STITCHING THE WESTERN PIEDMONT OF VIRGINIA:

Early Paleozoic Tectonic History of the Ellisville Pluton and the Potomac and Chopawamsic Terranes

44th Annual
Virginia Geological
Field Conference

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R. Tyler Sauer, and William C. Burton

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Cover Illustrations:

Main photo: medium-grained, porphyritic phase of the Late Ordovician-Early Silurian Ellisville pluton near Goldmine Creek, Louisa County. Compass is 7 cm wide.

Inset upper right: dike of Ellisville granodiorite intruding Mine Run Complex phyllite of the Potomac terrane near Lake Louisa, Louisa County.

Inset lower right: dikes of Ellisville granodiorite intruding Chopawamsic Formation volcaniclastic rock near Harris Creek, Louisa County.

2014 Virginia Geological Field Conference

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Early Paleozoic Tectonic History of the Ellisville pluton and the Potomac and Chopawamsic terranes

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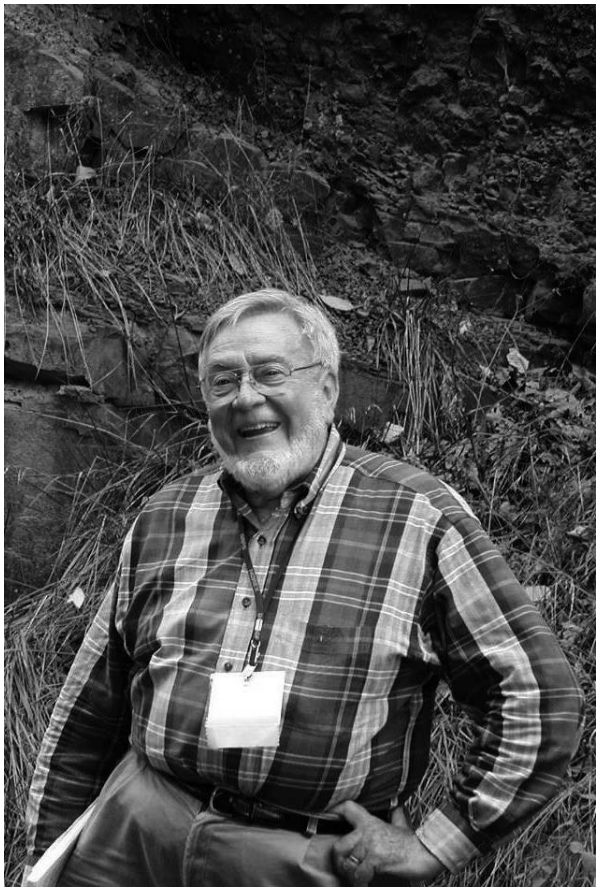
Dedication
John Manley Dennison
1934-2014

The 44th annual Virginia Geological Field Conference is dedicated to the memory of Dr. John M. Dennison, stratigrapher, field geologist, and professor. John taught at the University of Illinois from 1960-1965, the University of Tennessee at Knoxville from 1965-1967, and at the University of North Carolina at Chapel Hill from 1967 until he retired in 1999. He chaired the Geology Department at UNC from 1969 to 1974. Although John never lived or taught in Virginia, he made a lasting mark on Virginia geology, and he frequently admitted that his heart was here, especially in Blue Grass Valley.



John's career revolved around his interest in the Appalachians, and he made many significant contributions to Virginia geology, including Paleozoic stratigraphy, regional tectonics and structural development, unconformities, eustacy, and energy resources. John is probably best known for meticulous field mapping of Devonian shales and the Tioga bentonite. John's scientific curiosity was instrumental in the recognition that the dike swarm in Highland County is Eocene in age. He had a genuine knack for making scientific inferences and was a master of inductive geologic reasoning.

John was the author or co-author of over 100 publications, 16 books, and over 100 abstracts. He received the I.C. White Award in 1993, the Outstanding Educator Award from the Eastern Section of AAPG in 1997, and the John T. Galey Award from Eastern AAPG in 2006. He was a fellow of the Geological Society of America, and the American Association for the Advancement of Science. He was Chairman of the Southeastern Section of the Geological Society of America, and President of the Carolina Geological Society.

John was a warm, kind-hearted gentleman who always went out of his way for others. His impact on Appalachian geology will continue to grow through the many grad students, colleagues and friends whom John actively inspired and encouraged. He went out of his way to share his work and interests, and to encourage others to build on, challenge, or disagree with anything he did. To quote John, "Geology is made up of mostly people, a few rocks, and some interesting restaurants along the way."

2014 Virginia Geological Field Conference
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Introduction

The theme of the 2014 Virginia Geological Field Conference is the tectonic development, economic geology, and seismicity of the western Piedmont of Louisa County, Virginia. It is timely for the conference to turn its attention here, for during the past decade these aspects of western Piedmont geology have garnered the renewed attention of researchers. In terms of regional tectonics, it has been hypothesized that the major structure in the region, the Chopawamsic fault system, represents the most significant boundary in the Appalachian orogen, the main Iapetan suture (Hibbard et al., 2014). Economically, recent elevated market values of metals—particularly that of gold—has spurred reconsideration of the economic geology of the western Piedmont. Finally, the August 23, 2011, M5.8 earthquake, with its epicenter in our field area, startled the North American east coast and has revived awareness of the seismic potential of the region.

This renewed interest in the geology of the western Piedmont of north-central Virginia has led to new detailed bedrock mapping, detailed surficial mapping, high-resolution U-Pb TIMS zircon geochronology, U-Pb LA-ICP-MS detrital zircon geochronology, radiogenic isotope geochemistry, major/minor/REE geochemistry, and geophysical studies (e.g. Bailey et al., 2005, 2008; Bailey and Owens, 2012: Berti et al., 2012; Burton et al., 2014; Burton, in progress; Harrison, 2012; Horton et al., 2010, in press; Hughes, 2010, 2014; Hughes et al., 2013a, 2013b, 2014, in press a, in press b; Malenda, in progress; Owens et al., 2013; Spears and Gilmer 2012; Spears et al. 2013, Terblanche, 2013; Terblanche and Nance, 2012). A host of institutions have taken part in the research, including North Carolina State University, the Virginia Department of Mines, Minerals, and Energy, the U.S. Geological Survey, Virginia Tech, Lehigh University, and the College of William and Mary. Many of these investigations remain active. The majority of the data presented herein is the product of research conducted from 2010 to 2014 by geologists at North Carolina State University.

This field trip guide is intended to complement a Geological Society of America field guide (Hughes et al., 2014) that covers the western Piedmont geology along strike to the northeast in the vicinity of Fredericksburg. Geologic mapping and geochronologic and geochemical sampling were coordinated between these two areas as part of a study funded in part by the National Science Foundation and the USGS EDMAP program. Some of the stops in this guide have previously been written up in past field guides (Hughes, 2010; Burton et al., 2014) and are reused here because of their ease of access for large groups and because of new data that update the context and our understanding of the outcrops.

Regional Tectonic Context

The western Piedmont of north central Virginia (Fig. 1) is bisected into two major crustal blocks, including a mainly metaclastic tract to the west, and a magmatic tract to the east, by the Chopawamsic fault system (Hibbard et al., 2014). In the field trip area, the metaclastic tract is known as the Potomac terrane and the magmatic tract is termed the Chopawamsic terrane. There is no known basement in either terrane. However, rocks in the metaclastic Potomac terrane are interpreted to have been derived from Laurentia,

based upon their geographic position, depositional relationship with known Laurentian sedimentary rocks to the west, and limited detrital zircon analyses, (Evans, 1984; Drake, 1989; Pavlides, 1989; Pavlides et al., 1994; Horton et al., 2010). Some models also considered the Chopawamsic terrane to be of Laurentian origin, solely on the basis of its geographic position and an inferred depositional relationship with the Potomac terrane. However, consideration of the stratigraphic character and lead isotope signature of the Chopawamsic terrane has led to the hypothesis that it is peri-Gondwanan in origin (Hibbard et al., 2014). If the Chopawamsic terrane originated as part of the peri-Gondwanan realm it implies that the Chopawamsic fault system marks the main suture of the global scale early Paleozoic Iapetus Ocean.

In 2010, the Appalachian research group at North Carolina State University set out to investigate the relationship between the Potomac and Chopawamsic terranes. Older geologic maps (e.g. Pavlides, 1981, 1989; Pavlides et al., 1994) depict a granodiorite body, the Ellisville pluton, as intrusive into both terranes across the Chopawamsic fault system in Louisa County. However, no description of this relationship could be found in the literature. With funding from the USGS EDMAP program and NSF, we set out to determine if the Ellisville pluton stitched the Potomac and Chopawamsic terranes; specifically, we directed our studies at the nature, contact relationships, and age of the pluton. We have also directed studies at determining the kinematics of the Chopawamsic fault system, the age of the Potomac and Chopawamsic terranes, and the paleogeographic affinity of the Chopawamsic terrane in order to test the hypothesis that the fault represents the main Iapetan suture. Our results are interspersed with an overview of the geological elements of the region below.

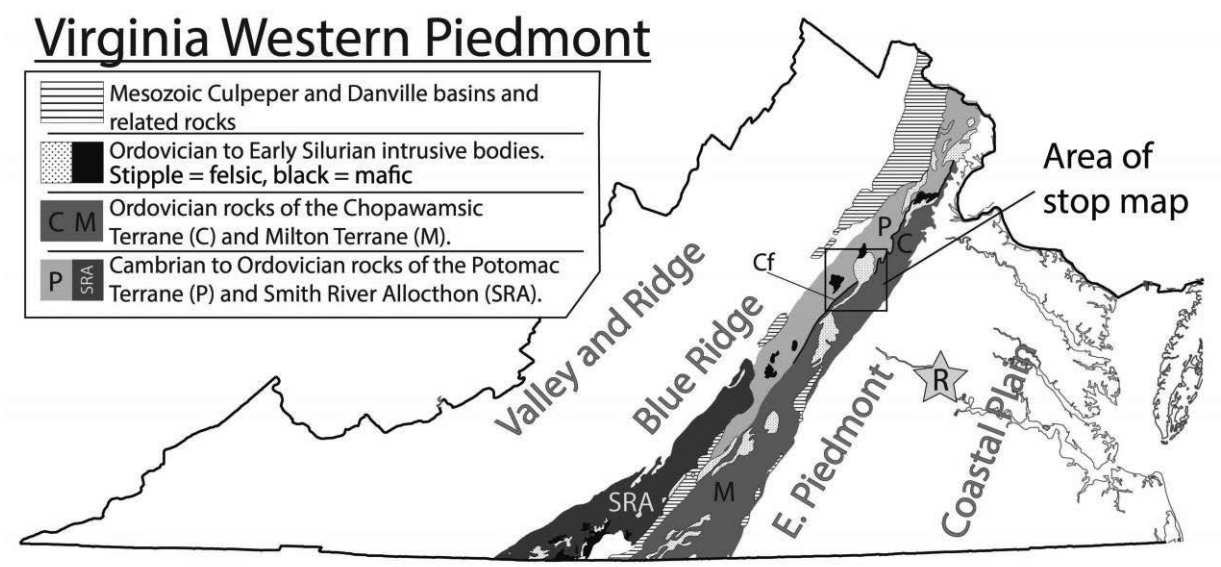

Figure 1: Generalized geologic map of the western Piedmont of Virginia. Cf = Chopawamsic fault, R = Richmond. Geology modified from Hibbard et al. (2006). Stop map is on back cover of guidebook.

Potomac terrane: This composite block of crust is comprised of low-grade metaclastic units interpreted to be derived from the Laurentian craton in the early Paleozoic (Drake, 1989; Pavlides, 1989; Horton et al., 2010; Hibbard et al., 2014). Schists, metasandstones, and metagraywackes of the Potomac terrane were intruded by a suite of Ordovician–Silurian granitoid bodies; the oldest known pluton is the Occoquan granite (ca. 472 Ma; Aleinikoff et al., 2002). In addition to this cross-cutting relationship, detrital zircon analyses (Hughes et al., in press b) from the Potomac terrane reveal zircon grains as young as ca. 500 Ma. These data, considered in combination with the oldest rocks intrusive into the Potomac terrane, indicate that at least some parts of the composite Potomac terrane were deposited in the Late Cambrian to Early Ordovician, between ca. 500 – 470 Ma.

Map scale granitoid bodies in the Potomac terrane have previously been referred to as "blocks" by some researchers (Pavlides, 1989). Some of these blocks were previously interpreted to be derived from the Chopawamsic terrane (Pavlides, 1989). Three of the largest of these bodies have been dated with the U-Pb zircon TIMS method at 473 – 469 Ma (Hughes et al., 2014) and, based upon their age, appear to be consistent with derivation from the Chopawamsic arc. However, because of the lack of any detrital zircons younger than ca. 500 Ma recovered from the nearby Potomac terrane metaclastic rocks, these bodies are now considered to be either intrusive or tectonically emplaced into the metaclastic terrane (Hughes et al., 2014).

Chopawamsic terrane: This crustal block is the metamorphosed vestiges of the Early - Middle Ordovician Chopawamsic volcanic arc. It consists of a metamorphosed suite of bi-modal volcanic rocks and associated metasedimentary rocks. The Chopawamsic arc was once thought to be Cambrian (Pavlides, 1981; Mixon et al., 2000) and directly related to the crustal block of Carolinia (e.g. Glover et al., 1997). However, high resolution U-Pb zircon TIMS geochronology on metavolcanic and metaigneous rocks from the Chopawamsic terrane shows that the arc was active between 474 – 465 Ma (Coler et al., 2000; Hughes et al., 2013b, 2014, this guide), thus leading to modifications in tectonic models suggested for the development of the western Piedmont (Hughes et al., 2014). Considering the chronological constraints outlined above, it appears that the Potomac and Chopawamsic terranes did not originate at the same time and were not depositionally linked.

Because ca. 1.1–1.0 Ga inherited zircons have been found in volcanic rocks of the Chopawamsic terrane, it has been interpreted to have been built upon Mesoproterozoic crust (Coler et al., 2000). An evolved Nd isotopic character also supports this hypothesis (Coler et al., 2000). However, the crustal affinity of this "geochronological basement" is unknown, as Mesoproterozoic xenocryst zircons have been recovered from magmatic rocks in both Laurentian and Gondwanan crustal realms.

Two pre-existing lines of evidence favor, although do not prove, a peri-Gondwanan origin for the Chopawamsic arc. First, the arc is overlain by black slate and phyllite (successor basins described below); this sequence of arc rocks overlain by black fine-grained metaclastic rocks is one of the defining characteristics of the peri-Gondwanan Iapetan arcs in the northern Appalachians (Williams

et al., 1988) and it is uncommon in peri-Laurentian arcs. Secondly, lead isotopic compositions of volcanic-hosted massive sulfide (VHMS) deposits in the Chopawamsic arc are relatively radiogenic (Pavlides et al., 1982; Swinden et al., 1988) and identical to those of peri-Gondwanan VHMS deposits of the northern Appalachians.

Detrital zircon results from meta-sedimentary units in the Chopawamsic terrane include grains that are mostly coeval with the age of the Chopawamsic volcanics (Hughes et al., in press b). About 10% of the grains from Chopawamsic metasedimentary rocks analyzed do have ages that are Cambrian to Cryogenian and are potentially derived from a peri-Gondwanan source.

Chopawamsic fault system: The Chopawamsic fault is the principal boundary between the Chopawamsic and Potomac terranes. However, further northeast (near Storck, VA) and to the southwest of the field trip area—from the Ellisville pluton to at least the James River, a narrow, possibly discontinuous, belt of "exotic rocks" (see discussion below) intervene between the two terranes. Although the contact is unexposed, these exotic units are presumably in fault contact with both terranes. Because of the unknown relationship between the bounding faults on either side of these exotic units, we refer to them as part of the Chopawamsic fault "system" in these areas. The exotic belt to the southwest of the field trip area may be bounded on its northwest side by the Shores fault (equivalent to the Byrd Mill fault [Burton et al., 2014]), which we consider part of the Chopawamsic fault system.

Although poorly exposed, the system has been interpreted as a steeply dipping thrust zone emplacing the Chopawamsic terrane, and—where present—exotic units, over the Potomac terrane (e.g. Brown, 1986; Pavlides, 1989, 1990, 1994; Pavlides et al., 1994; Mixon et al., 2000, 2005) with a sinistral component of slip (Hughes, 2010; Hughes et al., 2013a).

In the field trip area, our recent research has demonstrated that the Chopawamsic fault is intruded by the ca. 444 Ma Ellisville biotite granodiorite (Hughes et al., 2013a). By using the age of the cross-cutting Ellisville pluton (Hughes et al., 2013a) and the youngest high-precision U-Pb zircon TIMS age of known Chopawamsic volcanism (465 Ma, see: Stop 2-3 of Hughes et al., 2014) in the hanging wall, it can be surmised that the Chopawamsic fault is a Middle – Late Ordovician structure, active sometime between 465 – 444 Ma. Because it marks the boundary between the two terranes and there is no evidence for post Ordovician movement (i.e. no offset in the Ellisville pluton), this window of time is also interpreted to mark (1) the accretion of the Chopawamsic terrane to the Potomac terrane on the leading edge of Laurentia, and (2) the possible closure of the Iapetus Ocean.

Exotic units: Recent investigations have identified mappable units of rock along the Chopawamsic fault system that appear to be distinct from either the bordering Potomac or Chopawamsic terranes (Hughes et al., in press b; Burton et al., in press); we informally refer to these as "exotic units." They have been identified along the Rappahannock and South Anna rivers and are potentially correlative (Hibbard, pers. comm., 2012) with the Shores mélange (Brown, 1986). These rocks are generally metaclastic, but in some places contain bodies of metaigneous rock. These exotic units represent the only exposed

remnants of features that may have existed between the Potomac and Chopawamsic terranes prior to their juxtaposition. Detrital zircon analyses from some of these rocks show contribution from a collection of Cryogenian to Cambrian (ca. 800 – 500 Ma) and Paleoproterozoic (ca. 2.0 Ga) sources, a hallmark of peri-Gondwanan terranes (Bailey et al., 2008; Hughes et al., in press b).

The geographic position of these peri-Gondwanan-derived metaclastic rocks at the western margin of the Chopawamsic arc lends further support to the interpretation of a peri-Gondwanan-affinity for the Chopawamsic terrane. Future investigation is required to determine their relationship to both the Chopawamsic and Potomac terranes.

Successor basins: The Chopawamsic terrane is unconformably overlain by metaclastic rocks that were deposited after Late Ordovician igneous bodies that intrude the terranes had been uplifted to the surface. This package of slates, schists, quartzites, and volcanic tuffs is preserved in the Arvonia and Quantico sub-basins that directly overlie the Chopawamsic arc and some latest Ordovician plutonic rocks that intruded the terrane, likely after it docked with Laurentia. Detrital zircon analyses from metasedimentary rocks of the successor basin system indicate that they were likely derived from both the Potomac and Chopawamsic terranes (Hughes et al., in press b). Although Late Ordovician fossils are reported from parts of the successor basins (Darton 1892; Dale 1906; Watson and Powell 1911; Stose and Stose 1948; Smith et al. 1964; Brown 1969; Tillman 1970; Pavlides 1980; Kolata and Pavlides 1986; Hibbard et al. 2014), our detrital zircon study indicates that the youngest sediments had to have been deposited in the Silurian or later.

Summary of Paleozoic tectonic history: Our recent studies in the vicinity of Louisa County have produced a new perspective on the tectonics of the western Piedmont. Our research demon-strates the following:

- The Potomac terrane appears to be Late Cambrian to Early Ordovician and originated proximal to Laurentia.
- The Chopawamsic terrane is an Early-Middle Ordovician arc that did not provide detritus to the older Potomac terrane.
- The Ellisville pluton intrudes both the Potomac and Chopawamsic terranes, stitching them at ca. 444 Ma.
- The Chopawamsic fault system, the contact between the Potomac and Chopawamsic terranes, was active in the Late Ordovician, probably as a thrust with a sinistral component of motion.
- Some exotic rock units along the Chopawamsic fault system contain a Gondwanan detrital signature, suggesting that the Chopawamsic terrane is of peri-Gondwanan crustal affinity.

The timing and kinematics of the Chopawamsic fault suggest that it is a manifestation of the Late Ordovician Cherokee orogeny (Hibbard et al., 2012) that marked the collision of the peri-Gondwanan crustal block of Carolinia with Laurentia. Although our studies imply that the Chopawamsic terrane is likely peri-Gondwanan, we still require more data to state this with absolute confidence. In this vein, our ongoing studies are focused on the Pb and Nd signatures of plutons and Hf

signatures of individual zircons in the Potomac and Chopawamsic terranes.

Economic History of the Area

In Louisa County, the Mineral District consists of three parallel alignments of pyritic base and precious metal mines and prospects (Fig. 2). Base and precious metal deposits were exploited from the early 1800s until the Civil War, then again from 1865 until the 1920s. Pre-Civil War mines were worked from shallow cuts and pits and focused on iron and minor precious metals in leached and oxidized gossans exposed in outcrop.

After the War Between the States, underground mines were developed on pyritic and precious metal deposits in the district. The most extensive of these workings was developed at the Arminius mine, which is located on Contrary Creek ~1.5 km NNE of the town of Mineral. Arminius was served by three or more inclined shafts and development extended to 1,100 ft. below surface with over 2,500 ft. of drifts on 10 working levels. During this period, sulfur from pyrite was the principal commodity of interest; it was used to produce sulfuric acid. Pyrite ore was shipped to offsite refiners around the country via railroad. In the 1920s, new technology to extract native sulfur from Gulf Coast sediments became a more cost effective means of collection and put the mines in the Mineral district out of business.

Work in the Mineral District ceased from the 1920s until 1950. In 1951, the New Jersey

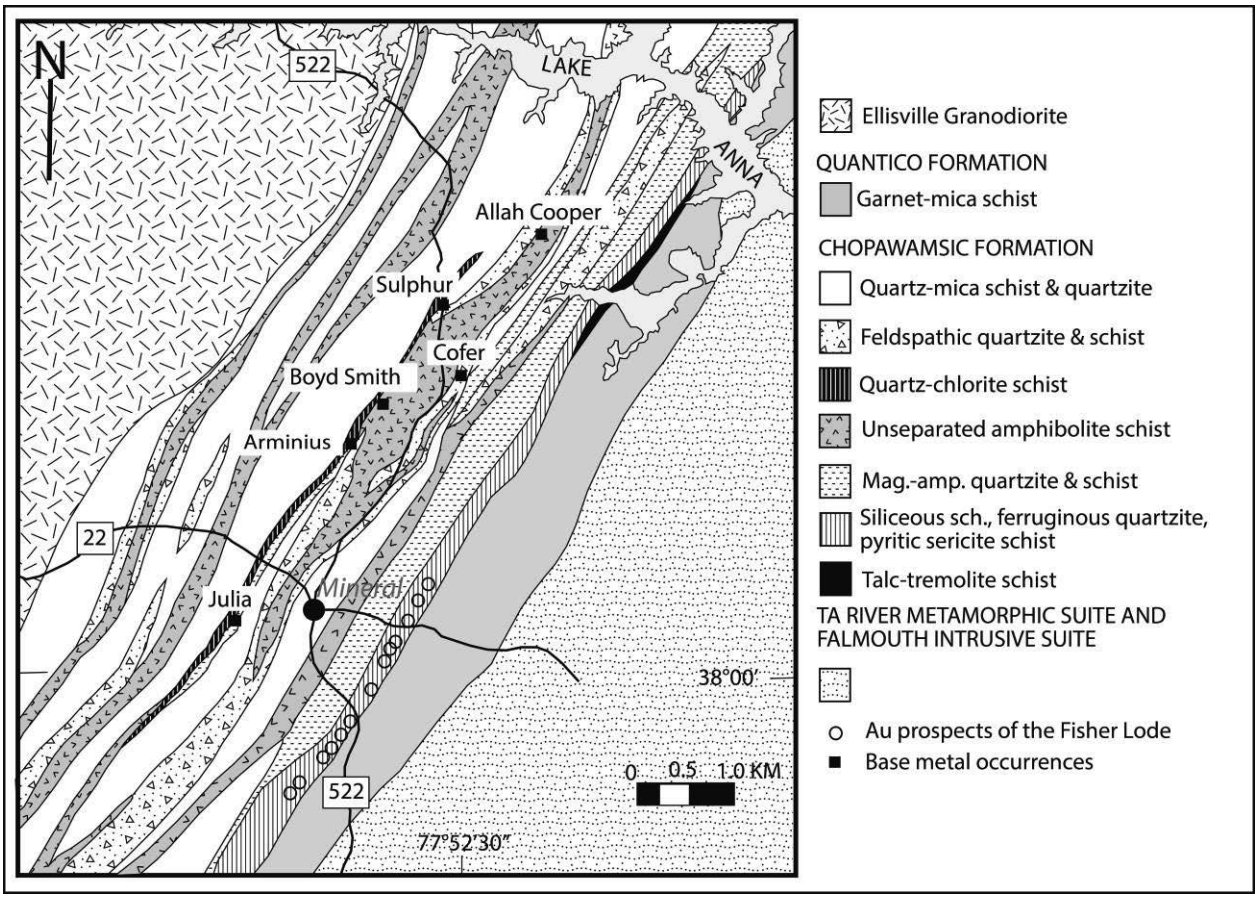

Figure 2: Detailed geologic map of the bedrock in the Mineral District area. Map from Sauer (1984).

Zinc Co. (NJZ) leased previously exploited properties in the district as part of their regional exploration program in central Virginia. During this period, the commodities of interest were zinc from sphalerite, copper from chalcopyrite and lead from galena. Pyrite continued to be collected for sulfuric acid production. At Arminius, the workings were dewatered and rehabilitated. Accessible levels were mapped and sampled and drilling was undertaken to test for deep extensions of the Arminius ore body. Approximately 20 ft. of mineralization was penetrated at 2,100 ft. below the surface and it remains open in three directions. NJZ calculated 3.38 million tonnes of ore remained at Arminius but the grade was not economic at 1950s base metal prices.

Activity in the district again ceased between 1958 and 1973 when NJZ and Callahan Mining Corp. (CMC) formed Piedmont Mineral Assoc. (PMA) with CMC as the operator. Its primary objective was to further define grade and tonnage of the recently discovered Cofer deposit. PMA calculated a resource of 1.328 million tonnes, however, the laterally discontinuous nature of numerous massive sulfide lenses precluded the development of undiluted tonnage. The venture was dissolved and CMC continued with their exploration of airborne electromagnetic anomalies in the district and elsewhere in the Chopawamsic Formation.

In 1979, CMC formed a joint venture with Boliden Metal, AB. This venture systematically drilled deep holes beneath and between the Sulphur and Boyd Smith mines. Massive sulfide mineralization was encountered in most of the holes but reserves were not significantly increased. No further work was recommended and the venture continued in Virginia exploring for gold until 1982.

Recent Seismic Activity

On August 23, 2011, a M5.8 earthquake occurred ~8km below Louisa County and was felt by more people than any other earthquake in United States history (McNamara et al., 2011; Chapman, 2013). Seismicity in the region is common in an area recognized as the Central Virginia Seismic Zone (CVSZ). Known events in the CVSZ are geographically diffuse and haven't been compellingly correlated with previously mapped faults, likely because of poor epicentral locations and a lack of detailed geologic mapping in much of the area. The 2011 seismic event served as a costly reminder that seismogenic structures do exist in the CVSZ and are capable of causing significant damage. In Louisa County, estimates of damage exceeded $80 million, most of that specific to county school buildings (Dennen, 2011).

Because many ductile faults in the Virginia Piedmont have a brittle overprint (e.g. Bourland, 1976; Bobyarchick and Glover, 1979; Bourland et al, 1979; Weems, 1981; Gates, 1986, 1997; Pavlides, 1987, 1989, 2000; Pavlides et al., 1983, 1994; Spears and Bailey, 2002; Bailey et al., 2004; Spears et al., 2004; Spears, 2010; Henika, 2012; Hollis and Bailey, 2012; Quinlan, 2012; Spears and Gilmer, 2012), it is important to carefully map and thoughtfully interpret the geology of the epicentral area to better understand the rupture of the 2011 event and seismicity in the CVSZ. Some such mapping took place before the event (Hughes, 2011) and other mapping has been spurred by the earthquake (e.g.: Spears et al., 2013; Burton et al., 2014) with still more mapping being conducted in the area (Burton, in progress; Carter, in progress; Malenda, in progress). Because of the preponderance of ductile features in the region that show a record of reactivation in the shallow crust, and the local

coincidence of the projection of ductile features observed at the surface with a robust aftershock dataset, a similar modern seismogenic exploitation of relict ductile fabrics has been proposed for the 2011 Virginia earthquake (Hughes et al., in press a; Burton et al., in press).

Acknowledgements

The authors thank the following parties for their assistance in making the 2014 VGFC a reality: the Virginia Museum of Natural History, the Louisa County High School Culinary Arts program, Deborah Pettit, numerous hospitable Louisa County property owners, and the 2014 VGFC officers: Scott Eaton, Robin Reed, Matt Heller, and Chuck Bailey. We also appreciate Mark Carter and Rich Harrison for their expedient reviews of this field guide. Mark Carter's review of and logistical assistance for this field trip are only his latest acts of generosity. His offerings of pizza, BBQ, home-brews, discussion, and friendship over the past years have provided for a richer experience in the Piedmont of Virginia. The results reported from North Carolina State University geologists were supported by a Geological Society of America graduate student grant to Stephen Hughes, USGS EDMAP grant G10AC00265 and National Science Foundation grants EAR-1048476 to Jim Hibbard, and EAR-1048472 to Brent Miller.

Logistical Concerns

Buses will transport participants from the Best Western in Zion Crossroads for the entirety of the field trip. No personal vehicles are allowed. No trip log is provided, although precise geographic coordinates (WGS-84 coordinate system) are included for each stop. The total mileage from Stop 1 to Stop 9 is approximately 56 miles (90 km). Some field trip stops listed as optional may be cut from the itinerary in the interest of time.

All stops on the trip, other than road cuts, are on private property. Permission should be obtained to access stops independently of the Virginia Field Conference.

The stop map is located on the back cover of the guidebook.

Description of Stops

Stop 1. Phyllite and Metasandstone of the Potomac terrane, Byrd Mill, South Anna River

Just East of the Byrd Mill Road (SR-649) Bridge over the South Anna River
37.988168°N, 78.080062°W

Stop Leaders:
Stephen Hughes and Jim Hibbard

**At this outcrop, an opportunity to fall into the South Anna River will afford itself; please be careful on the outcrop, especially when it is wet—as is likely to be the case because it is our first stop in the morning. Please also be extremely careful and expedient exiting and boarding the buses as they will have to temporarily stop in the lane of traffic.*

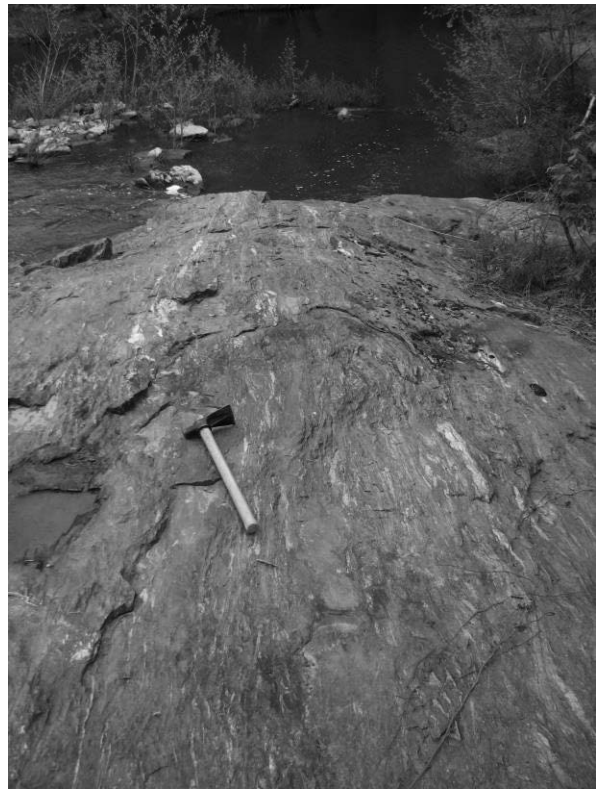

Figure 3: Pavement outcrop of phyllite and metasandstone with concordant, pre- to syn-tectonic quartz veins, Stop 1.

Remnants of the antebellum Byrd Mill dam provide the backdrop for the metamorphosed sedimentary rocks here, which are a portion of the Potomac terrane called the Mine Run Complex (Pavlides, 1989). The Mine Run Complex has been subdivided into four zones based upon geophysical characteristics and the presence of what were once considered to be detrital exotic "blocks" in the metaclastic matrix. The rock here at Byrd Mill is part of zone III, defined by its strong aeromagnetic signature and inclusion of local map-scale mafic bodies. The rock is mostly a magnetic phyllite, pinstriped with thin, commonly discontinuous veins of quartz (Fig. 3). Magnetite has a porphyroblastic texture in thin-section and can be easily detected in the field with a hand-held magnet. In some places, the phyllite is interlayered with fine-grained quartz metasandstone.

There are at least two phases of foliation here, and in most places they are parallel to each other with a general orientation of 225°/80°NW. In very few places in outcrop, the first foliation (S_1) can be seen to be folded (F_2) and cut by the second foliation (S_2). This relationship has also been observed in thin section (Fig. 4; Hughes et al., 2013a). The discontinuous quartz veins are parallel to the two generations of foliation and all of these features may be a result of progressive deformation. Many of the quartz veins and

layers in the phyllite and metasandstone are isoclinally folded, in some places with limbs being partially transposed. A few asymmetric fabrics on sub-horizontal surfaces of the outcrop consistently show a dextral sense of shear (Fig. 5).

In this area, other outcrops of the same rock type have fold axes trending/plunging at 30°/30° on an axial plane striking/dipping at 30°/85°SE. These outcrop scale measurements are consistent with more than 60 foliation measurements made upon rocks in zones III and IV of the Mine Run Complex in the Ferncliff Quadrangle. Stereonet analysis suggests that the area west of the Chopawamsic fault is folded at map scale with a fold axis trending/plunging 33°/31° (Hughes, 2010). The continuity of structural style across the units has also been used to suggest that the contact between units III and IV of the Mine Run complex could be stratigraphic (Hughes, 2011) rather than faulted (Pavlides, 1989; 1990; Mixon et al., 2000).

The bedrock here also includes quartz veins that are much larger and also younger than the pinstripe variety found concordant with the foliation (Fig. 6). Two examples of this generation are exposed here are have an attitude of 155°/50°SW. A pervasive joint set is has an attitude of 295°/88°N, which is nearly orthogonal to the orientation of the foliation.

We collected six samples from the Potomac terrane for detrital zircon U-Pb LA-ICPMS analysis at the Micro Analysis facility at Memorial University of Newfoundland. One sample in the study was taken from an outcrop ~3.5 km to the WNW of the Byrd Mill outcrop. The results of these analyses (Hughes et al., in press b) include more than six hundred individual ages for zircon grains that were deposited into the pile of sediments that is

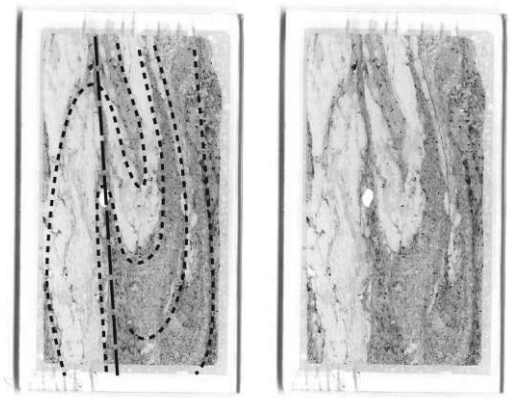

Figure 4: Scanned image of a thin section from Stop 1. An earlier foliation—shown as the stippled line—is cut by a later foliation—shown as the dashed line. Thin section is 4.5 cm long. Non-annotated image shown beside annotated image. Modified from Hughes et al. (2013a).

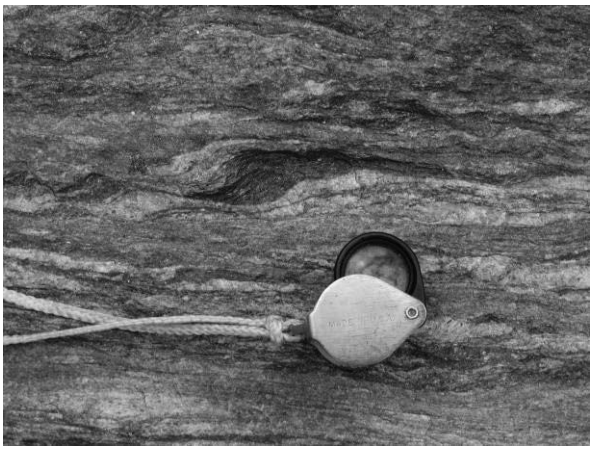

Figure 5: Subhorizontal outcrop surface with asymmetric fabric indicating dextral shear sense at Stop 1.

Figure 6: A late syn- to post-kinematic quartz vein at Stop 1.

now the Potomac terrane. The major findings of this study were that the majority of zircons analyzed originally crystallized in the Mesoproterozoic with peak modes at 1.015 Ga and 1.120 – 1.150 Ga and the youngest grains analyzed crystallized at ca. 500 Ma (Fig. 7). These results are consistent with previous models that assign a Laurentian cratonic source for the Potomac terrane.

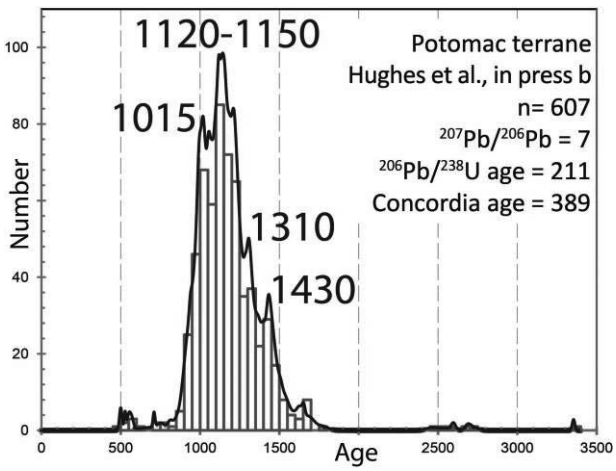

Figure 7: Detrital zircon plot from samples of the Potomac terrane. These results are consistent with a Laurentian source for the Potomac terrane. Modified from Hughes et al. (in press b).

incised by the South Anna River. The felsic volcanic rock here is interpreted to be a metamorphosed crystal tuff within the Chopawamsic Formation. However, in some parts of the outcrop, there are pitted and knobby surfaces which are suggestive of a fragmental volcanic component to some layers in the rock. The majority of rock here consists of a very fine-grained quartz, muscovite, and biotite matrix with larger, relict medium-grained quartz phenocrysts (Fig. 8).

Geochemical analysis of a sample from this locale shows it includes 76% SiO_2, 12% Al_2O_3, 4.5% K_2O, 2% Iron Oxides, 2% Na_2O, 1% CaO, 0.25% MgO, and 0.15% TiO_2. The chemistry and mineralogy of this rock and other felsic volcanic rocks in the Chopawamsic terrane is consistent with that of a rhyolite (Fig. 9A). Rare earth element data normalized to primitive mantle values (Sun and McDonough, 1989) show consistent niobium and titanium depletion and suggest the rocks were formed in a suprasubduction zone setting or formed from recycling of pre-existing supra-subduction zone rocks (Fig. 9B).

STOP 2: CHOPAWAMSIC FORMATION FELSIC VOLCANIC, PLEASANT VIEW FARM

SOUTH SIDE OF THE SOUTH ANNA RIVER, ABOUT 0.7 KM DOWNSTREAM FROM THE VA-208 (COURTHOUSE ROAD) BRIDGE OVER THE RIVER
37.980801°N, 78.040714°W

STOP LEADER: STEPHEN HUGHES

This outcrop of felsic volcanic rock in the Chopawamsic Formation is situated on the flank of a prominent, four kilometer long ridge that trends parallel to the regional foliation. We'll examine the ridge where it has been

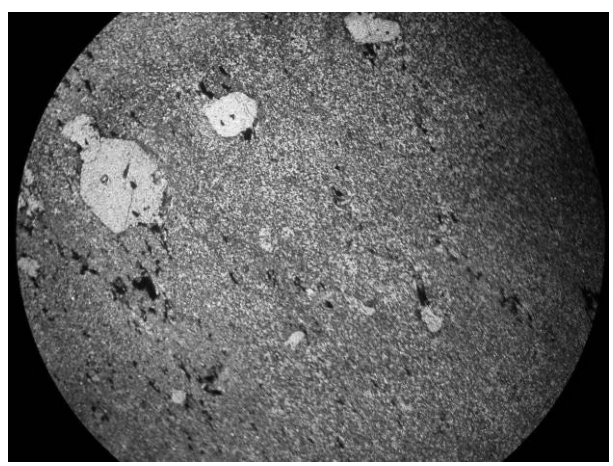

Figure 8: Photomicrograph from the outcrop at Stop 2. Medium-grained quartz phenocrysts in a fine-grained quartz, muscovite, and biotite matrix.

Many parts of the Chopawamsic Formation in the surrounding area include mafic interlayering or, more commonly, a quartz-biotite granofels (Burton et al., 2014) that may represent epiclastic sediment within the Chopawamsic Formation (Hughes, 2011). The preserved volcanic textures in the rock at this outcrop made it an appealing target for geochronological analysis. Zircons from this site were analyzed by the high-precision U-Pb CA-TIMS method at the Radiogenic Isotope Geosciences Laboratory at Texas A&M. The results from 5 individual dissolved zircon analyses yield an age of 468.2 ± 1.1 Ma (2σ confidence level, Fig. 10). This age is consistent with other high-precision dates (474 – 465 Ma) that have come out of the Chopawamsic Formation (Coler et al., 2000; Hughes et al., 2013b).

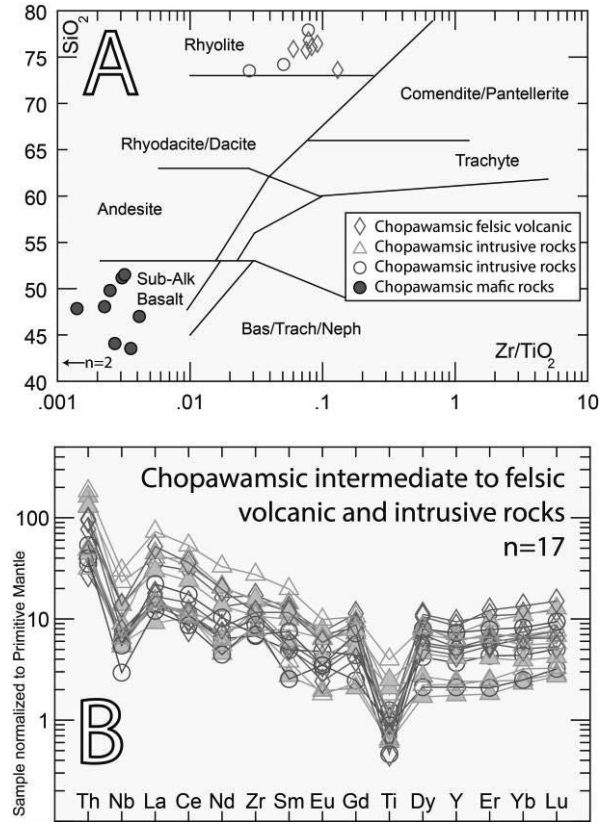

Figure 9: Geochemical plots for rocks from the Chopawamsic terrane. A) SiO_2 vs. Zr/TiO_2 plot after Winchester and Floyd (1977). Felsic volcanic rocks from the Chopawamsic Formation, including a sample from Stop 2, are rhyolitic in composition. B) Rare earth element compositions normalized to primitive mantle values of Sun and McDonough (1989). All samples have niobium and titanium depletion. Figures modified after Hughes et al. (2014).

STOP 3: EXOTIC UNIT, PAYNE FARM

NORTH SIDE OF THE SOUTH ANNA RIVER, ABOUT 2.5 KM UPSTREAM FROM THE VA-208 (COURTHOUSE ROAD) BRIDGE OVER THE SOUTH ANNA RIVER
37.985565°N, 78.067593°W

STOP LEADERS:
BILL BURTON, STEPHEN HUGHES, AND JIM HIBBARD

This hillside pavement (Fig. 11) just north of the South Anna River exposes a rock with unusual and complex features that may represent part of a block-in-phyllite mélange. It has been previously included as part of the Mine Run Complex (Burton et al., 2014) but the rock here does not resemble any other

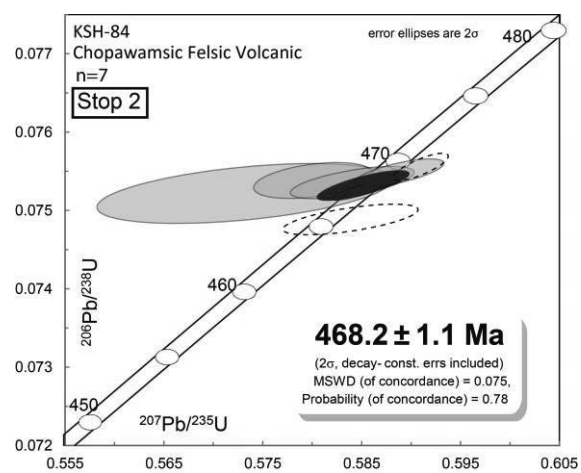

Figure 10: U-Pb concordia plot for analyses of individual zircons taken from a sample at Stop 2. Dashed ellipses include those not used in the age calculation. Dark ellipse represents the weighted mean of 5 analyses.

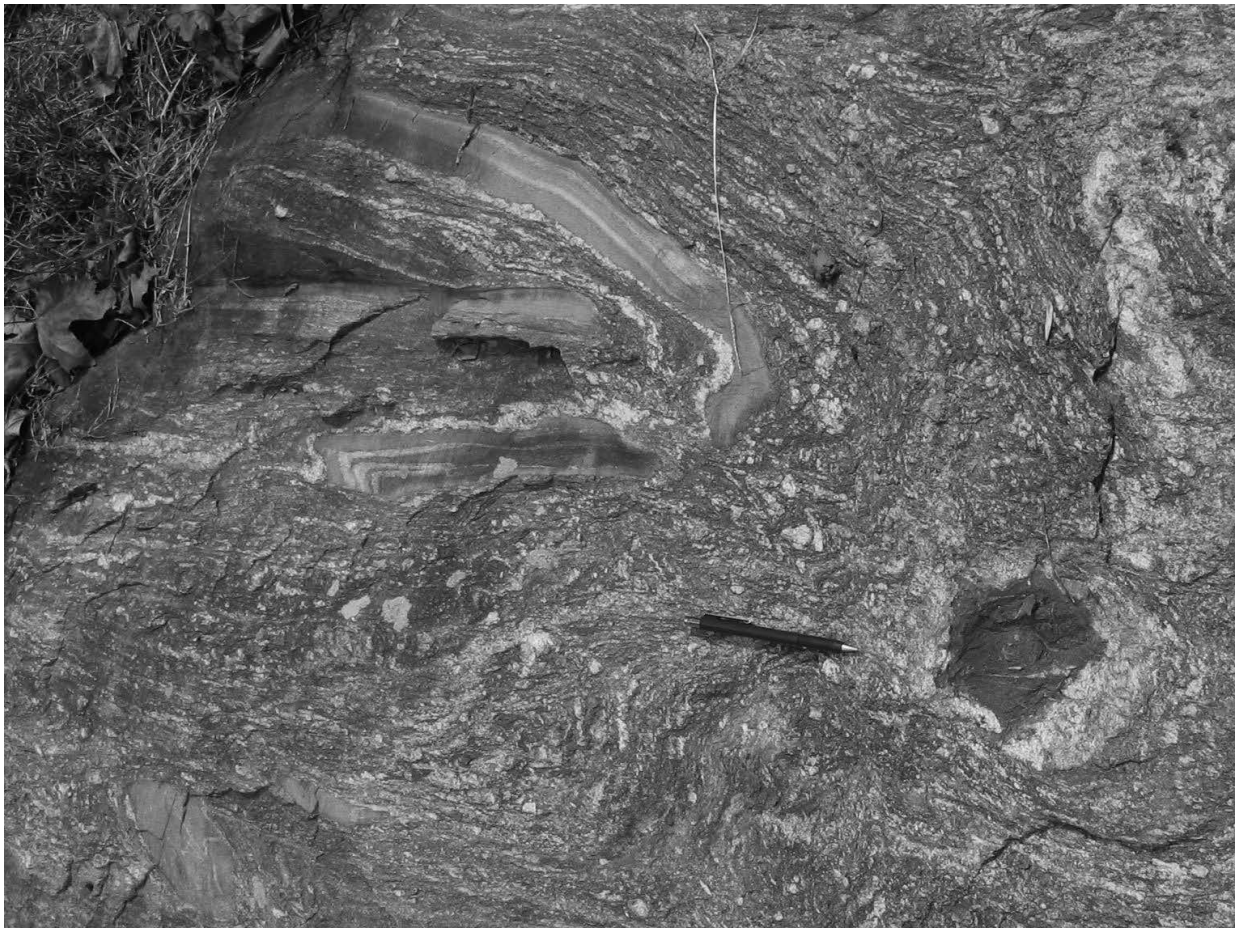

Figure 11: Granofels (left) and mafic (right) blocks in quartzofeldspathic matrix. Note truncated layering in the folded granofels block.

rocks of the Mine Run Complex to the north (See Stop 1; Hughes, reconnaissance mapping). It is now suspected that these rocks are a distinct unit not related to the Mine Run Complex. This outcrop is part of a narrow zone just west of the Chopawamsic Formation and includes pebbly meta-graywacke, blocks of ultramafic rock, and sparse gabbroic rock not found in the units to either side of this belt (Burton et al., 2014). The southeast contact of this belt has been mapped to be the Chopawamsic fault (Burton et al., 2014, in press). The northwest contact of this belt has been called the Byrd Mill fault (Burton et al., 2014), which may be part of the greater Chopawamsic fault system (see above).

The composition and character of this belt in the Ferncliff quadrangle is consistent with descriptions of the Shores Complex along the James and Hardware rivers (Evans, 1984; Brown, 1986). The Shores Complex lies 30 km along strike to the southwest, where metagraywacke is the dominant rock type, followed by schist and phyllite, sheets and lenses of greenstone, and rare blocks of metagabbro. Planned U-Pb dating of detrital zircon and Ar/Ar dating of mica in this outcrop aims to shed light on any regional correlations

that can be made with this newly recognized belt.

In this pavement exposure (Fig. 11), the irregularly-shaped blocks range up to about 25 cm in diameter and include a light gray, thinly layered, fine-grained, folded biotite gneiss; a dark, massive mafic to ultramafic rock rimmed with leucocratic segregation; a garnet-rich dacitic slab (Fig. 12); and clasts of white quartzofeldspathic rock. These blocks are in a gray, fine- to coarse-grained, foliated, tightly folded, mica-quartz-feldspar matrix, with abundant augen of white feldspar and quartz, which may represent sheared metagraywacke. The thin layering in the block of gneiss is truncated at the contact with surrounding matrix, and the leucocratic rim around one of the mafic blocks suggests chemical dis-equilibrium between the block and matrix (Fig. 11). The truncated blocks and the augen fabric in the matrix together suggest that the blocks have been transposed in a sheared matrix.

Matrix and blocks together are folded by closely-spaced, northeast-plunging folds that are similar in style to some of those seen in the rocks at Byrd Mill in Stop 1 and that are interpreted by Burton et al. (2014) as regional second-generation (F_2) folds that are possibly Ordovician.

In thin section, the tightly folded matrix consists of quartzofeldspathic layers containing recrystallized quartz intergrown with sericitized plagioclase, chlorite after biotite, secondary muscovite and epidote, and abundant secondary magnetite. This assemblage is consistent with the greenschist-facies peak regional metamorphic grade observed in surrounding rocks. Ultramafic rocks just west of this locality consist mostly of tremolitic to actinolitic amphibole, talc, chlorite, and magnetite. Similar to the rocks in the Mine Run Complex to the west, there is abundant porphyroblastic magnetite. This magnetite corresponds to a strong regional aeromagnetic anomaly that appears to wrap around the Ellisville pluton in the Louisa quadrangle just to the north; this is a focus of current investigation by USGS researchers.

In the area mapped by the USGS to date, including the Ferncliff (Burton et al., 2014) and Louisa (Burton, in progress) quadrangles, this is only one of two localities in the belt that has these mélange-like features so well displayed; far more abundant are medium- to coarse-grained, massive metagraywacke, fine-grained phyllite, and metamafic and ultramafic rocks that are interleaved with the other rock types on a scale of tens of meters. Two car-sized

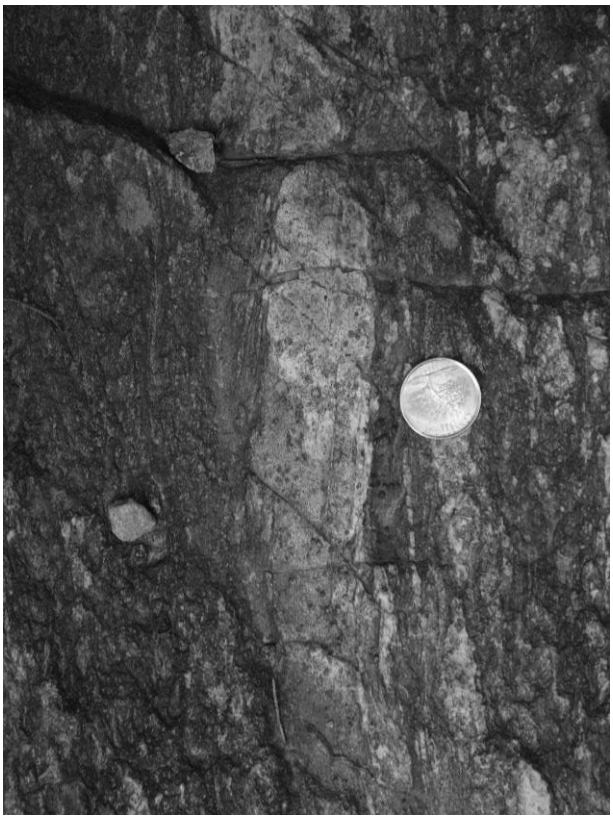

Figure 12: Garnet-rich, dacitic volcanic slab in the matrix at Stop 3.

blocks of very coarse-grained amphibole-plagioclase gabbro have also been observed.

Stop 4: Ellisville pluton, Beech Nut Drive, Blue Ridge Shores community

Near the Eastern intersection of Beech Nut Drive and North Lakeshore Drive
38.11823°N, 78.01932°W

Stop Leaders:
Stephen Hughes, Jim Hibbard, and Bill Burton

The Ellisville pluton (Hopkins, 1960) has a tadpole-shaped map pattern that underlies ~210 km^2 in Louisa, Orange, Spotsylvania, and Fluvanna counties. The pluton consists mostly of fine- to medium-grained biotite granodiorite. In some places, the granodiorite has a porphyritic texture with euhedral orthoclase and microcline feldspar crystals up to three cm long. The pluton is mostly homogenous granodiorite, although minor diorite has been reported in some parts of the pluton (Hopkins, 1960; Burton et al., 2014; see Stop 9) It is texturally heterogeneous with two main phases of granodiorite: (1) the main medium-grained, locally porphyritic, older phase of biotite granodiorite and (2) a volumetrically smaller fine-grained biotite granodiorite (Pavlides and Cranford, 1982; Hughes et al., 2013a). The relationship of these phases has only been seen in a few outcrops, which suggests that the fine-grained phase is younger than the medium-grained phase (Fig. 13); Hughes et al., 2013a; see Stop 9).

The rock at Stop 4 is part of the medium-grained phase of the pluton, which is commonly porphyritic. This outcrop has a massive texture and includes some pegmatitic

Figure 13: Relationship of the two phases of granodiorite in the Ellisville pluton. Here, the medium-grained phase is displayed as brighter wisps, possibily generated during assimilation, in the fine-grained phase. Outcrop is in Ferncliff quadrangle at 37.95390N, 78.04521W. Figure from Hughes et al. (2013)

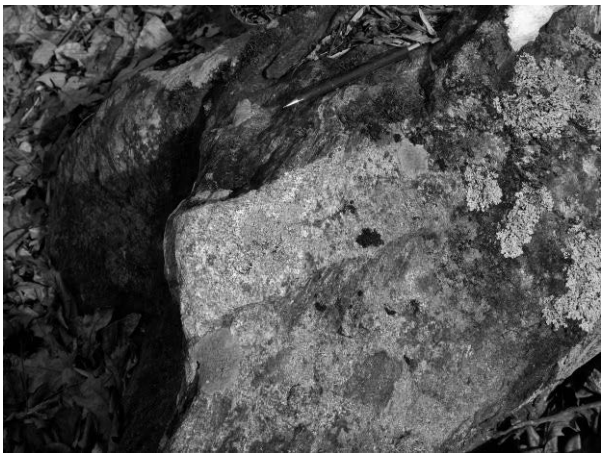

Figure 14: Dike of Ellisville granodiorite (parallel to pencil) cutting strongly foliated biotite schist of the Potomac terrane, just south of Lake Louisa.

segregations and fine-grained dark xenoliths. Mapping of the pluton (Hopkins, 1960; Hughes, 2011) has shown that massive and porphyritic textures are much more common in the "head" of the pluton but do exist throughout the body.

Detailed mapping of the pluton has proven that it is intrusive into both the Potomac and Chopawamsic terrane (Pavlides, 1989; Pavlides et al., 1994; Hughes et al., 2013a; Burton et al., 2014; Burton, in progress). The intrusive contact has been directly observed in both the Potomac and Chopawamsic terranes (cover photo, Fig. 14, Hughes et al., 2013a; Burton, in progress). Because the pluton stitches both terranes, the age of the pluton can be used to determine a latest possible age of motion on the Chopawamsic fault system, which separates the two terranes.

Both the fine- and medium-grained phases of biotite granodiorite were sampled for high-precision U-Pb zircon TIMS geochronological analysis. The laboratory results agree with field observations that the fine-grained phase (437 ± 4 Ma) is younger than the more voluminous medium-grained phase (444 ± 4 Ma) (Hughes et al., 2013a). Because no previous mapping has found evidence significant structural offset in the Ellisville pluton, the ca. 444 Ma age of the bulk of the Ellisville pluton granodiorite is used as a latest date of movement on the Chopawamsic fault system. This constraint, considered in conjunction with the youngest high-precision age (ca. 465 Ma) of the Chopawamsic Formation (see Hughes et al., 2014 stop 2-3), indicates that motion on the fault occurred sometime during a period between 465 – 444 Ma—Middle to Late Ordovician.

In the vicinity of this outcrop, recent mapping of the western margin of the Ellisville pluton in the Louisa quadrangle (Burton, in progress) shows that the western contact of the main body of the pluton crosses the west end of Lake Louisa and angles south-southeast from there. The country rocks are predominately fine-grained phyllites ~1 km from the pluton contact, but acquire a coarser-grained, recrystallized texture near the contact. Figure 15 shows a cut slab of dike cutting country rock from a contact locality

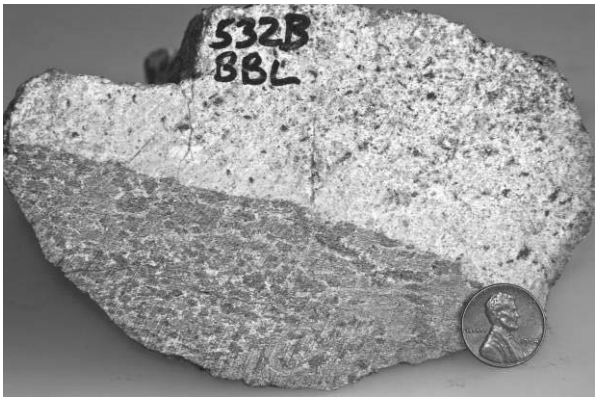

Figure 15: Sawn slap of contact between Ellisville granodiorite (top) and recrystallized Potomac terrane country rock (below). Note the thin chill margin (finer-grained) in the granodiorite next to the contact.

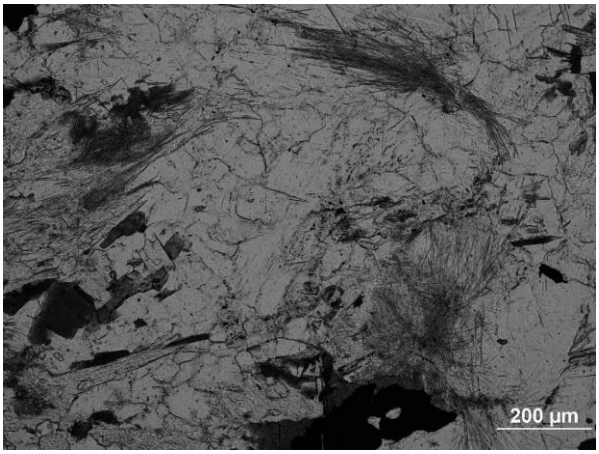

Figure 16: Thin section (plane polarized light) of portion of sawn slab (Fig. 15) showing sprays of fibrolitic sillimanite (fibrolite) in upper and lower right overgrowing assemblage of quartz, plagioclase, biotite, and muscovite. Secondary magnetite overgrows biotite at bottom.

south of the lake. A thin section from this slab (Fig. 16) shows bundles and sprays of fibrolitic sillimanite overgrowing the foliated, green-schist-facies assemblage of biotite, muscovite, quartz, and plagioclase, with secondary magnetite also abundant. This observation confirms the prograde thermal overprint in the country rock described by others (Pavlides, 1989; Pavlides et al., 1994).

Pavlides et al. (1994) noted that the country-rock schists near the pluton contact were more tightly folded than rocks farther away, and they ascribed this increase in deformation to forceful intrusion of the pluton. The recent mapping west of the pluton margin in the Louisa quadrangle has also documented an intensification in folding of the rocks as one approaches the pluton, but the style of folding matches that of the regional F_2-generation folds described in the Ferncliff quadrangle (Burton et al., 2014). Within ~1 km of the plutonic contact, both fold axes and dominant foliation rotate from the regional northeast trend into parallelism with the igneous contact, locally resulting in northwest-trending structures. Mapping to date, however, suggests that the rock units in the Ferncliff quadrangle extend northeastward right to the pluton contact, and that the northwest-trending structures—F_2 folds and axial-planar S_2 foliation—represent a structural overprint on this trend. From these observations, we infer that the pluton intruded roughly synchronous with regional F_2 deformation, suggesting that D_2 is Late Ordovician. The regional aeromagnetic anomaly (e.g. Snyder, 2005) that wraps around the west margin of the pluton may also be thermal in origin and not indicative of any stratigraphic trend. Further mapping is needed to test this idea.

Stop 5: (OPTIONAL) Ellisville pluton quarry blocks, Mt. Pleasant Church Road (SR-624)

Large gravel parking lot to the west of SR-624 is rimmed by boulders from the quarry immediately east of SR-624
38.070194°N, 77.927678°W

Stop Leaders:
Stephen Hughes and Jim Hibbard

This stop is located in a parking lot immediately to the west of the Cedar Mountain quarry—our sampling location for the fine-grained biotite granodiorite phase of the Ellisville pluton dated to be ca. 437 Ma (Hughes et al., 2013a). The quarry has not been active for at least the past five years and possibly longer. Although this is one of the largest exposures of the pluton, it is not the type locale, which is a small quarry ~7 km to the WNW just north of White Creek (Hopkins, 1960).

One interesting compositional feature of the Ellisville pluton observed here is the presence of primary, magmatic epidote (Fig. 17; Pavlides et al., 1994; Hughes et al., 2013a). Usually a product of metamorphism or alteration, the epidote in the Ellisville pluton has been interpreted to be magmatic in origin (Pavlides et al., 1994; Hughes et al., 2013a). Features of magmatic epidote include euhedral crystal faces that are in sharp contact with biotite and/or contain cores of primary igneous minerals (Zen and Hammarstrom, 1984; Schmidt and Poli, 2004). The presence of magmatic epidote, which may crystallize at 0.7 to 0.3 GPa in intermediate composition melts (Schmidt and Poli, 2004), in the Ellisville pluton is consistent with previous

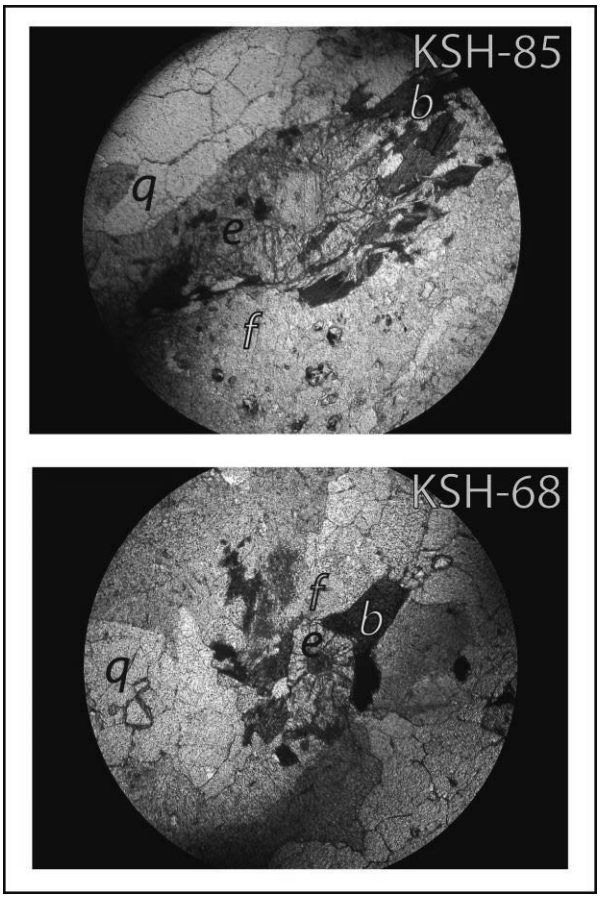

Figure 17: Photomicrographs (plane polarized light) of magmatic epidote in the Ellisville pluton. Diameter of field of view measures 2.5mm. Abbreviations: b = biotite, e = epidote, f = feldspar, q = quartz. Figure modified from Hughes et al., (2013a).

geobarometric estimates of 0.6 to 0.45 GPa for the body (Pavlides et al., 1994).

Magmatic epidote is one of the criteria, along with geochemical analyses, geochronological analyses, and field observations, that was used to conclude a co-magmatic relationship amongst all the granodiorite herein mapped as part of the Ellisville pluton. Consideration of this collective information demonstrates that the Ellisville pluton head and tail represent a single pluton that stitches the Potomac and Chopawamsic terranes (see Hughes et al., 2013a and above).

STOP 6: CHOPAWAMSIC FORMATION: HYDROTHERMALLY ALTERED ROCKS AT CONTRARY CREEK

OUTCROP IN CONTRARY CREEK JUST WEST OF US-522 BRIDGE
38.065183°N, 77.879847°W

STOP LEADER: TYLER SAUER

The purpose of this stop is two-fold: (1) to present an overview of the Mineral District mines and prospects and (2) to examine hydrothermally altered rocks of Chopawamsic Formation at Contrary Creek in the footwall of the Sulphur to Arminius mineralized zone.

Geology of the Mineral District: Volcanogenic massive sulfide (VMS) deposits in the Mineral District are hosted by the Chopawamsic Formation (see Fig. 2). The district is a 13 km long, 5 km wide area (Neuschel, 1970; Pavlides et al., 1974; Hodder et al., 1977) and consists of three parallel mineralized zones. The western alignment includes the Sulphur, Boyd Smith, Arminius and Julia deposits. The central alignment contains the Allah Cooper and Cofer deposits. The eastern alignment is collectively referred to as the Fisher Lode (Taber, 1913; Luttrell, 1966) and is gold-only shallow underground workings and prospects.

In the district, Chopawamsic Formation rocks are at epidote amphibolite facies (Duke, 1983; Sauer, 1984). The most common rock type observed is light colored biotite sericite schist (volcaniclastics) in laterally continuous, thick layers (Feuer, 1980; Duke, 1983). They are interleaved with equally continuous, thick alternating amphibolite, coarse-grained chlorite-carbonate-amphibole schist (mafic

volcanic and mafic volcaniclastic sediments) and blue quartz-eye-bearing feldspathic quartzite and schist (felsic volcanics). These mafic and felsic rocks recur throughout the section in pairs, probably as the result of folding. No volcanic rocks of intermediate composition have been documented (Duke, 1983).

Geology from Sulphur to Arminius Mines: The following description and rock relationships are from an area 3.7 km long and 0.6 km wide extending from the northeast end of the Sulphur mine property then southwest through Boyd Smith to the south end of the Arminius property. Because of limited outcrop, geologic information comes from more than 79,000 feet of diamond drill core completed by NJZ and CMC from 1952 to 1980. These data are projected to a vertical longitudinal section (Fig. 18). The rocks are divided into three major groupings, including (1) hanging wall rocks to the main massive sulfide zone, (2) the main massive sulfide zone, and (3) footwall rocks to the main massive sulfide zone.

Hanging wall rocks (HW): are foliated to massive, abruptly alternating and laterally discontinuous mix of biotite-sericite schist (volcaniclastic sediments) with abundant lithic fragments, fine-grained amphibolite (mafic volcanic), coarse-grained carbonate-chlorite-epidote-amphibole schist (mafic volcaniclastic sediment). Rocks with lithic fragments occur throughout the section but

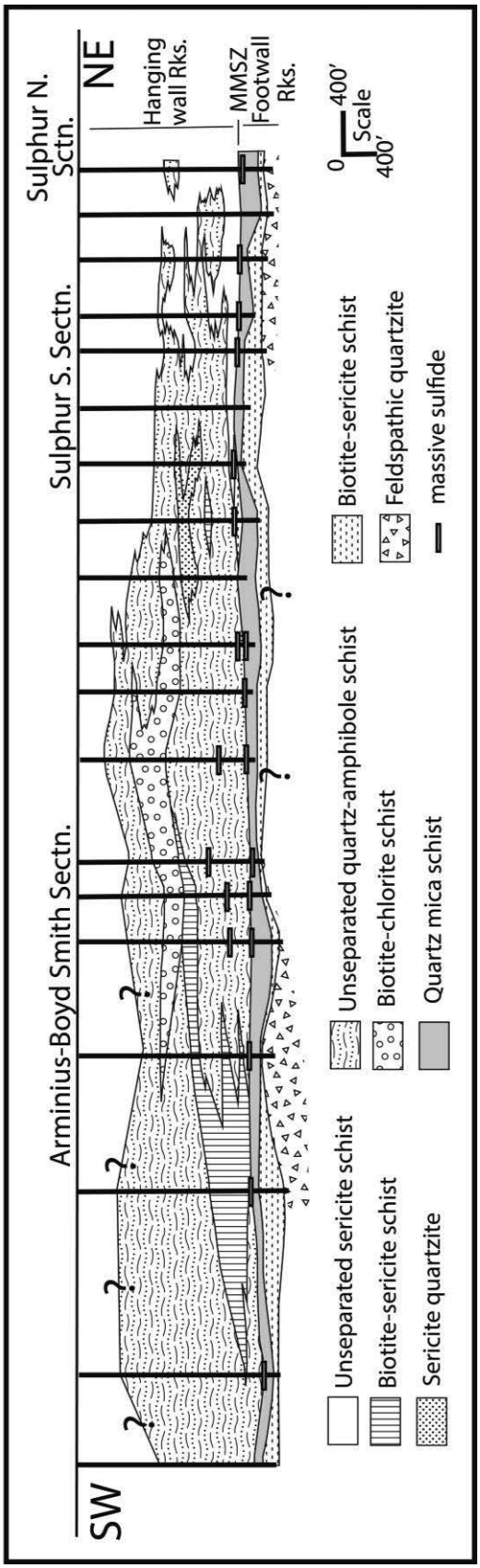

Figure 18: Geological cross section along Contrary Creek after Sauer (1984). Along-strike section of the geology from Sulphur (NE) to Arminius (SW) mines (see Fig. 2 for locations). Thick vertical lines represent drill hole control on the subsurface geology; MMSZ = main massive sulfide zone.

are most common at the north end. To the south, mafic rocks become more prominent.

Main Massive Sulfide Zone (MMS): Pyrite-rich massive sulfide zones with variable base metal content, minor silver and little gold were the ores exploited at Sulphur, Boyd Smith, and Arminius deposits. Individual sulfide zones are stratiform and stratabound with mostly sharp contacts with over- and underlying rocks. They are discontinuous and lenticular in plan with average strike lengths of 1,100 ft. and 14.6 ft. in thickness. Individual ore bodies have a linear form, plunging steeply to the northeast. Locally, small, thick pods of high grade mineralization (up to 15% Zn) occurs in HW rocks, e.g. at Boyd Smith.

Massive ore has greater than 50% pyrite that ranges from fine- to coarse-grained ± quartz, pyrrhotite, sphalerite, galena, chalcopyrite, and magnetite. Disseminated ore occurs within and between individual massive zones.

VMS deposits of the Mineral District are interpreted as synsedimentary and volcanogenic in origin produced by ascending metal-charged hydrothermal fluids precipitating sulfide minerals at the seawater/rock interface (Duke, 1979a, 1979b, 1980; Craig, 1980; Pavlides et al., 1982; Hodder et al., 1977).

Footwall Rocks (FW): In contrast to the lithologic variability described in the HW section, the footwall section consists of three rock types that extend continuously the entire 2.3 mile strike length from Sulphur to Arminius and beyond (Sauer, 1984). In structurally descending order away from the MMS, these include quartz mica schist, biotite sericite schist, and feldspathic quartzite.

Quartz mica schist (QMS) ranges from quartz chlorite to quartz sericite with a distinctive accessory mineral assemblage of biotite, almandine garnet, staurolite, chloritoid, kyanite and locally magnetite, pyrite and base metal sulfide minerals. QMS varies in thickness from 49 ft. to 295 ft., with sharp upper contacts with MMS bodies, and is gradational into underlying rocks.

The biotite sericite schist (BSS) exhibits the same lateral persistence as the overlying QMS. True thickness is unknown as drilling ceased upon encountering this rock type. Its upper contact is gradational and is marked by a gradual decrease in chlorite, accessory minerals and a corresponding increase in Na and K feldspar minerals.

BSS is uniformly light gray and strongly foliated with closely spaced bands of biotite. Biotite can also be randomly dispersed through the quartz sericite matrix giving the rock a "salt and pepper" appearance (Sauer, 1984). Small almandine garnet is common throughout.

The feldspathic quartzite (FQ) is the structurally lowest rock type encountered in the FW section. It is not observed in every drill hole but enough has been cored in deeper drill hole penetrations to demonstrate it is a consistent part of the FW section. Total thickness is unknown and its upper contact with BSS can be sharp to gradational or rapidly alternating over tens of feet. FQ is typically light gray to white, massive to weakly foliated with spherical blue quartz "eyes" and 0.5mm feldspar scattered through the quartz-rich groundmass. Feldspar grains and blue quartz eyes are interpreted as primary phenocrysts. FQ is interpreted to represent a rhyodacite mantled by its volcaniclastic detritus, now observed as BSS.

Proposed Origin of Footwall Section: Deposition of FW rocks started with

extrusion of the FQ rhyodacite, probably as flows and crystal tuffs. Subaqueous extrusion results in rapid quenching, pervasive sodium metasomatism of feldspar and silicification, as exhibited by its massive texture. Quenching physically disaggregated most of the rhyodacite into broad sheets of moderately sorted, layered volcaniclastic sediments (BSS and QMS above) that mantle and interfinger with the less common rhyodacite flows.

Deposition of volcanic and volcaniclastic sediments was followed by a period of basinal stability and non-deposition. During this hiatus, heat, possibly retained in rhyodacite by insulating volcaniclastic cover, initiated convective circulation of seawater and led to formation of the main massive sulfide body. Local thick massive sulfide accumulations are probably associated with transecting faults that provide more focused fluid discharge and secondary basin accumulation sites. Their orientation is now seen as the down-plunge orientation of individual ore bodies.

Following sulfide deposition, basinal insability returned, as indicated by the wide variety of coarse clastic and volcanic sediments of the HW. Fortunately, the onset of this more vigorous sedimentary environment did not disrupt and erode the underlying massive sulfide ore bodies.

Environmental Impacts: After intermittent mining operations for over 150 years, Contrary Creek is quite dissimilar from most natural Piedmont drainages. It is arguably the worst affected acid mine drainage site in Virginia (Robbins et al., 1995). In the late 1970s, ~30 acres of land, mostly waste piles, remained barren from the mining activity that had mostly ceased ~50 years earlier (Hinkle and Hill, 1984). From Hinkle and Hill (1984):

> The toxic nature of the mine waste resulted in the continuous leaching of acid and heavy metals into ... Contrary Creek rendering it essentially void of aquatic life. The severe acid mine drainage problem along this stream and associated fish kills downstream had been recognized for years.

A study by the Environmental Protection Agency was prompted by the proposition of a new reservoir (Lake Anna) to support a nuclear power plant downstream of Contrary Creek. The Lake Anna dam was completed in 1972. In 1974, the average pH of samples taken at the mouth of Contrary Creek was 3.3, while the pH of samples taken above all mine sites was 6.8 (Hinkle, 1982). Reclamation efforts to mitigate surface runoff introduction of acids and heavy metals began in 1976 and included re-grading spoil piles and introducing soil amendments such as wastewater sludge (from the District of Columbia), lime, fertilizer, and seeding. The final results from these efforts, published in 1984, indicated "little overall improvement in the water quality of Contrary Creek in terms of pH and acidity" (Hinkle and Hill, 1984). The pH values in Contrary Creek at that time were reported to be 2.5 – 3.5 (Herlihy and Mills, 1984). The lack of improvement is likely due to the overwhelming amount of waste material in the immediate channel of the stream and in groundwater flow paths. Although the report from the EPA was optimistic about the future development of water quality along Contrary Creek after their reclamation efforts, the average pH of the stream has since been measured at an average of 3.5 (Bell et al., 1990) and 2.8 – 4.6 (Anderson, 1996). Soil sampling has shown that metal toxicity remains high and pH levels remain anomalously low, below 4 and 5 (Szulczewski et al., 2011).

The type of iron staining and flocculates in the creek are often referred to as "yellow-boy" and are a result of pyrite oxidation by acidophilic autotrophic bacteria (Robbins et al., 1995). Contrary Creek remains on the list of Virginia impaired waters for the following pollutants/conditions: PCB (polychlorinated biphenyl), Cadmium, Copper, Zinc, and pH (Virginia Department of Environmental Quality, 2012). Many abandoned drifts and shafts have caved in and remain open to the atmosphere and surface water (Fig. 19).

At the Stop: Exit bus and proceed down slope to exposures on south side of Contrary Creek. This outcrop is an example of QMS described above. The Sulphur mine mineralized zone is located up dip but there are no drill hole penetrations below this section. Rock foliation strikes between N 25-30°E and dips steeply to the SE. Locally, a NE dip to the foliation is observed. Note the green to white quartz chlorite and quartz sericite groundmass with poikiloblastic clots and bands of biotite, red garnet and black, metallic magnetite. Light brown, stubby staurolite is also common. Other minerals described above (see "footwall rocks") are difficult to observe in outcrop and are detected easier in thin section.

Figure 19: Collapsed mine workings near Stop 6.

Another noteworthy observation is the abrupt, almost 90 degree, turn to the east that Contrary Creek takes on the east side of the bridge crossing. This turn corresponds with an equally abrupt decrease in airborne magnetic and electromagnetic signatures seen to the southwest. Within the exploration community there has been much speculation as to its origin. This abrupt change in drainage and geophysical expression has previously been hypothesized to reflect a bounding fault on a volcano-tectonic basin into which volcaniclastic sediments and VMS collected.

STOP 7: LINEATED CHOPAWAMSIC FORMATION NEAR YANCEYVILLE MILL

OUTCROP IS IN THE EAST BANK OF YANCEYVILLE ROAD (SR-646) JUST SOUTH OF THE BRIDGE OVER THE SOUTH ANNA RIVER
37.938749°N, 77.982337°W

STOP LEADERS:
STEPHEN HUGHES AND JIM HIBBARD

**Because this outcrop is a road-cut, please be very careful on Yanceyville Road. Do not meander in the road. Move with a purpose.*

The location of this outcrop is in the area with the most intense (level VIII) interpreted Mercalli scale intensity (Heller and McGowan, 2012) recorded from the August 23, 2011, Virginia earthquake. That earthquake is the largest magnitude ever recorded in the Central Virginia Seismic Zone and was felt by more people than any other in U.S. history (McNamara et al., 2011; Carter et al., 2012).

The rock of interest here has been termed a "world class outcrop" by one of the field trip leaders. It is a lineated pebble- to boulder-sized fragmental metavolcanic rock (Fig. 20A & 20B). The fragmental clasts are fine-grained, garnet-bearing, felsic to intermediate composition, and lie in a compositionally similar volcanic matrix. In thin section, the clasts and matrix consist of fine-grained quartz, orthoclase, biotite, and garnet. Some quartz crystals have been modified into deformed ribbons parallel to the maximum stretching direction. Orthoclase crystals have not been elongated, but commonly have long axes aligned with the fabric.

The fabric and fragmental texture of the rock have previously been interpreted to be the product of tectonic boudinage (Burton et al., 2014). The main line of evidence that they cite in support of this interpretation is the rarity of fragmental facies in the area. Pavlides et al. (1982) noted the same rarity of fragmental rocks at the surface but they also reported that fragmental felsic to intermediate rocks have been noted in several places in the subsurface. Also, the fragmental nature of the rock is best seen on faces of the outcrop perpendicular to the lineation. Considering the extreme lineation here, these faces are likely very close to the circular sections of the strain ellipsoid; circular sections show the original texture of the rock prior to deformation (e.g. Lisle, 1985). Consequently, we interpret the rock here to represent an originally fragmental volcanic rock, rather than a product of boudinage.

The previous description of this outcrop (Burton et al., 2014) noted that clast aspect ratios plotted on a Flinn diagram (Flinn, 1962) demonstrate the L-tectonite character of the fabric. This Flinn diagram analysis is invalid, as strain ratios, not clasts dimensions should be plotted on the diagram. However, we do agree that the strong L>>S tectonite fabric here is unmistakable from simple visual inspection; clasts have aspect ratios of 15+:2.6:1. The

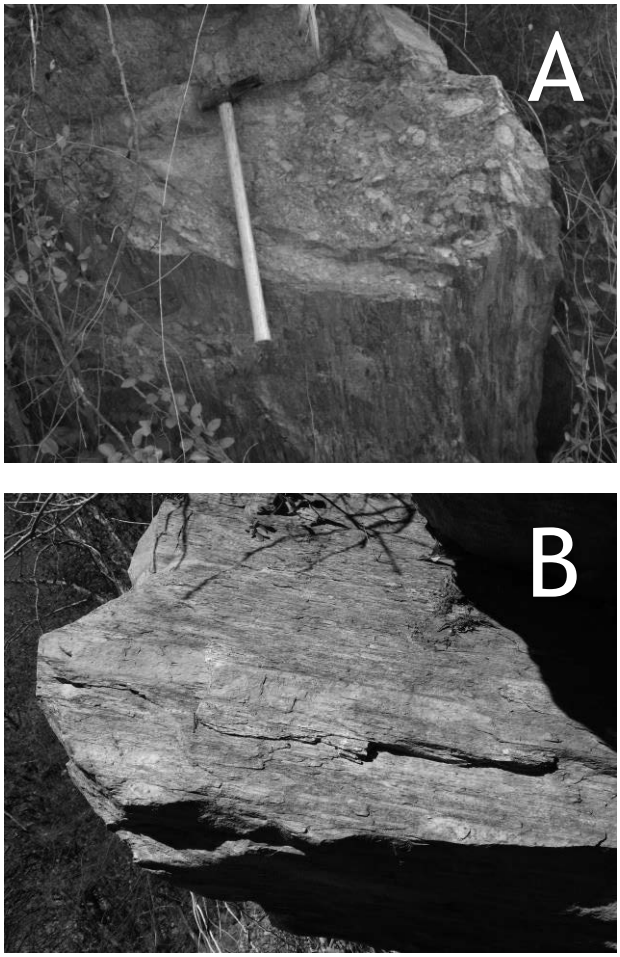

Figure 20: Lineated fragmental volcanic of the Chopawamsic Formation near Yanceyville Mill. A) View looking parallel to the maximum stretching direction. B) View looking orthogonal to the maximum stretching direction. Both views are of the same outcrop.

exceptional length of the features makes the long axis difficult to fully measure, because whole clasts cannot be observed. The fabric has a trend/plunge of 070°/35°.

The outcrop here lies no further than 600m from the contact with the Quantico Formation to the east. To the north of 38°N latitude, this boundary between the Quantico and Chopawamsic formations has been mapped as the Long Branch fault (Pavlides, 1990; Pavlides et al., 1994; Mixon et al., 2000, 2005). The termination of the fault at 38°N latitude on the state geologic map of Virginia (VDMR, 1993) is clearly an artifact of mapping boundaries. Results from recent mapping (Hughes, 2011; Spears et al., 2013; Burton et al., 2014) favor a southern extension for the Long Branch fault into this area. Trends in regional and local geophysical data support the extension of the fault to the south as features from the north continue uninterrupted to the south of 38°N latitude (Snyder, 2005; Shah et al., 2012). However, the location of the fault at this latitude does not lie at the contact of the Quantico and Chopawamsic formations. Here, the ductile Long Branch fault lies west of that contact and trends very close to the lineated Yanceyville outcrop (Spears et al., 2013; Burton et al., 2014).

Similar linear features have been observed northwest of this location (see Stop 8) and demarcate a local 2-3 km wide zone of strain that has previously been unrecognized. Hughes et al. (in press a) refer to this zone as the Bend of River high strain zone. Attitudes of planar (37°/42°SE) and linear fabrics in the high strain zone spatially coincide with the aftershock plane (34°/52°SE) associated with

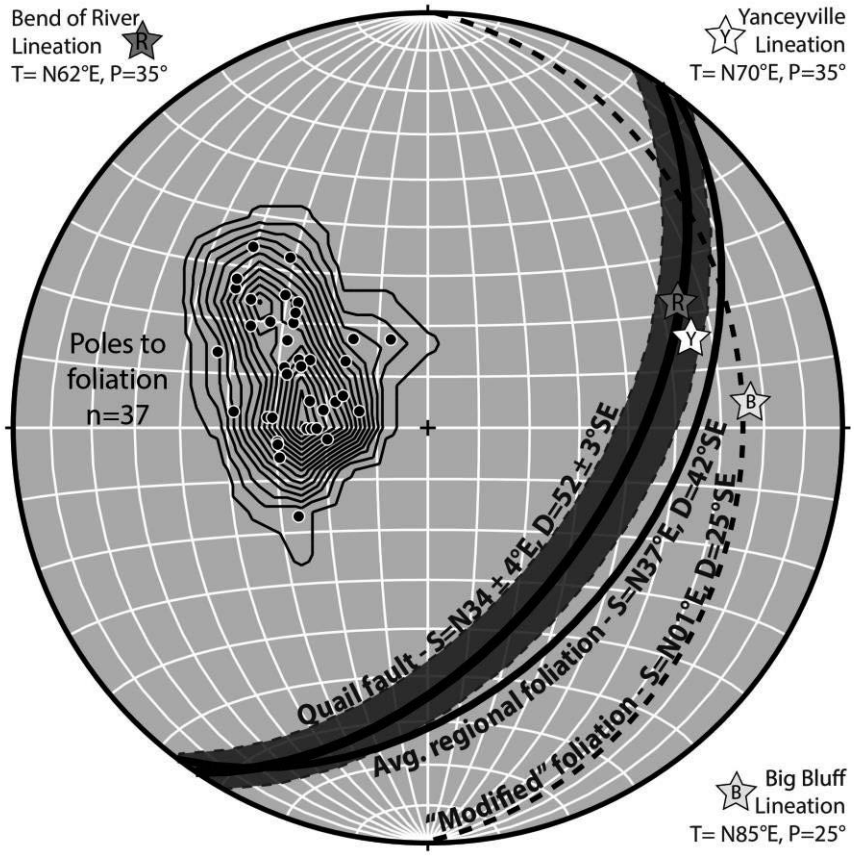

Figure 21: Stereographic projection showing the correlation of Linear and Planar features in the Bend of River high strain zone with the orientation of the aftershock plane, sometimes called the Quail fault (Horton et al., 2012). Figure from Hughes et al. (in press a)

the August 23, 2011 mainshock (Fig. 21). The correlation of the down dip/plunge projection of ductilely deformed rocks at the surface and the planar aftershock sequence have led to the conclusion that the rupture and orientation of the 2011 Virginia earthquake exploited pre-existing ductile fabrics in the bedrock (Hughes et al., in press a; Burton et al., in press).

Stop 8: (OPTIONAL) Bend of River bi-modal Chopawamsic Formation, South Anna River

Drive 750m down Bend of River Road west from Yanceyville Road (SR-646), outcrop is located ~100m to the east of the boat ramp on the river.
37.95984°N, 78.00155°W

Stop Leaders:
Stephen Hughes and Jim Hibbard

The boat ramp nearby is built upon felsic volcanic rock of the Chopawamsic Formation but the bi-modal, layered outcrop ~100m to the east is the target of this stop.

The outcrop includes alternating, ~1m thick, layers of felsic and mafic metavolcanic rock (Fig. 22). Some of the rock here may be epiclastic—that is, a volcanic rock re-worked by sedimentary processes.

At the base of a mafic layer, there are lineated clasts that have a trend/plunge of 062°/35° (Fig. 23), which is similar to the orientation of the linear fabric seen at Stop 7. This outcrop demarcates the western border of the local Bend of River high strain zone associated with the Long Branch fault (Hughes et al., in press a). An analysis of aftershocks recorded after the mainshock show an up-dip projection of the causative fault plane of the 2011 Virginia earthquake that trends 70m to the southeast of this outcrop according to Hughes et al. (in press a). Burton et al. (2014;

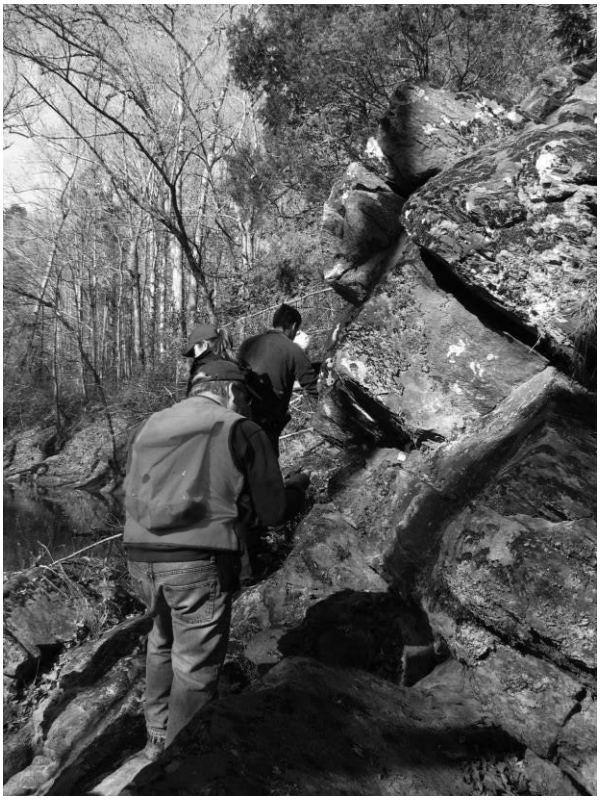

Figure 22: Interlayered felsic and mafic meter-scale layers dipping moderately to the southeast. Figure from Hughes et al. (in press a).

Figure 23: Lineated clasts at the base of mafic layer at Stop 8. These clasts are deformed in a similar fashion and oriented in the same manner as the lineated features at Stop 7. Figure from Hughes et al. (in press a).

in press) project the fault ~1 km farther to the west. The spatial coincidence of the projections of the ductile fabrics observed in the Bend of River strain zone and the causative fault—as defined by aftershocks—of the 2011 earthquake suggests control of modern seismicity in the Central Virginia Seismic zone by relict, inherited fabrics and structures.

The age of the Long Branch fault has been surmised to be late Paleozoic and related to the Alleghanian orogeny (Pavlides et al., 1994; Pavlides, 2000). In collaboration with Bill Hames at Auburn University, we collected a sample from the mafic layer here for individual crystal hornblende $^{40}Ar/^{39}Ar$ analysis. The results indicate that argon retention in hornblende initiated at 330.6 ± 3.4 Ma (Fig. 24). The results suggest that the hornblende in the rock here cooled through the hornblende closure temperature (~550 to 500°C) in the Late Mississippian. These results are consistent with the previous interpretations that the Long Branch fault—which we interpret to be responsible for the deformation at this outcrop and at Stop 7—is a structure related to the Alleghanian orogeny.

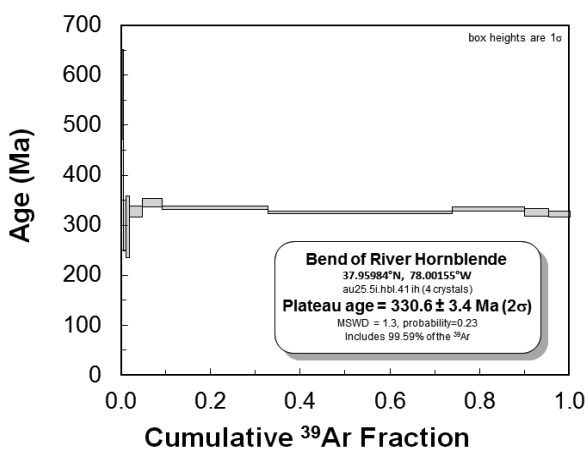

Figure 24: $^{40}Ar/^{39}Ar$ geochronology for hornblende sampled from the mafic composition rock at Stop 8. A plateau age of ca. 331 Ma was obtained. Four crystals were analyzed.

Stop 9: (OPTIONAL) Intrusion of fine-grained Ellisville granodiorite into medium-grained Ellisville granodiorite, Hopkins Farm

Two kilometers along a heading of 248° from the intersection of Roundabout Road (SR-604) and Horseshoe Farm Road (SR-714)
37.96548°N, 78.03728°W

Stop Leader: Stephen Hughes

This outcrop is one of the best locations to see the relationship between the two phases of granodiorite in the Ellisville pluton (Fig. 25). Inclusions of some medium-grained granodiorite in the area of fine-grained granodiorite suggest that the fine-grained phase is the younger of the two. The dike of fine-grained granodiorite is tabular and nearly vertical.

The sample that yielded a zircon crystallization age of ca. 444 Ma for the medium-grained phase of the Ellisville pluton was taken from an outcrop on the east bank of the South Anna River about 1.15 km to the ESE (see Hughes et al., 2013a). This age was used as the stitching date for the pluton as the medium-grained texture is by far the most voluminous in the pluton.

About 1 km to the ENE of here in a cow pasture is a small outcropping of a Chopawamsic Formation xenolith within the Ellisville pluton. The contact between the two units is well exposed in weathered rock and does not appear tectonic (Fig. 26).

Figure 25: Field relationship of two phases of granodiorite in the Ellisville pluton at Stop 9. Dike of fine-grained Ellisville granodiorite within the more common medium-grained phase. Note inclusions of coarser-grained material in the younger fine-grained granodiorite.

Figure 26: Exposure of contact between the Ellisville pluton and a xenolith of the Chopawamsic Formation near the southeastern margin of the pluton tail. This relationship demonstrates the intrusive nature of the Ellisville pluton with the Chopawamsic Formation country rock. Site is ~1 km ENE of Stop 9.

Stop 10: (OPTIONAL) Carysbrook phase of the Columbia pluton, Carys Creek wayside, US-15

Turn right off of US-15 after driving 1.5 km south of the intersection with Carysbrook Road (SR-615). Outcrop is in front of the building (currently a real estate office) on top of the small knob to your right.
37.79975°N, 78.239907°W

Stop Leader: Stephen Hughes

This stop (Fig. 27) is distant from the others in this guide. It is included in order to highlight the potential co-magmatic relationship between the Ellisville and Columbia plutons.

Many different mapping configurations have been presented for the relationship between the plutons including: (1) the connection of the Ellisville and Columbia plutons via the Ellisville tail (VDMR, 1963; Good et al., 1977; Duke, 1983; Spears and Bailey, 2002); (2) the mapping of distinct plutons, yet labeling portions of the Columbia pluton as the Ellisville pluton (Conley and Johnson, 1975; Conley 1978; Duke, 1983) and (3) mapping of a northern extension of the Columbia pluton (Taber, 1913; Jonas, 1932; Smith et al., 1964; Bailey et al., 2005)

The northwestern portion of the Columbia pluton has sometimes been labeled as the Carysbrook pluton, independent of the Columbia pluton (Stose and Stose, 1948; VDMR, 1993). However, the most recent mapping in the area shows the Carysbrook as one of three phases present in the larger Columbia pluton (Bailey et al., 2005).

Geochemical analyses from the Carysbrook phase of the Columbia pluton are very similar to analyses from the Ellisville pluton (see results and synopsis in Hughes et al., 2013a). Both are granodioritic and locally include feldspar phenocrysts up to 2-3 cm in length (Bailey et al., 2005; Hughes, 2011). Although only the Ellisville pluton has been dated using the high-precision U-Pb zircon TIMS method, existing zircon analyses from the Carysbrook phase of the Columbia pluton are consistent with the Late Ordovician age of the Ellisville pluton. The main phase of granodiorite in the Ellisville pluton has been dated at 444 ± 4 Ma (Hughes et al., 2013a) and the Carysbrook phase of the Columbia pluton has been dated at 444 ± 11 Ma (Sinha et al., 2012; Wilson, 2001).

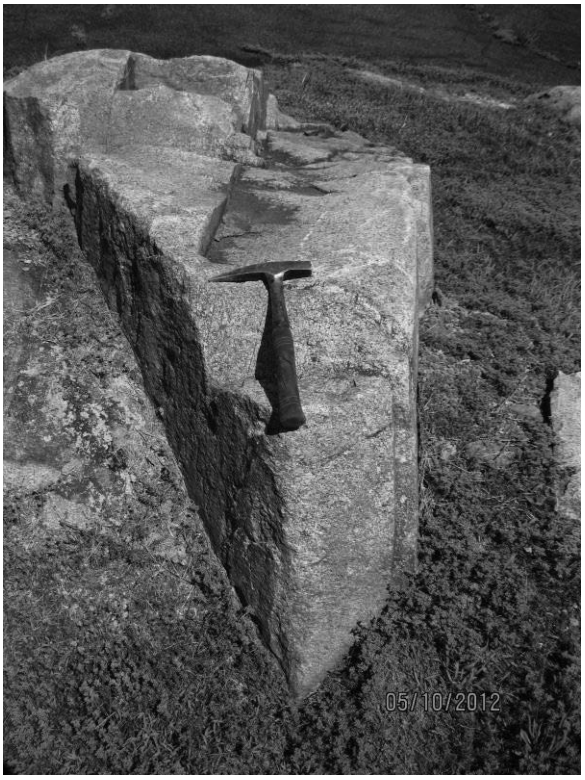

Figure 27: Outcrop of the Carysbrook phase of the Columbia pluton at Stop 10.

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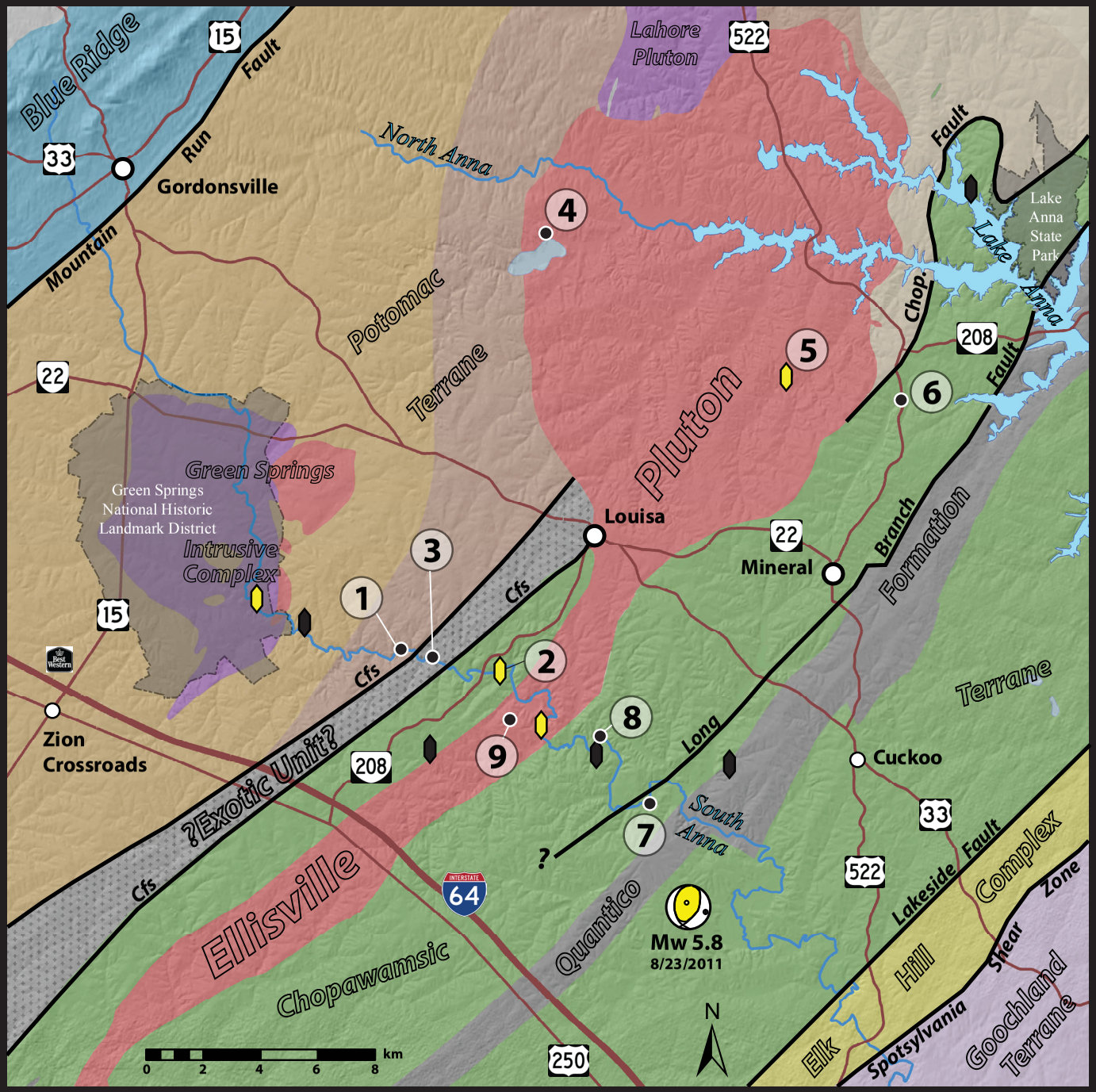

2014 Virginia Geological Field Conference

Stop Map

Explanation

- Stop #
- Stop location
- Igneous zircon sample site
- Detrital zircon sample site

- Chopawamsic Formation — Metavolcanic, metasedimentary rocks
- Mine Run Complex (IV, III, II) — Sub units of phyllite, metasandstone
- Possible melange — Metaclastic matrix with mafic bodies
- Quantico Formation — Schist, slate, metasandstone
- Felsic Intrusive Rock — Granodiorite, granite
- Mafic Intrusive Rock — Gabbro, diorite
- Blue Ridge — Metabasalt, phyllite, schist
- Elk Hill Complex — Horn./biotite gneiss, pegmatite, etc.
- Goochland terrane — Gneiss, amphibolite, granite, etc.

Geology modied from (Duke, 1983; Pavlides, 1990, 1995; VDMR, 1993; Mixon et al., 2000; Hughes, 2011; Spears et al., 2004, 2013; Burton et al., 2014; and our own reconnaissance mapping. Cfs = Chopawamsic fault system. Displayed zircon sample sites are from Hughes et al., 2013a, in press b, in progress; and Burton, in progress.