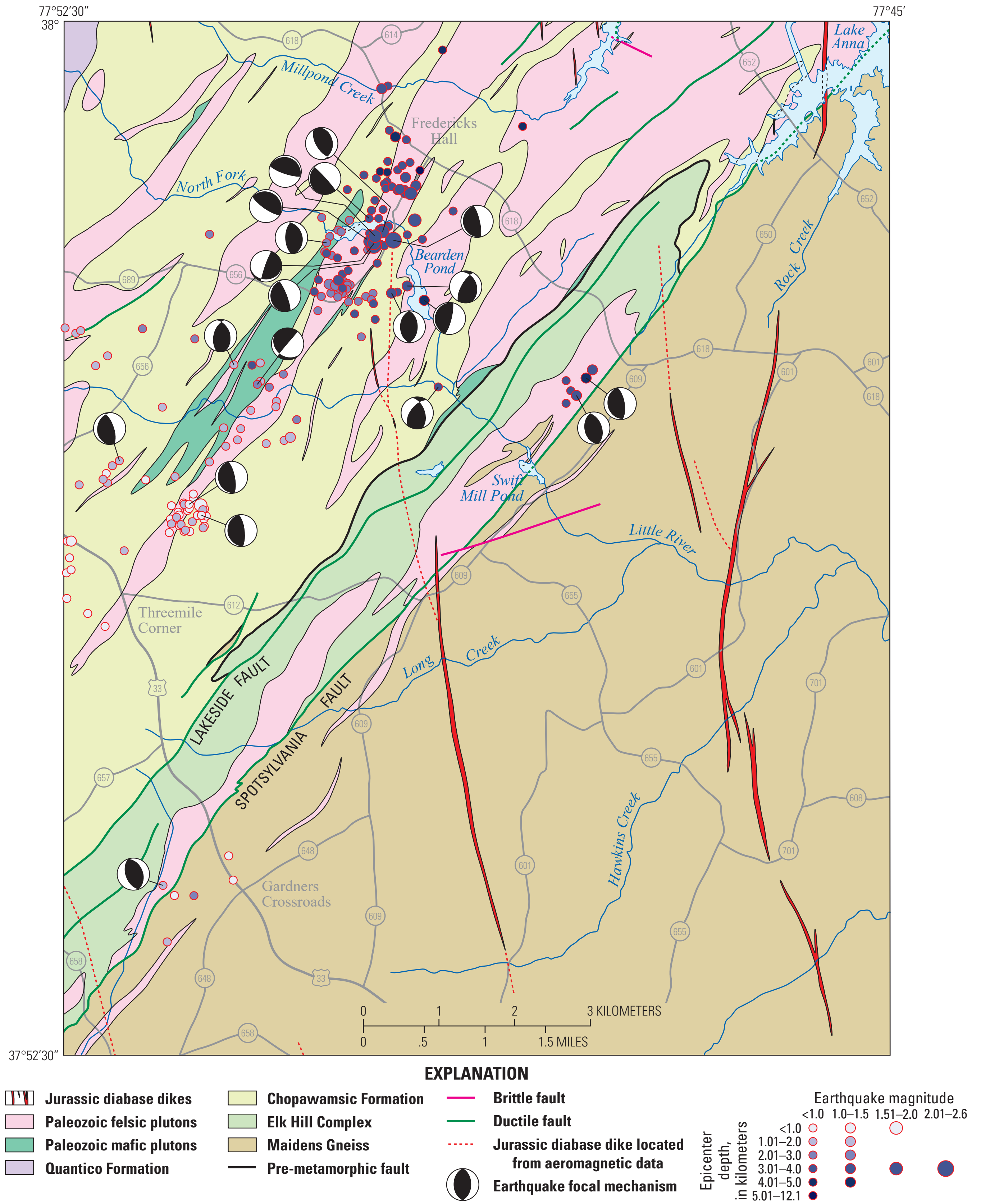
The Quail fault is a reverse fault with a strike of N. 28° E. and southeast dip of about 50° (Chapman, 2013, 2015) and is located on the south-adjoining Pendleton 7.5-minute quadrangle within rocks of the western belt of the Chopawamsic Formation (Spears and others, 2013). Aftershocks indicate its depth is between about 3 km and 8 km; no corresponding surface rupture was observed.

On the Buckner 7.5-minute quadrangle, a linear but diffuse cluster (about 6 km long and 2 km wide) of mostly shallow (less than 4.9 km) aftershocks defines the Fredericks Hall fault, which strikes N. 35° E. with a near vertical dip (Horton and others, 2015) within rocks of the eastern belt of the Chopawamsic terrane (fig. 16). Many aftershocks are concentrated north and west of Bearden Pond and southwest of Fredericks Hall. These aftershocks are also deeper and stronger than others on the quadrangle. There are also distinct groups of aftershocks northeast of Swift Mill Pond and northeast of Threemile Corner, as well as a few scattered aftershocks west of Gardners Crossroads. Most focal mechanisms for earthquakes on the Buckner quadrangle are north-northwest to south-southeast oriented reverse faults (Wu and others, 2015). A few aftershocks near Bearden Pond are located near a Jurassic dike that is associated with a narrow, north- to northwest-trending magnetic anomaly high (fig. 8). There is no apparent relation between the aftershocks in the main cluster and a fault mapped at the surface, but the outlier northeast of Swift Mill Pond and west of Gardners Crossroads may be related to the Lakeside or Spotsylvania faults at depth. The cluster that defines the Fredericks Hall fault occupies a sheet intrusion of granodiorite of Elk Creek. Continued research by the USGS and its partners is focused on determining the influence that pre-existing rock structures (such as foliations and joints) have on the location and slip orientation of aftershock fault ruptures within the regional stress field (Horton and others, 2016, 2017a, b).

Joints

Joint orientations vary across the quadrangle. In the Chopawamsic terrane (Chopawamsic Formation rocks and intrusive Ordovician to Silurian granodiorite of Elk Creek [map unit SObg]), the dominant joint set strikes to the northeast and dips to the southeast, and a secondary joint set strikes to the southeast and dips to the southwest (fig. 17*A*, *B*). Joint sets are nearly orthogonal in the intrusive Ordovician to Silurian granodiorite of Elk Creek (figs. 5*D*, 17*B*). In the Maidens Gneiss, the dominant joint set strikes to the northwest and dips to the northeast (fig. 17*C*). The two dominant joint sets in Elk Hill Complex rocks reflect the dominant sets in adjacent terranes (fig. 17*D*).

Figure 16 (facing page). Map of the Buckner 7.5-minute quadrangle showing general geology, structural features, and focal mechanisms and aftershock epicenters from the magnitude 5.8 earthquake that occurred near Mineral, Virginia, on August 23, 2011. These aftershock epicenters define the Fredericks Hall fault (at depth). Not all earthquakes or focal mechanisms are shown. Earthquake data are from McNamara and others (2014).


77°52'30"
38°
77°45'
37°52'30"
Lake Anna
Millpond Creek
Fredericks Hall
North Fork
Bearden Pond
Swift Mill Pond
Little River
Rock Creek
Threemile Corner
Long Creek
Hawkins Creek
Gardners Crossroads
LAKESIDE FAULT
SPOTSYLVANIA FAULT
618
614
652
650
689
656
609
601
612
33
657
648
658
655
701
608
0 1 2 3 KILOMETERS
0 .5 1 1.5 MILES
EXPLANATION
Jurassic diabase dikes
Paleozoic felsic plutons
Paleozoic mafic plutons
Quantico Formation
Chopawamsic Formation
Elk Hill Complex
Maidens Gneiss
Pre-metamorphic fault
Brittle fault
Ductile fault
Jurassic diabase dike located from aeromagnetic data
Earthquake focal mechanism
Earthquake magnitude
<1.0
1.0–1.5
1.51–2.0
2.01–2.6
Epicenter depth, in kilometers
<1.0
1.01–2.0
2.01–3.0
3.01–4.0
4.01–5.0
5.01–12.1

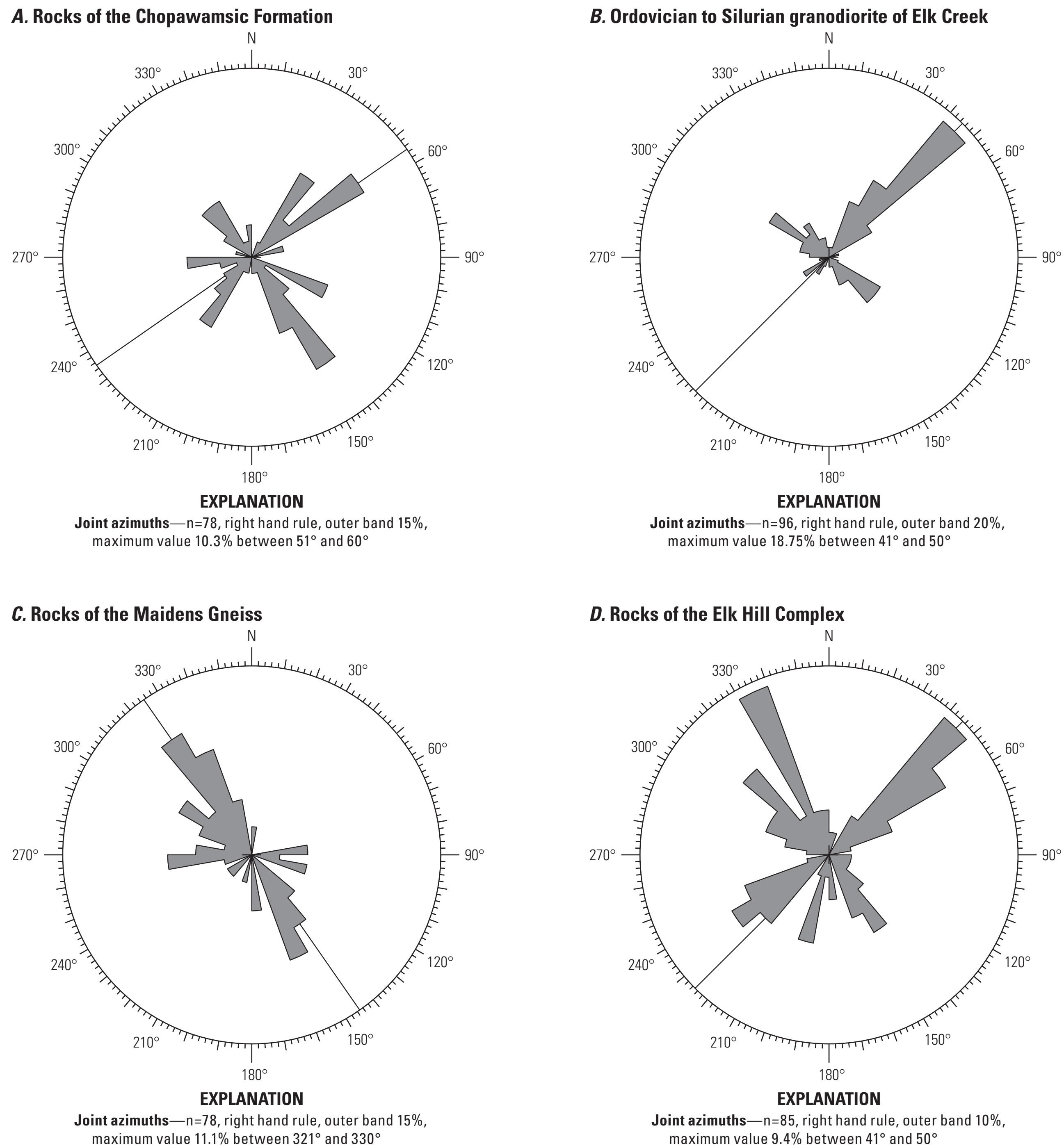


Figure 17. Directional rose diagrams of joints in (*A*) rocks of the Chopawamsic Formation (map units Ocu, Ocf, Oci, Ocm, and Ocum), (*B*) Ordovician to Silurian granodiorite of Elk Creek (map unit SObg), (*C*) rocks of the Maidens Gneiss (primarily map unit DYmm), and (*D*) rocks of the Elk Hill Complex (map units Zmg, Za, Zf, and Obtg). Joint orientations vary across the quadrangle. In the Chopawamsic terrane (rocks of the Chopawamsic Formation and intrusive Ordovician to Silurian granodiorite of Elk Creek), the dominant joint set strikes to the northeast and dips to the southeast, and a secondary joint set strikes to the southeast and dips to the southwest. In rocks of the Maidens Gneiss, the dominant joint set strikes to the northwest and dips to the northeast. The two dominant joint sets in rocks of the Elk Hill Complex reflect sets in adjacent terranes. Stereograms were generated using Stereonet software (version 9.3.2) by Richard W. Allmendinger (Allmendinger and others, 2012; Cardozo and Allmendinger, 2013). Terms: %, percent; n, number of structural measurements.

Metamorphism

Metamorphic grade increases from the west to east across the central Virginia Piedmont (Burton and others, 2015b). Except for Jurassic diabase dikes, all rocks on the Buckner 7.5-minute quadrangle were metamorphosed to amphibolite facies during the Alleghanian orogeny. These rocks increase in metamorphic grade from lower amphibolite facies (garnet to kyanite zone) in the Quantico Formation and Chopawamsic Formation in the west to upper amphibolite facies in the Goochland terrane and Maidens Gneiss in the east. Many rocks in the map area are not of the proper composition to preserve Barrovian metamorphic index minerals.

The age(s) of metamorphism are not fully known. $^{40}Ar/^{39}Ar$ geochronology of amphibole from the west-adjacent Pendleton 7.5-minute quadrangle (Burton and others, 2015b) indicates cooling through about 500 °C at about 300 to 310 Ma and a sample of muscovite from kyanite-muscovite-quartz schist of the Chopawamsic Formation on this quadrangle (fig. 4*B*) yielded an $^{40}Ar/^{39}Ar$ plateau age of about 287 Ma (fig. 18). Using the SHRIMP-RG method, Carter and others (2020) reported zircon rim ages of about 253 to 331 Ma from Ordovician to Silurian granodiorite of Elk Creek (map unit SObg; intrusive into rocks of the Chopawamsic Formation) and Ordovician hornblende-biotite tonalitic gneiss (map unit Obtg; intrusive into rocks of the Elk Hill Complex). Rims on elongate metamorphic zircons from mica gneiss of the Elk Hill Complex also yielded ages of about 318 to 334 Ma. These ages are broadly associated with the Alleghanian orogeny and demonstrate pervasive amphibolite-facies Alleghanian metamorphism in rocks west of the Spotsylvania fault. However, Carter and others (2020) also reported that the cores of elongate but metamorphic zircons from mica paragneiss yielded a mean age of 439.4±7.3 Ma, which indicated that metamorphism from the Taconic orogeny affected rocks of the Elk Hill Complex after intrusion of hornblende-biotite tonalitic gneiss (dated at about 452 Ma). Foliation preserved in xenoliths within hornblende-biotite tonalitic gneiss provides field evidence for Taconian deformation in these rocks. Taconian metamorphism in the Chopawamsic terrane to the west occurred at about 450 Ma and before intrusion of the Ellisville pluton (dated at about 444 Ma) that stitches the Chopawamsic fault, the major fault boundary that separates rocks of the Chopawamsic terrane from those of the Potomac terrane farther west (Hughes and others, 2013; Burton and others, 2015a, b; McAleer and others, 2017; Burton and others, 2019). These data provide circumstantial evidence that the concordant contact between mica gneiss and overlying rocks of the Chopawamsic Formation is a pre-metamorphic fault. Zircons from gneisses of the Ordovician Chopawamsic Formation analyzed by Carter and others (2020) using the SHRIMP-RG technique did not preserve Taconian metamorphic rims.

In rocks of the Goochland terrane and Maidens Gneiss east of the Spotsylvania fault, Farrar (1984) interpreted granulite-facies metamorphism in Mesoproterozoic State Farm Gneiss and overlying Maidens Gneiss to be associated with the Mesoproterozoic Grenville orogeny. However, Shirvell and others (2004) determined that the timing of granulite-facies metamorphism in these rocks was Devonian in age by using in-place electron microprobe Th-U-total Pb chemical dating of monazite. Pervasive overprinting amphibolite-facies metamorphism and deformation is demonstrably related to the Alleghanian orogeny (Burton and others, 2000; Shirvell and others, 2004).

These data indicate that the Chopawamsic terrane was not affected by widespread Taconian amphibolite-facies metamorphism during the formation of the Chopawamsic volcanic arc at about 460 to 474 Ma, or during the intrusive event 4 to 18 million years later. However, rocks of the Elk Hill Complex did experience Taconian amphibolite-facies metamorphism at about the same time that rocks in the western Piedmont Province and western portion of the Chopawamsic terrane were experiencing lower greenschist-facies (at least biotite-zone) metamorphism (Burton and others, 2015b). Whether rocks of the Elk Hill Complex and Chopawamsic terrane were adjacent at this time along a pre-metamorphic fault remains unknown. There is no evidence for Devonian metamorphism and deformation related to the Acadian orogeny in rocks of the Chopawamsic terrane and Elk Hill Complex, indicating that these terranes were not adjacent to the Goochland terrane during that metamorphic event. However, all three terranes experienced amphibolite-facies metamorphism and deformation during the late Paleozoic Alleghanian orogeny.

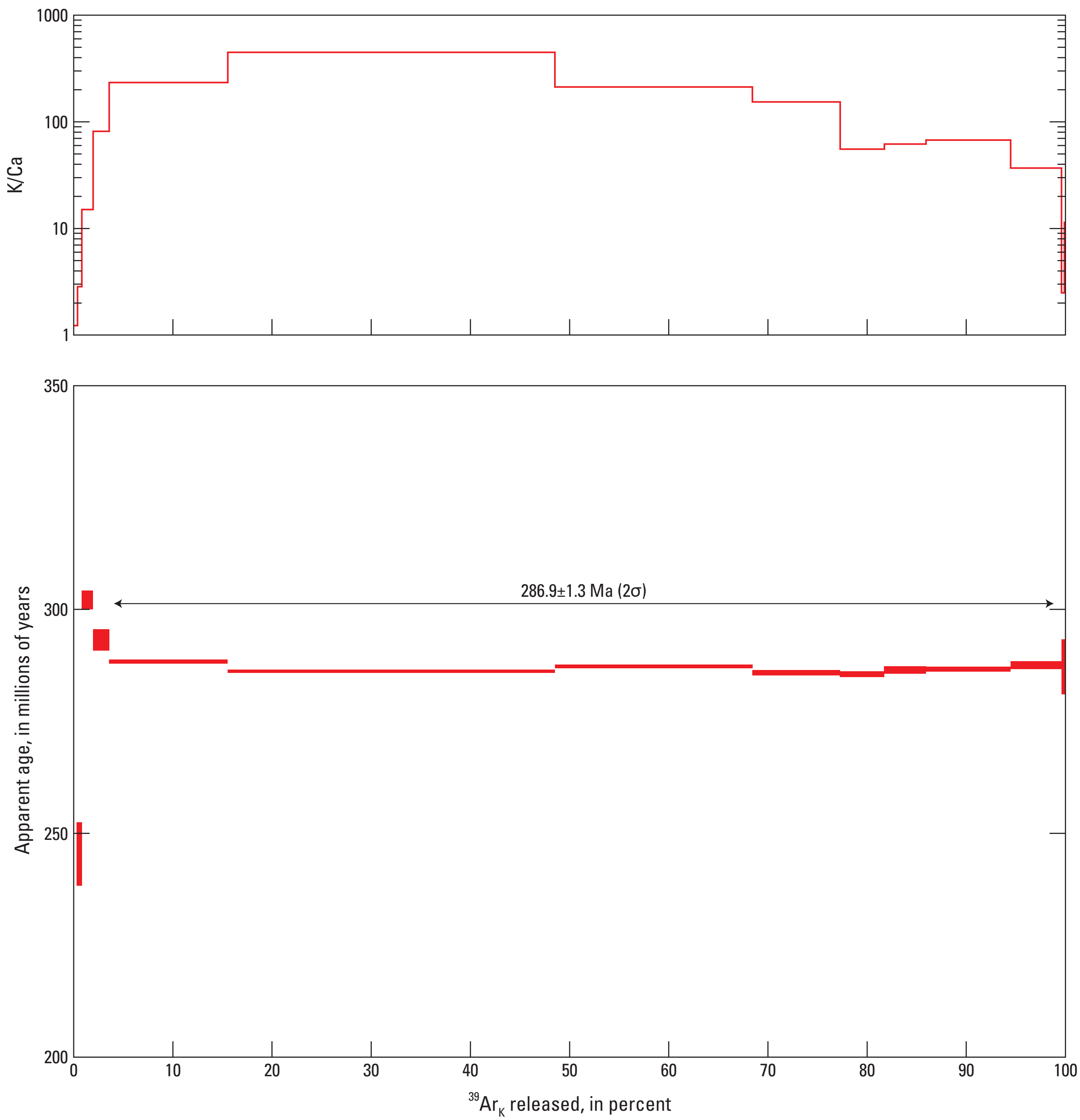


Figure 18. Plateau diagram showing a muscovite $^{40}Ar/^{39}Ar$ plateau age for a sample of strongly foliated kyanite-muscovite-quartz schist (part of map unit Ocf) of the Chopawamsic Formation (sample number BK-0208; see Powell and others [2024]). A 1.116-milligram multi-grain aliquot of 250–400 micrometer muscovite was dated. Double headed arrows indicate the steps used in calculating the plateau age (286.9±1.3 Ma [2σ]). Abbreviations: σ, standard deviation; $^{39}Ar_K$, argon-39 (^{39}Ar) produced from reaction with potassium-39 (^{39}K) during irradiation; K/Ca, atomic ratio of potassium and calcium; Ma, mega-annum.

Economic Geology

The “Mineral Resources of Virginia” catalog (available online through the Virginia Department of Energy [Geology and Mineral Resources Program] website at https://energy.virginia.gov/webmaps/GeologyMineralResources/ or through the ScienceBase data repository at https://www.sciencebase.gov/catalog/item/4f4e4ad9e4b07f02db684ec0) lists muscovite as the only commodity on the Buckner 7.5-minute quadrangle. This muscovite was prospected at a single site (ScienceBase identification number 151A-401; https://www.sciencebase.gov/catalog/item/4f4e4939e4b07f02db587c8d) approximately 1 km south of Threemile Corner. This prospect was not revisited during mapping, but the pit or shaft and adjacent spoil piles are clearly shown on the shaded relief image (fig. 19). The prospect is located in felsic metasedimentary and metavolcanic rocks (map unit Ocf) that include muscovite-rich schists. The prospect is located in a linear, 4-km-long radiometric potassium anomaly that is visible in the ternary gamma spectrometry data (fig. 20). It is not known if the anomaly is represented by muscovite mica along its entire length. This prospect is also located near iron- and manganese-bearing surficial deposits of the highest-level terrace deposits (Nt_7); some exploration of these surficial deposits may have occurred at the site too.

Calver and others (1964) analyzed a single clay sample from the Buckner quadrangle (sample number R-01970), which was collected along the east side of Buckner Road approximately 3.2 km northeast of Mt. Garland. Several auger holes were drilled to a depth of 1.3 m in soil and saprolite and a composite sample was analyzed. Mineral composition of this sample was 40–50 percent kaolin, 35–40 percent quartz, 5–8 percent montmorillonite, 2–3 percent mica, 2 percent iron (as hydroxides), and 0–5 percent feldspar. Although the bloating test was negative and the fired hardness was reported as “hard” at 2,100 degrees Fahrenheit, the clay was determined to have no potential commercial use.

In 1987, Energy USA drilled an exploratory conventional oil well approximately 1 km southwest of the intersection of Buckner Road and Bethany Church Road (State Route 655) near Chisholm Lake. The well was drilled to a depth of 2,215 feet in rocks of the Maidens Gneiss. The well was dry (no oil recovered). Additional information for this plugged well can be found at https://energy.virginia.gov/webmaps/Gas_Oil/.

Several small, abandoned dimension stone quarries are present throughout the quadrangle. All of these quarries exploited natural rock ledges to remove blocks for local use in foundations (for example, fig. 21) and chimneys. Two abandoned borrow pits for fill material and a quarry for crushed stone are located 1.15 km southeast of Fredericks Hall in the north-central part of the quadrangle. These borrow pits and quarry provided fill material and crushed stone for construction and maintenance of the Chesapeake and Ohio Railroad; an abandoned spur line runs past both borrow pits to the quarry site (fig. 22).

Several unique anthropogenic features on the landscape were identified during field mapping and during analysis of the shaded relief images. These are circular pits with a rim of spoil (fig. 23). These features appear to be more than 50 years old given the size of trees in and near the pits as well as the degree of soil development on the spoil piles framing the pits. Most pits are located adjacent to streams or are on hill slopes above streams. These features are present in nearly all bedrock map units and in all three major terranes on the quadrangle. For most, the proximity to water indicates that these features are not abandoned wells. Some pits may be prospects, but there is no indication of the commodity prospected in the walls of the pits or in the spoils that were observed during field mapping.

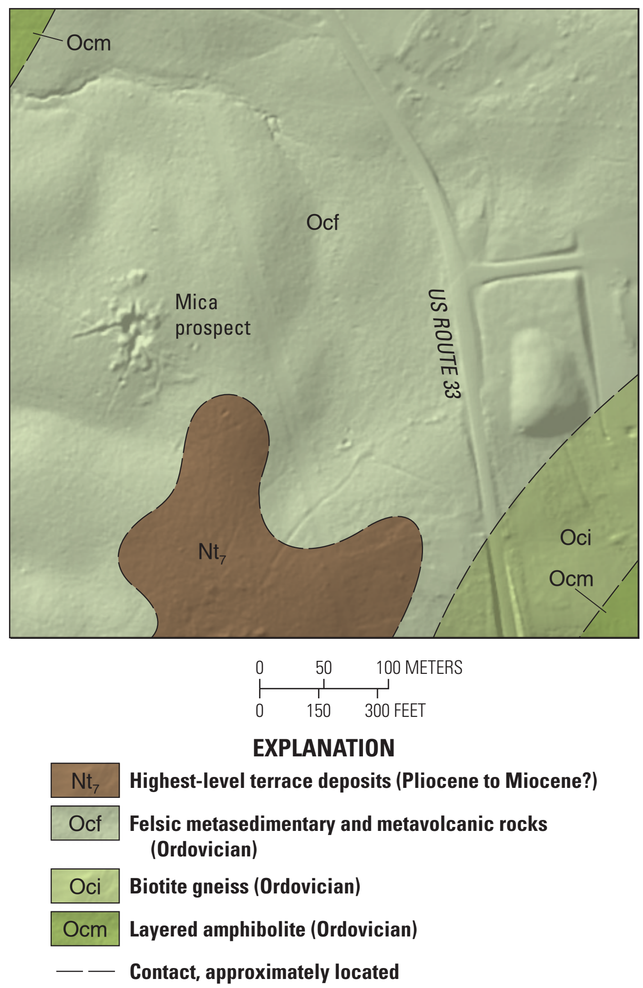


Figure 19. Shaded relief raster image derived from 1-m lidar data showing a mica prospect (located at lat 37.92117° N., long 77.86417° W.) west of U.S. Route 33 in the central-western part of the Buckner 7.5-minute quadrangle. This prospect is recorded in the Mineral Resources of Virginia database, which is populated and maintained by the Virginia Department of Energy, Geology and Mineral Resources Program.

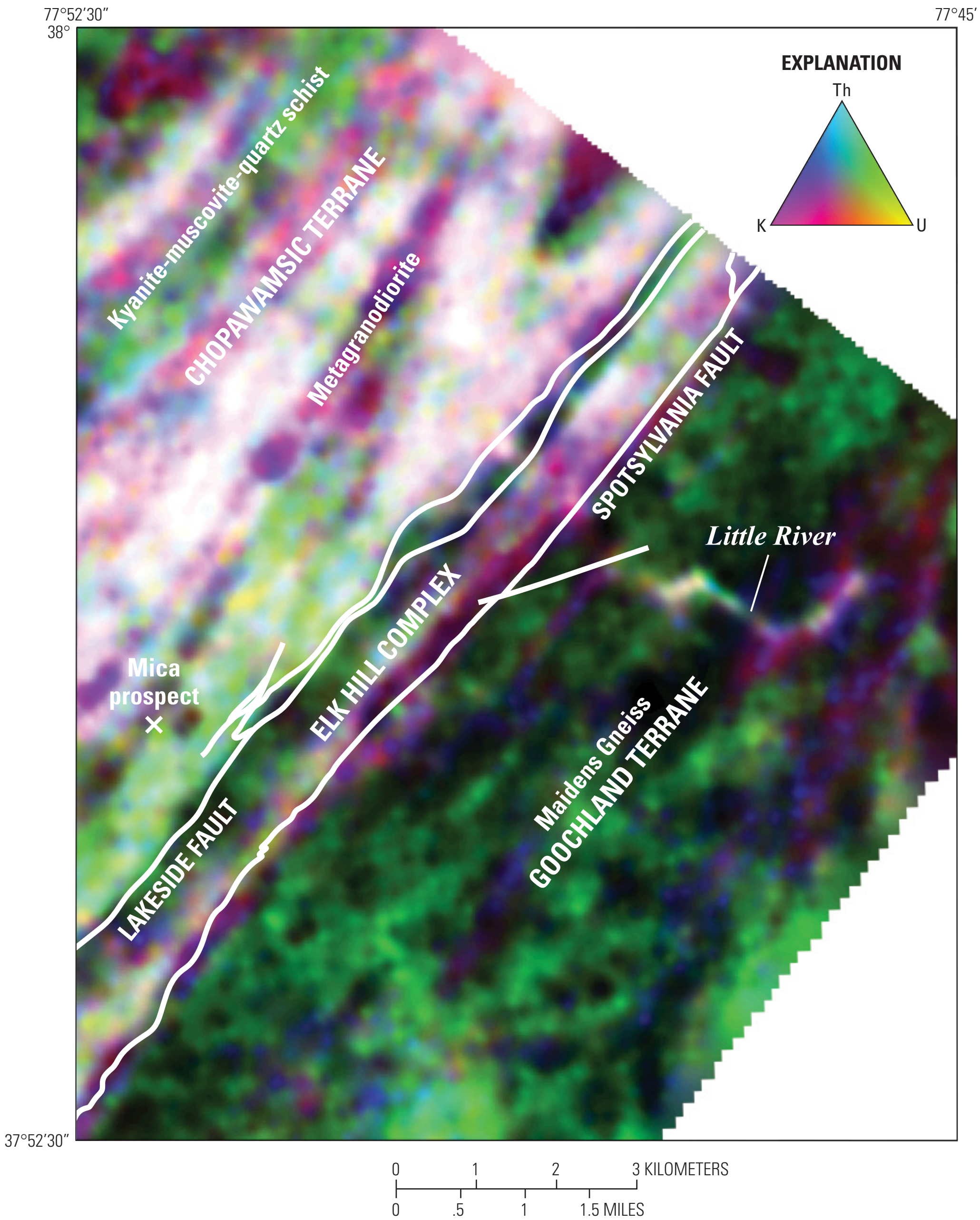


Figure 20. Ternary gamma spectrometry data map showing near-surface relative amounts of potassium (K; purple), thorium (Th; cyan), and uranium (U; yellow) for part of the Buckner 7.5-minute quadrangle. These data help show the Lakeside and Spotsylvania faults as well as rocks of the Elk Hill Complex and Goochland terrane. A mica prospect is shown in relation to a radiometric potassium anomaly. Geophysical data are from Shah (2014) and Shah and others (2015).

Figure 21. Photograph of rough-hewn and uncut field stones of altered ultramafic rock (soapstone; map unit Ocum) that were used as foundation blocks in the Buckner 7.5-minute quadrangle (photograph locality 27 on the map). The map board (approximately 23 centimeters wide) is shown for scale. Photograph by Mark Carter, U.S. Geological Survey.

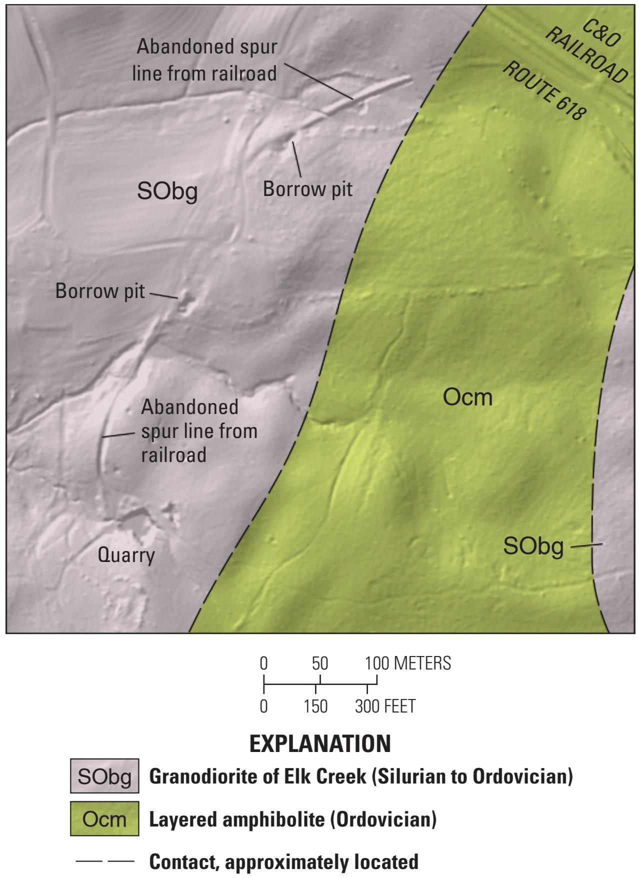


Figure 22. Shaded relief raster image derived from 1-m lidar data showing a crushed-stone quarry (located at lat 37.97569° N., long 77.81301° W.) and two borrow pits in the north-central part of the Buckner 7.5-minute quadrangle. Crushed stone was used for construction and maintenance of the nearby Chesapeake and Ohio (C&O) Railroad. A spur line connected the quarry to the main rail.

Figure 23. Photograph and shaded relief raster image derived from 1-m lidar data showing examples of enigmatic circular pits located during mapping of the Buckner 7.5-minute quadrangle. These features are clearly anthropogenic, but their purpose is still unclear. Some of these may be prospects, but little evidence exists in the pit or spoils as to what commodity (possibly gold, kyanite, or mica) was prospected. *A* (photograph locality 28 on the map), Photograph of a pit, about 5 meters in diameter and 2 meters in depth. For scale, the beech tree (left of the photograph) growing from the pit is approximately 0.5 meters in diameter. Photograph by Mark Carter, U.S. Geological Survey. *B*, Shaded relief raster image showing another pit located during mapping (located at lat 37.97897° N., long 77.85190° W.). Most pits are near streams (as is this one), which indicates that they are not abandoned wells. Most pits may be gold prospects, but this pit may be a kyanite prospect given its proximity to kyanite-bearing schist.

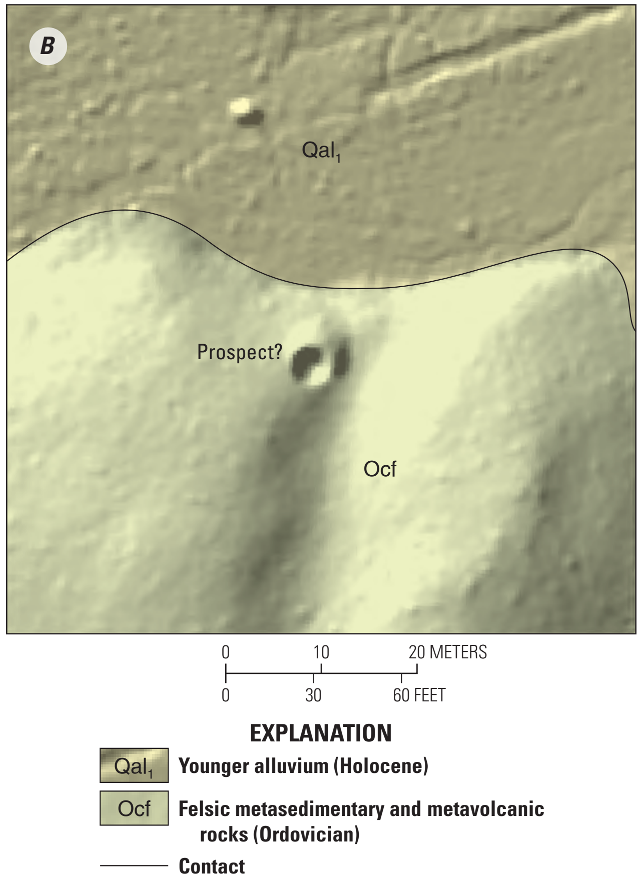


Figure 23.—Continued

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