U.S. Department of the Interior

U.S. Geological Survey

Scientific Investigations Map 3429

opaques, and comprises a large body southeast of Ellisville Granodiorite that also contains layers of amphibolite (Ocm) or muscovitebiotite-quartz-plagioclase granofels (Oc) that are one to several meters thick. A thermal ionization mass spectrometry (TIMS) U-Pb crystallization age of approximately 468 Ma is reported by Hughes and others (2014b) (sample location 18 on geologic map and in table 1), and a SHRIMP U-Pb crystallization age of about 460 Ma is reported by McAleer and others (2018) (sample location 21 on geologic map and in table 1) Amphibolite (Ordovician)—Dark green, fine-grained, hornblendeplagioclase amphibolite and chlorite-actinolite greenschist Granofels and phyllite (Ordovician)—Gray, fine-grained, muscovitebiotite-quartz-plagioclase granofels, schist, and phyllite. Considered a

metavolcaniclastic rock of intermediate (andesitic) composition.

METASEDIMENTARY, METAVOLCANIC, AND

ULTRAMAFIC ROCKS

Quantico Formation (Silurian) (Pavlides, 1980)—Medium-fine-

grained garnet-chlorite-biotite-muscovite-quartz schist. Chloritoid

locally overgrows the dominant  $S_2(?)$  schistosity, indicating post- $S_2(?)$ 

crystallization; garnets and larger biotite grains are rotated with

respect to the dominant schistosity, indicating pre- to early- $S_2(?)$ 

crystallization. Dashed unit contacts on the map are from airborne

radiometric potassium-uranium-thorium data. An analysis of detrital

zircons from the basal quartzite in the Pendleton quadrangle yielded

a minimum age of approximately 430 Ma (maximum age of deposi-

Lepidoblastic texture of biotite±muscovite is intergrown with quartz and plagioclase. Rare relict plagioclase phenocrysts are present. Locally, the unit is garnetiferous and contains decimeter- to meter-scale interlayers of fine-grained metafelsite (Ocf) and amphibolite (Ocm) Metagraywacke and phyllite of Shores complex (Cambrian to Neoproterozoic?)—Gray, massive to weakly foliated, mediumgrained, pebbly muscovite-chlorite-biotite-plagioclase-quartz metagraywacke and biotite-chlorite-muscovite phyllite. Metagraywacke contains rounded to subangular clasts of plagioclase and lesser quartz in a fine-grained matrix of quartz, plagioclase, and mica. Typically, the unit contains small (<1 mm) euhedral magnetite crystals and rare garnet. U-Pb analysis of detrital zircons in a quartz-rich horizon yielded a youngest detrital age (maximum age of deposition) of about 900 Ma (Holm-Denoma and others, 2016) (sample location 14 on geologic map and table 1). The unit comprises part of a prominent regional aeromagnetic lineament along with rocks of the Alleghanian-overprinted belt of the Byrd Mill formation (CZba). The unit is similar to rocks containing mafic and ultramafic bodies that are exposed along the James River at Shores, Va., described by Brown (1986) Ultramafic and mafic rocks of Shores complex (Cambrian to Neoproterozoic?)—Dark-green, massive, fine- to medium-grained chlorite-actinolite amphibolite, and lesser, fine-grained talcserpentinite schist and fine- to coarse-grained plagioclase-hornblende gabbro. Retrograde epidote and chlorite are present along with secondary opaques. The rock is thought to represent slivers of

basin at approximately 460 to 445 Ma (Ordovician) that separated the Chopawamsic volcanic arc and Laurentia Byrd Mill formation (informal name) of Shores complex with strong Alleghanian orogenic overprint (Cambrian to Neo**proterozoic?)**—Fine- to medium-fine-grained, well-foliated to finely layered, epidote-chlorite-muscovite-quartz metagraywacke, metasiltstone, and phyllite; commonly with thin (mm-scale) ribs of secondary, fine-grained, white quartz that is parallel to schistosity (not shown with quartz vein symbols on map). The layers (including quartz ribs) are commonly deformed by open to tight, north-plunging Alleghanian (F<sub>2</sub>) folds; folding was accompanied by the growth of small (<1 mm) euhedral magnetite crystals and coarse muscovite. The unit marks the transition zone between rocks with late Ordovician (Taconic orogeny) <sup>40</sup>Ar/<sup>39</sup>Ar plateau cooling-age spectra (sample location 5 on geologic map and in table 1) to the northwest from those with Pennsylvanian-Permian (Alleghanian) plateau cooling-age spectra (sample locations 11–13) to the southeast. The unit comprises part of a prominent regional aeromagnetic lineament along with other rocks of the Shores complex (£Zsm, £Zsum). Near the contact with the Ordovician Ellisville pluton, the rock becomes coarse grained and contains overgrowths of fibrous sillimanite (fibrolite) due to contact metamorphism. €Zbf is a fine-grained quartz-plagioclase metawacke. €Zbu is a fine-grained ultramafic rock that occurs at a single exposure in the map area and may represent an olistolith from the closure of

oceanic crust that were emplaced during the closure of a small ocean

the ocean basin that formed the Shores complex Byrd Mill formation (informal name) of Shores complex (Cambrian to Neoproterozoic?)—Fine-grained, generally finely layered, epidotebiotite-chlorite-muscovite-plagioclase-quartz metagraywacke and phyllite. Near the contact with the Ordovician Green Springs pluton, the rock becomes coarser grained and contains garnet and coarse biotite due to contact metamorphism. ¿Zbm is a fine-grained, phyllitic, epidote-chlorite greenstone. ¿Ezbg is a pebbly metagraywacke that contains blue quartz and very fine grained felsite clasts up to 5 mm in diameter. The unit is well exposed along the South Anna River at and upstream of Byrd Mill Hardware formation (informal name) (Cambrian to Neoproterozoic?)—Fine-grained to very fine grained, fissile, light-gray to silvery, chlorite-muscovite-quartz phyllite and metasiltstone. The unit is mapped in the adjacent Zion Crossroads quadrangle by N.H. Evans (written commun., 2017)

**EXPLANATION OF MAP SYMBOLS** ——— Contact—Approximately located, dotted where concealed by water or surficial material. In cross section, dotted where projected above the —...AM...- Airborne geophysical contact—Located with the assistance of aeromagnetic or airborne radiometric data Taconic biotite isograd—Represents the first appearance (southeast side of isograd) of biotite in regional metamorphic mineral assemblages Taconic garnet isograd—Represents the first appearance (southeast side of isograd) of garnet in regional metamorphic mineral assemblages Alleghanian garnet isograd—Represents the first appearance (southeast side of isograd) of garnet in regional metamorphic mineral Garnet-bearing contact zone—Approximately located, dotted where concealed by water or surficial material.

where concealed by water or surficial material. [Approximately located, dotted where concealed by water or surficial materials; queried where questionable. In cross section, dotted where projected above the bedrock surface; dashed below bedrock surface. In cross section, arrows indicate relative motion where known]

Sillimanite-bearing contact zone—Approximately located, dotted

△ \_ \_ △ First-generation thrust or transpressional fault—Sawteeth on upper plate; formed early during late Ordovician deformation and metamorphism (D<sub>1</sub>) of the Taconic orogeny. Byrd Mill and **Second-generation thrust or transpressional fault**—Sawteeth on upper plate; semiductile fault that formed during Pennsylvanian deformation and metamorphism (D2) of the Alleghanian orogeny. Includes unnamed faults cutting the neck of the Ellisville pluton △ \_ \_ △ Second-generation thrust or transpressional fault reactivated as a Mesozoic (or younger?) brittle fault zone—Sawteeth on upper plate; ductile shear fabric (D<sub>2</sub>) along the fault is locally overprinted by brittle structures such as gouge and cataclasis, and late-quartz and hematite mineralization. Includes the Harris Creek, Roundabout Farm, and Long Branch faults

[Approximately located, dotted where concealed by water or surficial materials. In cross section, dotted where projected above the ground surface. Fold symbols show trace of axial surface and direction of dip of limbs]

Overturned anticline — Syncline Overturned syncline

——— Anticline

PLANAR FEATURES [Point of observation is at the intersection of two or more symbols, if present. Symbols may be combined with linear feature symbols] **Strike and dip of first-generation schistosity (S<sub>1</sub>)**—Formed by biotite, muscovite, chlorite, and (or) amphibole in layered metasedimentary and metavolcanic rocks during late Ordovician deformation and

greenschist- to amphibolite-facies regional metamorphism  $(D_1)$  of the

Taconic orogeny. S<sub>1</sub> is parallel to compositional layering or bedding

 $S_0$  where present and is axial planar to  $F_1$  folds in layered rocks

Strike and dip of first-generation schistosity (S1e) in Ellisville pluton—Formed by biotite during late Ordovician to early Silurian deformation and metamorphism (D<sub>1</sub>) of the Taconic orogeny, but is slightly younger than the first-generation schistosity  $(S_1)$  in layered metasedimentary and metavolcanic rocks. Some S<sub>1e</sub> schistosity present in the main Ellisville pluton body may in part be a magmatic

Strike and dip of axial plane of first-generation (F1) fold of primary compositional layering or bedding (S<sub>0</sub>) in layered metasedimentary and metavolcanic rocks—Contains axial-planar S<sub>1</sub> schistosity; formed during D<sub>1</sub> in the late Ordovician (Taconic orogeny). F<sub>1</sub> folds are uncommon in the map area

Strike and dip of second-generation schistosity (S2)—Formed by muscovite, biotite, chlorite, and (or) amphibole during Pennsylvanian deformation and greenschist- to amphibolite-facies regional metamorphism (D<sub>2</sub>) of the Alleghanian orogeny Strike and dip of axial plane of second-generation (F2) fold of

metavolcanic rocks—Locally contains axial planar S2 schistosity that formed during D<sub>2</sub> in the Pennsylvanian (Alleghanian orogeny). Common and conspicuous in Alleghanian-overprinted Byrd Mill formation rocks (€Zba) Strike and dip of semiductile shear fabric—Accompanied by retro-

first-generation schistosity (S<sub>1</sub>) in layered metasedimentary and

grade (lower-greenschist facies) mineralization and associated with late movement on deformational event  $D_2$  thrust or transpressional faults within and along margins of the Ellisville pluton. Sense of shear, where present, is weak and dextral

Strike and dip of spaced cleavage or kink band—Probably latest Pennsylvanian or earliest Permian in age, reflecting late Alleghanian deformation  $(D_3)$ . These planar features are uncommon in the map

+ Strike of vertical pegmatite dike—One to several centimeters in width. Probably derived from the Ellisville Granodiorite during the latest Ordovician

**Strike and dip of quartz vein**—One to several centimeters in width. Probably associated with Pennsylvanian (Alleghanian orogeny) greenschist- to amphibolite-facies regional metamorphism

Strike and dip of joint—Most joint measurements are not shown on map to preserve visual clarity, but the figure 10 summary (stereonets and azimuth-frequency diagrams) and the accompanying geographic information systems (GIS) database includes all joint measurements from this study

LINEAR FEATURES [Point of observation is at the intersection of two or more symbols. Symbols are combined with planar feature symbols Trend and plunge of  $F_1$  fold axis (L<sub>1</sub>)—Indicates either (1) the hinge of outcrop-scale F<sub>1</sub> fold; (2) the intersection of bedding or primary compositional layering  $(S_0)$  with first-generation schistosity  $(S_1)$ ; or (3)a mineral lineation and mullion fabric in the vicinity of the Green

Bedrock geology mapped by William C. Burton (2012–2015)

Quaternary terrace deposits mapped by Richard W. Harrison,

GIS database and cartography by E. Allen Crider Jr. (2014–2017)

Helen F. Malenda, and Frank J. Pazzaglia (2012–2013)

Cartography by Linda M. Masonic (2018–2019)

Edited by David A. Shields (2018–2019)

E. Allen Crider Jr. (2012–2014)

Otr Upland residual gravel deposits (late Pleistocene)—Wide, gently-

sloping uplands that are thinly mantled with gravel and sand of possible

alluvial origin. Deposits are heterogeneous and contain colluviated vein

quartz and angular to subangular quartzite cobbles. Quartzites are

primarily ferruginous with hard, iron-rich weathering rinds that are

greater than 1 millimeter (mm) thick. Very locally, clasts of the

Cambrian Antietam Quartzite have been found associated with these

INTRUSIVE AND VEIN ROCKS

Diabase (Early Jurassic)—Medium- to fine-grained, dark-gray diabase

occurring as dikes 10 to 40 m wide. Contains an intergranular to

ophitic texture consisting of augite and calcium plagioclase with

opaques and minor biotite as accessory minerals (Mixon and others,

2000). Dikes of this unit rarely crop out, and weather into float

aggregations of rounded cobbles and boulders that have a distinctive

light- to dark-brown weathering rind as much as 1 to 2 centimeters

(cm) thick. Aeromagnetic data was used to help determine the

location of unit contacts (designated as "AM") on the geologic map

Vein-quartz breccia (Early Jurassic)—Hematite-cemented and found

as float only. Associated with the easternmost pair of two north-

south-trending Jurassic diabase dikes (Jd) at a location where Jd

crosses the Harris Creek fault near the center of the Ferncliff quad-

Pvq Vein quartz (Permian?)—Massive, white, unfoliated, typically highly

SOeg Granodiorite of Ellisville pluton (Silurian or Ordovician)—Buff to

half a kilometer (km) to the south

early Mesozoic age

rangle, and also associated with dike (Jd) at one other location about

fractured, map-scale quartz veins. The map geometry indicates the

veins crosscut older ductile features, suggesting a late Paleozoic or

light-gray weathering, massive to moderately foliated, medium-fine-

grained to medium-grained to locally coarse-grained, equigranular to

weakly porphyritic biotite-microcline-quartz-plagioclase plutonic rock.

Microcline ranges from 5 to 15 percent by volume; hornblende is

locally present. Zoisite, allanite, epidote, and muscovite are common

accessory minerals. The narrow Ellisville pluton "neck" in the Ferncliff

quadrangle typically has a moderately well-defined foliation, expressed

by biotite, that suggests synkinematic emplacement; the main body in

the Louisa quadrangle is typically massive to weakly foliated. Late

Paleozoic (Alleghanian) fabric, where present, is defined by quartz

ribbons, plagioclase retrograded to sericite and clinozoisite, and biotite

retrograded to chlorite. A 443.7±3.30 mega-annum (Ma, million

years before present) uranium-lead (U-Pb) zircon crystallization age on

the Ellisville pluton was reported by Hughes and others (2013) (sample

location 19 on geologic map and in table 1); a finer-grained, slightly

more mafic, 437 Ma "late phase" granodiorite of Hughes and others

(2013) was not recognized during the mapping of this report. The unit

mapped as SOgg in the Louisa quadrangle is the granodiorite of the

medium-grained, equigranular to weakly porphyritic biotite-

hornblende-quartz-plagioclase diorite. Locally, contains medium to

coarse-grained biotite-hornblende gabbro and medium-fine-grained

amphibolite. Zoisite, sphene, rutile, and opaques are accessory

minerals. The unit is located in three places in the Ferncliff guadrangle

near the southeastern contact of the Ellisville neck (SOeg and SOed),

and may represent an older, more mafic phase of the pluton

Green Springs pluton, which resembles that of the Ellisville pluton

Diorite of Ellisville pluton (Silurian or Ordovician)—Gray, massive,

CONTOUR INTERVAL 20 FEET FOR LOUISA OUADRANGLE

CONTOUR INTERVAL 10 FEET FOR FERNCLIFF QUADRANGLE

NATIONAL GEODETIC VERTICAL DATUM OF 1929

**DESCRIPTION OF MAP UNITS** 

UNCONSOLIDATED SURFICIAL MATERIAI

af Artificial fill—Sandy and gravelly materials in areas filled for construction

Qal Unconsolidated alluvial materials (Holocene)—Clay, silt, sand, and

of roads, highways, bridges, and dams for small water bodies

gravel, including both locally derived vein quartz and bedrock as well

as rounded cobbles remobilized from older fluvial deposits. Alluvium

that is proximal to the South Anna River frequently contains legacy

fine-grained material resulting from the construction and maintenance

of mill dams along the river in the 19th and 20th centuries. The unit

contacts are determined directly with a bare-earth digital elevation

model and hillshade that was derived from lidar: therefore contacts

may not match the older topographic base. Wide areas of Qal on

North Fork Hickory Creek (including Lake Louisa) may include

unmapped terrace deposits; parts of mapped alluvium at the head of

tributaries to Hickory Creek may represent reworked upland gravels.

Bedrock map symbols shown in surficial material are from underlying

Lowest and youngest terrace deposit that consists of gravel, sand, silt,

and clay in varying amounts. Straths emerge as a distinct landform

downstream of Roundabout Creek and are typically 3 to 6 m (meters)

above the channel. Gravel is highly varied in size; larger clasts are

oblong and rounded, smaller clasts are angular to subangular and more

spherical. Up to 50 percent of the deposit is polycrystalline or vein

quartz. Soils are yellow and are commonly associated with the Alta

Vista and Fork soil series. An optically stimulated luminescence (OSL)

age from Roundabout Farm was determined to be about 17 kilo-

annum (ka, thousand years before present) (Harrison and others,

by the following two facies: (1) coarse-grained facies, with large,

angular to subrounded, water-worn, and locally ventifacted cobbles of

vein quartz and lesser friable quartzite in a matrix of heavily gleyed,

mica-rich clay with lenses of medium-grained sand; and (2)

fine-grained facies, with bluish-gray to mottled orange-brown silty fine

sand with scattered coarser lenses. Soils are orange brown and associ-

ated with the Masada soil series. Top of the terrace is typically 2 to 3

m above Qt<sub>5</sub>. At Roundabout Farm, the terrace is possibly deformed

by fracturing and faulting of tectonic origin (Burton and others,

Ot<sub>4</sub>a Fill and strath terrace (late Pleistocene)—Well stratified, typically

2014). OSL ages range from about 28 to 22 ka at Roundabout Farm

channel facies with red gravelly sand that is overlain by red and

brownish-red overbank silt and fine sand. Clasts of gravel are

subrounded to rounded pebbles and cobbles consisting mostly of

polycrystalline quartz. The unit is 2 to 3 m thick and typically overlain

by Qt<sub>4</sub>b; it only emerges as a distinct landform downstream in the

Pendleton quadrangle. The unit weathers to the Turbeville soil series.

The unit yielded an infrared stimulated luminescence (IRSL) age of

81.5 ka just downstream from the confluence of Harris Creek

Upland alluvial terrace deposits and landforms at least 15 m above the

modern river channel that consist mostly of colluviated gravels, but

with locally in-place stratified, impacted sandy gravel that is cemented

by red clay and overlain by deeply weathered red soils of the

Turbeville soil series. Clasts are composed of subrounded to rounded,

white to off-white polycrystalline quartz and white to ochre quartzite

and lesser ferruginous quartzite. Upland terrace deposits at

Roundabout Farm yield OSL ages ranging from about 43 to 25 ka

(Harrison and others, 2015). The unit includes  $Qt_1$ ,  $Qt_2$ , and  $Qt_3$  of

Upland terrace deposits, undifferentiated (late Pleistocene)—

Ot<sub>4</sub>b Major fill terrace (late Pleistocene)—3 to 5 m thick and characterized

Floodplain and tributary fan terrace (Holocene to late Pleistocene)—

outcrops too small to show at map scale

(fig. 1) (Harrison and others, 2015)

(Pazzaglia and others, 2015)

Pazzaglia and others (2015)

NO VERTICAL EXAGGERATION

-S<sub>1</sub> schistosity (formlines) -

Quaternary alluvium mapped by Richard W. Harrison and

Springs pluton (SOgg) Trend and plunge of F<sub>2</sub> fold axis (L<sub>2</sub>)—Indicates either (1) the hinge of outcrop-scale  $F_2$  folds; (2) the intersection of first-generation ( $S_1$ ) schistosity with the  $F_2$  axial plane or axial-planar schistosity ( $S_2$ ); or Trend and plunge of shear-related mineral lineation (L<sub>3</sub>) in late-Paleozoic semiductile shear fabric—Indicates direction of shear,

not sense of shear  $\stackrel{38}{\longrightarrow}$  Plunging **←** Horizontal **OTHER FEATURES** 

Outcrop or float location—Rock outcrop locations without strike-and-dip measurements, or float of diabase (Jd), vein quartz (Pvq), or vein-quartz breccia (Jvqb) <sup>12</sup> Geochronology rock sample location—Sample location is at the nearest strike-and-dip symbol on the geologic map. Number next to symbol refers to sample location number (1–21) in table 1 Mineral observation location—Observation of mineral is at the strike-and-dip symbol nearest the location symbol. Letter next to symbol is the mineral that was determined to be present by

petrographic analysis: **B**, biotite; **G**, garnet; or **S**, sillimanite

Fe<sub>x</sub> Mineral prospect, pit, or open pit—Au, gold; Fe, iron. Locations on

**DISCUSSION** INTRODUCTION

**♦ Quarry**—Inactive

map are from Spears and Upchurch (1997)

Geologic mapping of the Ferncliff and Louisa 7.5-minute quadrangles was completed as part of a broader project, undertaken jointly between the U.S. Geological Survey, the Virginia Division of Geology and Mineral Resources (VDGMR), and other Federal and State agencies to better understand the causative mechanisms of the magnitude-5.8~(M5.8) earthquake that occurred near Mineral, Va., on August 23, 2011. Preliminary project results are summarized in Burton and others (2014, 2015b) and in Pazzaglia and others (2015). The map area is located in the central Virginia seismic zone, which has a long record of historical as well as prehistoric seismicity, the latter reported by a recent study of paleoliquefaction features by Tuttle and others (2015). This joint project includes detailed mapping of seven quadrangles in the epicentral region of the Mineral, Va., earthquake, in order to improve our understanding of the geologic framework of the central Virginia seismic zone as a whole. The epicenters of the M5.8 mainshock and most of the aftershocks occurred in the Pendleton, Va., 7.5-minute quadrangle, which adjoins the Ferncliff quadrangle on the east side. The well-located aftershocks and fault-plane solutions appear to outline a northeast- to southwest-trending, southeast-dipping thrust fault at 3 to 8 kilometers depth (Quail fault of Horton and others, 2015) that projects to the surface in the Ferncliff quadrangle and is considered to be the causative fault of the 2011 Mineral, Va., earthquake (Quail fault not shown on map). Preliminary results of geologic mapping in the Pendleton quadrangle are summarized in Burton and others (2014, 2015b). The Louisa guadrangle adjoins the Ferncliff quadrangle on the north side and shares many of the same northeast-trending lithologic belts, as well as important evidence of contact relations between these belts and the Ordovician Ellisville pluton. The South Anna River crosses the approximate surface projection of the Quail fault in the Ferncliff quadrangle, and the nature and distribution of its stream terrace deposits provide possible clues to long-term neotectonic activity involving the fault (Burton and

**ALLUVIAL DEPOSITS** Alluvial sand and gravel deposits (QaI) underlie the channels of the South Anna River and its tributaries, and were mapped in the Ferncliff and Louisa quad-

rangles using both the topographic base maps and lidar coverage. Qal consists of

clay, silt, sand, and gravel, including both locally-derived vein quartz and bedrock,

and rounded cobbles remobilized from older fluvial deposits. Alluvium proximal

SURFICIAL GEOLOGY

others, 2014; Berti and others, 2015; Pazzaglia and others, 2015).

to the South Anna River frequently contains legacy fine-grained material resulting from the construction and maintenance of mill dams along the river in the 19th and 20th centuries. South Anna River terrace deposits

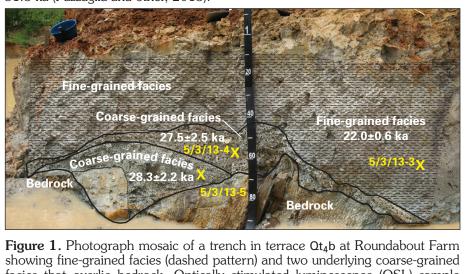
Four terrace deposits were mapped based on relative elevations above the modern stream channel, including units Qt<sub>5</sub>, Qt<sub>4</sub>b, Qt<sub>4</sub>a, and Qtu (undifferentiated upland terrace deposits). The dominant lithology in these deposits is white polycrystalline or vein quartz, with white to ochre quartzites becoming more of a component in the higher, upland gravels. Qt<sub>5</sub>, the youngest terrace deposit, is a floodplain and tributary fan deposit of gravel, sand, silt, and clay on straths typically 3 to 6 m above the channel. Qt<sub>4</sub>b is a major fill terrace, 3 to 5 m thick, with a coarse-grained and a fine-grained facies.  $Ot_4a$  is typically a red, gravellysand channel facies overlain by a brownish-red overbank silt and fine sand, 2 to 3 m thick, that is typically buried by Qt<sub>4</sub>b but emerges as a strath terrace downstream of Horseshoe Farm in the putative footwall of the Quail fault. Unit Qtu consists of upland alluvial terrace deposits of gravel, sand, silt, and clay, and landforms at various elevations above the  $Qt_5$ ,  $Qt_4b$ , and  $Qt_4a$  terraces. It is cemented by distinctive dense, red clay that is absent in the younger (lower) terraces. Qtu most commonly occurs on hill crests or high on hill slopes from 35 feet (ft) to greater than 50 ft above Qt<sub>5</sub>. One Qtu deposit at Roundabout Farm is

cut by a vertical fracture of probable tectonic origin (Burton and others, 2014).

Significance of terrace deposits in determining neotectonic uplift Correlation of South Anna River terrace deposits across the approximate surface projection of the causative fault for the 2011 Mineral earthquake (Quail fault) allows for an assessment of possible neotectonic uplift on the southeast hanging-wall side of the fault. Since the Mineral earthquake produced no discernable fault scarp, any detected uplift of terraces would likely reflect the cumulative effect of multiple prehistoric seismic events. Berti and others (2015) made preliminary correlations, based on geomorphology, and concluded that several meters of uplift have occurred on the hanging wall since formation of the terraces. OSL dating of terraces (see below) is being undertaken to refine these correlations, and Pazzaglia and others (2015) used dated terraces in the footwall of the Quail fault to calculate rapid uplift rates that suggest a neotectonic component.

Ages of South Anna River terrace deposits have been determined using the optically stimulated luminescence (OSL) and infrared stimulated luminescence (IRSL) dating techniques. At Roundabout Farm, just north of the South Anna River at the junction of the river with Harris Creek, multiple terrace deposits at differing elevations show a range of late Pleistocene ages, as reported by Harrison and others (2015). A clast-supported gravel and sand deposit about 20 m above the river, mapped as Qtu, yielded an age of 42.8±3.2 ka, whereas at approximately 18 m above the river it yielded OSL ages of 34.3±2.6 ka from the base and 25.1±2.6 ka from the top. A similar but younger (Qt₄b) deposit about 11 m above the river yielded ages of 26.9±1.1 ka and 23.8±1.0 ka, and is cut by fractures thought to be of tectonic origin. A Qt<sub>4</sub>b sand and silt overbank deposit at approximately 10 m above the river yielded ages of 22.0±0.6 ka (fig. 1 fine-grained facies), while an underlying cross-bedded gravel and sand deposit yielded ages of 27.5±2.5 and 28.3±2.2 ka (fig. 1, coarse-grained facies). An overbank deposit of fine sand and silt about 8.5 m above the river (Qt<sub>5</sub>) was dated at 17.2±0.70 ka. An OSL age from Qt4a at Rodgers Farm, just below the confluence of Harris Creek and underlying  $Qt_4b$  shown on the map, was dated at

Terrace deposit ages



facies that overlie bedrock. Optically stimulated luminescence (OSL) sample locations from both fine- and coarse-grained facies are shown with an "X" with the associated sample number (for example, 5/3/13-4). Determined OSL ages and the associated error for the three samples are in kilo-annum (ka, thousand years before present). Black heavy lines are lithologic contacts. Tick marks on the black measuring tape are in tenths of a meter. 1 meter = 3.28 feet.

**BEDROCK LITHOLOGIES** METASEDIMENTARY AND METAVOLCANIC ROCKS

The Ferncliff and Louisa quadrangles are underlain by a series of northeast-

to southwest-trending lithologic belts that include metavolcanic, volcaniclastic,

and metasedimentary rocks of the Chopawamsic and Quantico Formations, and metasedimentary and metavolcaniclastic rocks northwest of the Chopawamsic Formation that were mapped by Pavlides (1989) as part of the Mine Run Complex. The regional metamorphic grade is greenschist to amphibolite facies, progressing from lower-greenschist facies in the northwest part of the map area to amphibolite facies in the southeast part of the map area. The Chopawamsic Formation (Southwick and others, 1971) includes welllayered metavolcanic and metavolcaniclastic rocks of felsic, mafic, and intermediate compositions, in the form of felsic metatuff and metarhyolite (metafelsite, Ocf), greenschist and amphibolite (Ocm), and muscovite-biotite granofels and schist (Oc) (fig. 2). An Ordovician age for the Chopawamsic Formation is supported by a zircon U-Pb age of 468.2±1.10 Ma (Hughes and others, 2014b) from a sample of felsic metatuff (sample location 18 on geologic map and in table 1), and a SHRIMP U-Pb crystallization age of about 460 Ma is reported by McAleer and others (2018) (sample location 21 on geologic map and in table 1). Tectonically, the Chopawamsic Formation is considered to represent an ancient island arc that is part of a far larger terrane (Carolinia block of Hibbard and others, 2010) that

accreted to ancestral North America (Laurentia) in the Late Ordovician.



Figure 2. Photograph showing layered granofels and phyllite (Oc) of the Chopawamsic Formation. The approximately 41 centimeters (16 inches)-long rock hammer is shown for scale.

A distinctive, ferruginous quartzite in the Chopawamsic Formation that has

been metamorphosed into a magnetite-bearing chlorite-garnet-muscovite-biotitequartz schist (Ocqs) is thought elsewhere to be associated with massive sulfide deposits of exhalative origin (Conley, 1987; Peters and Owens, 2011); in the study area it is associated with deposits of iron with secondary manganese (mineral prospects shown on geologic map), and forms a prominent aeromagnetic high. No detrital zircon was identified in the Ocqs quartzite sample (sample location 16 on geologic map and in table 1), which suggests a chert origin for the quartzite that was deposited in an ocean-floor, exhalative setting (Conley, 1987). The Quantico Formation (Pavlides, 1980) (Sqs) is a garnetiferous biotitemuscovite schist whose protolith was probably deposited unconformably as a successor basin on the Chopawamsic volcanic arc terrane and that was subsequently deformed into a regional-scale synform (Mixon and others, 2000). The synform is poorly exposed in the Ferncliff quadrangle, but is much better exposed in the adjacent Pendleton, Va., quadrangle, as shown in Burton and others (2014, 2015b). Recent detrital and igneous U-Pb dating supports the successor-basin model and a latest Ordovician to Silurian age for the Quantico

Formation (Holm-Denoma and others, 2016; Regan and others, 2017). Northwest of the Chopawamsic Formation is a distinctive, narrow belt containing lithologies not found elsewhere in the map area, including poorly sorted metagraywacke (€Zsm) (fig. 3) and ultramafic and mafic bodies (€Zsum). Here, the belt is informally considered part of the Shores complex after a belt of similar lithologies exposed along the James River near Shores, Virginia (Brown, 1986). It corresponds in approximate location to mélange zone III of the Mine Run Complex of Pavlides (1989). The juxtaposition ultramafic rocks suggests an accretionary wedge that was formed by closure of an ocean basin during accretion of the Carolina terrane to Laurentia, with the implication that the belt is fault-bounded (Chopawamsic and Byrd Mill faults). The timing of this accretion and accompanying faulting is discussed below. The northwestern part of the map area contains fine-grained, locally finely bedded phyllite and metagraywacke that represent deep-water slope and rise sediments shed from the margin of Laurentia, as suggested by detrital-zircon data of Hughes and others (2014a). This package of Laurentian slope-rise metasediments corresponds to Mine Run Complex mélange zone IV of Pavlides (1989), and is here divided into three lithologic belts on the map based on primary composition and subsequent deformation and alteration. The southeasternmost lithologic belt, here informally called the "Byrd Mill formation of Shores complex with strong Alleghanian orogenic overprint" (map units €Zba, €Zbf, and €Zbu) is highly folded and contains (1) abundant secondary white quartz ribs parallel to schistosity (fig. 4), and (2) disseminated, small euhedral magnetite crystals. Based on the interpretation of  $^{40}$ Ar/ $^{39}$ Ar age spectra (sample locations 4 and 7 on geologic map and in table 1), this unit probably represents a late-Paleozoic

phyllite that contains a much weaker Alleghanian orogenic overprint. Recent mapping by N.H. Evans (written commun., 2017) in the Zion Crossroads quadrangle (adjacent to the Ferncliff quadrangle to the west), also includes Byrd Mill formation rocks in the Shores complex. The northwesternmost belt, informally called the Hardware formation (£Zh), is a fine-grained to very fine grained phyllite and metasiltstone that is also mapped in the adjacent Zion Crossroads quadrangle (N.H. Evans, written commun., 2017). These three lithologic belts comprise the "Mine Run Complex mélange zone IV" of Pavlides (1989). Granodiorite plutons

The Ferncliff and Louisa quadrangles contain parts of two plutonic bodies that

are Late Ordovician or early Silurian in age, the Ellisville pluton and the Green

east-dipping slab (Pavlides and others, 1994; Shah and others, 2015).

orogenic overprint superposed on early-Paleozoic fabric. The middle lithologic

belt, here called the "Byrd Mill formation of Shores complex" (map units €Zb,

€Zbm, and €Zbg), is a fine-grained, locally finely layered metagraywacke and

Springs pluton. The Ellisville pluton (SOeg and SOed) is granodiorite in composition with only minor diorite, whereas the Green Springs pluton is diorite with lesser granodiorite; only the latter composition (granodiorite) occurs in the Louisa quadrangle (SOgg). A portion of the map-view "balloon-like" main body of the Ellisville pluton is exposed in the Louisa quadrangle, where the granodiorite is mostly medium to coarse grained and massive. A weak biotite foliation is locally present. The granodioritic phase of the Green Springs pluton that is exposed in the Louisa quadrangle is also mostly medium to coarse grained and massive. The Ellisville pluton has an unusual elongate-southwestward extension into the Ferncliff quadrangle that is referred to here as the "Ellisville neck." The Ellisville neck consists mostly of medium-grained biotite granodiorite (SOeg) like the main body, but is also foliated throughout its exposure in the Ferncliff quadrangle. Analysis and modeling of airborne gravity and aeromagnetic surveys of the main body of the Ellisville pluton and the Ellisville neck suggest the pluton geometry is a deep-seated,

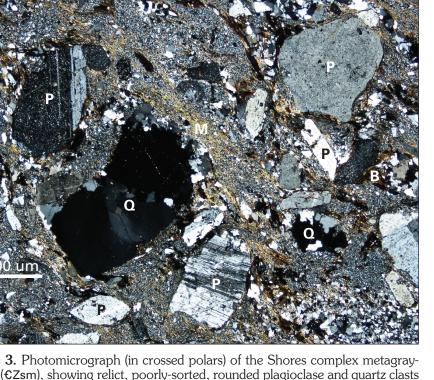


Figure 3. Photomicrograph (in crossed polars) of the Shores complex metagraywacke (€Zsm), showing relict, poorly-sorted, rounded plagioclase and quartz clasts in a tine-grained quartzoteldspathic matrix. Abbreviations: **P**, plagioclase; **Q** quartz; **M**, fine-grained secondary muscovite (sericite) defining weak metamorphic foliation; **B**, secondary biotite intergrown with chlorite.  $1,000 \, \mu m = 1$  millimeter.

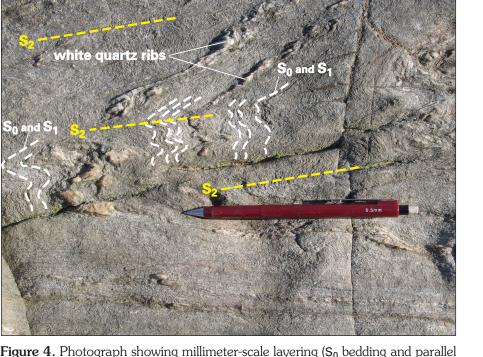
Three small bodies of medium- to coarse-grained hornblende diorite and gabbro (SOed) occur within the Ellisville granodiorite near the southeastern contact of the Ellisville neck with adjacent Chopawamsic Formation rocks. Although cross-cutting evidence was not observed in the map area, this more mafic phase is thought to be older than the granodioritic main phase, based on cross-cutting relations between similar rocks in the Green Springs pluton (Rossman, 1991) and based on the older relative age of the mafic Lahore pluton adjacent to the Ellisville pluton to the north (445.6 Ma and 440.9 Ma, respectively) (Sinha and others, 2012). Hughes and others (2013) obtained a U-Pb zircon age of approximately 444 Ma for medium-grained granodiorite from the Ellisville neck in the Ferncliff quadrangle (sample location 19 on geologic map and in table 1), while a finer-grained, slightly more mafic (but still granodioritic) phase from the main body of the pluton in the Mineral quadrangle yielded an age of approximately 437 Ma (Hughes and others, 2013). Sinha and others (2012) obtained a U-Pb zircon age of 432±7 Ma

for the mafic phase of the Green Springs pluton in the adjacent Keswick quadran-

gle, while Burton and others (2015a) obtained an amphibole  $^{40}$ Ar/ $^{39}$ Ar plateau

age of 451±2 Ma from the same locality, which agrees more closely with the age

of 448±3 Ma obtained for the Green Springs pluton by Wilson (2001).



S₁ schistosity; dashed white lines) in well-sorted Byrd Mill metagraywacke (€Zba) that is deformed by an Alleghanian F<sub>2</sub> fold. Notice the secondary white quartz ribs that are parallel to the S<sub>0</sub> bedding and S<sub>1</sub> schistosity. The red pencil is 13.5 centimeters (5.4 inches) long and oriented at a slight angle to the axial plane of the F<sub>2</sub> fold, which is parallel to the spaced  $S_2$  cleavage (dashed yellow lines).

Diabase dikes (Jd) as much as several tens of meters thick trend northeast to northwest across all other units in the map area. The dikes rarely crop out but they produce float of rounded cobbles that were used to trace the dikes across the

Diabase dikes and quartz veins

landscape during mapping. The dikes are also visible in aeromagnetic data obtained for the area (Shah and others, 2015), which were used to map portions of some of the dikes. The dikes are assumed to be Early Jurassic in age due to their similarity to Jurassic dikes found in the surrounding area and the adjacent quadrangles (Ragland and others, 1992). Veins of massive, white quartz (Pvq) up to a few tens of meters thick are widespread throughout the area, but only a few have large enough exposures to be mapped. The mapped veins trend mostly northeast and are up to a km in length. They are thought to be late Paleozoic or early Mesozoic in age due to their crosscutting relationships with respect to the surrounding rocks.

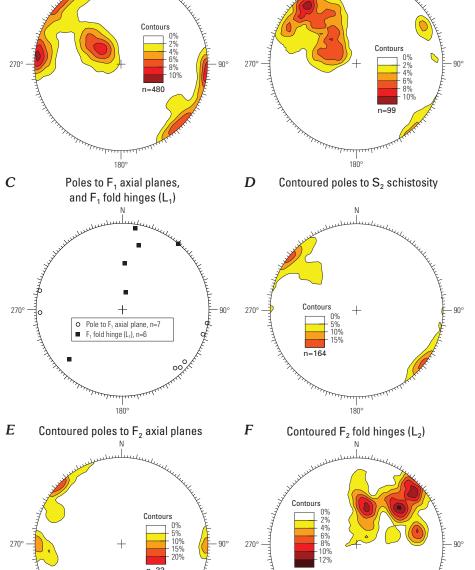
Paleozoic tectonism experienced by the rocks in the Ferncliff and Louisa quadrangles occurred primarily during two deformational episodes, one during the early Paleozoic (D<sub>1</sub>) and one in the late Paleozoic (D<sub>2</sub>). Approximate ages of the two deformational episodes have been confirmed by recent 40Ar/39Ar mineral cooling ages (Burton and others, 2015a; McAleer and others, 2017), discussed more below.  $D_1$  produced (1) the dominant regional schistosity  $S_1$ , (2) rarely observed tight to isoclinal folds  $(F_1)$ , (3) pre- to early-metamorphic thrust faults, and (4) a regional metamorphic gradient that appears to range from lower-greenschist to amphibolite facies (northwest to southeast across the map area). D<sub>2</sub> was also widespread, overprinting D<sub>1</sub> structures with S<sub>2</sub> schistosity, F<sub>2</sub> folds and D<sub>2</sub> faults, and was accompanied by a metamorphic overprint that also ranged from lower-greenschist in the northwest to amphibolite in the southeast. Results of measured outcrop-scale D<sub>1</sub> and D<sub>2</sub> ductile structures are summarized in

Contoured poles to S<sub>1e</sub> schistosity

eight stereonets in figure 5A-H.

A Contoured poles to S<sub>1</sub> schistosity

PALEOZOIC DUCTILE STRUCTURES AND METAMORPHISM



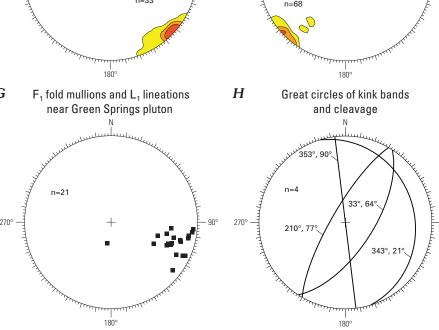
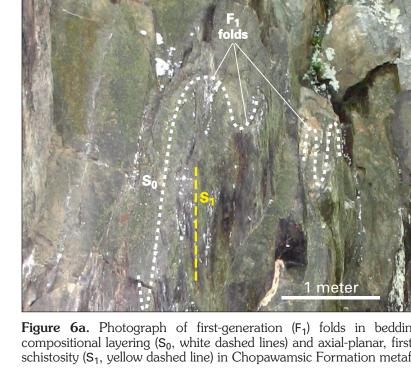


Figure 5. Stereonet diagrams showing the results of measured outcrop-scale Definition (Taconic), D<sub>2</sub> (Alleghanian), and D<sub>3</sub> (late-Alleghanian) ductile structures in the Ferncliff and Louisa quadrangles, Virginia. A-B, contoured poles to first-generation (Taconic) schistosity, S<sub>1</sub> and S<sub>1e</sub>, in non-plutonic and plutonic rocks, respectively C, poles to  $F_1$  axial planes of first-generation ( $F_1$ ) folds (open circles), and hinges of  $F_1$  folds (L<sub>1</sub>) (filled squares). D, contoured poles to second-generation (Alleghanian) schistosity (S<sub>2</sub>). E, contoured poles to axial planes of second-generation (Alleghanian) folds ( $F_2$ ).  $F_2$ , contoured  $F_2$  fold hinges ( $L_2$ ).  $G_2$ , first-generation ( $F_1$ ) fold mullions and mineral lineations  $(L_1)$  near the Green Springs pluton (SOgg). H, great-circles to late-Alleghanian kink bands and cleavage planes; results of measured strike and dip are shown (for example, "210°, 77°"). All stereonets are lower hemisphere projections. The number of measurements is indicated by "n" for each stereonet. Stereonets were plotted using the Structural Data Integrated System Analyser (DAISY, version 4.85) software by Salvini (2012).

S<sub>0</sub> (bedding and compositional layering) and S<sub>1</sub> schistosity (formlines) 1000 feet = 305 meters
Surficial deposits not shown



**Figure 6a.** Photograph of first-generation (F<sub>1</sub>) folds in bedding and (or) compositional layering (S<sub>0</sub>, white dashed lines) and axial-planar, first-generation schistosity (S<sub>1</sub>, yellow dashed line) in Chopawamsic Formation metafelsite (Ocf).

Figure 6b. Photomicrograph (in plane-polarized light) of an isoclinal F<sub>1</sub> fold in metasiltstone of the Bird Mill formation with compositional layering  $(S_0, \text{ curved})$ dashed line) and axial-planar S<sub>1</sub> schistosity (straight dashed line) that consists of

fine-grained biotite, chlorite, and muscovite.  $500 \, \mu m = 0.5 \, millimeters$ . Early-Paleozoic D<sub>1</sub> deformation D<sub>1</sub> was an early-Paleozoic, northwest-southeast compressional event that produced a widespread first-generation schistosity (S<sub>1</sub>) that is expressed by biotite

and lesser muscovite and is axial planar to upright, tight to isoclinal, northeast-trending F<sub>1</sub> folds in metasedimentary, metavolcanic, and metavolcaniclastic deposits (figs. 6a, 6b). F<sub>1</sub> folds and associated L<sub>1</sub> lineations are rarely observed in outcrop, but a belt of Chopawamsic Formation quartzite and schist (Ocqs) is interpreted as a map-scale F<sub>1</sub> syncline, as it is bounded on either side by metafelsite (Ocf) and is parallel to regional S1 schistosity. Outcrop- and map-scale F1 tolds are observed in adjacent metafelsite (fig. 6a; cross section B-B'). This syncline is along strike with the Long Island syncline of Smith and others (1964), although that syncline is mapped in younger, successor-basin metasediments that are equivalent to the Arvonia Formation. Modeling of the aeromagnetic anomaly associated with the Ocqs belt suggests that it extends to less than 1 km depth below the surface, and possibly only extends to a depth of 500 m below the surface (A.K. Shah, oral commun., 2016). The belt of Ocqs can be traced northeastward to an intrusive contact with the Ellisville pluton (SOeg, SOed) along Harris Creek, where S<sub>1</sub>-bearing quartzite is surrounded by granite and pegmatite. Elsewhere along the margin of the pluton, apophyses of the pluton can be observed cutting  $S_1$  in country rock (fig. 7). Therefore,  $D_1$  and  $S_1$  in the layered rocks must predate the intrusion of the 444-Ma Ellisville pluton.

However, the Ellisville neck also has a biotitic schistosity (S<sub>1e</sub>) that, because of

(1) its uniform distribution throughout the Ellisville neck, (2) textural equilibrium of

the biotite with quartz and feldspar, and (3) the general parallelism with the S<sub>1</sub>

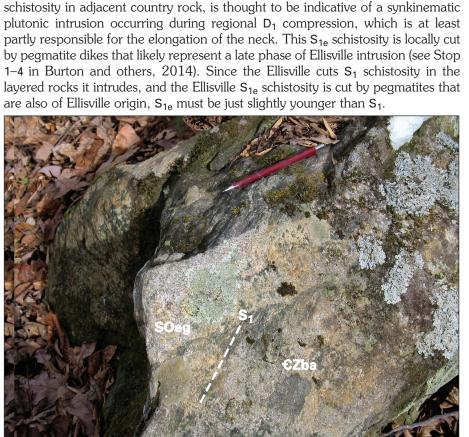


Figure 7. Photograph of apophysis of Ellisville granodiorite (SOeg) crosscutting S<sub>1</sub> foliation in the Byrd Mill formation (CZba). The 13.5 centimeters (5.4 inches)-long red pencil is shown for scale.

Two synclines in the Quantico Formation (Sqs) in the southeast corner of the map area could also represent early Paleozoic folds. However, recent U-Pb analysis of detrital zircons obtained from the Quantico Formation in the adjacent Pendleton quadrangle yielded a few ages that post-date intrusion of the Ellisville pluton (Holm-Denoma and others, 2016); therefore, these folds must be younger than the  $Ocgs F_1$  fold, and perhaps younger than the  $S_{1e}$  schistosity in the Ellisville neck. In cross section B-B', one of the folds is labeled "post-Taconic(?)" East- to west-trending minor folds and associated fold mullions and mineral lineations in Byrd Mill formation phyllite and metagraywacke (£Zb) occur north and south of the Green Springs pluton at regional metamorphic conditions below biotite grade (west of the biotite isograd) in the Louisa quadrangle. The minor folds have coarse-grained, axial-planar biotite. Since the biotite is a product of contact metamorphism by the early-Paleozoic Green Springs pluton (see discussion on metamorphism, below), the folds and associated mullions and lineations are interpreted to be  $F_1$  and  $L_1$ , respectively, and the result of  $D_1$  (early-Paleozoic) deformation, perhaps as a result of a buttressing effect by the Green Springs pluton during late-D<sub>1</sub> deformation. This same buttressing during D<sub>1</sub> deformation caused S<sub>1</sub> schistosity in the surrounding rocks to wrap around the pluton. Two thrust faults are mapped as D<sub>1</sub> (early Paleozoic) in age, the Byrd Mill and Chopawamsic faults. These faults bound the narrow metagraywacke- and ultramafic-bearing belt (£Zsm and £Zsum) of the Shores complex that, as discussed above, appears to represent the closure of a small ocean basin between the Chopawamsic volcanic arc and Laurentia. The faults are early D<sub>1</sub>; that is, movement on the faults was early in the development of  $S_1$  schistosity and the regional metamorphic gradient. Therefore, they are represented only by a change in lithologies across the faults. Any associated fault fabric that may have been present was transposed and recrystallized, and the faults were subsequently deformed by D<sub>1</sub> deformation. Closure of the basin, and the accretion of the Chopawamsic arc (part of the Carolina terrane) to Laurentia, was likely the signature Taconic tectonic event in this part of the Appalachian orogen, and the

driving force behind regional  $D_1$  deformation. Late-Paleozoic D<sub>2</sub> deformation S<sub>2</sub> schistosity locally overprints S<sub>1</sub> schistosity and is characterized by the

secondary growth of mica (particularly muscovite), and over much of the map

area it is characterized by retrograde mineralization marked by cloudy biotite grains, biotite and garnet breaking down to form chlorite, and fractured and (or) rotated plagioclase grains. S<sub>2</sub> schistosity in the form of semiductile shear fabric characterizes D<sub>2</sub> faults, and is accompanied by retrograde metamorphism. The D<sub>2</sub> Harris Creek fault is found along the contact of the Ellisville neck and the Chopawamsic Formation, on or near the approximate surface projection of the Quail fault. If neotectonic reactivation of a pre-existing structure has occurred to produce the Quail fault, the Harris Creek fault represents the most likely candidate for reactivation. D<sub>2</sub> faults splay out from the Harris Creek fault through the interior of the Ellisville neck as well, including the well-studied Roundabout Farm fault and other unnamed faults (Burton and others, 2015b). All these faults are interpreted as thrust faults, based on locally exposed fold-thrust fabrics (fig. 8). In addition, a subhorizontal shear lineation  $L_3$  is locally found along the Harris Creek fault and other D<sub>2</sub> faults, indicating that they have a translational component and therefore can be considered transpressional faults. Mapping by Burton in the Mineral, Va., quadrangle (Carter and others, 2019) indicates that all of the fault strands from the Harris fault, including the Roundabout Farm and unnamed faults, converge back into the Harris Creek fault to the northwest, marking the boundary of the main body of the Ellisville pluton and the Chopawamsic Formation. The Harris Creek and Roundabout Farm faults became the focus for later, brittle deformation (discussed below). F<sub>2</sub> folds are common in Byrd Mill formation (£Zba) metagraywacke and phyllite just northwest of the Byrd Mill fault in the form of open to tight, upright folds with moderately north-plunging  $L_2$  fold hinges (fig. 5F), where they are accompanied by secondary mineralization. The secondary mineralization is represented by thin (mm-scale) veins of white quartz that are subparallel to compositional layering  $(S_0)$  and  $S_1$  schistosity (fig. 4), and sub-mm-scale euhedral crystals of magnetite. F2 folds and secondary magnetite occur in other rocks of the Shores complex (€Zsm, €Zsum) as well. The zone of secondary mineralization extends north around the Ellisville pluton and is the probable source for a

Grade and age of metamorphism Mineral assemblages in the lithologic belts of the map area indicate that the

regional aeromagnetic high (Snyder, 2005). The consistently north-plunging  $F_2$ 

folds may reflect broadly distributed strain associated with Alleghanian dextral

metamorphic grade increases from northwest to southeast across the map area,

from lower-greenschist to amphibolite facies, but this explanation is complicated by the fact that the area experienced tectonism in both the early and late Paleozoic by  $D_1$  and  $D_2$  deformation, respectively, with  $D_2$  partially overprinting  $D_1$ . Regional-grade muscovite-chlorite assemblages (lower-greenschist facies) are stable in Hardware (£Zh) and Byrd Mill (£Zb) formation rocks in the northwest portion of the map area, with the D<sub>1</sub> biotite isograd occurring west of the zone of strong, late Paleozoic overprint that is present in Byrd Mill formation rocks (£Zba). Relict Taconic garnets are found in Alleghanian-overprinted Byrd Mill formation metasiltstone and phyllite (EZba) and in Shores complex metagraywacke and phyllite (€Zsm); on the map, the Taconic garnet isograd is placed just northwest of the Byrd Mill fault. Relict Taconic amphibole is stable (upper greenschist-facies metamorphism) in Shores complex ultramafic and mafic rocks (¿Zsum) (McAleer, 2017). Based on the first occurrence of garnet in Alleghanian fabrics, the Alleghanian garnet isograd is placed on the map in Chopawamsic Formation metafelsite (Ocf) just northwest of the belt of quartzite and schist (Ocqs). Alleghanian amphibole is present in Chopawamsic Formation (Oc) rocks over the eastern part of the map area (Hughes and others, 2014b). In the adjacent Pendleton quadrangle, growth of staurolite occurred in Quantico Formation metapelitic schist (Sqs), although this mineral was not observed in the Ferncliff quadrangle. Contact aureoles surrounding the Ellisville and Green Springs plutons were responsible for local increases in metamorphic grade adjacent to their plutonic contacts. In the Louisa quadrangle, tibrous sillimanite (tibrolite), indicative of sillimanite-grade metamorphism, was observed in samples collected less than 0.5 km from the contact of the Ellisville pluton, while garnets and larger flakes of dark-brown biotite, which are suggestive of staurolite-grade metamorphism, were observed in phyllite adjacent to the Green Springs pluton, northwest of the regional biotite isograd. A contact aureole with stable sillimanite is consistent with the estimated temperature and pressure of emplacement of the Ellisville pluton at approximately 760°C and 4 to 6 kilobars, respectively (Pavlides and others, 1994). No increase in metamorphic grade was detected in Chopawamsic Formation rocks adjacent to the Ellisville neck in the Ferncliff quadrangle. A recent geochronological transect across the region, to determine <sup>40</sup>Ar/<sup>39</sup>Ar closure ages for amphibole, muscovite, and potassium feldspar included samples collected from the Ferncliff and Louisa quadrangles (Burton and

map and in table 1). 40Ar/39Ar ages (table 1) are imprecise, but record a west to east decrease in ages, which is interpreted to reflect the increasing grade of an Alleghanian metamorphic overprint on Taconic metamorphism. An amphibole with a correlation age of approximately 450 Ma was obtained from the Shores complex (£Zsum) (sample location 5 on geologic map and in table 1); an amphibole plateau age of 451±2 Ma was obtained from Green Springs diorite in the adjacent Keswick quadrangle; a muscovite plateau age of 294±1.5 Ma was obtained from Chopawamsic Formation quartzite and schist (Ocqs) (sample location 11 on geologic map and in table 1); and an amphibole plateau age of 311±4 Ma was obtained from a 1-m-thick amphibolite layer in Chopawamsic Formation granofels and phyllite (Oc) east of the Ellisville neck (Burton and others, 2015a; McAleer and others, 2017) (sample location 13 on geologic map and in table 1). The northwesternmost presence of Alleghanian ages, or the Alleghanian disturbance of Taconic ages, appears to correlate with the zone of D<sub>2</sub> deformation and secondary mineralization in the Byrd Mill formation (€Zba), which is therefore considered to be Alleghanian in origin. The secondary mineralization resulted from the introduction of fluids from the southwest during Alleghanian orogeny tectonic loading, resulting in growth of euhedral magnetite and the injection of

quartz veins. Determining the original southwestward extent and grade of Taconic

metamorphism would be difficult due to the Alleghanian overprint.

others, 2015a; McAleer and others, 2017) (sample locations 1–13 on geologic



centimeters (5.4 inches)-long red pencil is in the footwall; the white eraser on the pencil points to the fold hinge in the thrust fault. EVIDENCE FOR POST-PALEOZOIC DEFORMATION AND

**NEOTECTONISM** The last deep-seated, ductile deformation in the region occurred in the late Paleozoic, followed by early Mesozoic uplift that was accompanied by shallow, brittle deformation and the formation of continental rift basins along the length

of the Appalachians during the initial breakup of Pangea. The southern terminus of the early Mesozoic Culpeper basin is located about 20 km north of the map area. Rift basin formation in the southern Appalachians was followed by the emplacement of diabase dikes around 200 Ma (Schlische and others, 2002). A number of these Jurassic dikes (Jd) pass through the map area, cutting obliquely across all lithologies and ductile structures with geometries that are clearly indicative of brittle conditions. The dikes represent the last major tectonicallyrelated structures in the region; lack of obvious offset along the dikes indicates that any subsequent deformational features are subtle. Cenozoic and Mesozoic brittle structures along the Harris Creek

and Roundabout Farm faults Roundabout Farm, located at the confluence of Harris Creek and the South Anna River, is close to the approximate surface projection of the Quail fault and

includes the Harris Creek fault, which is the faulted contact between the Ellisville neck and the Chopawamsic Formation. Trenches were dug on the farm to look for brittle structures and evidence of neotectonic reactivation of the Harris Creek and Roundabout Farm faults (Burton and others, 2015b). The trenches showed evidence of brittle deformation along both faults, including brecciated quartztourmaline veins, slickensides, and clay gouge; the geometry of en echelon quartz-tourmaline veins in the Roundabout Farm fault zone suggest dextral transpression (Burton and others, 2015b). Small northeast-trending, southeastand northwest-dipping thrust faults in the fault zone offset Quaternary soil horizons developed in saprolitized Chopawamsic Formation granofels and phyllite (Oc) by several tens of centimeters (fig. 9), indicating a Quaternary age for the faulting (Burton and others, 2015b). Detailed discussion of trenching results is presented in Burton and others (2014, 2015b). Southwest along the Harris Creek fault about 3 km from Roundabout Farm, two approximately north- to south-trending diabase dikes (Jd) cross the fault and the contact between the Ellisville neck and the granofels and phyllite of the Chopawamsic Formation (Oc). Precise mapping of diabase float near the contact suggests that the dikes do not continue uninterrupted across the fault. The westernmost dike northwest of the fault is truncated at the fault and splits into two branches southeast of the fault. The easternmost dike has a splay on the northwest side of the fault and may be offset 10 to 20 m as it crosses the fault to the southeast. Where the eastern dike intersects the fault, and in a small area to the south near the dike, float of a hematite-quartz breccia (Jvgb) is present that contains clasts of Chopawamsic Formation metavolcanic rock. The quartz may have originated from hydrothermal activity associated with the dike, but later experienced some form of cataclasis. Hematite-quartz breccia is a common feature associated with early Mesozoic faults in the Appalachians (Burton and others, 2005). The breccia, along with the quartz-tourmaline veins and clay gouge that is exposed in the Roundabout Farm trenches, can be considered evidence for early Mesozoic extensional reactivation of the Harris Creek and Roundabout Farm faults.

Other brittle faults in the map area Brittle faults with measurable offsets are present elsewhere in the map area. The most notable location, in the Louisa quadrangle, is a 2-m-deep excavation made in saprolite for the foundation of Louisa Tractor Supply, on the south edge of the town of Louisa (area on map labeled "Sewage Disposal"), near the southwest contact of the Ellisville pluton (SOeg). The faults are mostly north- to northeast-striking, northwest-dipping reverse faults that show offsets up to a meter in layers in Chopawamsic Formation and in intruding aplite and pegmatite dikes from the nearby pluton (Carter, 2015). Dips on the faults decrease from about 70 degrees to 25 degrees as the faults approach the B soil horizon, and the faults are characterized by slickensided clay gouge and (or) manganese oxide coating (Carter, 2015). The fault offset could not be confirmed as extending into the B soil horizon, which would suggest a Quaternary age for deformation (Carter, 2015). Another unnamed reverse fault observed in a tall cutbank of saprolite, south of Green Springs in the Louisa quadrangle, cuts moderately east-dipping layers of Byrd Mill formation phyllite and metagraywacke (£Zb). Similar to the faults in the foundation excavation noted above, this fault strikes north to northeast and dips about 70 degrees to the northwest, with an offset of a few centimeters. The narrow fault zone is occupied by a thin seam of fractured milky quartz and clay gouge.

The orientations of most joints and joint sets observed in outcrop were measured in the map area. For sets of closely spaced, coplanar joints (joint sets), the strike and dip of one representative joint was determined and multiplied by the number of joints. Figure 10A-H shows stereonets and azimuth-frequency diagrams that summarize the measured orientations of outcrop-scale joints from lithologic units in the map area. The results indicate that that the joints in most of the map units have a strong preferred northwest-striking orientation (fig. 10B-F, H), roughly orthogonal to the general trend in strike of the Paleozoic ductile structures S<sub>4</sub>, S<sub>5</sub>, E<sub>4</sub>, and E<sub>5</sub>. The preferred northwest-striking orientation includes joints in the Jurassic diabase dikes (Jd) (fig. 10H), which indicates that joints with this preferred northwest-striking orientation formed after 200 Ma. The northwest-striking orientation implies joint formation by a northwest-southeast principle compressive stress, coupled with northeast-southwest extension. There are two exceptions to the dominant northwest-striking orientation of joints in the map area that include joints in the Green Springs pluton (fig. 10G) and joints in the Chopawamsic Formation that are southeast of the Ellisville neck

number on | Quadrangle | from previous | Map unit

preferred northeast-striking orientation for joints in the Green Springs pluton was determined to be one set of closely spaced joints that dominated a small set of field measurements (n=30); note that a less preferred, northwest strike was also determined to be present in joints of the Green Springs pluton (fig. 10G). More intriguing are the joints in the Chopawamsic Formation measured southeast of the Ellisville neck (fig. 10A), where a large dataset (n=405) of field measurements showed a range of northeast to northwest joint orientations. This region most closely corresponds to the approximate surface projection of the Quail fault, which was responsible for the 2011 Mineral, Va., earthquake and many of the aftershocks that occurred. The range of joint orientations suggests that the area was subjected to a greater variety of directional stresses than the area northwest of the Ellisville neck; some of these joints could be related to Mesozoic extension, and some joints may be the result of neotectonic forces. Due to the limited outcrop exposure and a high degree of decomposition and weathering (weather-

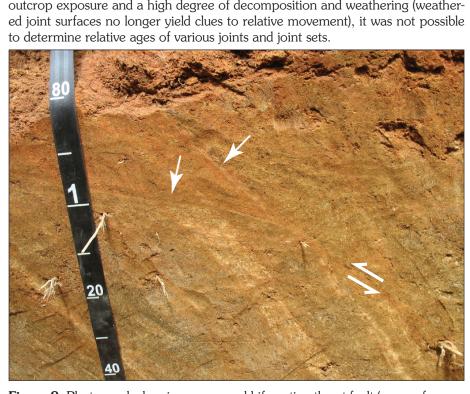
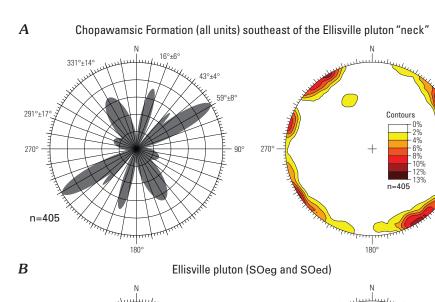
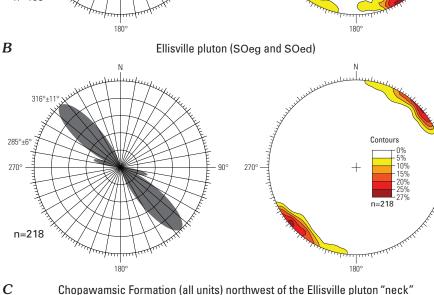
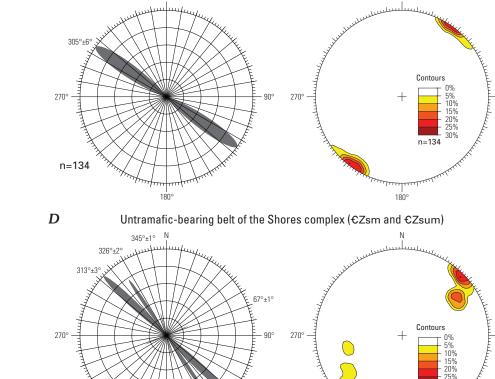
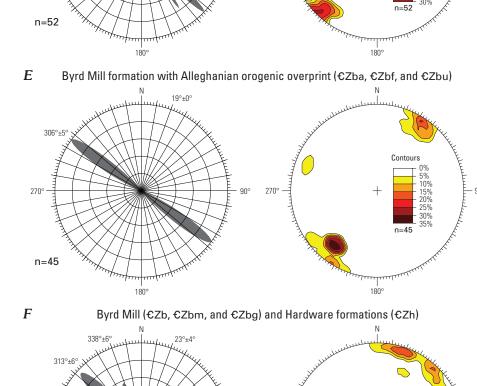


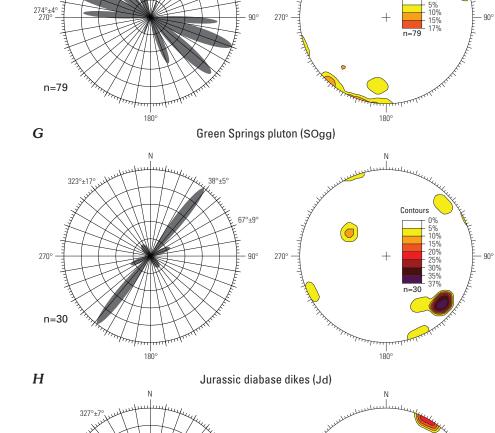
Figure 9. Photograph showing an upward-bifurcating thrust fault (sense of movement shown by half arrows) in saprolitized layers in Chopawamsic Formation granofels and phyllite (Oc). Full arrows show the locations of the splays of the thrust fault. Tick marks on the black measuring tape are in tenths of a meter. Figure from Burton and other (2015b). 1 meter = 3.28 feet.

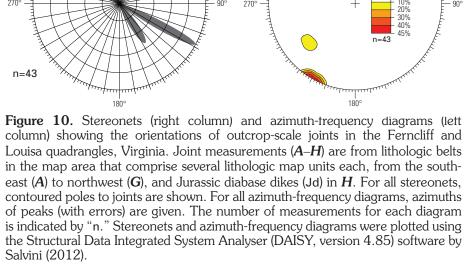












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Table 1. Bedrock sample locations (1–21) and age results from the Ferncliff and Louisa quadrangles, Virginia. [Note that the sample locations (1–21) on the geologic map are located at the nearest strike and dip symbol. Metamorphic ages were determined using muscovite, amphibole, and potassium feldspar using 40Ar/39Ar analysis (sample locations 1–13); sedimentary provenance ages were determined using detrital zircon U-Pb analysis (sample locations 14–17, and 20); and igneous crystallization ages were determined using zircon U-Pb analysis (sample locations 18, 19, and 21). Samples from locations 1-16 and 21 were collected and analyzed by the USGS, and samples from locations 17–20 were collected and analyzed by K. Stephen Hughes of North Carolina State University. <sup>40</sup>Ar/<sup>39</sup>Ar age of amphibole from sample location 5 is from McAleer (2017). The U-Pb crystallization age for igneous zircon from sample location 18 is from Hughes and others (2014b) and the U-Pb crystallization age for igneous zircon from sample location 19 is from Hughes and others (2013). Detrital zircon U-Pb peak ages (sample locations 17 and 20) are from figure 4 of Hughes and others (2014a). Preliminary <sup>40</sup>Ar/<sup>39</sup>Ar age-data (sample locations 1–13) are discussed in Burton (2015a), McAleer (2017), and in the "Grade and age of metamorphism" section. Preliminary detrital zircon U-Pb age-data (sample location 14) is discussed in Holm-Denoma (2016). The U-Pb crystallization age for igneous zircon from sample location 21 is from McAleer and others (2018). Abbreviations: Ar, Argon; LA-ICP-MS, laser ablation inductively coupled plasma mass spectrometry; Ma, mega-annum (million years before present); SHRIMP, sensitive high-resolution ion microprobe; TIMS, thermal ionization mass spectrometry; U-Pb, uranium-lead. Notes: a, Neoproterozoic detrital muscovite preserved; b, no age reported, muscovite partially altered to kaolinite; c, excess <sup>40</sup>Ar in muscovite, age greater than age of map unit; d, no zircon found in sample]

used for analysis

map		Stady				
1	Louisa	BBL-615	€Zbm, €Zb	amphibole and muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	405–425
2	Louisa	K14-05-13F	€Zba	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	405–425
3	Louisa	BBL-696	€Zb	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	405-425ª
4	Louisa	K14-05-13E	€Zba	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	330–365
5	Louisa	K14-05-13C	€Zsum	amphibole	<sup>40</sup> Ar/ <sup>39</sup> Ar	~450
6	Louisa	K14-05-13D	€Zsm	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	<330
7	Ferncliff	K14-04-25A	€Zba	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	330–390
8	Ferncliff	K14-05-13A	€Zsm	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	b
9	Ferncliff	K14-05-12G	€Zsm	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	<330
10	Ferncliff	K14-05-25B	Oc	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	С
11	Ferncliff	BBF-160	Ocqs	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	294±1.5
12	Ferncliff	K14-04-25C	Ос	muscovite	<sup>40</sup> Ar/ <sup>39</sup> Ar	285±2
13	Ferncliff	K14-05-12H	Ос	amphibole	<sup>40</sup> Ar/ <sup>39</sup> Ar	311±4
14	Ferncliff	BBF-220	€Zsm	detrital zircon	U-Pb (LA-ICP-MS)	~900–2,800
15	Ferncliff	BBF-180	Qal	detrital zircon	U-Pb (LA-ICP-MS)	d
16	Ferncliff	BBF-160	Ocqs	detrital zircon	U-Pb (LA-ICP-MS)	d
17	Ferncliff	KSH-11-08	€Zb	detrital zircon	U-Pb (LA-ICP-MS)	1,010; 1,134; 1,420
18	Ferncliff	KSH-84	Ocf	igneous zircon	U-Pb (TIMS)	468.2±1.10
19	Ferncliff	KSH-86	SOeg	igneous zircon	U-Pb (TIMS)	443.7±3.30
20	Ferncliff	KSH-11-39	Oc	detrital zircon	U-Pb (LA-ICP-MS)	458
21	Ferncliff	BBF-019	Ocf	igneous zircon	U-Pb (SHRIMP)	460±4

- Apparent dip of  $\mathsf{S}_0$  (bedding and compositional layering) and  $\mathsf{S}_1$  schistosity (formlines)

Base from U.S. Geological Survey, 1960, 1:24,000; revised in 1969

1,000-meter Universal Transverse Mercator grid ticks, zone 17

10,000-foot grid ticks based on Virginia coordinate system, north zone,

Additional modifications to base map were made from lidar imagery in 2016

South Anna

Upland residual

Ellisville and

plutons

fault (Taconic)

Formation

(volcanic arc)

Accretionary wedge (

(Mine Run Complex

mélange zone III

of Pavlides, 1989)

metasediments

(Mine Run Complex -

mélange zone IV

of Pavlides, 1989)

Surficial deposits not show

Reactivated fault

Laurentian slope-rise Byrd Mill fault

Green Springs

Byrd Mill fault (Taconic) CZbf CZba CZb

€Zbu 🔁

Intrusive and

**CORRELATION OF MAP UNITS** 

**Unconsolidated Surficial Materials** 

Qal

Metasedimentary,

metavolcanic,

and ultramafic rocks

**QUATERNARY** 

- JURASSIC

PERMIAN(?

SILURIAN

ORDOVICIAN

(Brown, 1986) NEOPROTEROZOIC(?)

North American Datum of 1983

and Maryland coordinate system

NO VERTICAL EXAGGERATION  $\square$  S<sub>0</sub> (bedding and compositional layering) and S<sub>1</sub> schistosity (formlines)  $\square$