VIRGINIA DIVISION OF GEOLOGY AND MINERAL RESOURCES
OPEN-FILE REPORT 07-03

SUMMARY OF THE GEOLOGY OF THE BON AIR QUADRANGLE: A SUPPLEMENT TO THE GEOLOGIC MAP OF THE BON AIR QUADRANGLE, VIRGINIA

Mark W. Carter, C. R. Berquist, Jr., and Heather A. Bleick

COMMONWEALTH OF VIRGINIA
DEPARTMENT OF MINES, MINERALS AND ENERGY
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Edward E. Erb, State Geologist

CHARLOTTESVILLE, VIRGINIA
2008

COVER PHOTOS. Xenoliths and schlieren in Petersburg Granite. **A** – Biotite-muscovite granitic gneiss. A dashed line marks strong foliation in the rock. Edge of Brunton compass is about 3 inches (7.6 centimeters) long. Outcrop coordinates – 37.54853°N, 77.69229°W, NAD 27. **B** – Amphibolite xenolith (marked by an "a") in layered granite gneiss phase of the Petersburg Granite. Faint layering can be seen in granite between hammerhead and xenolith. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5050°N, 77.5893 °W, NAD 27. **C** – Foliation in amphibolite xenolith (marked by a dashed line). Hammerhead is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.5229°N, 77.5790°W, NAD 27. **D** – Schlieren (marked by an "s") in foliated granite phase of the Petersburg Granite. Schleiren are oriented parallel to the foliation in the granite. Field of view in photograph is about 2 feet by 3 feet (0.6 meter by 0.9 meter). Outcrop coordinates – 37.5147°N, 77.5352°W, NAD 27.

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SUMMARY OF THE GEOLOGY OF THE BON AIR QUADRANGLE: A SUPPLEMENT TO OPEN-FILE REPORT 07-03 – GEOLOGIC MAP OF THE BON AIR QUADRANGLE, VIRGINIA

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ABSTRACT

The Bon Air quadrangle is the first 1:24,000-scale geologic map to be completed through the STATEMAP geologic mapping program in the Richmond area. Located along the Fall Line in this part of Virginia, the quadrangle is underlain by a range of stratigraphy: Paleozoic Petersburg Granite and Triassic Newark Supergroup rocks serve as basement to overlying Coastal Plain cover sediments of Quaternary to Tertiary age. Petersburg Granite consists of four phases – subidiomorphic granite, porphyritic granite, foliated granite, and layered granite gneiss. Foliations in Petersburg Granite, traditionally interpreted to have been produced by igneous-flow, may be partly tectonic in origin. This granite was used as building stone in the late 1800's and early 1900's for construction of numerous public buildings in Richmond and Washington DC. Regional stratigraphic correlations between fall zone units on the Bon Air quadrangle with well-defined stratigraphy to the east are established with the aid of geochemical analyses: clayey silt beneath high-level Tertiary gravels correlates with Miocene lower Chesapeake Group formations; high- and mid-level Tertiary gravels may correlate with upper Chesapeake Group strata. Newly recognized units include: low-level Tertiary gravels (equivalent to the upper Pliocene Bacons Castle Formation), Quaternary-Tertiary gravels (equivalent to the lower Pleistocene to upper Pliocene Windsor Formation), and Quaternary-Tertiary alluvial and colluvial valley fill deposits. These valley fill deposits may have originated as debris flows generated by Cenozoic faulting. Carolina Bays occur above high-level Tertiary gravels and above upper Chesapeake Group sediments, suggesting that they are no older than Pliocene, if all of the bays formed contemporaneously. Regional joint sets occur within Coastal Plain units, while parallel sets occur in Petersburg Granite. These joints partly influenced slope failure throughout the Richmond area during Hurricane Isabel and Tropical Depression Gaston in 2003 and 2004, respectively. Mesozoic silicified cataclasites cut Petersburg Granite and juxtapose Triassic rocks of the Tuckahoe sub-basin. Younger faults offset Coastal Plain units as young as Pliocene. Some of these faults appear to be reactivated. All map units on the quadrangle exhibit properties that should be considered by urban planners, and some units pose serious environmental concerns.

Keywords: STATEMAP, Petersburg Granite, silicified cataclasite, Newark Supergroup, Bon Air gravel, Chesapeake Group, Cenozoic faults, Inner Coastal Plain, Fall Line, fall zone, Carolina Bays, building stone, landslides, groundwater.

INTRODUCTION

This summary report accompanies Open-File Report 07-03 – Geologic Map of the Bon Air Quadrangle, Virginia. The Bon Air quadrangle is bounded by 37º 30' to 37º 37' 30" North latitude and 77º 30' to 77º 37' 30" West longitude. The map includes parts of Henrico, Chesterfield, and Goochland counties, and the city of Richmond (Figure 1). Chippenham Parkway and Parham Road (Virginia Highway 150) provide north-south access across the quadrangle. Broad Street (U.S. Highway 250), Interstate I-64, Patterson Avenue (Virginia Highway 6) and Midlothian Turnpike (U.S. Highway 60) provide east-west access in the northernmost, northern, central, and southern portions of the quadrangle, respectively. Major hydrologic features include James River and its high-order tributaries – Deep Run, Tuckahoe Creek, and Powhite Creek – and Upham Brook, a tributary of Chickahominy River.

The purpose of this summary is to provide additional information and data not included on the geologic map. There is some overlap between the map and summary for emphasis and elaboration.

In 2005, the Virginia Department of Mines, Minerals and Energy, Division of Mineral Resources began a multi-year geologic mapping project in the Richmond metropolitan area (Figure 1) through the STATEMAP program. The Bon Air quadrangle is the first of a series of 1:24,000-scale geologic maps to be completed and compiled through this project. The quadrangle was selected because 1) the area is continuing to experience rapid growth and development, both in residential and light service/industrial markets, and 2) field evaluation of previously published data (i.e., Goodwin, 1980) provided introductory experience in the regional geologic framework before detailed mapping begins on unpublished quadrangles in the Richmond area.

SUMMARY OF SIGNIFICANT CHANGES

New mapping has resulted in new interpretations to the geology of the Bon Air quadrangle from Goodwin's (1980) published map. Changes were made based on observations at abundant new outcrops from urban development and natural-formed exposures from recent Hurricane Isabel in 2003 and Tropical Depression Gaston in 2004. These changes are highlighted below, with more thorough discussions of each in succeeding sections:

- Four phases of Paleozoic Petersburg Granite – subidiomorphic granite, porphyritic granite, foliated granite, and layered granite gneiss – are now recognized and mapped rather than the two phases originally portrayed by Goodwin (1980). In addition, the outcrop belt of "porphyritic granodiorite" shown by Goodwin (1980) in the western half of the quadrangle has been altered.
- In the northwestern part of the quadrangle, the boundaries of Triassic Newark Supergroup rocks in the Tuckahoe sub-basin (Wilkes and Lasch, 1980) have been expanded to the northeast. Exposures of Triassic rocks and bounding silicified cataclasite zones in the headwaters of Flat Branch indicate that the Tuckahoe sub-basin extends north-

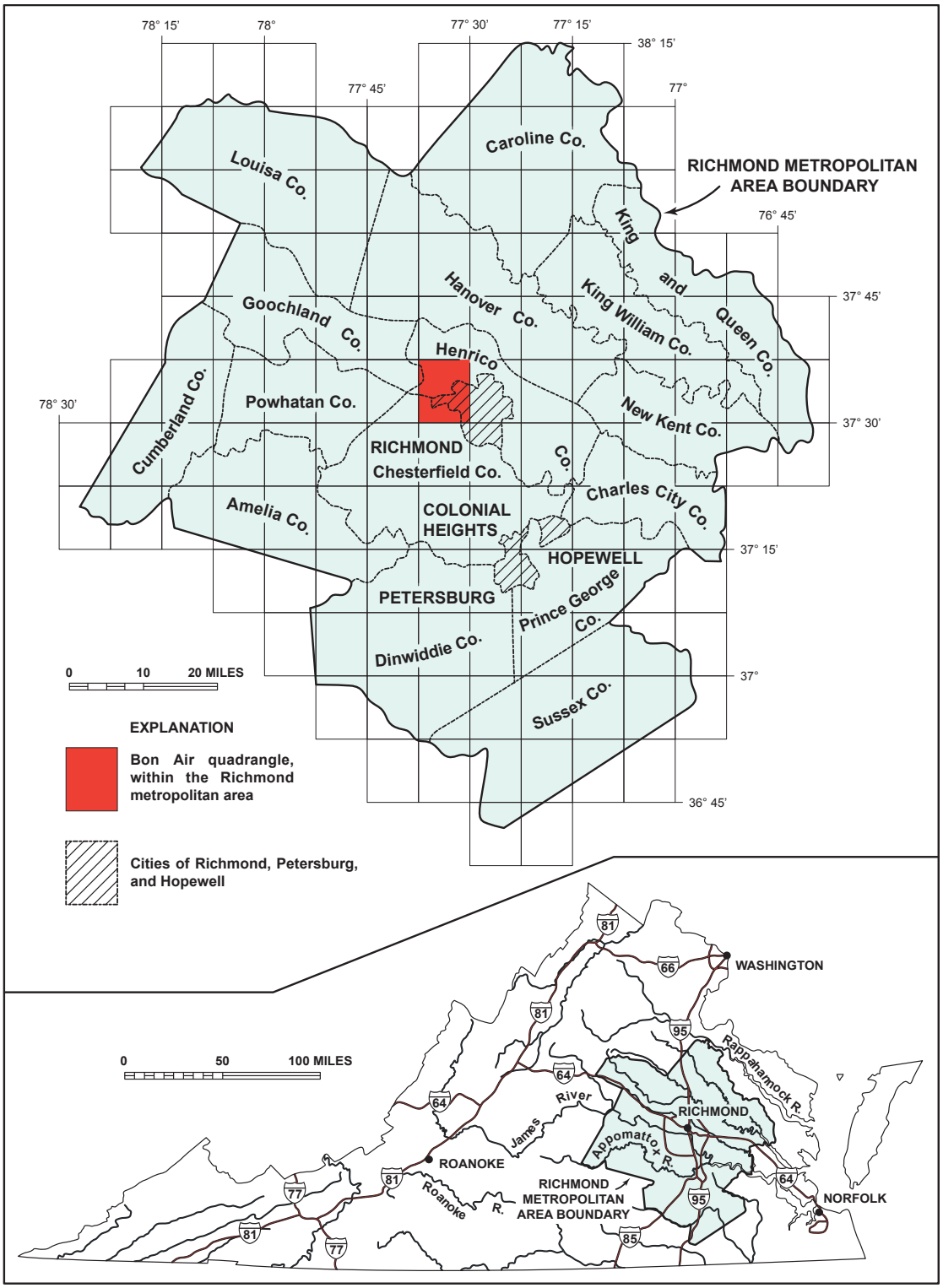

Figure 1. Geography of the Richmond metropolitan area, showing the location of the Bon Air quadrangle.

east and possibly connects with the Deep Run sub-basin (Wilkes and Lasch, 1980) on the adjoining Glen Allen quadrangle (Goodwin, 1981).

- The age of at least one silicified cataclasite zone ("Mzb" in this report, "pq" of Goodwin, 1980, who described the unit as "closely jointed, highly fractured granite with quartz filling the fractures and joints") is well constrained in the north-central part of the quadrangle. Here, in the Pemberton Road area, a 2-foot- (0.6-meter-) thick zone of silicified cataclasite crosscuts and incorporates fragments of Jurassic diabase. Lithologic similarities between this silicified cataclasite zone and others throughout the quadrangle suggest a Mesozoic or younger age for these structures.
- Distribution of high-level Tertiary gravels ("Tg_1" in this report; "g_1" of Goodwin, 1980) and upper Chesapeake Group sand and gravel ("Tcu" in this report; "sg" of Goodwin, 1980) remains similar, with few additions and modifications. For example, two small deposits of high-level Tertiary gravel were located near Wedgewood in the north-central part of the quadrangle. Minor changes to the distribution of upper Chesapeake Group sand and gravel occurred in the eastern part of the quadrangle in the Wistar Road, Upham Brook, Windsor Farms, and Beaufont Spring areas.
- More significant changes were made to the distribution of mid-level Tertiary gravels ("Tg_2" in this report; "g_2" of Goodwin, 1980, who shows two deposits of mid-level Tertiary gravel: one in the east-central part of the quadrangle, south of James River in the vicinity of Gravel Hill and another in the west-central part of the quadrangle, north of James River, at Dorset Woods). New mapping demonstrates that mid-level Tertiary gravels occur throughout the quadrangle at elevations ranging from approximately 200 to 250 feet above present sea level. Deposits occur in the south-central part of the quadrangle along Powhite Creek from Bon Air to Gravel Hill, in the west-central part of the quadrangle south of James River from Holiday Hills westward, in the central part of the quadrangle north of James River in the River Road Hills area, in the northeastern part of the quadrangle along Upham Brook, and in the northwestern part of the quadrangle, along Flat Branch and Deep Run in the Pump Road area. Many of these deposits constitute only a thin (less than 5 feet, or 1.5 meters thick) surface veneer of gravel, which may account for their absence on Goodwin's (1980) published geologic map. These deposits are likely erosional remnants of formerly more extensive gravels.

New data from recent detailed geologic mapping, not compiled in Goodwin's (1980) previous report, include:

- Several new units have been recognized or added to the geologic map. Clayey silt, correlated with Miocene lower Chesapeake Group ("Tcl" in this report), underlies high-level Tertiary gravels in the southwestern part of the quadrangle. This unit, first noted by Goodwin and Johnson (1970) but not compiled by Goodwin (1980), crops out in the headwaters and tributaries of Powhite Creek, where it is more than 15 feet (4.5 meters) thick locally. Lower Chesapeake Group clayey silt also crops out beneath upper Chesapeake Group sand and gravel in the southeastern part of the quad-

rangle near Westover Heights (Kenneth R. Meggison, written communication, 2007). Low-level Tertiary gravels ("Tg_3" in this report) cap hills and mantle slopes along both banks of James River, Powhite Creek, and the upper reaches of Upham Brook, at elevations ranging from 130 to 200 feet above present sea level. Quaternary-Tertiary gravels ("QTg_4"in this report) occur on low hills at an elevation of about 120 feet above present sea level in the vicinity of Willow Oaks Country Club near the confluence of Powhite Creek and James River in the central-eastern part of the quadrangle. Isolated deposits of Quaternary-Tertiary alluvial and colluvial valley fill ("QTac" in this report), consisting of variably lithified pebbly feldspathic sand, occur as channel fill and mantle side slopes throughout the quadrangle (Carter and others, 2007a).

- The map is now populated with hundreds of new structural measurements in Coastal Plain sediments and basement rocks (Petersburg Granite and Triassic Newark Supergroup), which are integral for regional groundwater research and local environmental assessments and remediation (Carter and others, 2006). Regional jointing has been recognized and mapped in clayey silt of the lower Chesapeake Group, and in variably lithified pebbly feldspathic sand of various Coastal Plain units (Carter and others, 2006; 2007a).
- Map patterns based on new detailed mapping, analysis of borehole data, and compilation of previous work in the area (e.g., Johnson and others, 1987) highlight the role of Cenozoic-age faulting in this part of Virginia. At several localities, apparent offsets in the basal elevations of high-level Tertiary gravels, mid-level Tertiary gravels, and upper Chesapeake Group sand and gravel may be attributed to faults that are now mostly covered beneath colluvium and urban development. Some of these faults appear to be reactivated. Many Quaternary-Tertiary alluvial and colluvial valley fill deposits, mostly south of James River in the central-western part of the quadrangle, appear to thicken, thin, or be offset and juxtaposed against fractures and silicified cataclasite zones within Petersburg Granite, suggesting Cenozoic reactivation of these structures. Lastly, a fault documented by Johnson and others (1987) to offset Petersburg Granite, lower Chesapeake Group clayey silt, and high-level Tertiary gravel in a tributary of Powhite Creek southeast of Beaufont Spring, is also compiled on the geologic map.
- Goodwin (1980) restricted the occurrence of elliptical to subcircular depressions, first described by Johnson and Goodwin (1967) as Carolina Bays, to the relatively flat upland surface underlain by high-level Tertiary gravel in the southwestern part of the quadrangle. Another potential Carolina Bay has been tentatively identified on the flat surface underlain by upper Chesapeake Group sand and gravel south of Westover Heights in the southeastern part of the quadrangle.

STRATIGRAPHY

The Richmond metropolitan area occupies a varied geologic setting. Located along the Fall Line[1] in this part of Virginia, the region hosts a wide range of stratigraphy (Figures 2 and 3). Petersburg Granite and Triassic Newark Supergroup rocks serve as basement to overlying Coastal Plain cover sediments. Coastal Plain stratigraphy in the Richmond area ranges from Quaternary to Cretaceous. East of the Fall Line, the stratigraphy forms an eastward thickening, contiguous pile of fluvial, deltaic, estuarine, and marine sediments of the Inner Coastal Plain subprovince. West of the Fall Line, discontinuous Quaternary to Tertiary fluvial and colluvial gravel deposits characterize Coastal Plain units of the fall zone subprovince. Lithologies within these gravel deposits are generally similar; mapping is based in greater part on elevation and morphology, with few pronounced exceptions. The paucity of paleontologic data from these units requires that detailed mapping and analytical methods, notably geochemical comparisons, provide temporal correlations between these deposits in the fall zone with better defined stratigraphy to the east (Carter and others, 2007a, 2007b).

BASEMENT ROCKS

Rocks of the Petersburg Granite

Petersburg Granite underlies a large region of central-eastern Virginia, from near Ashland in Hanover County southward to Dinwiddie in Dinwiddie County (Figure 2). Its outcrop belt is bounded to the north and west by the Richmond-Taylorsville Triassic basins, and is covered by Coastal Plain sediments to the south and east. Wright and others (1975) obtained a discordant U-Pb isotope age of 330 ± 8 m.y. from two samples of Petersburg Granite, whereas Lee and Williams (1993) reported a slightly younger zircon age of 314.5 ± 2.1 m.y. Granites of similar composition, texture, geochemistry, and presumed age crop out in the Goochland-Raleigh and southern Roanoke Rapids terranes in Virginia (Husted, 1942; Bottino and Fullagar, 1968; Poland, 1976; Reilly, 1980; Sinha and Zietz, 1982; Horton and others, 1993; Speer and Hoff, 1997). Many of these have historically been correlated with Petersburg Granite (Calver and others, 1963). A host of similar granites also crop out in the North Carolina Piedmont (Fullagar and Butler, 1979; Farrar, 1985; Russell and others, 1985; McSween and others, 1991; Coler and others, 1997).

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[1] In this part of Virginia, the Fall Line, as geologically defined here, is the boundary, at land surface, between the westernmost conterminous Coastal Plain units and Piedmont rocks (Figure 2). In the Richmond area (on the Bon Air, Glen Allen, Richmond, Chesterfield, and Drewrys Bluff quadrangles) the westernmost contact between upper Chesapeake Group sediments and Petersburg Granite marks the Fall Line; this contact ranges from an elevation of about 235 to 260 feet above sea level on the Bon Air and Chesterfield quadrangles. This contact also locally marks the base of the Chippenham scarp (Johnson and Peebles, 1984; Thornburg scarp of Mixon, 1978), which separates the Midlothian upland (Johnson and Peebles, 1983) from the Richmond plain (Johnson and Peebles, 1984).

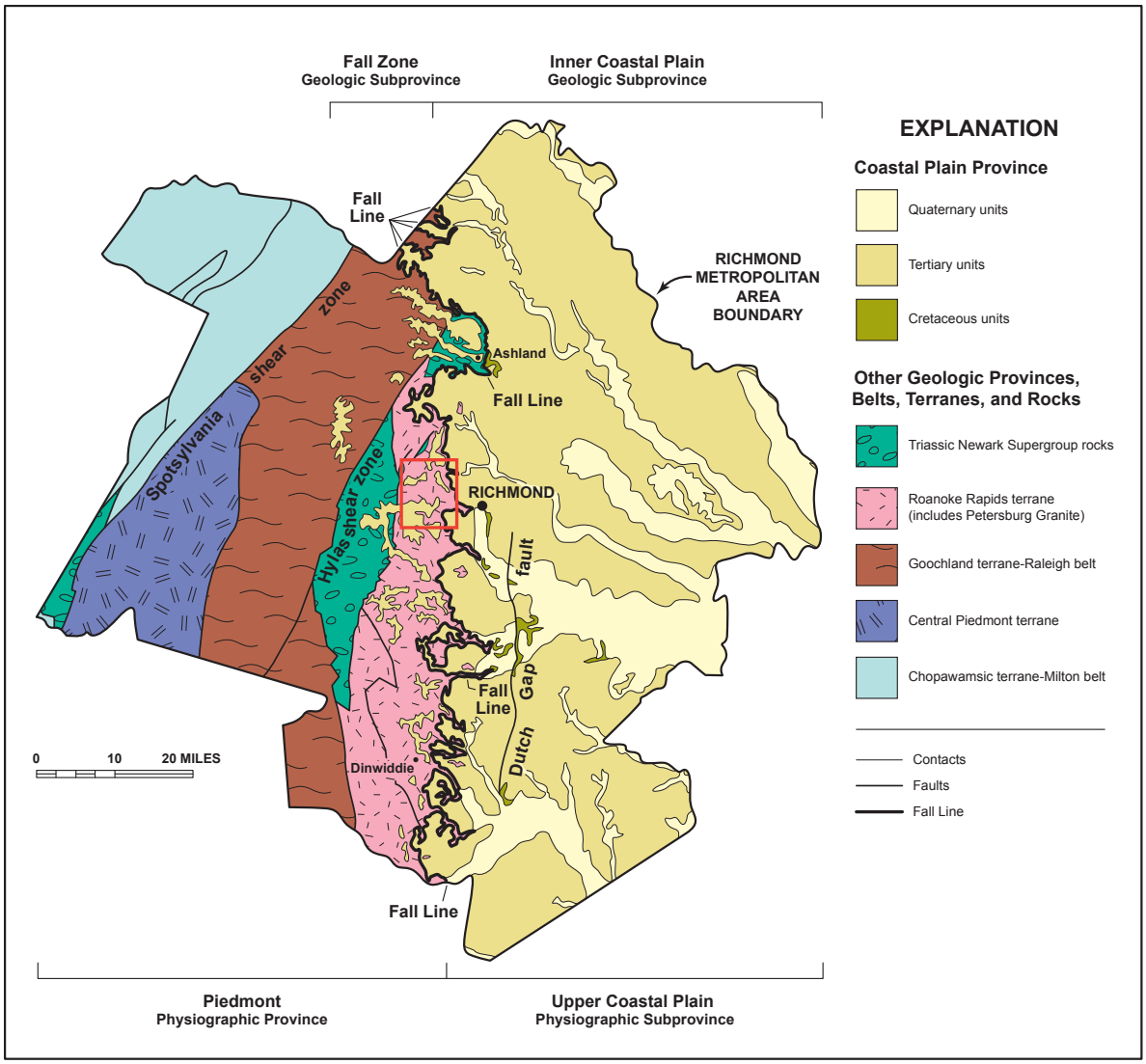

Figure 2. Geologic and physiographic provinces and subprovinces in the Richmond metropolitan area. Bon Air quadrangle shown by red rectangle on map. The "Fall Line" as geologically defined here, is the boundary, at land surface, between the westernmost conterminous Coastal Plain units and Piedmont rocks in this part of Virginia. The Inner Coastal Plain geologic subprovince extends from the Fall Line eastward. The fall zone subprovince (of the Coastal Plain geologic province) extends westward from the Fall Line to include all of the discontinuous Quaternary to Tertiary fluvial and colluvial gravel deposits in central-eastern Virginia. The Fall Line also marks the boundary between the Piedmont physiographic province and the Upper Coastal Plain physiographic subprovince. Geology compiled mostly from the Geologic Map of Virginia (Virginia Division of Mineral Resources, 1993). Other sources include Bobyarchick and Glover (1979), Horton and others (1991), and Spears and others (2004).

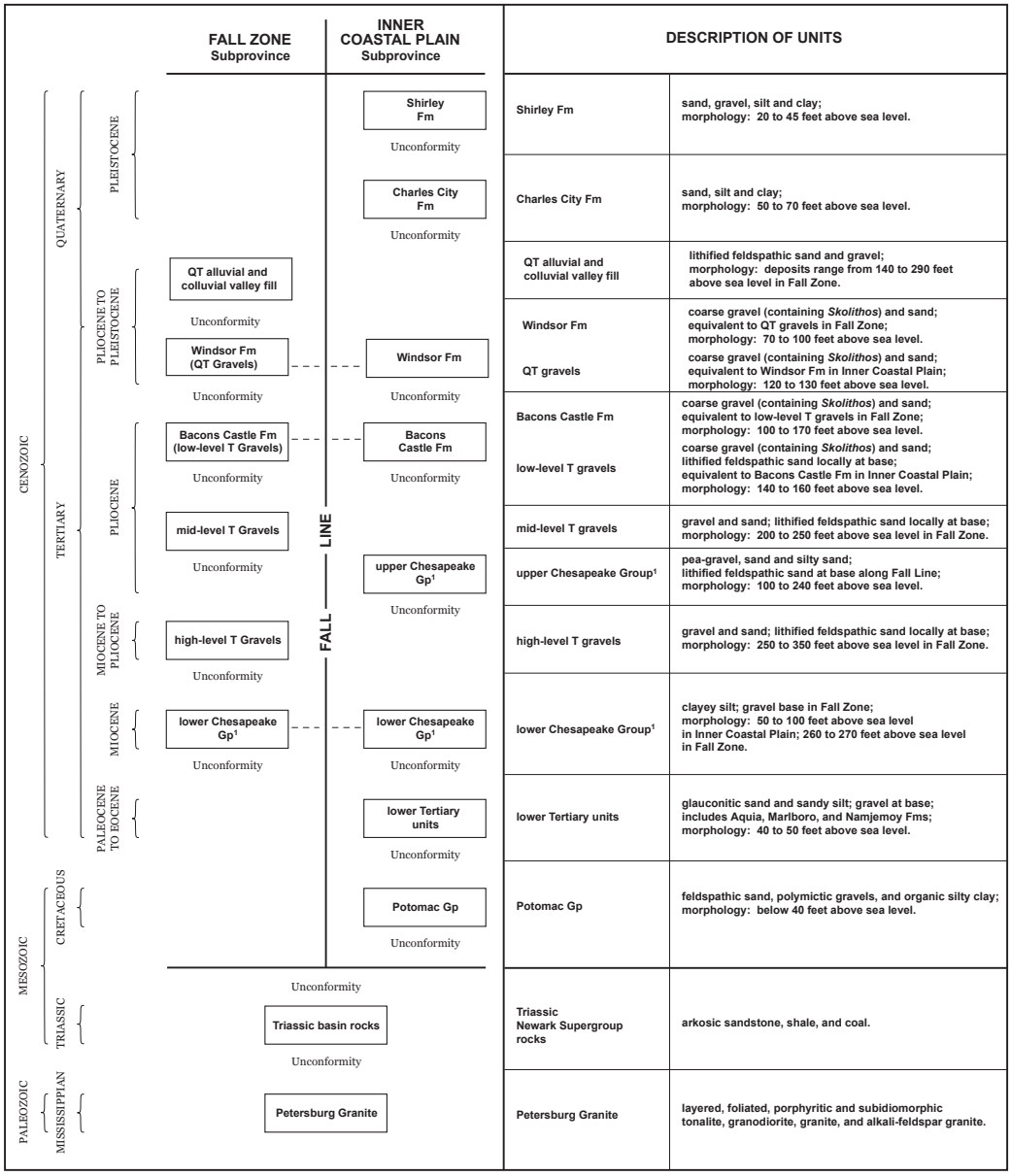

Figure 3. Stratigraphy, correlation, and brief description of Coastal Plain units across the fall zone and Inner Coastal Plain subprovinces (dashed line denotes equivalency of units across the Fall Line). Inner Coastal Plain units rest unconformably above Triassic Newark Supergroup rocks and Petersburg Granite.

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[1]In the Richmond area, the Chesapeake Group is subdivided into upper and lower units based on lithology and age. The upper Chesapeake Group consists of yellow to reddish-yellow sand and gravel, and most likely correlates with the Pliocene Yorktown Formation as an up-dip nearshore facies. The lower Chesapeake Group consists of blue-gray silty clay, and correlates in part with the Miocene Eastover, Choptank, and Calvert Formations. We have not conducted detailed sedimentologic or paleontologic studies to confidently subdivide these lower Chesapeake Group formations in this area.

Although traditionally portrayed as a single, homogenous pluton, (e.g., Calver and others, 1963), Watson (1906) described three types of granitic rocks from the Richmond and Petersburg areas: light-gray granite, dark blue-gray granite, and porphyritic granite. Bloomer (1939) elaborated on the intrusive relationships between Watson's granites. Goodwin (1970, 1980, 1981) recognized three phases but mapped only two on the Bon Air quadrangle: uniform granite and porphyritic granodiorite. Bobyarchick (1978) recognized massive, porphyritic, and foliated igneous phases. New detailed mapping on the Bon Air quadrangle supports the validity of subdivisions within the Petersburg Granite, and abundant outcrops provide the necessary exposure to accurately delineate them. These subdivisions challenge the validity of a single geochronometric date for the entire outcrop belt. On the Bon Air quadrangle, Petersburg Granite is subdivided into four mesoscopic phases, from youngest to oldest: subidiomorphic granite, porphyritic granite, foliated granite, and layered granite gneiss. These most closely correspond to the three phases of Bobyarchick (1978).

Subidiomorphic Granite

Subidiomorphic granite occupies a large area of the central-northern portion of the Petersburg outcrop belt on the Bon Air quadrangle, but it also occurs as small, discontinuous pods and lenses within other phases. Subidiomorphic granite is light-bluish-gray and generally fine- to medium-grained, with a texture that is typically hypidiomorphic-granular (subidiomorphic). Locally, it is porphyritic, with pale pink potassium feldspar phenocrysts typically less than 0.75 inch (2 centimeters) in length (Figure 4A). In outcrop, subidiomorphic granite is typically massive, but locally it is weakly foliated.

Modes of several samples of subidiomorphic granite average about 34.8% potassium feldspar, 31.8% quartz, 16.8% plagioclase, 5.7% muscovite, 4.8% biotite, 1.8% epidote, 0.8% apatite, 0.7% hornblende, 0.5% carbonate, 0.2% fluorite, 0.2% ilmenite/magnetite, and 0.2% zircon, with traces of allanite, chlorite, and garnet (Figure 5; Table 1).

Subidiomorphic granite locally contains pods, lenses, zones, or xenoliths of foliated granite and layered granite gneiss, and is cross-cut by younger porphyritic pegmatite and aplite dikes. Major element geochemistry suggests this phase is the youngest, because it is the most evolved (Figure 6). This is also the most recognized phase of the Petersburg Granite, described to some extent by all previous workers.

Porphyritic Granite

Porphyritic granite occurs along the southwestern flank of the Petersburg outcrop belt on the quadrangle, and as thin, discontinuous pods and lenses within other phases. Porphyritic granite is grayish-blue, medium- to coarse-grained, with pale-pink potassium feldspar phenocrysts over 1 inch (2.5 centimeters) in length that are commonly oriented subparallel to a faint to strong foliation (Figure 4B). The groundmass is dominated by quartz, plagioclase, and biotite; quartz in hand specimen is typically medium-gray to light-bluish-gray.

Modes of several samples of porphyritic granite average about 29.3% potassium feld-

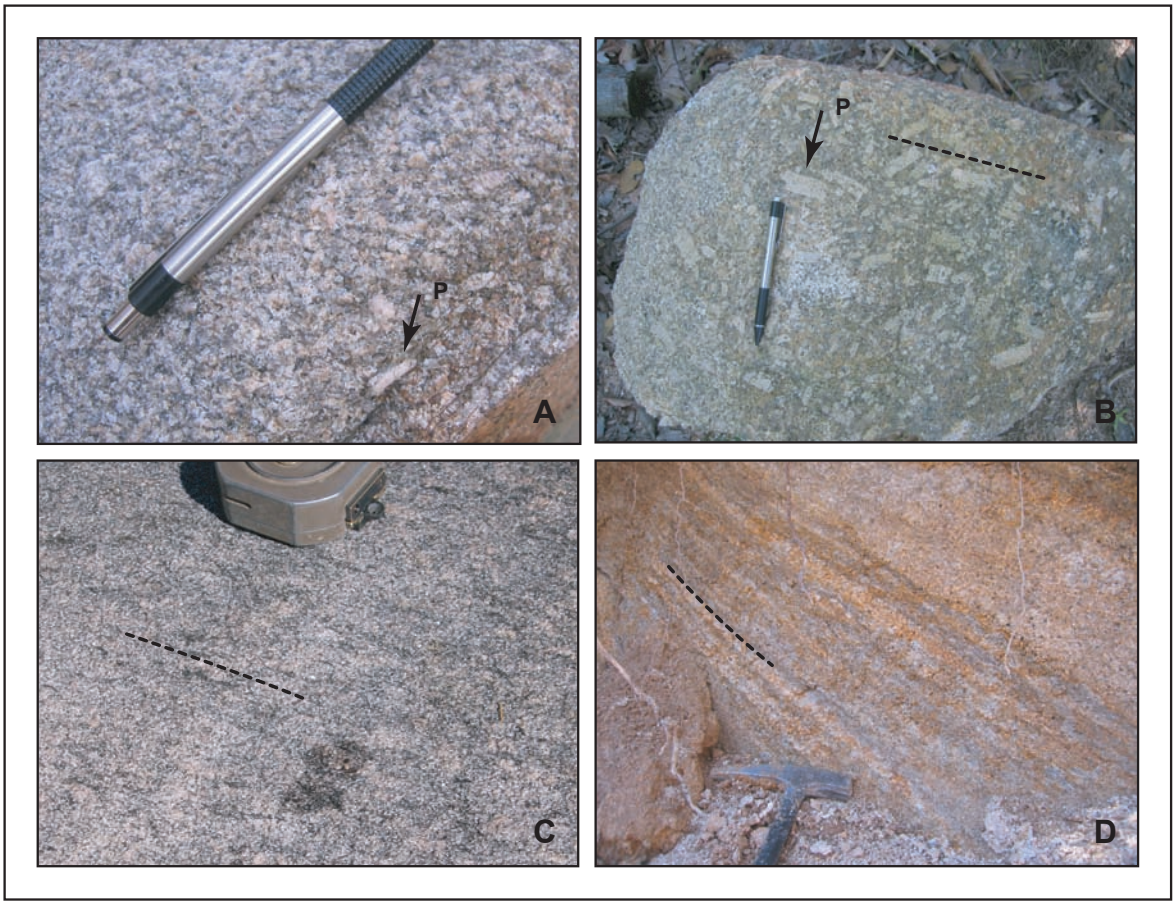

Figure 4. Phases of the Petersburg Granite. **A** – Subidiomorphic phase. Notice the small (up to 0.75 inch or 2 centimeters) potassium feldspar phenocrysts (marked by an arrow and "P"). The matrix consists mostly of quartz and plagioclase. The pencil is about 4 inches (10 centimeters) long. Outcrop coordinates – 37.5715°N, 77.5618°W, NAD 27. **B** – Porphyritic phase. Notice the large (up to 1.5 inches, or 4 centimeters) potassium feldspar phenocrysts (marked by an arrow and "P"), which are very weakly aligned (foliation is marked by a dashed line) in this float block. The pencil is about 4 inches (10 centimeters) long. Outcrop coordinates – 37.5508°N, -77.5653°W, NAD 27. **C** – Foliated phase. The foliation (marked by a dashed line) is defined by a strong alignment of phyllosilicate minerals. Edge of Brunton compass is about 3 inches (7.6 centimeters) long. Outcrop coordinates – 37.5090°N, 77.313°W, NAD 27. **D** – Layered granite gneiss phase. Foliation (marked by a dashed line) is defined by a strong alignment of both quartz-feldspar and phyllosilicate minerals, segregated into distinct quartz-feldspar and biotite-quartz-feldspar rich layers. Hammerhead is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.4556°N, 77.5515°W, NAD27 (outcrop is on the Chesterfield quadrangle).

Table 1a. Modes (calculated from 200 point counts per thin section) of samples collected on the Bon Air and other quadrangles in the Richmond metropolitan area (samples from others quadrangles are labeled in the table). Rock unit abbreviations: QTac – Quaternary-Tertiary alluvial and colluvial valley fill; Tg_2 – mid-level Tertiary gravels; K – Cretaceous Potomac Group; Mzb – Mesozoic silicified cataclasite; TRns – Triassic Newark Supergroup; Pzpg – subidiomorphic phase, Paleozoic Petersburg Granite; Pzpp – porphyritic phase, Petersburg Granite; Pzpf – foliated phase, Petersburg Granite; Pzpl – layered granite gneiss phase, Petersburg Granite; mg – mafic gneiss. Latitude/Longitude coordinates in NAD 27. Mineral abbreviations: K-spar – potassium feldspar; Plag – plagioclase; Opx – orthopyroxene; Bt – biotite; Hbl – hornblende.

SAMPLE	ROCK UNIT	QUADRANGLE	LATITUDE/ LONGITUDE	Quartz	Plag	K-spar	Bt	Musc	Sericite/ Clay Minerals	Chlorite	Talc	Opx	Hbl	Act	Trem	Apatite	Allanite	Sphene	Garnet	Zircon	Fluorite	Hematite	Ilmenite/ Magnetite	Epidote	Clino	Carbonate
9970	QTac	Bon Air	37.60989/ -77.58620	41.5	3	6			23													22.5	0.5			3.5
9952	Tg_2	Bon Air	37.50957/ -77.55706	51	4.5	10.5	trace	trace	30.5													3.5				
9957	Tg_2	Bon Air	37.52238/ -77.52586	50	Trace	3	trace													0.5		46.5				
9956	Tg_2	Bon Air	37.57917/ -77.55849	52	2	6.5	trace		14.5													22.5	trace			2.5
9969	Tg_2	Bon Air	37.52661/ -77.62322	32	3	13.5			23													25.5				3
10133	K	Dutch Gap	37.3838/ -77.3157	48.5	3.5	13.5	1	1	19.5											trace		11.5	trace			1.5
9972	TRns	Bon Air	37.6153/ -77.6124	53.5	5.5	17.5	3	trace	18.5	trace										trace			trace	1		1
9967	Mzb	Bon Air	37.53667/ -77.61371	97.5			trace	1												trace		1.5				
9966	Pzpg	Bon Air	37.5541/ -77.593	37	14.5	24	6	12					1.5			trace			trace	0.5			trace	3		0.5
10057	Pzpg	Chesterfield	37.4921/ -77.6243	32.5	15.5	42.5	1						0.5			1	trace			trace	0.5		0.5	trace		1
10157	Pzpg	Drewrys Bluff	37.4898/ -77.4278	26	20.5	38	7.5	5		trace						0.5								2.5		
9958	Pzpp	Bon Air	37.5456/ -77.5628	23	18.5	26.5	23.5													2				5		1
9960	Pzpp	Bon Air	37.6149/ -77.539	25	19.5	36.5	12	2					trace							trace		trace	trace	trace		
10055	Pzpp	Chesterfield	37.459/ -77.6179	24	38.5	25	7.5	0.5		1			trace			0.5	trace	trace		trace			1	2		
10161	Pzpf	Drewrys Bluff	37.4388/ -77.4365	19	35	22	13	3					trace			trace	trace	5.5		trace			trace	1		
10056	Pzpl	Chesterfield	37.4415/ -77.5788	31.5	35	3	30						trace				trace					0.5	trace	trace		
10163	Pzpl	Richmond	37.5232/ -77.421	48	22.5	18.5	8.5	2.5																trace		
10159	Pzpl	Drewrys Bluff	37.4898/ -77.4278	23.5	39.5	11.5	20.5	0.5		0.5						0.5		0.5						1.5	trace	1
9964	mg	Bon Air	37.5494/ -77.5769		trace		0.5				6.5	38		12	32.5							5.5	4.5			0.5

Table 1b. Rock type and thin section descriptions based on results from Table 1a.

SAMPLE	ROCK TYPE	THIN SECTION DESCRIPTIONS
9970	feldspathic sand	Subangular quartz and feldspar grains in a finer-grained matrix cemented with clay minerals, hematite and carbonate. Some feldspar grains are pristine, others reduced to clay minerals (which apparently supplies the mineralization for the cement. Few composite grains (foliated metamorphic quartz and granitic - quartz and feldspar). Few large hematite concretions - cores appear to be mostly clay minerals.
9952	feldspathic sand	Subangular to subrounded grains of strained quartz and feldspars (no composite clasts), cemented primarily with clay minerals and some hematite. Biotite and muscovite grains are detrital. No epidote or zircons. Sample is dissaggregated grainte.
9957	conglomerate	Rock consists mostly of subrounded to subangular grains of metamorphic (strained) quartz - single grains and composite grains of foliated quartz - with few detrital grains of feldspar, biotite and zircon. Cemented with hematite.
9956	feldspathic sand	subangular to angular grains of quartz (strained) and feldspar, few composite grains (foliated metamorphic quartz and granitic - quartz and feldspar), in a finer-grained matrix of clay minerals, quartz and feldspar, cemented with clay minerals, hematite and minor carbonate. Few large hematite concretions - cores appear to be mostly clay minerals. Fractures have hematitic weathering rind.
9969	feldspathic sand	subangular grains of quartz (strained) and feldspar, cemented by clay minerals and minor carbonate. Cementation appears to occur as feldspars reduce to sericite/clay minerals, then bonded with hematite and carbonate.
10133	conglomerate	Monocrystalline k-spar, few plaglioclase, and strained quartz grains, and composite grains of quartzite and granite; muscovite and biotite are detrital; cemented with clay minerals, hematite and minor carbonate.
9972	sandstone	Subangular to subrounded grains. Very few composite grains - those present are granitic (quartz and feldspar). Sericite/muscovite/biotite matrix, with hematite staining. Larger grains of biotite (brown pleochroic) and muscovite appear to be detrital (bent, broken grains with serrated, physically disintegrated edges). Carbonate, epidote and chlorite are alteration phases. Dissaggregated granite - very similar to arkose sections.
9967	silicified cataclasite	Quartz is only slightly strained (less strained than granite and sedimentary rocks). Zircons very small. Muscovite/biotite pristine. Three varieties of quartz: very fined-grained amorphous chalcedony is matrix within subangular to subrounded "ghost" grains. Within "ghost" grains are larger subangular single grains of slightly strained quartz. Filling "voids" between "ghost" grains, and as veins throughout sample, are large, elongate, undulose quartz crystals.
9966	subidiomorphic granite	Alignment of biotites; muscovite and hornblende are somewhat aligned to themselves, but are orthogonal to both biotite and each other. Biotite is brown to green pleochroic.
10057	subidiomorphic granite	Weathered sample; abundant sericite alteration of feldspars. Much more k-spar than plagioclase. Biotite is both brown and green pleochroic; hornblende is green pleochroic. Some myrmakite.
10157	subidiomorphic granite	Pristine sample. Some biotite altered to epidote and chlorite, muscovite is not aligned, biotite very weakly aligned. Few ubiquitous hornblende grains, which are partially altered to epidote. Slight metamorphic overprint.
9958	porphyritic granite	Biotite (pleochroic green) is aligned; feldspars altered to epidote and sericitic masses; Quartz is strained; Myrmekite present but not abundant.
9960	porphyritic granite	Biotite (pleochroic brown) not aligned; myrmekite in section; very little epidote; alteration marked by some sericite/muscovite in section.
10055	porphyritic granite	Bioite altered to both epidote and chlorite. Sphene associated with opaques and epidote. Myrmakite present.
10161	foliated granite	Sphene "phenocrysts". Abundant alteration; allanite, biotite and hornblende altered to epidote. Muscovite in sample.
10056	layered granite gneiss	Biotite (brown pleochroic) well aligned. Allanite altered to epidote, hematite and opaques.
10163	layered granite gneiss	Both quartz/feldspar and biotite show moderate alignment. Muscovite generally same orientation as biotite.
10159	layered granite gneiss	Myrmakite in sample. Biotite altered to epidote and chlorite. Some sphene associated with epidote. Feldspars partially altered to epidote and carbonate. No alignment of micas.
9964	amphibolite schist	Orthopyroxene within a foliated graoundmass of tremolite; larger actinolite crystals forming a cross-mineralization texture, orthogonal to the tremolite foliation; both pyroxene and amphibole altered to chlorite and talc; very few biotite grains; carbonate appears to be an alteration product.

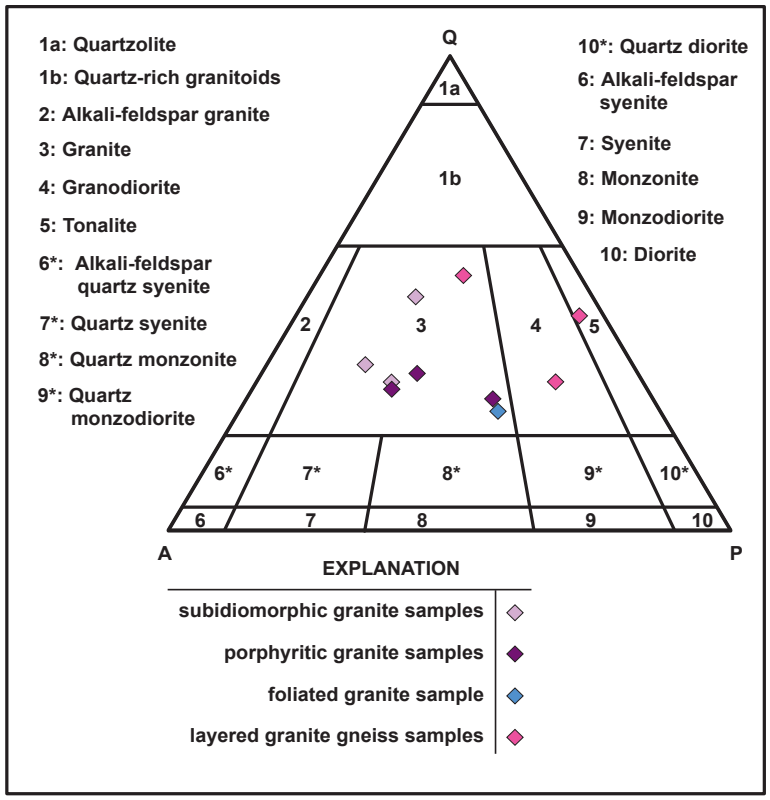

Figure 5. Classification of Petersburg Granite samples from modal analysis. Classification after Streckeisen (1976). Data provided in Table 1.

spar, 25.5% plagioclase, 24% quartz, 14.3% biotite, 2.3% epidote, 0.7% zircon, 0.3% chlorite, 0.3% ilmenite/magnetite, 0.3% carbonate, 0.2% muscovite, and 0.2% apatite, with traces of hornblende, allanite and sphene (Figure 5; Table 1).

Field relationships show that porphyritic granite is often associated with coarse- to very coarse-grained, medium-gray to light-bluish-gray quartz and pale pink potassium feldspar pegmatite. Where these pegmatites cross-cut older phases, their margins commonly consist of porphyritic granite, regardless of lithology. This association with late-stage pegmatite suggests that porphyritic granite may be the youngest phase of Petersburg Granite intrusion, but major element geochemistry suggests it is not as evolved as subidiomorphic granite (Figure 6).

Foliated Granite and Layered Granite Gneiss

Foliated granite and layered granite gneiss predominate the southeastern portion of the Petersburg outcrop belt on the quadrangle. These phases constitute the largest volume of Petersburg Granite recognized thus far in the Richmond area. Wright and others (1975) col-

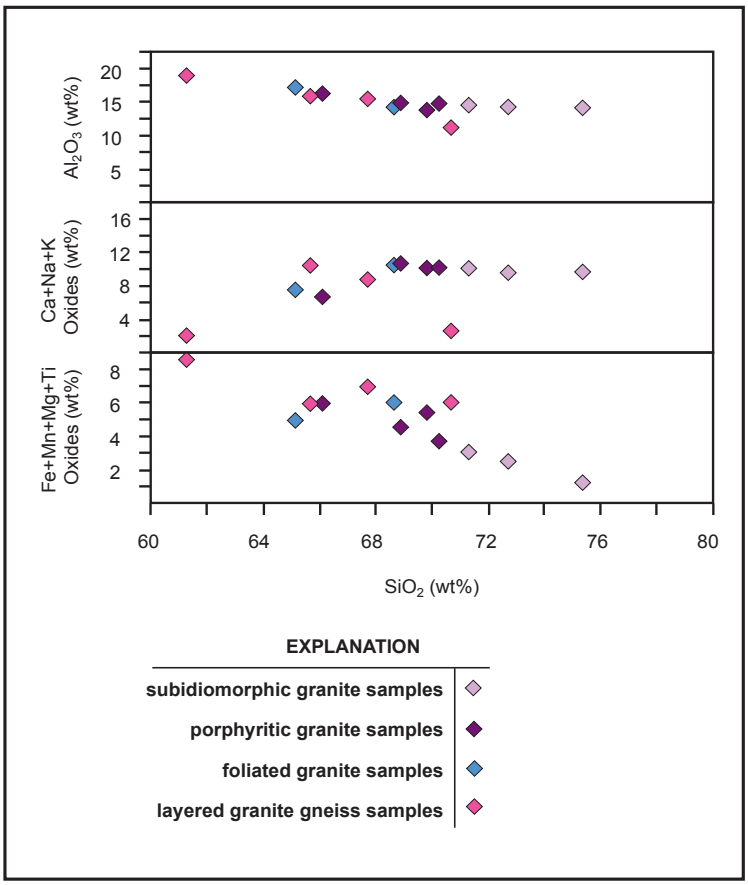

Figure 6. Major and minor element Harker diagrams for Petersburg Granite samples, from whole-rock geochemical analysis. Data for diagrams are provided in the Appendix.

lected a sample for age dating from layered granite gneiss near Willow Oaks Country Club on the Bon Air quadrangle (37.5356°N, 77.5028°W, NAD 27), although they describe their sample as non-foliated.

Foliated granite is light-bluish-gray. It is typically medium- to coarse-grained, but locally fine-grained. The granite is weakly to strongly foliated, with foliation defined primarily by aligned phyllosilicates (Figure 4C).

Layered granite gneiss is light-bluish-gray to medium-gray, and is distinctly compositionally layered. Layering, defined by alternating biotite- and quartz-feldspar-rich bands, ranges from 0.5 inch to several inches (1 centimeter to 1 decimeter) thick; individual layers are fine- to coarse-grained, and range from subidiomorphic to porphyritic (potassium feldspar phenocrysts are less than 0.5 inch, or 1 centimeter in length) in texture (Figure 4D).

One mode of foliated granite consists of 35% plagioclase, 22% potassium feldspar, 19% quartz, 13% biotite, 5.5% sphene, 3% muscovite, 1.5% ilmenite/magnetite, 1% epidote, and traces of hornblende, apatite, allanite, and zircon (Figure 5; Table 1). Layered granite

gneiss ranges from tonalitic to granodioritic to granitic in composition (Figure 5). Modes average about 34.3% quartz, 32.3% plagioclase, 19.7% biotite, 11.0% potassium feldspar, 1.0% muscovite, 0.5% epidote, 0.3% carbonate, 0.2% chlorite, 0.2% apatite, 0.2% sphene, 0.2% zircon, and 0.2% hematite, with traces of hornblende, allanite, ilmenite/magnetite, and clinozoisite (Table 1).

Relationships between these phases are ambiguous: both are strongly foliated; both are cross-cut locally by porphyritic granite, subidiomorphic granite, and pegmatite dikes; and map-scale phase contacts are generally concordant, although a few outcrop-scale exposures show discordant boundaries. Foliated granite occurs locally as enclaves or xenoliths within layered granite gneiss, but pods, lenses, or xenoliths of layered granite gneiss have also been observed in foliated granite. The consistently well-developed compositional layering in layered granite gneiss suggests that this phase is probably older than foliated granite, but they may be nearly coeval.

Xenoliths within Petersburg Granite

Felsic and mafic metamorphic rocks occur locally as enclaves within Petersburg Granite. These rocks are most likely xenoliths, screens, or possibly roof pendants of surrounding country rocks, but definitive correlations are lacking. As such, these rocks are older than the Petersburg Granite, but maximum age constraints are also lacking. A mode and whole-rock geochemical analysis of an amphibolite schist xenolith within Petersburg Granite on the quadrangle is provided in Table 1 and the Appendix.

Biotite-muscovite granitic gneiss (felsic gneiss, “fg” in this report) xenoliths are distinctly layered, consisting of constrasting bands of quartz-feldspar and phyllosilicate-rich layers, about 0.5 inch (1 centimeter) thick (Figure 7A). These are fine- to coarse-grained, granoblastic to porphyroclastic to lepidoblastic, strongly foliated rocks, and are distinguished in the field from layered granite gneiss by their much higher muscovite content and schistose character.

Mafic xenoliths include muscovite-biotite gneiss, amphibole-biotite gneiss, and schist, amphibolite and talc-amphibole schist (Figures 7B-C). These rocks are dark greenish-gray to dusky yellowish-brown, fine- to medium-grained, lepidoblastic to nematoblastic to locally granoblastic, and are strongly foliated. Their mafic composition and strongly foliated texture distinguishes them from Petersburg Granite, although small, outcrop-scale, biotite-rich schlieren do occur throughout the Peterburg Granite, particularly in subidiomorphic and foliated granite (Figure 7D).

Younger Intrusive Rocks

Aplite and other felsite dikes locally cross-cut all phases of Petersburg Granite. Swarms of aplite dikes tend to be associated with pegmatite, and are therefore assumed to be coeval with the waning stages of Paleozoic granitic intrusion.

Diabase of probable Jurassic age (Sutter, 1988; Hames and others, 2000) locally cross-

Figure 7. Xenoliths and schlieren in Petersburg Granite. **A** – Biotite-muscovite granitic gneiss. A dashed line marks strong foliation in the rock. Edge of Brunton compass is about 3 inches (7.6 centimeters) long. Outcrop coordinates – 37.54853°N, 77.69229°W, NAD 27. **B** – Amphibolite xenolith (marked by an "a") in layered granite gneiss phase of the Petersburg Granite. Faint layering can be seen in granite between hammerhead and xenolith. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5050°N, 77.5893 °W, NAD 27. **C** – Foliation in amphibolite xenolith (marked by a dashed line). Hammerhead is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.5229°N, 77.5790°W, NAD 27. **D** – Schlieren (marked by an "s") in foliated granite phase of the Petersburg Granite. Schleiren are oriented parallel to the foliation in the granite. Field of view in photograph is about 2 feet by 3 feet (0.6 meter by 0.9 meter). Outcrop coordinates – 37.5147°N, 77.5352°W, NAD 27.

cuts rocks of the Petersburg Granite. Diabase dikes range from several feet to about 10 feet (1 to 3 meters) thick. The rock is dark green to black, weathers to dark reddish-brown, and is aphanitic to fine-grained. Diabase commonly weathers to spheroidally rounded, dense boulders or punky cobbles, which can be traced along strike when outcrop is absent. These rocks are easily distinguished from older mafic gneiss xenoliths within the Petersburg Granite by their non-foliated texture and lack of metamorphic overprint.

Triassic Rocks of the Newark Supergroup

Rocks of the Triassic Newark Supergroup (Froelich and Olsen, 1984) crop out in the Richmond basin and in the subsidiary Tuckahoe and Deep Run basins (Wilkes and Lasch, 1980). These rocks have been studied and mapped since the early 1800's (e.g., Rogers, 1884). The seminal work of Shaler and Woodworth (1899) is still in use. The Richmond basin is one of more than two-dozen fault-controlled rift basins filled with fluvial to lacustrine sedimentary rocks that formed along the eastern North American margin during Mesozoic continental extension (for a complete discussion, see Manspeizer and others, 1989). The Richmond basin and its associated sub-basins are inferred to be half-grabens or tilted fault blocks (Wilkes and Lasch, 1980). The western boundary of the Richmond basin is a system of high-angle faults that overprinted earlier ductile fabrics within the Hylas shear zone (Bobyarchick and Glover, 1979). The eastern margin is generally considered to be stratigraphicaly unconformable above Petersburg Granite (Goodwin and others, 1986).

In the Bon Air quadrangle, Triassic rocks either unconformably overlie or are faulted against Petersburg Granite in the westernmost part of the quadrangle. Here, Newark Supergroup rocks in the Tuckahoe sub-basin consist of sandstone, shale, and coal ("lower barren beds" of Heinrich, 1878, and Shaler and Woodworth, 1899). Medium- to coarse-grained sandstone is arkosic, micaceous, locally carbonaceous, and locally granule- to pebble-conglomeratic. Shale is laminated to thin-bedded and locally contains abundant plant fossils. Both shale and sandstone are locally interbedded with thin beds of black coal. Farther west, in the core and western flank of the Richmond basin, these lithologies (and boulder conglomerate "Boscobel Bowlder [sic] bed" of Shaler and Woodworth, 1899) are mapped separately (Goodwin, 1970; Reilly, 1980).

The distribution of Triassic rocks on the quadrangle is, in part, based on soil data (U.S. Department of Agriculture, Natural Resources Conservation Service, 2006a). The Creedmoor, Mayodan, and Pinkston soil series form from weathered Triassic residuum (U.S. Department of Agriculture, Natural Resources Conservation Service, 2004). Triassic rocks have also been reported in the vicinity of Pump Road and Patterson Avenue (William E. Dvorak, Jr., personal communication, 2007) but were not observed at the surface during recent geologic mapping; granite crops out to the southwest and northeast of the intersection. Triassic rocks along Gayton Road, northwest of Canterbury, were mapped using borehole data.

A mode and whole-rock geochemical analysis of a Triassic sandstone sample is provided in Figure 8, and Table 1, and the Appendix.

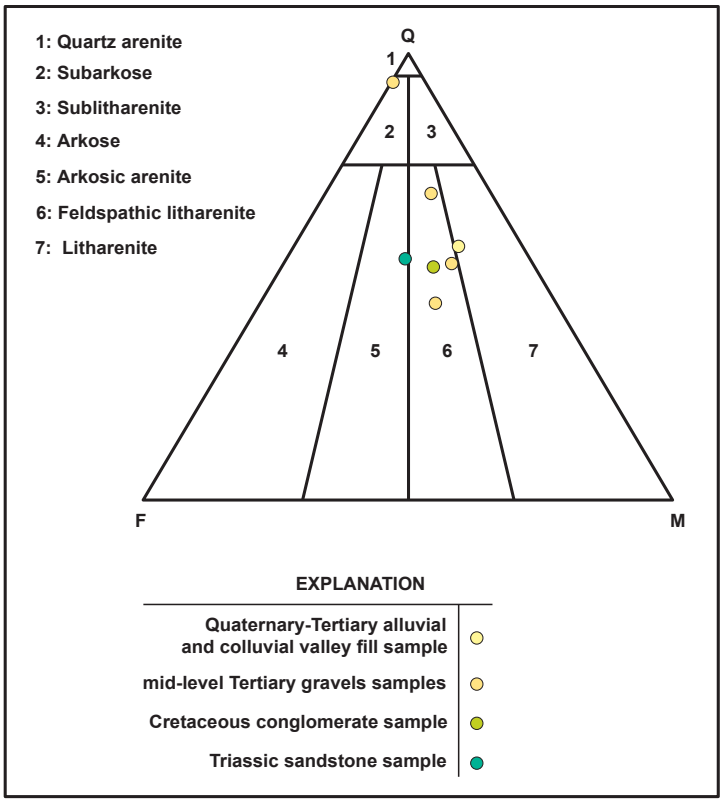

Figure 8. Classification and comparison of Coastal Plain and Triassic Newark Supergroup rocks from modal analysis. Classification after Folk (1974). Data provided in Table 1.

COASTAL PLAIN COVER SEDIMENTS

Sediments of the Miocene Lower Chesapeake Group[2]

Miocene sediments of the lower Chesapeake Group underlie a large portion of the Richmond area, cropping out in major tributaries of James and Chickahominy rivers east of the Fall Line. In the Inner Coastal Plain, these sediments unconformably overlie lower Tertiary sediments or Petersburg Granite, and are unconformably overlain by sediments of the Pliocene upper Chesapeake Group or Bacons Castle Formation (Figure 3).

In the Bon Air quadrangle, clayey silt assigned to the lower Chesapeake Group ("Tcl" in this report) crops out beneath high-level Tertiary gravel in the headwaters and tributaries of Powhite Creek in the southwestern part of the quadrangle (Goodwin and Johnson, 1970; Steenson, 1986; Johnson and others, 1987; Berquist and Goodwin, 1989; Johnson and Ward, 1990). Clayey silt also crops out beneath sand and gravel of the upper Chesapeake Group in the southeastern part of the quadrangle near Westover Heights (Kenneth R. Megginson, written communication, 2007).

Clayey silt is dark greenish-gray to medium bluish-gray (Figure 9A), but weathers moderate yellowish-brown. Subangular to subrounded quartz granules and abundant flakes of mica are common within a finer-grained matrix of clay, silt, and very fine sand. Iron-oxide mottling and staining from disseminated iron-sulfides are also common. Clayey silt is massive to finely laminated, and locally bedded with thin, discontinuous gravel layers, about 3 inches (approximately 8 centimeters) thick that consist of well-rounded clast-supported quartz pebbles. Easternmost exposures of this unit consist of grayish-yellow to grayish-orange, finely laminated, sandy silt and clay (Figure 9B). Sparse, unidentified mollusk and bivalve fossils have been found in the unit, indicating an estuarine to marine origin.

Clayey silt unconformably underlies high-level Tertiary gravels and unconformably

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[2] In the Richmond area, we subdivide the Chesapeake Group (Dall and Harris, 1892; Ward and Blackwelder, 1980; Ward, 1984) into upper and lower units based on lithology and age. The upper Chesapeake Group herein consists of yellow to reddish-yellow sand and gravel, and most likely correlates with the Pliocene Yorktown Formation as an up-dip nearshore facies (Ward and Blackwelder, 1980; Johnson and Peebles, 1984; Newell and Rader, 1982). The lower Chesapeake Group herein consists of blue-gray clayey silt, and correlates wholly or in part with the Miocene Eastover (Ward and Blackwelder, 1980; Johnson and Peebles, 1984), Virginia St. Marys (Clark and others, 1904; Gibson, 1982), Choptank (Clark and others, 1904; Abbott, 1978; Newell and Rader, 1982), and Calvert Formations (Clark and others, 1904; Clark and Miller, 1912; Newell and Rader, 1982). To the north near Ashland, Virginia, Weems (1986) subdivides the Chesapeake Group into allostratigraphic units – the lower sequence consists of the Calvert, Choptank, and St. Marys Formations (Shattuck, 1904; Newell and Rader, 1982) and the upper sequence consists of the Eastover and Yorktown Formations (Ward and Blackwelder, 1980; Newell and Rader, 1982). As we have not conducted detailed sedimentologic or paleontologic studies in this area, we cannot confidently subdivide constituent formations of the Chesapeake Group below the Yorktown Formation. Regional detailed mapping does not support allostratigraphic subdivision at the base of the Eastover Formation at this time.

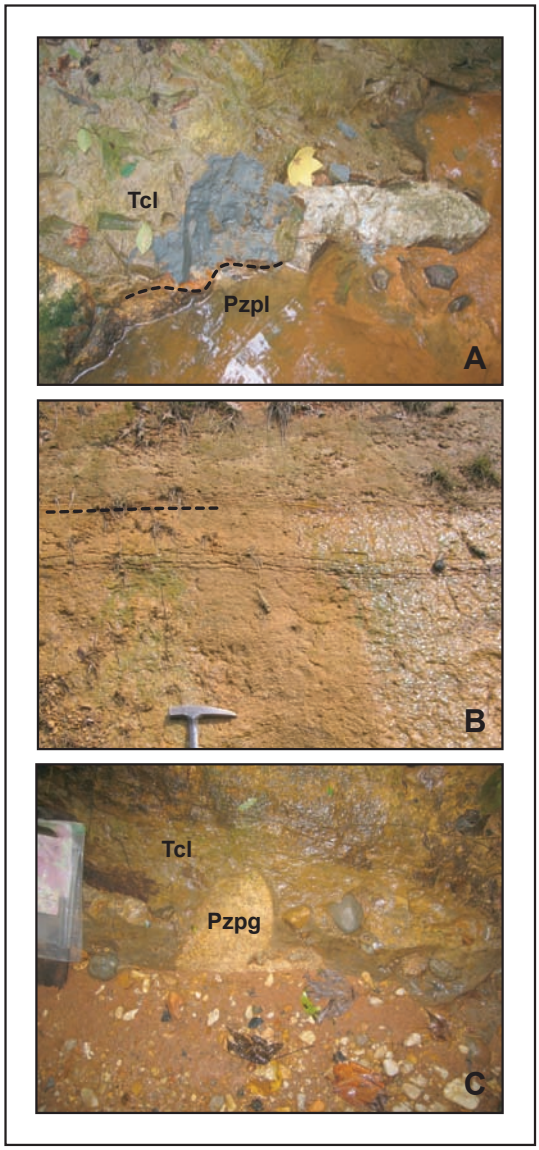

Figure 9. Clayey silt of the Miocene lower Chesapeake Group. **A** – Bluish-gray clayey silt overlying Petersburg Granite. Notice the yellowish-brown iron-oxide weathering rind caused by disseminated iron sulfides. A thin dashed line marks the unconformable contact between clayey silt ("Tcl") and Petersburg Granite ("Pzpl"). Field of view in photograph is about 2 feet by 3 feet (0.6 meter by 0.9 meter). Outcrop coordinates – 37.50678°N, 77.57452°W, NAD 27. **B** – Grayish-yellow to grayish-orange, finely laminated sandy silt and clay. A thin dashed line marks laminations in the sediments. The contact with overlying high-level Tertiary gravel is just out of view at the top of the photograph, and the contact with underlying Petersburg Granite is just out of view below the hammerhead, which is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.52134°N, 77.57156°W, NAD 27. **C** – Basal gravel lag deposit consisting of pebbles, cobbles, and boulders of quartz and granite within clayey silt ("Tcl"). A boulder of Petersburg Granite along the contact is marked with "Pzpg," but the contact with the underlying granite is buried beneath alluvium, just out of view at the bottom of the photograph. Edge of clipboard is about 12 inches (30.5 centimeters) long. Outcrop coordinates – 37.5220°N, 77.5899°W, NAD 27

overlies Petersburg Granite. A basal gravel lag deposit, up to about 1 foot thick (0.3 meter), occurs locally at the contact with the underlying Petersburg Granite and consists of clast- and matrix-supported subangular to well-rounded pebbles, cobbles, and boulders of quartz and granite (Figure 9C). The gravel lag is commonly iron-cemented. Where gravel is not present, the basal lithology locally consists of a thin zone of fine- to medium-grained quartz and feldspar sand, less than 1 foot (0.3 meter) thick. The unit attains its maximum thickness southeast of Robious near Huguenot County Park in the southwestern part of the quadrangle, where several boreholes have penetrated 18 feet of clayey silt beneath high-level Tertiary gravel.

Johnson and others (1987) consider this clayey silt to be middle Miocene (equivalent to the Choptank and/or Calvert Formations) or older in age, as it underlies high-level gravels they interpret to be upper Miocene (equivalent to the Eastover Formation). Clayey silt on the Bon Air quadrangle shares mesoscopic lithologic similarities with Miocene lower Chesapeake Group sediments south and east of Richmond on the Seven Pines and Drewrys Bluff quadrangles, and fossils indicate they share similar depositional environments. Geochemical comparisons (Figure 10) between samples from the Bon Air quadrangle and a suite east of the Fall Line are ambiguous, but suggest possible affinities. Of the suite east of the Fall Line, the one sample that most closely correlates with samples from the Bon Air quadrangle was collected from lower Chesapeake Group sediments about 10 feet (3 meters) above lower Tertiary sediments. This sample is likely equivalent to the Choptank and/or Calvert Formations; the other samples in the suite were collected from much higher in the section and are probably equivalent to the Eastover Formation. These data not only corroborate Johnson and others (1987) interpretation, but also suggest that geochemistry may be used to distinguish the constituent formations of the lower Chesapeake Group in the Richmond area. Continued mapping will test this hypothesis and should provide additional samples for analysis.

High-level Tertiary Gravels

Deposits of gravel and sand that cap the highest hills and underlie the relatively flat, upland topographic surface (the Midlothian upland of Johnson and Peebles, 1983) at elevations from 240 to 350 feet above present sea level in the western part of the Richmond area, have been studied for more than a century (e.g., Rogers, 1884). These gravels have been referred to as Appomattox (McGee, 1888), Columbia (Shaler and Woodworth, 1899), Lafayette (Shattuck, 1906; Darton, 1911), Brandywine (Clark, 1915; Wentworth, 1930), Citronelle (Doering, 1960), Midlothian (Mathews and others, 1965; Goodwin and Johnson, 1970), and Bon Air (Johnson and others, 1987). For a complete discussion of this research, see Steenson (1986), Johnson and others (1987), or Berquist and Goodwin (1989). Several ages have also been proposed, ranging from Cretaceous to Pleistocene (Darton, 1911; Wentworth, 1930; Hack, 1955; Goodwin and Johnson, 1970; Weems, 1986; Johnson and others, 1987). Prior to Steenson (1986), the most thorough study was that of Matthews and others (1965), who subdivided the upland gravels into a lower gravel member and upper loam member. These gravels are interpreted to be fluvial in origin (Hack, 1955; Goodwin and Johnson, 1970; Goodwin, 1970, 1980; Weems, 1981, 1986).

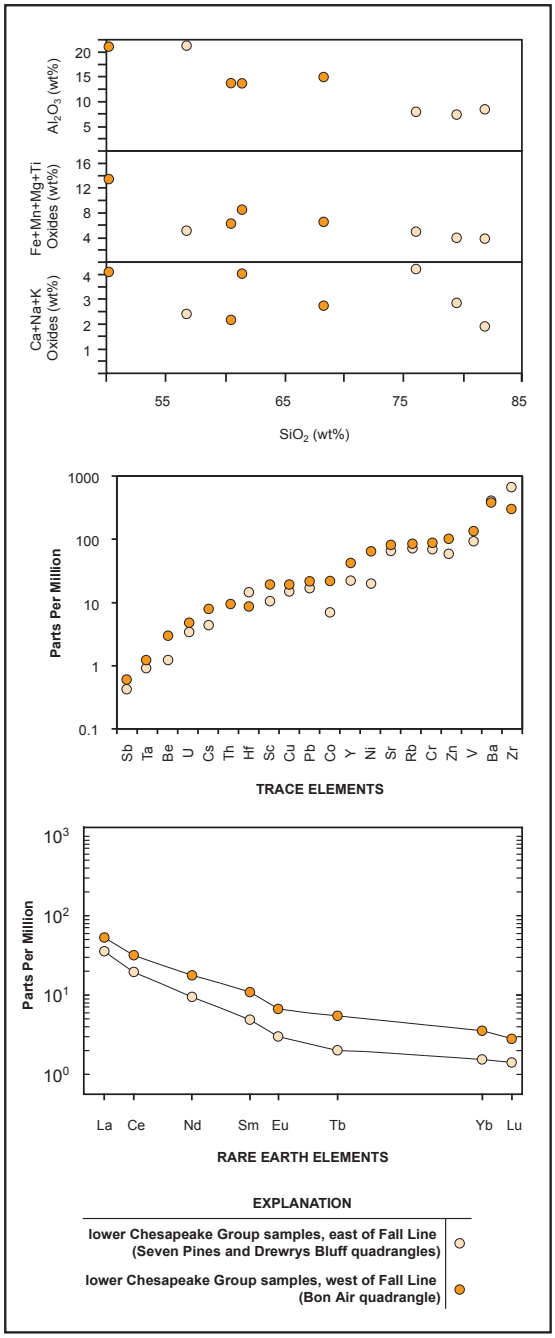

Figure 10. Major element Harker diagram (top) and trace and rare earth element spider graphs (middle, bottom) for lower Chesapeake Group samples from whole-rock geochemical analysis. Data for diagrams are provided in the Appendix. Values for trace and rare earth elements are averages. Spider graphs created using PetroGraph, version 1.0.5, by Maurizio Petrelli, Department of Earth Sciences, University of Perugia, Italy, and, for REEs, Chondrite Normalizing Value of Haskin and others (1968).

High-level Tertiary gravels (Tg_1 in this report) occur north of James River in the central-eastern part of the quadrangle, and south of James River in the central-western part of the quadrangle. Regionally, these gravels consist of yellowish-brown to reddish-brown sediment composed of abundant, well-rounded pebbles and cobbles in a sandy to clayey sand matrix (Figure 11A). Clast composition is dominantly vein quartz and quartzite (some containing the fossil *Skolithos*), with a few metamorphic and igneous clasts. Quartzite clasts are commonly deeply weathered to decomposed. Thorough iron-staining and partial iron-cementation are common. The unit is locally bedded. Finer subdivisions of Mathews and others (1965) were not readily observed and therefore not separated during recent mapping. New mapping confirms Goodwin's (1980) observations that gravels south of James River contain more clasts relative to matrix, and are more highly cemented and highly decomposed than those north of James River.

High-level Tertiary gravels unconformably overlie Petersburg Granite (Figure 11B) or Miocene clayey silt of the lower Chesapeake Group (Figure 11C). Locally, variably lithified pebbly feldspathic sand comprises the base of the unit above Petersburg Granite (Carter and others, 2007a). Although Goodwin and Johnson (1970) state that the gravel is conformable with underlying Miocene clayey silt, several new exposures (e.g., Figure 11C) confirm this contact to be scoured and unconformable as reported by Johnson and others (1987). The upper surface is erosional and overlying contact relationships are lacking. The unit attains a maximum thickness of about 50 feet (15 meters) in the vicinity of Robious in the southwestern part of the quadrangle.

Recent workers have suggested that high-level Tertiary gravels on the Bon Air and Midlothian quadrangles are middle Miocene or older (Johnson and others, 1987), in contrast to Weems' (1986) conclusion that correlative gravels to the north on the Ashland quadrangle are late Miocene or early Pliocene in age. New mapping in the Richmond area (Carter and others, 2007b) more closely supports Weems' (1986) interpretation. The unconformable contact with underlying lower Chesapeake Group clayey silt dictates that high-level Tertiary gravels can be no older than early Miocene, and may be as young as Pliocene if high-level Tertiary gravels are correlative with quartzite pebble gravel at the base of a measured section of upper Chesapeake Group sediments on the Richmond quadrangle near Chickahominy Bluffs (Figure 12). Geochemical comparisons (Figure 13) between high-level Tertiary gravel samples from the Bon Air quadrangle and Inner Coastal Plain units suggests a close association with Pliocene upper Chesapeake Group and Bacons Castle Formation sediments.

Sediments of the Upper Chesapeake Group

Pliocene sediments of the upper Chesapeake Group ("Tcu" in this report; "sg" of Goodwin, 1980) underlie the low, relatively flat topographic surface of the upper Coastal Plain from the Fall Line eastward (the Richmond plain of Johnson and Peebles, 1984). The westernmost extent of upper Chesapeake Group sediments defines the Fall Line in the Richmond area, ranging from an elevation of about 235 to 260 feet above present sea level on the Bon Air and Chesterfield quadrangles, and corresponds, in part, with the base of the Chippen-

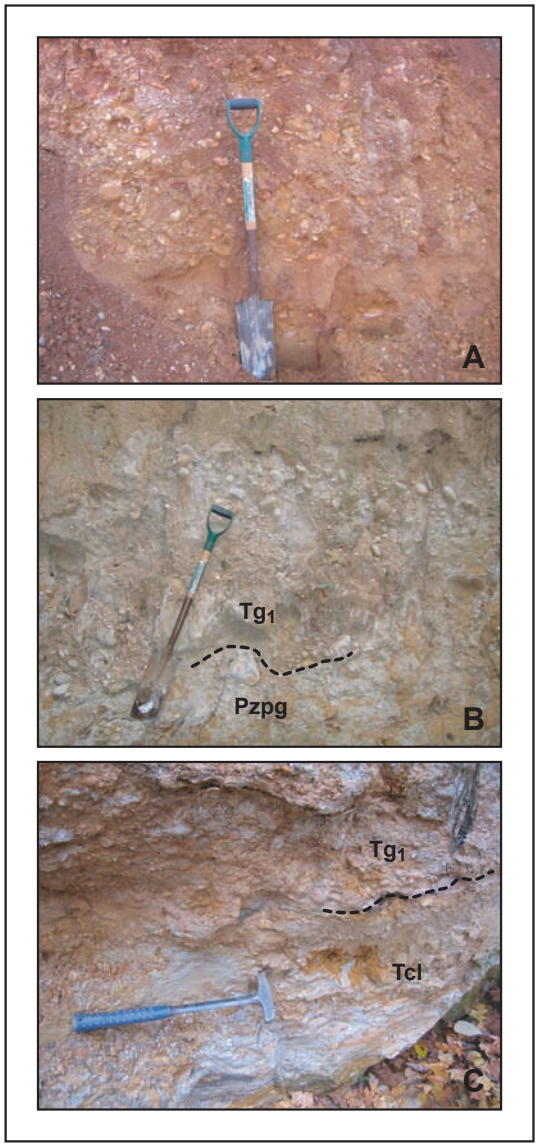

Figure 11. High-level Tertiary gravels. **A** – High-level Tertiary gravel south of James River near the intersection of Chippenham Parkway (Virginia Highway 150) and Huguenot Road (State Road 147) in the central part of the quadrangle. Notice the deep-red weathering profile of the outcrop. The contact with underlying Petersburg Granite is out of view several feet (about 2 meters) below the head of the shovel, which is approximately 3.5 feet (1 meter) long. Outcrop coordinates – 37.5422°N, 77.5440°W, NAD 27. **B** – High-level Tertiary gravel north of James River along Wistar Road in the northeastern part of the quadrangle. High-level Tertiary gravel here is not as intensely weathered as gravel south of James River. A dashed line in the photograph marks the contact between high-level Tertiary gravel ("Tg_1") and Petersburg Granite ("Pzpg") beneath the head of the shovel, which is approximately 3.5 feet (1 meter) long. Outcrop coordinates – 37.6229°N, 77.52035°W, NAD 27. **C** – High-level Tertiary gravels ("Tg_1") overlying laminated Miocene clayey silt of the lower Chesapeake Group ("Tcl"). The unconformable contact is marked by thin (about 1 inch or 2.5 centimeters thick) ferricrete layer, indicated by a dashed line to the right of the photograph. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5273°N, 77.5869°W, NAD 27.

PHOTOGRAPH	UNIT	TOP DEPTH (feet)	BASE DEPTH (feet)	DESCRIPTION
	upper Chesapeake Group	0.0	3.8	light yellow-orange, very fine sand
		3.8	5.1	orange-brown, fine to medium sand; rare pebbles
		5.1	6.6	orange-brown, coarse sand and gravel
		6.6	9.6	dark orange-brown to light-gray and yellow, slightly clayey, fine to coarse sand; flaser bedded; granules and pebbles common
		9.6	16.8	gray- to yellow-orange, laminated silty clay and flaser bedded clayey fine sand
		16.8	23.3	orange-brown, flaser bedded, clayey fine to medium sand
		23.3	27.0	yellow orange, slightly clayey, fine to medium sand, with rare pebbles
		27.0	30.0	dark-brown to rusty-red, clast supported gravels; matrix consists of fine to coarse sand
	lower Chesapeake Group	30.0	30.1	orange to light-gray clay, with subrounded quartz pebbles
		30.1	33.3	blue-gray to dark-brown silty clay; vertical burrows filled with fine sand, and ghost shells are common

Figure 12. Measured section through Chesapeake Group sediments at Chickahominy Bluffs (37.5819°N, 77.3911°W, NAD 27 – Richmond quadrangle). Upper Chesapeake Group sediments consist of an upper sand and gravel unit, middle silty clay and sand unit, and a lower basal gravel unit. Lower Chesapeake Group sediments consist of silty clay. Figure modified from Carter and others (2006, 2007b).

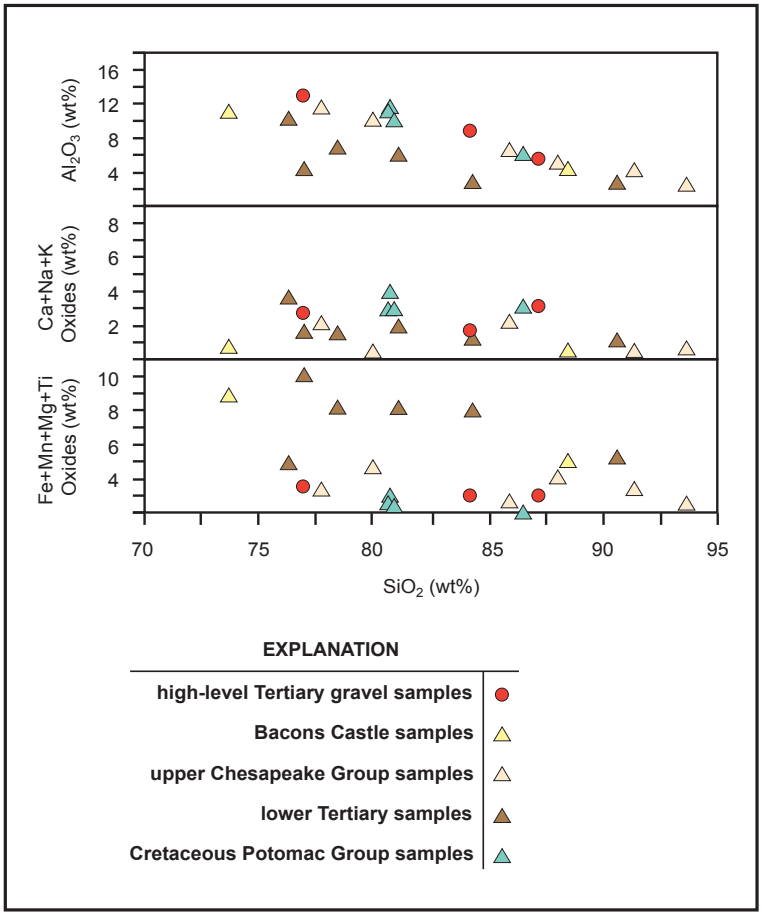

Figure 13. Major element Harker diagram for samples of high-level Tertiary gravel, Bacons Castle Formation, upper Chesapeake Group, lower Tertiary units, and Cretaceous Potomac Group from whole-rock geochemical analysis. Data for diagrams are provided in the Appendix.

ham scarp (Johnson and Peebles, 1984). Throughout the Richmond area, upper Chesapeake Group sediments unconformably overlie either Miocene sediments of the lower Chesapeake Group or Petersburg Granite, and are unconformably overlain by sediments of the Pliocene Bacons Castle Formation.

Sediments of the upper Chesapeake Group crop out along the eastern edge of the quadrangle. Grayish-yellow to moderate reddish-brown fine sand, with scattered, rounded quartz granules and pebbles, is the dominant lithology (Figure 14). Locally, sand is finely laminated, cross-bedded, or bedded with gravel stringers and layers, which are up to several feet (about 1 meter) thick and consist of well-rounded, clast-supported quartz and quartzite pebbles and cobbles. Iron-oxide mottling is common. Fine (pea-size) gravel typically mantles the topographic surface of the outcrop belt, distinguishing this unit from Quaternary

Figure 14. Lithified pebbly feldspathic sand at the base of the upper Chesapeake Group along a tributary of Reedy Creek in the southeastern part of the quadrangle. Shovel is approximately 3.5 feet (1 meter) long. Outcrop coordinates – 37.5079°N, 77.5162°W, NAD 27. Photo modified from Carter and others (2007a).

to Tertiary gravel deposits to the east and west, which typically contain coarser cobbles and boulders. Daniels and Onuschak (1974) and Goodwin (1980, 1981) suggest fluvial-marine environments for deposition throughout the region. Geochemical comparisons of several samples of upper Chesapeake Group sediments with other Coastal Plain units are provided in Figure 15.

In the northeastern part of the quadrangle, upper Chesapeake Group sediments appear to be overlain by mid-level Tertiary gravel. Here, gravel along Wistar road (at an elevation ranging from 215 to 240 feet above present sea level) gives way to a broad upland surface to the south around Dumbarton (ranging from 210 to 220 feet above present sea level), thickly mantled by abundant sand with very little pea-gravel. This sequence – sand and fine-grained gravel capped by a coarser-grained gravel – may correlate with the upper part of the measured section near Chickahominy Bluffs (Figure 12). The base of the unit at its unconformable contact with underlying Petersburg Granite ranges from quartz-pebble conglomerate to laminated clayey feldspathic sand, and is typically highly indurated to lithified (Carter and others, 2007a). The unit attains its maximum thickness of about 20 feet along the eastern edge of the quadrangle.

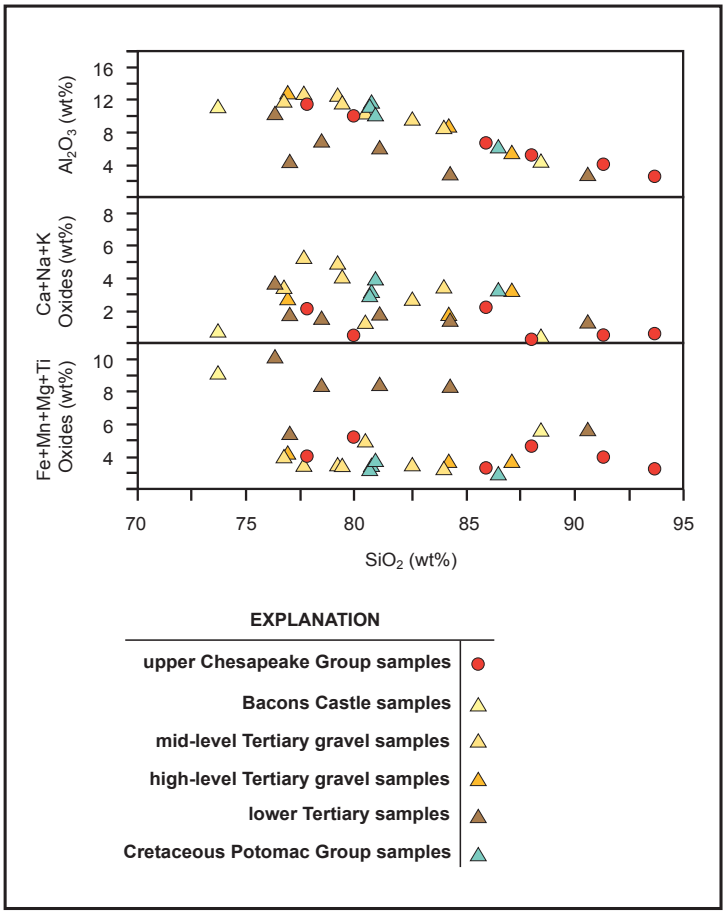

Figure 15. Major element Harker diagram for samples of upper Chesapeake Group sediments and other Coastal Plain units from whole-rock geochemical analysis. Data for diagrams are provided in the Appendix.

Goodwin (1980) places the contact between upper Chesapeake Group sand and gravel and Petersburg Granite at 240 feet above present sea level, following the transgressive depositional model presented in Daniels and Onuschak (1974). This elevation corresponds with the base of the Chippenham scarp as defined by Johnson and Peebles (1984). Only in one locality (south of Horsepen Branch, in the northeastern part of the quadrangle) does Goodwin (1980) show upper Chesapeake Group sediments in contact with high-level Tertiary gravel of the Midlothian plain, without an intervening 10- to 20-foot-high, granite-faced scarp. New mapping demonstrates that at three localities upper Chesapeake Group sediments overlie high-level Tertiary gravel. These localities include the Dumbarton area (northeastern part of the quadrangle), Windsor Farms (central-eastern part of the quadrangle), and along Midlothian Turnpike (U.S. Highway 60, southeastern part of the quadrangle). Stratigraphic relationships in these areas show that the Chippenham scarp is not as well defined as suggested by previous workers. From the Dumbarton area to Windsor Farms, the base of the scarp rises from about 240 feet to about 250 feet above present sea level. South of James River along Midlothian Turnpike, the scarp rises abruptly to more than 260 feet above present sea level. A gradual

eastwardly decrease in the basal elevation of high-level Tertiary gravels may account for the absence of a scarp in the Dumbarton, Horsepen Branch, and Windsor Farms area. Outcrops in the Beaufont Spring area, however, indicate that the scarp is not simply obscured by colluviation as suggested by Berquist and Goodwin (1989), but that sediments of the upper Chesapeake Group overlie high-level Tertiary gravel at an elevation above 260 feet. The formation of Pliocene dunes may account for the variable contact elevation (Berquist and Goodwin, 1989), or regional faulting may have broadly tilted the scarp face, south of James River.

Mid-level Tertiary Gravels

Previous workers in the Richmond area also recognized younger gravels occurring at lower elevations on both sides of James River (Mathews and others, 1965; Goodwin and Johnson, 1970; Goodwin, 1970, 1980, 1981; Berquist and Goodwin, 1989). On the Bon Air quadrangle, these gravel and sand deposits cap hills and mantle slopes at elevations ranging from about 200 to 240 feet above present sea level. Goodwin (1980) limits their distribution to the banks of the James River. New mapping shows these gravels to be much more extensive.

Mid-level Tertiary gravels occur throughout the quadrangle along both banks of the James River and its major tributaries – Tuckahoe Creek and Flat Branch, north of James River, and Powhite Creek, south of James River. Deposits also occur along Upham Brook, a tributary of Chickahominy River. Along Powhite Creek, abundant mid-level terrace gravels are generally restricted to the north bank.

Mid-level gravels consist of rounded quartz and quartzite pebbles (many containing the trace fossil *Skolithos*) in a pebbly feldspathic sand and clayey sand matrix. Iron-oxide staining is common. Locally, the unit is well bedded (Figure 16A). Commonly, the base of the unit is quartz-pebble conglomerate and pebbly feldspathic sand, which is highly indurated to lithified (Figure 16B). A suite of samples of variably lithified pebbly feldspathic sand from the base of the unit averages about 45% quartz, 22.7% sericite and other clay minerals, 17.2% hematite, 10.2% potassium feldspar, 3.2% plagioclase, and 1.8% carbonate, with traces of biotite, muscovite (both as detrital grains), and ilmenite/magnetite (Table 1). In thin section, feldspar is variably weathered to clay, which, with hematite, carbonate, and possibly authigenic silica, contributes to cementation. Hematite concretions are common. A few grains are granitic (composite of quartz and feldspar). Modes and geochemical comparisons with Triassic Newark Supergroup rocks and other Coastal Plain sediments are provided in Figures 8 and 17.

In most places, mid-level Tertiary gravels unconformably overlie Petersburg Granite or Triassic Newark Supergroup rocks (Figure 16B), but in the headwaters of Upham Brook in the northeast part of the quadrangle, mid-level gravels apparently either overlie, or are correlative, with upper Chesapeake Group sediments, constraining their maximum age to Pliocene or younger. The upper surface is erosional, and overlying contact relationships are lacking. The maximum thickness of these gravels is about 50 feet (15 meters) in the vicinity of Moreland Farms in the central-western part of the quadrangle.

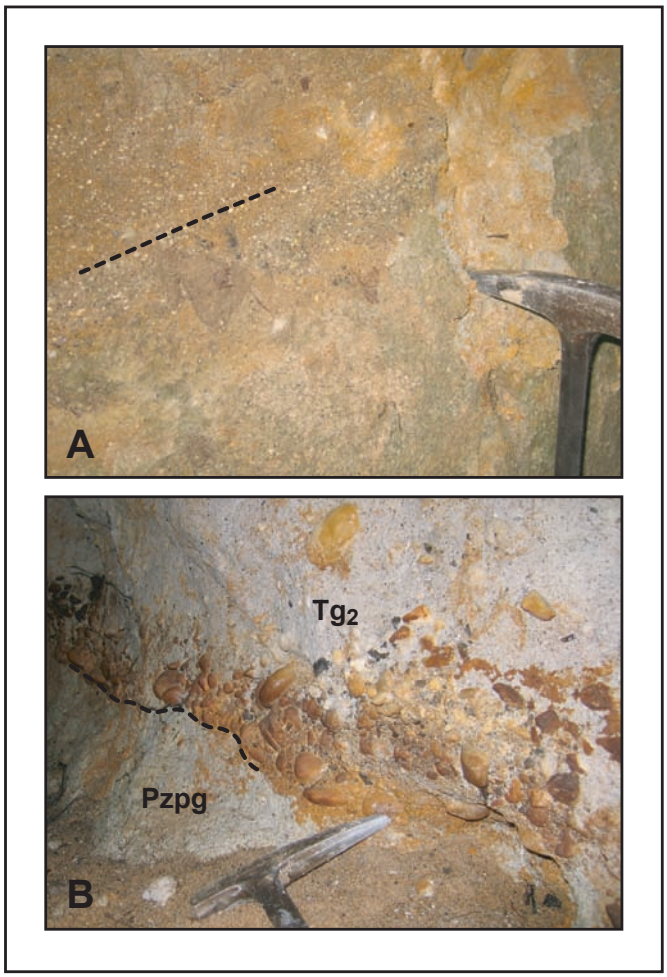

Figure 16. Mid-level Tertiary gravels. **A** – Bedded lithified pebbly feldspathic sand of basal mid-level Tertiary gravels on the campus of the University of Richmond in the central part of the quadrangle. Bedding is marked by a dashed line in the photograph, and dips approximately 11°NW toward James River. Hammerhead is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.5724°N, 77.5440°W, NAD 27. **B** – Basal gravel and lithified pebbly feldspathic sand of basal mid-level Tertiary gravels ("Tg_2") in a tributary of Upham Brook in the northeastern part of the quadrangle. Petersburg Granite ("Pzpg"), left and above hammerhead, underlies gravel along the contact shown by a dashed line. Hammerhead is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.6028°N, 77.5229°W, NAD 27.

Low-level Tertiary Gravels

Gravel and sand deposits also cap hills and mantle slopes at elevations ranging from about 130 to 160 feet above present sea level along both banks of James River and its major tributaries, including Powhite and Tuckahoe creeks. Gravel consists of rounded quartz and quartzite pebbles, cobbles, and boulders in a sandy matrix. Quartzite clasts with the trace

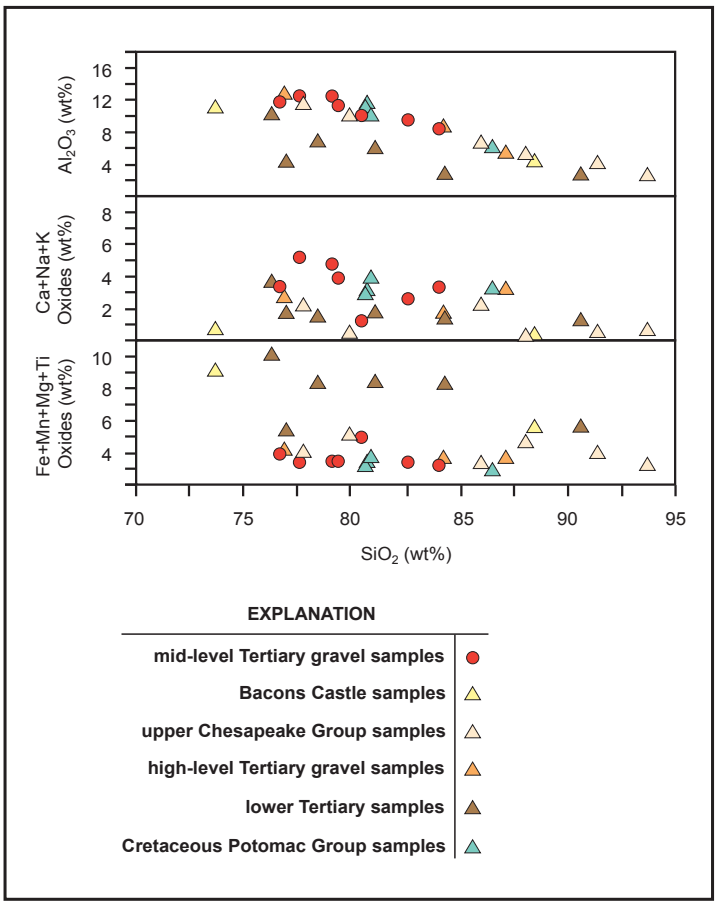

Figure 17. Major element Harker diagram for samples of mid-level Tertiary gravels and other Coastal Plain units from whole-rock geochemical analysis. Data for diagrams are provided in the Appendix.

fossil *Skolithos* are common. The base of the unit is locally quartz-pebble conglomerate and variably lithified, pebbly feldspathic sand (Carter and others, 2007a).

Low-level Tertiary gravels unconformably overlie Petersburg Granite (Figure 18) or Triassic Newark Supergoup rocks. Overlying contact relationships are lacking, as the upper surface is erosional. The maximum thickness of these gravels is about 20 feet (6 meters) in the vicinity of Willow Oaks Country Club in the central-eastern part of the quadrangle.

In the Drewrys Bluff quadrangle to the southeast, low-level Tertiary gravel deposits are mapped at the same elevation and laterally grade into upper Pliocene Bacons Castle Formation along Falling and Kingsland creeks (Carter and others, 2007b), providing an absolute correlation between these fall zone and Inner Coastal Plain stratigraphic units (Figure 3).

Figure 18. Basal lithified feldspathic sand of low-level Tertiary gravels on the south bank of James River in the central western part of the quadrangle. Unconformable contact with underlying Petersburg Granite is buried beneath colluvium in the lower half of the photograph. Visible part of hammer is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.5525°N, 77.6134°W, NAD 27.

Quaternary-Tertiary Gravels

The lowest deposits of gravel and sand occur on a few hills at an elevation of about 120 feet above present sea level in the central-eastern part of the quadrangle near the confluence of Powhite Creek and James River at Willow Oaks Country Club. These gravels consist of rounded quartz and quartzite pebbles, cobbles, and boulders within a sandy matrix. Most of the clasts contain the trace fossil *Skolithos*. The maximum thickness of these gravels is about 5 feet (1.5 meters). Morphology and lithology of this fluvial-estuarine terrace unit is consistent with the upper Pliocene to lower Pleistocene Windsor Formation downstream along James River (Figure 3).

Quaternary-Tertiary Alluvial and Colluvial Valley Fills

New detailed mapping on the quadrangle has identified the existence and extent of alluvial and colluvial valley fill (channel fill and side slope) deposits of probable Quaternary- to Tertiary-age. These deposits occur in drainages throughout the quadrangle, and are problematic in that they cannot be easily correlated or assigned to regional stratigraphic units based

solely on morphology. The deposits are isolated in drainages rather than capping hills (i.e., mid- and low-level Tertiary gravels or Quaternary-Tertiary gravels) or underlying broad, relatively flat topographic surfaces (i.e., high-level Tertiary gravels or upper Chesapeake Group sediments).

Valley fill is dominated by a distinctly characteristic lithology – variably lithified pebbly feldspathic sand[3] – which is very similar in appearance to local granite saprolite, but is distinct in that: 1) it contains rounded pebbles, which implies sedimentary transport and deposition; and 2) the lithology is typically very indurated to lithified (Carter and others, 2007a).

Mesoscopically, variably lithified feldspathic sand within Quaternary-Tertiary alluvial and colluvial valley fill is very light-gray to pinkish-gray fresh, but weathers to a light reddish brown, and is characterized by a fine- to medium-grained, angular to subangular quartz and feldspar sand and granule matrix. Unlike granite saprolite, the matrix contains very few mica minerals. Matrix-supported, well rounded to sub-rounded pebbles are diagnostic, and the sand is typically very indurated to lithified. Feldspar in the matrix is variably weathered to clay, which, with hematite, carbonate, and possibly authigenic silica, contributes to cementation. Pebbles, and locally cobbles and boulders, consist of quartz, quartzite (many containing the trace fossil *Skolithos*), and granite. These clasts are typically "fresh," but locally quartz and quartzite clasts are "punky" weathered (easily broken with hammer or hand) and granite clasts are saprolitized. Bedding, where present, is defined by clast-supported gravel lags ranging from less than 1 inch (2.5 centimeters) to nearly 1 foot (0.3 meter) thick (Figure 19A). A clast-supported gravel lag deposit, up to about 1 foot (0.3 meter) thick, typically occurs at the contact with the underlying granite (Figure 19B) and is locally iron cemented.

In thin section, one sample of lithified feldspathic sand from this unit consists of 41.5% quartz, 23% sericite and clay minerals, 22.5% hematite, 6% potassium feldspar, 3.5% carbonate, 3% plagioclase, and 0.5% ilmenite/magnetite (Table 1). Angular to subangular quartz and feldspar grains in the matrix are cemented with clay minerals, hematite, and carbonate. Many feldspar grains have been reduced to clay minerals, which apparently supplies the clay for the cement. Larger clasts within the matrix consist of monomineralogic grains of feldspar and strained quartz, and composite grains (i.e., foliated quartzite and quartz-feldspar granite), as well as a few large hematite concretions, the cores of which appear to consist primarily of clay minerals. Comparison of this mode to Triassic Newark Supergroup sandstone, Cretaceous Potomac Group conglomerate, and mid-level Tertiary gravel feldspathic sand is provided in Figure 8.

Quaternary-Tertiary alluvial and colluvial valley fill predominantly overlies Petersburg Granite along unconformable contacts (Figure 19C). Upper surfaces are erosional and overlying contact relationships are lacking. The deposits range in thickness from just a few feet (about 1 meter) to more than 20 feet (6 meters).

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[3] This lithology also locally comprises the basal sections of high-level, mid-level, and low-level Tertiary gravels and the Pliocene upper Chesapeake Group (Carter and others, 2007a).

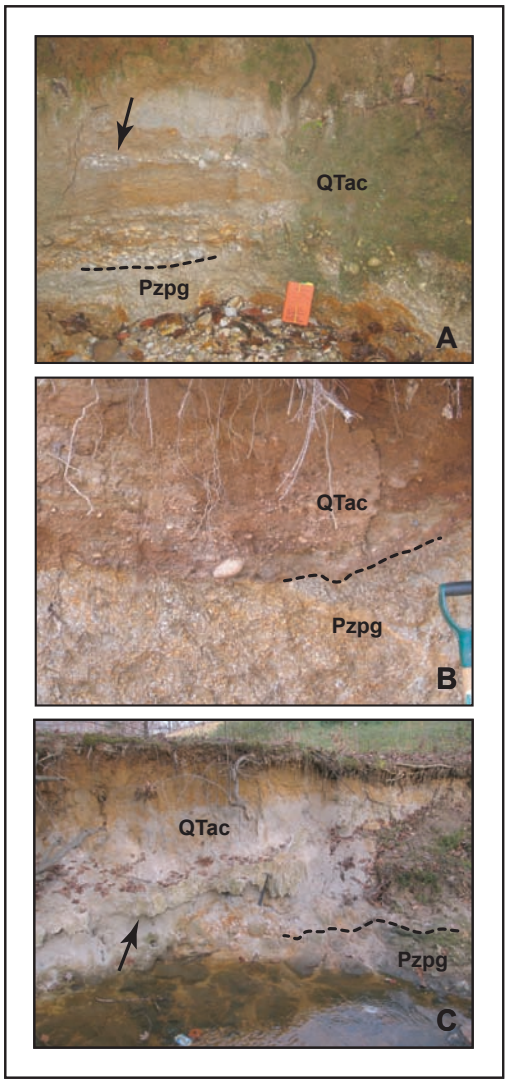

Figure 19. Quaternary-Tertiary alluvial and colluvial valley fill deposits. **A** – Bedded deposit of lithified pebbly feldspathic sand and gravel ("QTac") above Petersburg Granite ("Pzpg") in the headwaters of Spring Creek, in the southwestern part of the quadrangle. A clast-supported gravel layer (marked by an arrow) defines bedding within the deposit. Field book is about 7.5 inches (19 centimeters) long. Outcrop coordinates – 37.53292°N, 77.61932°W, NAD 27. **B** – Gravel layer at the base of Quaternary-Tertiary alluvial and colluvial valley fill deposits ("QTac") unconformably resting on Petersburg Granite ("Pzpg"). This outcrop is south of James River in the central part of the quadrangle. A dashed line in the photograph marks the contact between the units. Visible part of shovel handle is about 1 foot (30 centimeters) long. Outcrop coordinates – 37.5439°N, 77.5580°W, NAD 27. **C** – Variably lithified feldspathic sand in a Quaternary-Tertiary alluvial and colluvial valley fill deposit exposed along a tributary of Deep Run in the northwestern part of the quadrangle. A dashed line marks the contact between Quaternary-Tertiary alluvium and colluvium ("QTac") above Petersburg Granite ("Pzpg"). Arrow marks a zone of highly lithified feldspathic sand. Hammer, which rests on the highly lithified feldspathic sand layer, is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.6095°N, 77.5858°W, NAD 27.

Primary sedimentary features within these deposits hint at their depositional mode. Entrained matrix-supported clasts within feldspathic sand suggest a high-energy depositional environment. Clast-supported gravel and lags are more indicative of fluvial deposition. These observations suggest that alluvial and colluvial valley fill was deposited as periodic debris flows that mixed granite saprolite with reworked gravels from older or more distal units.

Variable lithification of pebbly feldspathic sand distinguishes Quaternary-Tertiary alluvial and colluvial valley fill deposits from younger (Holocene to late Pleistocene) surficial alluvium. The deposits are also generally higher in elevation than surficial alluvium. Modal analyses distinguish them from Triassic sandstone, which contains chlorite and epidote as low-grade metamorphic alteration phases (Table 1). Likewise, a mode and clast composition separate them from Cretaceous sediments (Table 1). Cretaceous polymict conglomerates contain volcanic clasts, and the trace fossil *Skolithos* is absent in quartzite clasts. In contrast, Quaternary-Tertiary alluvial and colluvial valley fill deposits contain no volcanic clasts and many *Skolithos*-bearing quartzite clasts. Geochemical comparisons (Figure 20) suggest an association with Pliocene-age sediments. Thus, there is reasonable circumstantial evidence to suggest that these deposits are Quaternary (early Pleistocene) to late Tertiary (Pliocene). Continued mapping in the Richmond area will test these hypotheses and should provide additional samples for analysis.

Carolina Bays of the Virginia Coastal Plain Near Richmond

Johnson and Goodwin (1967) and Goodwin and Johnson (1970) describe elliptical to subcircular depressions on the Midlothian upland underlain by high-level Tertiary gravels on the Bon Air and adjoining Midlothian quadrangles. The depressions are filled with 5 to 10 feet (1.5 to 3 meters) of massive, brownish-gray silty clay, with scattered rounded quartz pebbles, and are surrounded by low ridges or rims that range from 5 to 15 feet (1.5 to 4.5 meters) high. These rims consist of fine sand and are commonly best developed on the south and east sides. The depressions range in size from a few hundred feet to more than three-quarters of a mile in diameter, and, where elliptical, their major axes trend from N60°W to N80°W (Goodwin and Johnson, 1970). Similarities between these depressions and the well-studied Carolina Bays of the central and southern outer Atlantic Coastal Plain led Goodwin and Johnson (1970) to adopt the same nomenclature.

Although Goodwin (1970, 1980) restricts their distribution to the Midlothian upland, new mapping in the Richmond area (Carter and others, 2007b) significantly broadens their range. On the Bon Air quadrangle, another potential Carolina Bay has been tentatively identified on the Richmond plain underlain by upper Chesapeake Group sand and gravel south of Westover Heights in the southeastern part of the quadrangle. Although U.S. Geological Survey topographic maps indicate that this area is an elliptical hill, the pattern of residential development in and around the feature suggests a depression (i.e., the “peak” of the hill shown on topographic maps coincides with a pond and drainage ditch central to an apartment complex). An analysis of aerial photographs made prior to development is inconclusive. Similar depressions occur east of the Chippenham scarp on the Richmond plain (on the Chesterfield

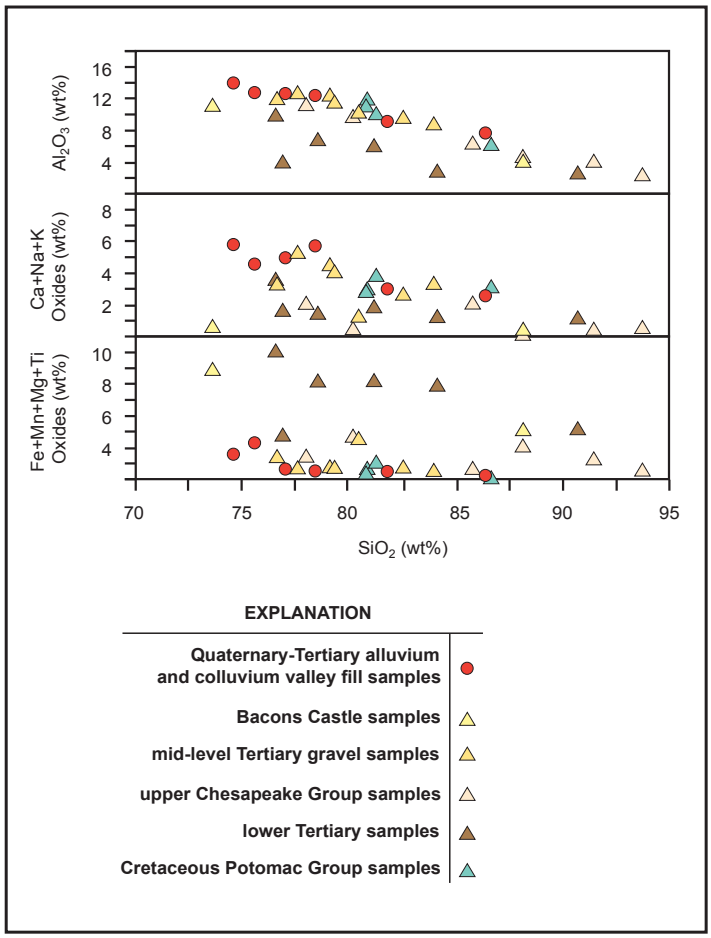

Figure 20. Major element Harker diagram for samples of Quaternary-Tertiary alluvial and colluvial valley fill and other Coastal Plain units from whole-rock geochemical analysis. Data for diagrams are provided in the Appendix.

and Drewrys Bluff quadrangles south and west of James River), and east of the Broad Rock scarp on the Norge upland (on the Richmond and Drewrys Bluff quadrangles, east of James River and south of its confluence with Almond Creek). These depressions were located and mapped using both remote sensing and U.S. Department of Agriculture (2004, 2006a, 2006b) soil data. The Coxville and Rains Soil Series typically occur within Carolina Bays.

Goodwin and Johnson (1970) speculate that Carolina Bays on the Midlothian upland could be older than late Tertiary because of their degraded topographic expression. Identification of additional Carolina Bays above upper Chesapeake Group and Bacons Castle Formation sediments on the Richmond and Norge uplands suggests that they are no older than lower Pleistocene to upper Pliocene, if all the bays formed contemporaneously, or that there were multiple periods of their formation in the Richmond area.

STRUCTURE

Structural features on the Bon Air quadrangle include multiple foliations in Petersburg Granite, significant joint sets in overlying Tertiary sediments, and map-scale Mesozoic and Cenozoic faults that cut from Paleozoic and Triassic basement rocks into Coastal Plain cover units. Foliations in Petersburg Granite, traditionally interpreted to be of igneous-flow origin, may be tectonic. Joint sets in Coastal Plain units appear to parallel sets in the Petersburg Granite. En echelon normal and reverse faults of three distinct trends occur mostly in the western half of the quadrangle, and some appear to offset units as young as Pliocene.

FOLIATIONS IN PETERSBURG GRANITE

Foliations occur in all phases of Petersburg Granite and in xenoliths. In layered granite gneiss, foliation is defined by both grain shape orientation of quartz and feldspar, and alignment of phyllosilicate minerals, which are segregated into distinct compositional layers (Figure 21A). In foliated granite (and where present in the subidiomorphic phase) foliation is predominantly expressed as a phyllosilicate alignment (Figure 21B), with no preferred orientation of quartz. Strong alignment of potassium feldspar phenocrysts and biotite in the matrix typifies foliation in porphyritic granite (Figure 21C). Demonstrably older foliations occur in felsic and mafic gneiss xenoliths (Figure 21D).

At map scale, foliation is generally concordant within and between granite phases (Figure 22). Bobyarchick (1978) notes that pre-intrusive foliations in larger xenoliths within the Petersburg Granite also lie concordant to granite foliations. All foliations in the Petersburg Granite are locally folded, and many folds appear to be tectonic (Figure 23). At map-scale, these folded foliations define regional map patterns.

Previous workers have suggested a generally igneous origin for foliations in Petersburg Granite, although Bobyarchick (1978) notes recrystallization and deformation in quartz, including undulatory extinction and early stages of subgrain development. Thin section analyses from samples collected during this study confirm Bobyarchick's (1978) observations that the granite has been weakly metamorphosed. Low-grade metamorphic assemblages, including biotite altered to chlorite, are common (Table 1). Geochemical analyses support Bobyarchick and Glover's (1979) proposal for syntectonic emplacement of the granite (Figure 24).

JOINTS IN PETERSBURG GRANITE AND COASTAL PLAIN SEDIMENTS

Jointing is common in both crystalline rocks of the Petersburg Granite (Figure 25A) and in competent units of the Coastal Plain (Figures 25B and 25C). Dailide and Diecchio (2005) report joint sets in the Petersburg Granite in the Richmond area that generally follow northeast and northwest trends. New data from the Bon Air and several other quadrangles in the Richmond metropolitan area are consistent with their observations (Figure 26A). Relative age relationships between trends are not known. Bobyarchick and others (1976) suggest

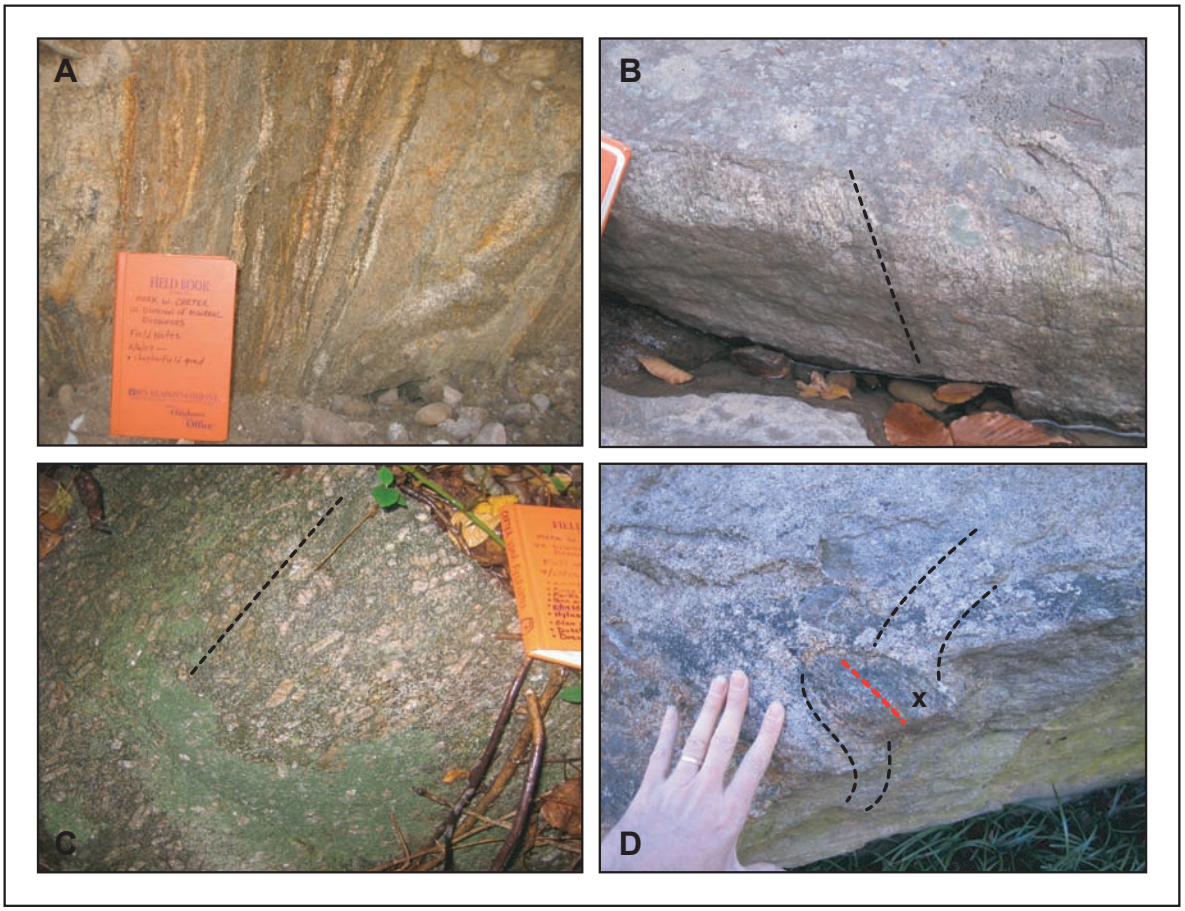

Figure 21. Foliations in Petersburg Granite. **A** – Compositional layering in layered granite gneiss. Long edge of field notebook is about 7.5 inches (19 centimeters). Outcrop coordinates – 37.4858°N, 77.6134°W, NAD 27 (outcrop is on the Chesterfield quadrangle). **B** – Foliation defined by biotite alignment (marked by a dashed line). The textural identifier for rocks of the foliated phase, this photo is from an outcrop within subidiomorphic granite, which is locally foliated. Field of view is approximately 1 foot (0.3 meter). Outcrop coordinates – 37.5461°N, 77.5626°W, NAD 27. **C** – Strong alignment of potassium feldspar phenocrysts in porphyritic granite (marked by a dashed line). Long edge of field notebook is about 7.5 inches (19 centimeters). Outcrop coordinates – 37.5230°N, 77.5871°W, NAD 27. **D** – Foliated amphibolite gneiss xenolith within foliated granite. Foliation in xenolith (marked by a red dashed line) is orthogonal to foliation in granite (marked by black dashed lines). Field of view is approximately 2 feet (0.6 meter). Outcrop coordinates – 37.4748°N, 77.5423°W, NAD 27 (outcrop is on the Chesterfield quadrangle).

that zeolite facies metamorphism expressed as laumontite mineralization along joint surfaces (Privett, 1974) is Mesozoic.

Several joint sets also occur in competent Coastal Plain cover sediments, mainly in Miocene clayey silt of the lower Chesapeake Group (Figure 25B) and in Quaternary to Pliocene lithified feldspathic sands (Figure 25C). Although traditionally believed by most

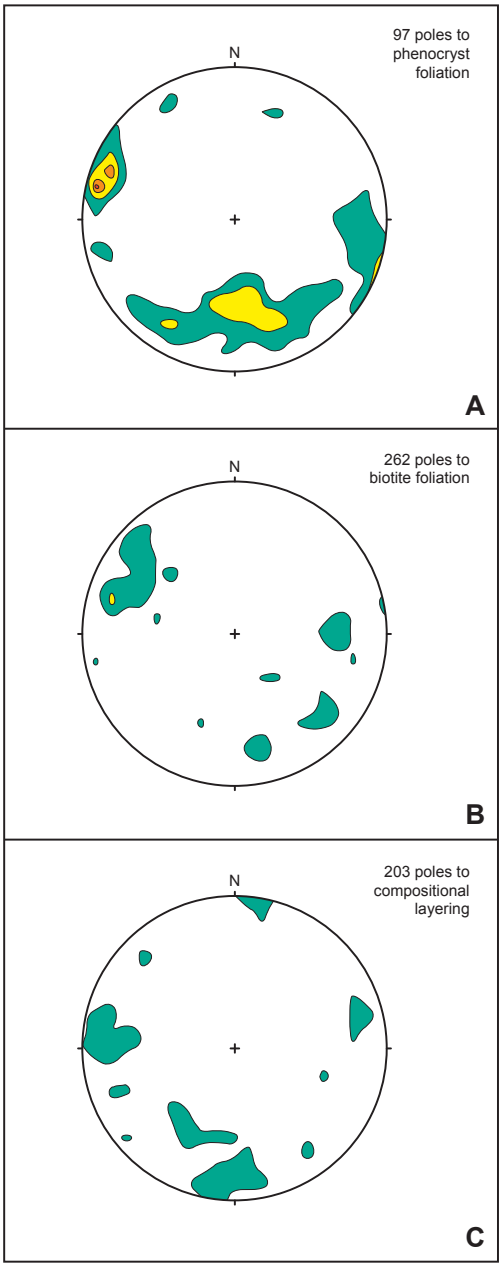

Figure 22. Equal-area, lower-hemisphere stereonets of poles to foliations in Petersburg Granite: **A** – Phenocryst foliation in porphyritic rocks. **B** – Foliation marked by biotite alignment, mostly from foliated granite. **C** – Compositional layering in layered granite gneiss. Data for stereonets collected from the Bon Air, Chesterfield, Richmond, and Drewrys Bluff quadrangles. Contour interval is 2 percent per 1 percent area for all stereonets, which were created using Stereonet For Windows, version 1.1.6, by Richard Allmendinger, Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York. Figure modified from Carter and others (2007b).

Figure 23. Folds in Petersburg Granite. **A** – Disharmoniously convoluted felsic schleiren in foliated granite along the James River. Folding in this schleiren is most likely igneous in origin. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5510°N, 77.5182°W, NAD 27. **B** – Parallel-concentric fold in layered granite gneiss. Pencil (marked by an arrow, and "P") marks the bearing and plunge of the fold axis. Field notebook is about 7.5 inches (19 centimeters) long. Outcrop coordinates – 37.4569°N, 77.5411 °W, NAD 27 (outcrop is on the Chesterfield quadrangle). **C** – Similar folds in layered granite gneiss. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.4646°N, 77.5304°W, NAD 27 (outcrop is on the Chesterfield quadrangle). **D** – Complex superposed folds. Isoclinal F_1 fold axis (marked by a black dashed line and "F_1") is overprinted by a series of parallel F_2 folds (axis of one fold is marked by a red dashed line and "F_2"). Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.4680°N, 77.5883°W, NAD27 (outcrop is on the Chesterfield quadrangle).

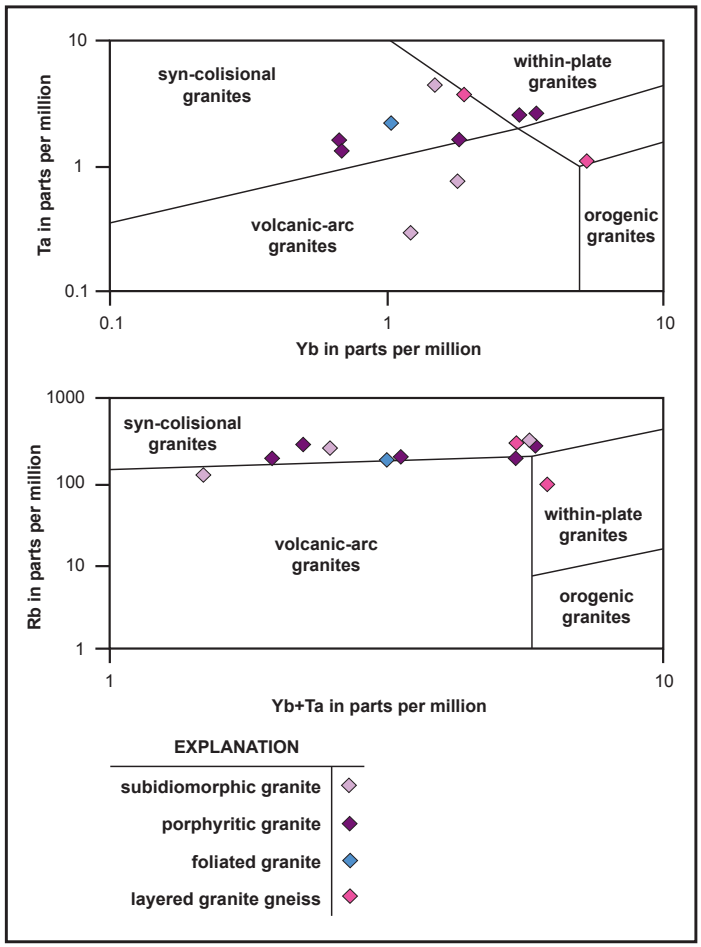

Figure 24. Tectonic discrimination diagrams (after Pearce and others, 1984) for Petersburg Granite samples from whole-rock geochemical analyses. Data for diagrams are provided in the Appendix. Discrimination diagrams created using PetroGraph, version 1.0.5, by Maurizio Petrelli, Department of Earth Sciences, University of Perugia, Italy.

earlier workers to be desiccation features, subvertical joint systems in these sediments follow distinct trends (Figure 26A). Some of these systems are parallel to sets both in the underlying granite (Figure 26B) and surface topographic lineaments (Newell and Rader, 1982; Carter and Berquist, 2005; Carter and others, 2006). Coastal Plain joints in the Richmond area are locally filled with limonite, clay, and possibly authigenic quartz (Carter and others, 2007a; 2007b). On the Bon Air quadrangle, joints in sediments that directly overly Petersburg Granite most likely formed from propagation of similarly oriented fractures in the granite.

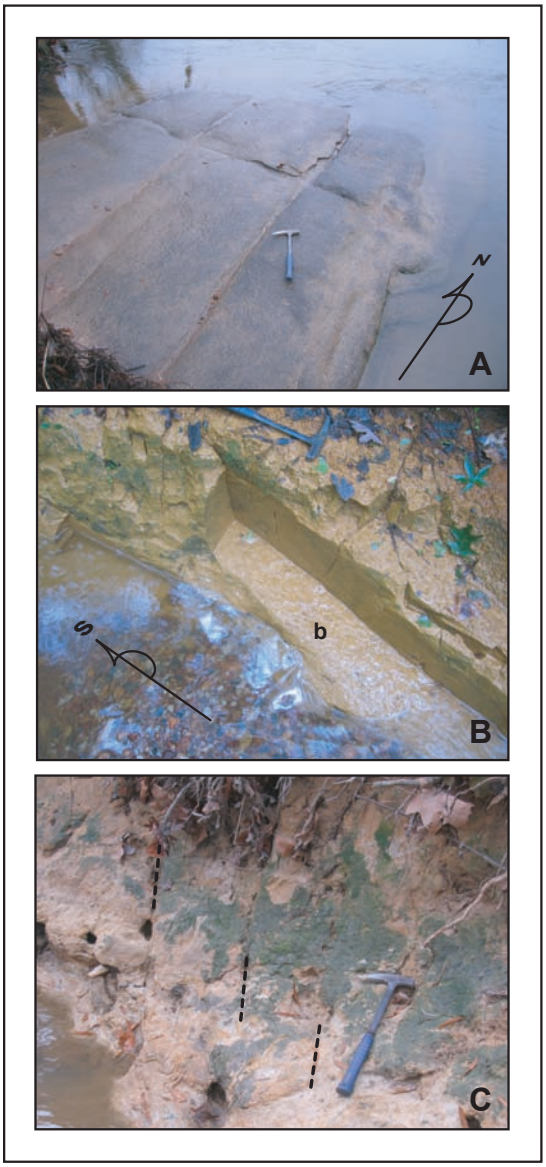

Figure 25. Joints in Petersburg Granite and Coastal Plain sediments. **A** – Two well-defined joint sets (striking N0ºE and N80ºW) in Petersburg Granite along James River in the central-eastern part of the quadrangle. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5498°N, 77.5150°W, NAD 27. **B** – Two well-defined joint sets (striking N3ºE and N88ºW) in Miocene clayey silt of the lower Chesapeake Group in a tributary of Powhite Creek in the southwestern part of the quadrangle. Bedding surface (marked by a "b") strikes N89ºE and dips about 4º to the south. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5220°N, 77.5899°W, NAD 27. **C** – Joints (trending N20ºE, marked by thin dashed lines) in low-level Tertiary alluvium and colluvium along Deep Run in the northwestern part of the quadrangle. These joints extend up from similarly oriented joints in underlying Petersburg Granite (beneath water in the lower-left corner of the photograph). Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.6139°N, 77.5910°W, NAD 27.

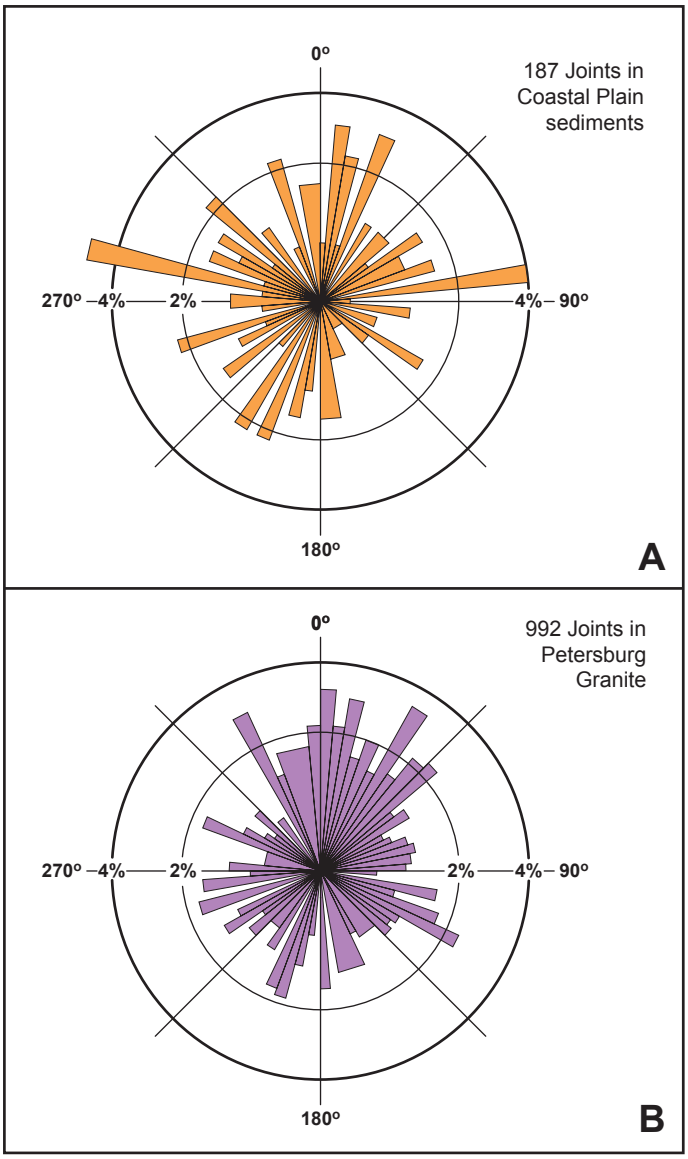

Figure 26. Unidirectional rose diagrams of joints in Petersburg Granite and Coastal Plain sediments throughout the Richmond metropolitan area. **A** – Rose diagram of 187 joints in Coastal Plain sediments. **B** – Rose diagram of 992 joints in Petersburg Granite. Data for rose diagrams collected from the Bon Air, Chesterfield, Richmond, and Drewrys Bluff quadrangles. Notice the E-NE and W-NW trends in Coastal Plain sediments; these are restricted to the sediments, whereas other regional trends in Coastal Plain sediments reflect trends in Petersburg Granite. Rose diagrams created using Stereonet For Windows, version 1.1.6, by Richard Allmendinger, Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York. Petals are defined by 5º increments. Figure modified from Carter and others (2007b).

FAULTS

Faults in the easternmost Piedmont and upper Coastal Plain in the Richmond area fall into three ages and two mechanisms of deformation. The Paleozoic, ductile-deformed Hylas shear zone (Bobyarchick and Glover, 1979; Gates and Glover, 1989) juxtaposes low-grade metavolcanic rocks and Petersburg Granite of the Roanoke Rapids terrane (Bobyarchick, 1978; Horton and Stoddard, 1986; Horton and others, 1989, 1991) over high-grade, multiply deformed, Mesoproterozoic to Paleozoic igneous and metamorphic rocks of the Goochland terrane (Farrar, 1984, 2001; Owens and others, 2004; Shirvell and others, 2004). Rooted within, and overprinting earlier dutile fabrics within the Hylas zone, is a system of Mesozoic high-angle brittle faults that form the western boundary of the Richmond basin and the Tuckahoe and Deep Run sub-basins (Bobyarchick and Glover, 1979; Wilkes and Lasch, 1980; Goodwin and others, 1986). These Mesozoic structures extend eastward to near the Fall Line. Near the Fall Line and eastward, Cenozoic brittle faults offset both basement rocks of the Piedmont and Inner Coastal Plain stratigraphy (Cederstrom, 1945; White, 1952; Dischinger, 1987), and likely root into older Paleozoic to Mesozoic structures (Mixon and Newell, 1977, 1978, 1982; Newell and Rader, 1982; Berquist and Bailey, 1999). Some Mesozoic structures on the quadrangle appear to have also reactivated in the Cenozoic.

On the Bon Air quadrangle, map-scale brittle faults are recognized either by silicified cataclasites within basement rocks or offsets in overlying Coastal Plain sediments. Small ductile shear zones of presumed Paleozoic-age were also observed in a few outcrops of Petersburg Granite (Figure 27), but all were too small for inclusion on the geologic map.

Silicified cataclasites, or intense swarms of chalcedony- and quartz-filled joints, fractures, and faults (Figure 28A) within country rock ("Mzb" in this report; "pq" of Goodwin, 1980) mark the traces of many map-scale faults on the quadrangle. Silicified cataclasite consists of white to very light-gray quartz fragments that range from pebble- to cobble-size, with fractures and voids between fragments filled with botryoidal masses, concentric growths, and vugs of drusy quartz crystals (Figure 28B). Fragments of country rock are also locally common within cataclasite. A mode and whole-rock geochemical analysis of a silicified cataclasite sample are provided in Table 1 and the Appendix.

Silicified cataclasite is resistant to weathering and erosion, with outcrops or abundant float typically capping hills. Thus, faults are easily traced along strike. Locally, silicified cataclasite grades into zones of chalcedony- and quartz-filled joint, fracture, or small fault swarms. Slickenlines are common on some mesoscale fault surfaces (Figure 28C). Silicified cataclasites on the Bon Air quadrangle were not observed to have overprinted earlier ductile fabrics within Petersburg Granite.

The age of at least one silicified cataclasite zone is well constrained in the north-central part of the quadrangle in the Pemberton Road area (Figure 28D). Here, a 2-foot- (0.6-meter-) thick zone of silicified cataclasite cross-cuts and incorporates fragments of Jurassic diabase. Lithologic similarities between this silicified cataclasite zone and others throughout the quadrangle suggest a Mesozoic age for these structures. This agrees with Bobyarchick and others (i.e., Bobyarchick and others, 1976; Bobyarchick, 1978; Bobyarchick and Glover,

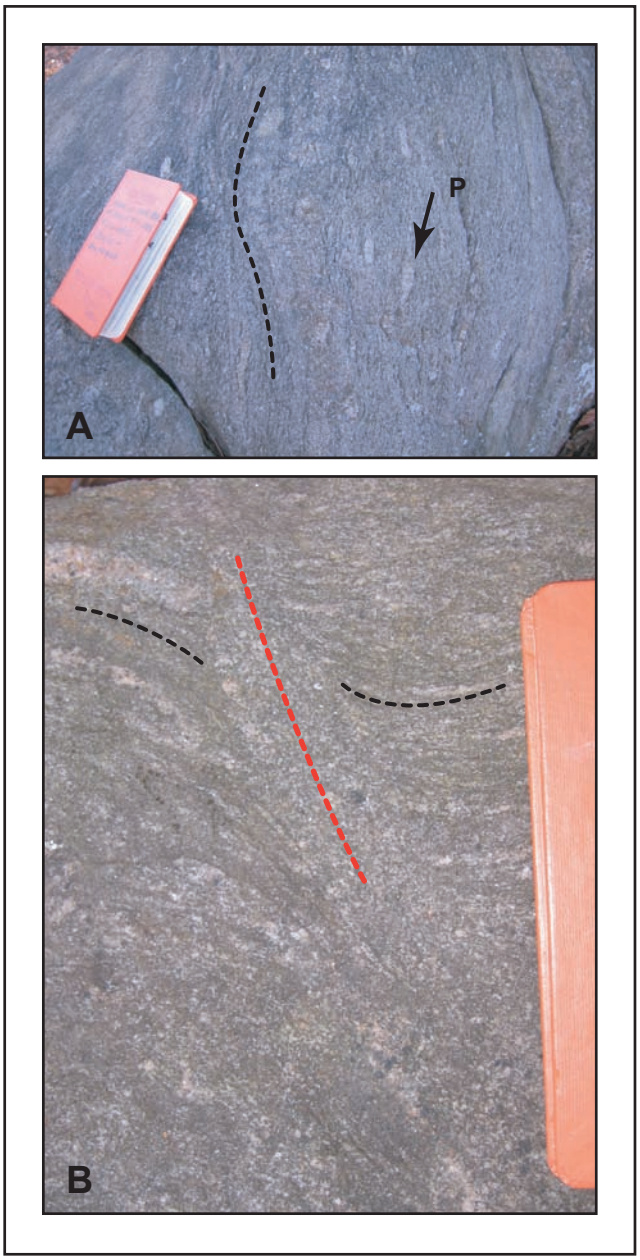

Figure 27. Outcrop-scale ductile shear zones within Petersburg Granite. **A** – Ductile shearing within porphyritic granite, south of James River in the central part of the quadrangle. Shearing has deformed potassium feldspar phenocrysts into porphyroclasts, marked by an arrow and "p". Shear zone is oriented N50ºE/80ºSE. Long edge of field notebook is about 7.5 inches (19 centimeters). Outcrop coordinates – 37.54603°N, 77.56109°W, NAD 27. **B** – Shear zone within foliated granite, east of Bon Air in the south-central part of the quadrangle. This shear, marked by a red dashed line in the photograph, cross-cuts and deforms earlier-formed foliation (marked by black dashed lines). Shear zone is oriented N24ºE/51ºSE. Field notebook is about 7.5 inches (19 centimeters) long. Outcrop coordinates – 37.52657°N, 77.54595°W, NAD 27.

Figure 28. Silicified cataclasites on the Bon Air quadrangle. **A** – Swarm of silicified cataclasites and chalcedony-filled fractures (marked by a black dashed line in the photograph) cross-cutting biotite gneiss, south of James River in the central-western part of the quadrangle. Foliation in biotite gneiss is marked by a red dashed line. Orientation of these cataclasites is N45ºE/75ºSE. Hammerhead is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.55126°N, 77.59850°W, NAD 27. **B** – Thin (1-inch- or 2.5-centimeter-thick) silicified cataclasite (marked by an arrow and "Mzb") cross-cutting subidiomorphic Petersburg Granite, north of James River in the central-western part of the quadrangle. This cataclasite is oriented N20ºW/70ºNE. Long-edge of field notebook is about 7.5 inches (19 centimeters). Outcrop coordinates – 37.5714°N, 77.6076°W, NAD 27. **C** – Slickenlines (marked by a dashed line) on a chalcedony-filled fracture cross-cutting layered granite gneiss. Slickenlines are oriented N55ºE/52º. Hammerhead is about 8 inches (20 centimeters) long. Outcrop coordinates – 37.5050°N, 77.5893°W, NAD 27. **D** – Weathered Jurassic diabase (Jd) and subiodiomorphic granite (Pzpg) cross-cut, truncated, and brecciated by thin (1-foot- or 0.3-meter-thick) silicified cataclasite zone (marked by arrows and "Mzb") in the north-central part of the quadrangle. Jurassic or younger age of this silicified breccia is indicated by these relationships in this outcrop. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.6101°N, 77.5746°W, NAD 27.

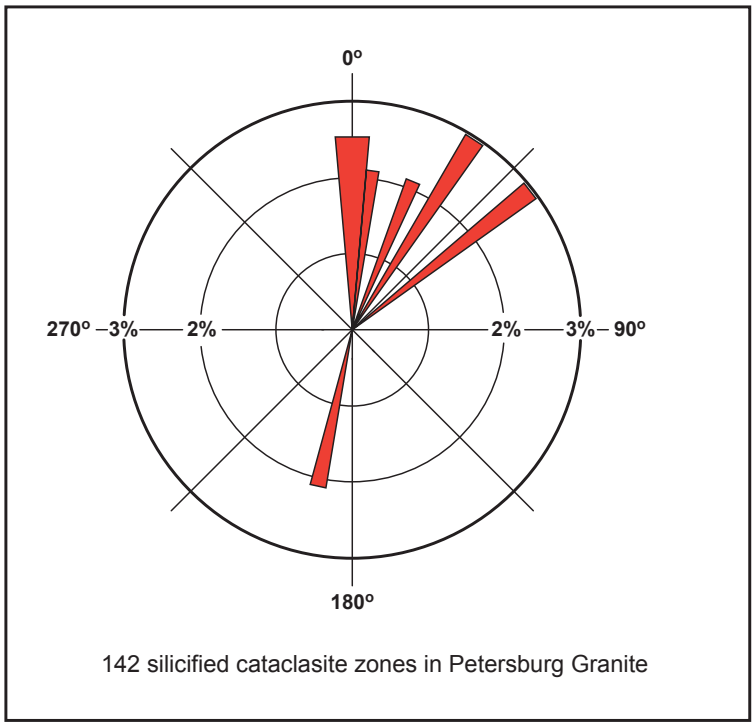

Figure 29. Unidirectional rose diagram of silicified cataclasite zones in Petersburg Granite. Data for rose diagrams collected from the Bon Air, Chesterfield, Richmond, and Drewrys Bluff quadrangles. The rose diagram was created using Stereonet For Windows, version 1.1.6, by Richard Allmendinger, Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York. Petals are defined by 5º increments. Only the largest petals are shown to reduce scatter. Figure modified from Carter and others (2007b).

1979), who correlate 220 Ma laumontite mineralization in vein fillings with quartz breccia silicification in the Hylas shear zone west of the Richmond basin.

In the northwestern half of the quadrangle, silicified cataclasites comprise a series of en echelon faults, which strike from about N0ºE to N55ºE, dip between 30º and 70º either to the east-southeast or west-northwest (Figure 29), and show either reverse or normal kinematics. Some of these faults bound, in part, the easternmost edge of the Richmond basin and the subsidiary Tuckahoe and Deep Run basins, and juxtapose Petersburg Granite and Triassic sedimentary rocks.

Other faults on the quadrangle appear to offset overlying Coastal Plain sediments and must be Cenozoic in age (Figure 30). At three localities – Westbriar (in the north-central part of the quadrangle), in the headwaters of Spring Creek (south of James River in the west-central part of the quadrangle), and north of Sheffield Court (south of James River in the central part of the quadrangle) – apparent offsets in the basal elevations of high-level Tertiary gravels may be attributed to faults that are now mostly covered beneath colluvium and urban development. The fault north of Sheffield Court also appears to have controlled deposition of Miocene clayey silt of the lower Chesapeake Group; clayey silt occurs to the west of the fault,

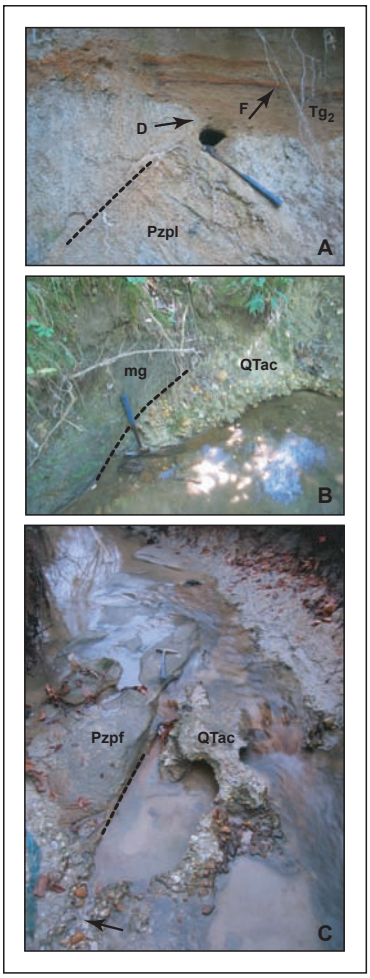

Figure 30. Evidence for Cenozoic faulting in Coastal Plain sediments on the Bon Air quadrangle. **A** – Base of mid-level Tertiary gravel (Tg_2) overlying layered granite gneiss of the Petersburg Granite (Pzpl). Sediments thicken slightly to the right of the branch line (at arrow "D") between a thin silicified cataclasite zone (indicated by a dashed line) and the contact between mid-level Tertiary gravel and the Petersburg Granite. Sediments were either faulted during deposition, with slight offset, or deposited above and draped over the exposed silicified cataclasite zone. Note that there is no offset in ferricrete layers above (marked by an arrow and "F"). Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5154°N, 77.5639°W, NAD 27. **B** – Potential high-angle reverse fault juxtaposing Quaternary-Tertiary alluvial and colluvial valley fill (QTac) with a xenolith of amphibolite and biotite schist (mg). The trace of the suspected fault surface, marked by a dashed line in the photograph, dips into the hill slope (into the plane of the photograph) at about 75º. Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5510°N, 77.5984°W, NAD 27. **C** – Quaternary-Tertiary alluvial and colluvial valley fill (QTac) juxtaposed against foliated Petersburg Granite (Pzpf). The trace of the suspected fault surface, marked by a thin dashed line, dips into the creek (into the plane of the photograph) at about 80º. Notice the gravelly composition of the sediments in the lower left corner of the photograph. Also notice that the fracture along which the granite and sediments are juxtaposed extends into the overlying sediments (marked by an arrow). Hammer is approximately 15 inches (38 centimeters) long. Outcrop coordinates – 37.5326°N, 77.5273°W, NAD 27.

but is absent to the east. A significant offset in Miocene clayey silt of the lower Chesapeake Group occurs in a series of boreholes near Midlothian Turnpike in the southwestern corner of the quadrangle. Southwest of Beaufont Spring, in the central-southern part of the quadrangle, Johnson and others (1987) document 10 to 15 feet (3.5 to 5 meters) of offset within Petersburg Granite, lower Chesapeake Group clayey silt, and high-level Tertiary gravels across the creek bed of a tributary of Powhite Creek southwest of Beaufont Spring.

Southwest of Gravel Hill, mid-level Tertiary gravels occupy a small graben structure. Another graben offsets the base of upper Chesapeake Group sand and gravel north of Westover Heights. An offset also occurs at the base of mid-level Tertiary gravels north of Lake Page (in the southeastern part of the quadrangle). North of Lorraine (north of James River in the west-central part of the quadrangle), a deposit of mid-level Tertiary gravel abruptly terminates against silicified cataclasite, suggesting Cenozoic reactivation of the structure.

Many Quaternary-Tertiary alluvial and colluvial valley fill deposits, mostly south of James River in the central-western part of the quadrangle, appear to thicken, thin, or be offset and juxtaposed against fractures and silicified cataclasite zones within Petersburg Granite, also suggesting Cenozoic reactivation of these structures.

Collectively, these observations point to this region of Virginia being structurally similar to an area in the Fall Zone approximately 30 miles (48 kilometers) to the south near Dinwiddie. There, Berquist and Bailey (1999) describe a set of northwest-southeast striking en echelon reverse faults that cut igneous rocks of the Piedmont and overlying Pliocene sediments, which tip out and are overlain by distinct cobble beds, suggesting that deposition and faulting were contemporaneous.

On the eastern half of the Bon Air quadrangle, the majority of faults that cut Cenozoic Coastal Plain cover sediments generally strike from N0ºW to N60ºW, though a few strike northeast. Like the Stafford and Brandywine fault systems farther north near Fredericksburg (Mixon and Newell, 1977), orientation of Cenozoic faults throughout the Richmond area more closely resembles regional trends of exposed and buried Mesozoic basins (Wilkes and others, 1989; Benson, 1992), and are likely not related to the Eocene Chesapeake Bay impact crater farther east (Powars and others, 1993; Powars and Bruce, 1999).

MINERAL RESOURCES

Although there are no active commercial quarries on the Bon Air quadrangle, the area boasts a rich mining history, most notably building and dimension stone production from a number of large quarries along James River and Powhite Creek. Smaller-scale sand and gravel operations for concrete and fill material were also once plentiful and contributed to growth and development in the area.

BUILDING STONE

More than 50 granite quarries operated along both banks of James River and its major tributaries near downtown Richmond from the 1830's to the 1940's (Watson, 1907; Webb

and Sweet, 1992). The granite was of exceptional quality, with widely spaced joints and uniform texture making it perfect for curbing stone, paving stone, and monuments (Watson, 1907; Darton, 1911; Steidtmann, 1945). On the Bon Air quadrangle, numerous building stone quarries (Table 2), including the Vieter (Figure 31), Westham (Figure 32A), Old Dominion, and McIntosh quarries produced monument stock, paving and curbing stone, and dimension stone for Richmond City Hall, the State Capitol, and the US Post Office in Richmond, and the Dwight D. Eisenhower Executive Office Building (formerly the State, War, and Navy Building) in Washington, DC (Watson, 1907, 1910; Darton, 1911; Steidtmann, 1945; Church, 1954; Lutz, 1954; Goodwin, 1980; Webb and Sweet, 1992). All of these operations were gradually abandoned by the late 1940's, because of urbanization after WWII (Saligman and others, 1993). Significant resources remain in place.

CRUSHED STONE

In addition to building and dimension stone, many quarries on the quadrangle yielded crushed stone and riprap for major public and commercial construction projects (Table 2). The Winston (formerly Mitchell and Copeland) quarries (Figures 32B and 32C) produced rock for construction of the City Settling Basins in the central-eastern part of the quadrangle in the early 1900's (Watson, 1907, 1910; Darton, 1911; Steidtmann, 1945; Church, 1954).

Figure 31. View of the Vieter (Old State) quarry (bs-901, coordinates: 37.535°N, 77.505°W, NAD 27). The name "Old State" was originally given to this quarry because its building stone was used to construct a wing of the State Capital Building, and the first workers at the quarry included about 300 state convicts. Field of view is approximately 300 feet wide.

Figure 32. Photographs of the Westham and the Winston and Company quarries. **A** – View of the largest of the Westham quarries (bs-604, coordinates: 37.556667°N, 77.527778°W, NAD 27). Opened as early as 1830, rock from this and other Westham quarries was used to construct the Dwight D. Eisenhower Executive Office Building (formerly the State, War, and Navy Building) in Washington, DC. Field of view in center of quarry is approximately 300 feet wide. **B** – View of part of the Winston and Company quarry (cs-601, coordinates: 37.551667°N, 77.506667°W, NAD 27). This quarry produced crushed stone and riprap for construction of the adjacent City Settling Basin about 1900. Field of view in foreground is approximately 100 feet wide. **C** – One of many small granite quarries along both banks of James River in the Richmond area. This quarry (bs-611, coordinates: 37.550833°N, 77.504722°W, NAD 27) may be part of the original Mitchell and Copeland operations, circa 1880's, or an earlier quarry used for building stone when the property was part of a private estate. Clipboard in center floor of quarry is about 12 inches long. **D** – Paving and curbing blocks on the floor of the Winston and Company Quarry demonstrates that high-quality stone was also used for building and dimension stone. Field book is about 7.5 inches long.

Riprap from the Smith quarry was used for river stabilization. The Hawkins quarry provided construction material for the Hampton Roads area (Watson, 1907, 1910; Darton, 1911; Steidtmann, 1945; Church, 1954; Lutz, 1954). Several of the crushed stone quarries also produced a limited amount of building stone (Figure 32D), and many of the larger building and dimension stone quarries also produced crushed stone, riprap, and ballast from waste material (Watson, 1907, 1910; Darton, 1911; Steidtmann, 1945).

Table 2. Listing of all known mineral resource quarries and pits on the Bon Air quadrangle. Rock unit abbreviations: QTac – Quaternary-Tertiary alluvial and colluvial valley fill; QTg_4 – Quaternary-Tertiary gravels; Tcu – upper Chesapeake Group; Tg_2 – Mid-level Tertiary gravels; Tg_1 – high-level Tertiary gravels; Pzpg – subidiomorphic phase, Petersburg Granite; Pzpp – porphyritic phase, Petersburg Granite; Pzpf – foliated phase, Petersburg Granite; Pzpl – layered granite gneiss phase, Petersburg Granite. Latitude/Longitude coordinates in NAD 27.

MAP ID	MRV ID	LATITUDE	LONGITUDE	COMMODITY	ROCK UNIT	DESCRIPTION OF WORKINGS
bs-404	127D-404	37.5675	-77.599444	building stone	Pzpp	Quarry site shown in USDA, NRCS Soil Survey Geographic (SSURGO) database for Henrico County, Virginia. Site not field checked during mapping. Probably building stone quarry in operation when property was part of plantation estate. Reference: USDS, NRCS (2006).
bs-501	127D-501	37.563611	-77.571111	building stone	Pzpp	10'x10'x5' high working faces; 20'x20'x5' deep pit. Several excavations into bank north of James River and Kanawha Canal, and one deep pit south of canal. Quarries probably in use for building stone when property was part of private estate.
bs-502	127D-502	37.563333	-77.570278	building stone	Pzpp/Pzpg	10'x10'x10' high working face. Probably in use for building stone when property was part of private estate.
bs-503	127D-503	37.558611	-77.549722	building stone	Pzpf	75'x25'x25' high working face. No additonal information other than location and size (not referenced in published records).
bs-504	127D-504	37.566111	-77.578611	building stone	Pzpp	Quarry site shown in USDA, NRCS Soil Survey Geographic (SSURGO) database for Henrico County, Virginia. Site not field checked during mapping. Probably building stone quarry in operation when property was part of private estate. Reference: USDS, NRCS (2006).
bs-602	127D-602	37.558611	-77.531389	building stone	Pzpg	One of the three Westham Quarries. Several large openings. Opened as early as 1830, discontinued by 1897. Richmond City Hall and Dwight D. Eisenhower Executive Office Building (formerly the State, War and Navy Building) in Washington DC constructed from these quarries. References: Watson (1907, 1910); Darton (1911); Steidtmann (1945); Church (1954); Lutz (1954); Goodwin (1980).
bs-603	127D-603	37.558333	-77.529444	building stone	Pzpg	One of the three Westham Quarries.
bs-604	127D-604	37.556667	-77.527778	building stone	Pzpg	Largest of the three Westham quarries at 800'x200'x180' deep working face.
bs-605	127D-605	37.55	-77.525	building stone	Pzpf	One of the Wade Quarries. Site not field checked during mapping. References: Darton (1911); Goodwin (1980).
bs-606	127D-606	37.549722	-77.522222	building stone	Pzpf	One of the Wade Quarries. Site confirmed as quarry, but not thoroughly field checked during mapping. Reference: Darton (1911).
bs-608	127D-608	37.551944	-77.5225	building stone	Pzpf	One of the Wade Quarries. 100'x25'x15' deep working face. Reference: Darton (1911).
bs-609	127D-609	37.547222	-77.515556	building stone	Pzpf	Green Quarry. Numerous granite blocks with close-spaced, small-diameter drill marks, but no pit or quarry observed. Area covers less than 0.25 acre. Reference: Darton (1911).
bs-610	127D-610	37.548333	-77.501111	building stone	Pzpg	Quarry site shown in USDA, NRCS Soil Survey Geographic (SSURGO) database for Henrico County, Virginia and USGS Bon Air, VA topographic map. Site not field checked during mapping. May be part of orignial Mitchell and Copeland operations.
bs-611	127D-611	37.550833	-77.504722	building stone	Pzpg	25'x20'x15' deep working face. May be old Mitchell and Copeland workings.
bs-612	127D-612	37.560278	-77.514444	building stone	Pzpg	Numerous granite blocks with close-spaced, small-diameter drill marks, but no pit or quarry observed. Current landowner has no historical information. Area covers less than 0.25 acre.
bs-805	127D-805	37.526389	-77.546111	building stone	Pzpf	Numerous granite blocks with close-spaced, small-diameter drill marks, but no pit or quarry observed. Area covers less than 0.1 acre.
bs-901	127D-901	37.535	-77.505	paving/curbing blocks, crushed stone from waste	Pzpl	Vieter (also known as Old Dominion, Capitol, State or Old State) Quarry. 600'x225'x100' deep. Opened about 1870, using state convicts. Orignial workings consisted of two large openings (Hawkins to west, Albin Netherwood to south, or another, now reclaimed?) Furnished stone for State Capitol addition and US Post Office in Richmond. References: Watson (1910); Darton (1911); Steidtmann (1945); Church (1954); Goodwin (1980); Webb and Sweet (1992).
bs-902	127D-902	37.533611	-77.504167	paving blocks	Pzpl	Granite Station (also known as Granite Development Co., Old Dominion Granite Development Co. or Albin Netherwood). 50' deep. Several openings. Site not field checked during mapping. References: Watson (1907, 1910); Darton (1911); Steidtmann (1945); Goodwin (1980).
bs-903	127D-903	37.5325	-77.513611	building stone	Pzpl	Old Dominion (Middendorf) Quarry. Several large quarries. Site not field checked during mapping. References: Watson (1907, 1910); Steidtmann (1945); Church (1954); Lutz (1954); Goodwin (1980).
bs-904	127D-904	37.5325	-77.512222	building stone	Pzpl	Krimm (also known as Krim or Kremm) Quarry. Several quarries, all now completely reclaimed by Powhite Parkway. Site not field checked during mapping. References: Watson (1907, 1910); Darton (1911); Steidtmann (1945); Church (1954); Lutz (1954); Goodwin (1980).
bs-909	127D-909	37.528056	-77.515278	monumental stock, curbing/paving blocks, and crushed stone	Pzpl	McIntosh (or Mackintosh, formerly Flat Rock) Quarry. 250'x125'x45' deep; ~2 acres. Several quarries. Stone from these quarries used for the approaches, steps and wings of the State Capitol addition. Site not field checked during mapping. References: Watson (1907, 1910); Darton (1911); Steidtmann (1945); Church (1954); Lutz (1954).
cs-101	127D-101	37.59	-77.619444	crushed stone	Pzpg	Quarry site shows on USGS 1964 topographic base map of the Bon Air quadrangle. Presumed crushed stone quarry. Area now developed; no evidence for operation.
cs-601	127D-601	37.551667	-77.506667	crushed stone, riprap, curbing/paving blocks	Pzpf	Winston and Co. Quarry. 200'x200'x100' high working face; ~ 1 acre. Crushed stone and riprap used in construction of City Settling Basin, circa 1900. Curbing/paving blocks on floor of quarry also indicate rock used as building stone. Several other quarries worked along same bluff. References: Watson (1907, 1910); Darton (1911); Steidtmann (1945); Church (1954).
cs-607	127D-607	37.553611	-77.515278	construction stone (riprap)	Pzpf	Smith Quarry. 40-50' working face. Rock used in James River for stabilization. Site not field checked during mapping. References: Watson (1907, 1910); Darton (1911); Church (1954).
cs-908	127D-908	37.535	-77.508056	construction stone (riprap)	Pzpl	Hawkins Quarry. Construction material for Hampton Roads area. Site now completely reclaimed by Powhite Parkway. References: Watson (1907, 1910); Church (1954); Lutz (1954).
fill-102	127D-102	37.619444	-77.622222	saprolite or earth material	Pzpg	50'x50'x8' deep, with additional smaller workings to SW. Probably used locally for fill material during development of area, or VDOT roadwork.
fill-401	127D-401	37.577778	-77.617778	saprolite or earth material	Pzpp	Two abandoned fill material pits, each 50'x30'x15' deep, probably used during development of area.
fill-402	127D-402	37.571389	-77.607222	saprolite or earth material	Pzpg	30'x30'x10' deep, probably used intermittently by James River Golf Club as fill material pit.
fill-403	127D-403	37.573333	-77.622222	saprolite or earth material	Pzpf	Site shows on USGS 1964 topographic base map of the Bon Air quadrangle. Presumed fill material pit. Area now developed as part of James River Golf Club; no evidence for operation, but grounds keeper at Golf Club states that area readily floods.
sg-301	127D-301	37.619444	-77.535278	sand and gravel	QTac	Small pit and stock pile here. Pit is approximately 10'x10'x5' deep, stock pile is roughly same dimensions. Probably used during construction of school to west.
sg-302	127D-302	37.620556	-77.518611	sand and gravel	Tg_1	Large area (several acres) quarried and stock piled. Site shows on USGS 1964 topographic base map of the Bon Air quadrangle. Probably used during construction of nearby developments.
sg-303	127D-303	37.6025	-77.510833	sand and gravel	Tcu	very small gravel pit, 10'x10'x1' deep, probably used for fill material during construction of business park.
sg-304	127D-304	37.618889	-77.528333	sand and gravel	Tg_1	Small gravel pit and stock pile here. Probably used during construction of nearby developments.
sg-613	127D-613	37.570278	-77.526667	sand and gravel	Tg_1	Site not field checked during mapping. Reference: Darton (1911).
sg-701	127D-701	37.501389	-77.595278	sand and gravel	Tg_1	Large pit operated by Karl N. Reidelbach.
sg-702	127D-702	37.501667	-77.593889	sand and gravel	Tg_1	Large pit operated by Karl N. Reidelbach. Reference: Goodwin (1980).
sg-703	127D-703	37.5025	-77.590833	sand and gravel	Tg_1	Small pit operated by Karl N. Reidelbach. Site not field checked during mapping, but appears to be reclaimed by apartment complex.
sg-704	127D-704	37.504722	-77.623333	sand and gravel	Tg_1	Site not field checked during mapping. Reference: Goodwin (1980).
sg-801	127D-801	37.502222	-77.545278	sand and gravel	Tg_1	Site now reclaimed by apartment complex Reference: Goodwin (1980).
sg-802	127D-802	37.510833	-77.570278	sand and gravel	Tg_1	Site shows on USGS 1964 topographic base map of the Bon Air quadrangle. Probably used during construction of nearby developments. Site not field checked during mapping.
sg-803	127D-803	37.5075	-77.570278	sand and gravel	Tg_1	Site shows on USGS 1964 topographic base map of the Bon Air quadrangle. Probably used during construction of nearby developments. Site not field checked during mapping.
sg-804	127D-804	37.524722	-77.581389	sand and gravel	Tg_1	Site shows on USGS 1964 topographic base map of the Bon Air quadrangle. Probably used for fill material by railroad. Site not field checked during mapping.
sg-905	127D-905	37.528611	-77.531944	sand and gravel	Tg_2	Large area (~45 acres) quarried, probably by VDOT for construction of Powhite and Chippenham Parkways.
sg-906	127D-906	37.529167	-77.538056	sand and gravel	Tg_2	100'x75'x10' deep pit, apparently still used intermittently by railroad for fill material.
sg-907	127D-907	37.5375	-77.501667	sand and gravel	QTg_4	30'x30'x6' deep, used intermittenly by Willow Oaks Golf Course for fill material.

COAL

Commercial coal production from the Richmond Triassic basin occurred from 1748 to 1927. The Richmond Coalfield provided coal for heat and light to homes and businesses from Richmond to Boston, and spurred development of Richmond's early infrastructure, including Midlothian Turnpike and the James River and Kanawha Canal (Wilkes, 1988). A majority of the recorded coal mines, pits, and shafts in the Richmond and subsidiary basins occur on the adjacent Glen Allen (Deep Run District), Midlothian (Carbon Hill and Midlothian Districts), and Hallsboro (Clover Hill District) quadrangles (Goodwin, 1970; Goodwin, 1981; Wilkes, 1988). On the Bon Air quadrangle, one prospect pit is located approximately southwest of Gayton (c-103, coordinates: 37.606667°N, 77.615833°W, NAD 27). This pit is shown on Plate XXXI of Shaler and Woodworth (1899), but its location on the vintage topographic base map is difficult to accurately place on modern maps and images. The area is now developed, and no evidence for mining activity was found during recent mapping. The prospect is shown on the geologic map for archival compilation.

FILL MATERIAL

Several small-scale borrow pits for fill material were located during recent mapping (Figure 33, Table 2). Landowners and developers probably used saprolite and soil from these pits. One of the pits (fill-403, coordinates: 37.573333°N, 77.622222°W, NAD 27) has been completely reclaimed. None of the other pits covers more than 0.1 acre (10 square meters).

SAND AND GRAVEL

Most of the Coastal Plain units on the quadrangle have been exploited for sand and gravel. Numerous small pits and larger quarries (Table 2), nearly all abandoned or reclaimed, provided abundant local material for construction and fill. The largest quarry (sg-905, coordinates: 37.528611°N, 77.531944°W, NAD 27) covers approximately 45 acres (0.45 square hectometers) and probably supplied material for construction of Powhite and Chippenham parkways. Another site (sg-302, coordinates: 37.620556°N, 77.518611°W, NAD 27) in the northeast part of the quadrangle covers about 2 acres (200 square meters) and was probably used during construction of an adjacent shopping mall. Abundant material remains stockpiled at the site and could be available for use. Several pits have been completely reclaimed and developed as residential projects. Two pits (sg-701 and sg-702) have been reclaimed as settling basins and landscape ponds in a business park. Two pits still appear to be in intermittent use; one pit (sg-907, coordinates: 37.5375°N, 77.501667°W, NAD 27) is used by Willow Oaks Golf Club for grounds maintenance. Another pit (sg-906, coordinates: 37.529167°N, 77.538056°W, NAD 27) is used by the Norfolk Southern Rail Line for fill material. Although urbanization likely led to the closure of nearly all of the sand and gravel operations on the quadrangle, reserves in all units remain plentiful (Wentworth, 1930; Daniels and Onuschak, 1974).

Figure 33. Small abandoned borrow pit for fill material (fill-102, coordinates: 37.619444°N, 77.622222°W, NAD 27). Granite saprolite in the working face could be easily removed with loader for local use. Horizontal tree in foreground is approximately 20 feet long.

ENVIRONMENTAL AND LAND USE ISSUES

Detailed geologic mapping is the first step toward derivative environmental studies. All map units on the Bon Air quadrangle pose particular environmental and land use issues that should be considered by urban planners. Other problems, such as landslides and groundwater pollution in perched water tables, bridge multiple map units. Typical characteristics of soil, saprolite, and weathered rock, and significant issues for each unit, are highlighted below. Some information (i.e., soil characteristics and relative permeability estimates) is modified from Goodwin (1980).

MODIFIED LAND

Fill material from extensive cut and/or fill through grading and excavation for urban development is widespread throughout the Bon Air quadrangle. Clayey, silty, sandy, gravelly, or rocky fill is shallow to very deep. Drainage is poor to moderate, and permeability is low to moderate. Advances in technology, increased oversight, and awareness of potential settling and failure during and after construction have resulted in recently modified land being generally stable.

CAROLINA BAYS

Clay-rich soils within Carolina Bays are characteristically poorly drained. Without proper engineering, the low permeability of the soils poses severe limitations for construction. In addition, Carolina Bays typically hold fragile (and environmentally protected) wetland ecosystems (Ross, 1987) and should be avoided during construction.

ALLUVIUM

Alluvial deposits range from shallow to very deep, with variable drainage and permeability. Areas underlain by alluvium are prone to frequent or periodic flooding. Seasonal perched water tables are common within the clayey, silty, sandy, and gravelly stratified deposits. Most of the areas underlain by alluvium on the geologic map are within restricted flood zones or environmental protection areas, so construction in these areas should be avoided.

QUATERNARY-TERTIARY ALLUVIAL AND COLLUVIAL VALLEY FILL

Variably lithified pebbly feldspathic sand within this unit contributes to several environmental and land use issues. Shallow to deep soils above weathered feldspathic sand are clayey, sandy to gravelly, and are moderately well-drained and moderately permeable. Lithified feldspathic sand is nearly impermeable, except along joints and fractures. Seasonal perched water tables in weathered material above lithified feldspathic sand are common. Lithification also makes feldspathic sand much more difficult and expensive to excavate than "soft" granite saprolite or unlithified Coastal Plain sediments. Heavy equipment, and potentially blasting, are required for removal. Construction in this unit may experience significant time and monetary setbacks if not properly planned for in advance. Impacts on regional urban development are limited because isolated deposits are discontinuously distributed, mostly in streams.

QUATERNARY-TERTIARY GRAVELS

Clay, silt, sand, and gravel of this unit contribute to a moderately drained, moderately permeable, clayey, sandy, pebbly, and bouldery soil, but the unit is thin (about 5 feet, or 1.5 meters thick), so seasonal perched water tables are common above the contact with the underlying granite. These deposits are easily excavated, but very large boulders within the unit may be difficult to remove without heavy equipment. The limited distribution of these deposits on the quadrangle reduces their impact on regional urban development.

LOW-LEVEL TERTIARY GRAVELS

Sediments of low-level Tertiary gravel deposits produce sandy, pebbly, and bouldery soils. These soils are typically well-drained, with generally high permeability in the shallow subsurface. Variably lithified pebbly feldspathic sand at the base of the unit contributes to decreasing permeability at depth. Thick deposits should pose little or no problems for surface excavations (except that very large boulders within the unit may be difficult to remove without heavy equipment). Excavations nearer the periphery of the deposits may encounter both seasonal perched water tables and underlying granite bedrock.

MID-LEVEL TERTIARY GRAVELS

Clayey, sandy to pebbly soils above mid-level Tertiary gravel deposits are typically well-drained and moderately permeable. Permeability decreases with depth, where the unit is underlain by variably lithified pebbly feldspathic sand, or Petersburg Granite. Thick deposits should pose little or no problems for surface excavations. Excavations nearer the periphery of the deposits may encounter both seasonal perched water tables and underlying granite bedrock. In the largest and thickest deposits (those in the vicinity of Gravel Hill and Dorset Woods), discontinuous layers and lenses of sand and gravel within the unit may cause heavy loads (i.e., building foundations) to differentially settle.

SAND AND GRAVEL OF THE UPPER CHESAPEAKE GROUP

Soils and strata of this unit are clayey and sandy to pebbly. The unit is well-drained with moderate to high permeability. Permeability decreases at depth, where the unit is underlain by variably lithified pebbly feldspathic sand, or discontinuous ferricrete, ironstone, or clay-rich layers are encountered. Seasonal perched water tables above these lithologies are common. The unit is very thin along the Fall Line; excavations here may encounter both seasonal perched water tables and underlying granite bedrock. Thicker deposits should pose little or no problems for surface excavations, but discontinuous layers and lenses of sand and gravel within the unit may cause heavy loads (i.e., building foundations) to differentially settle.

HIGH-LEVEL TERTIARY GRAVELS

Clay-, sand-, and pebble-rich soils above high-level Tertiary gravel deposits are typically very deep, well-drained, and moderately permeable. North of James River, the unit is relatively thin (5 to 15 feet, or 1.5 to 4.5 meters thick), so seasonal perched water tables are common above the contact with the underlying granite. South of James River, high surface permeability within sandy loam (upper loam member of Matthews and others, 1965) decreases with depth. Seasonal perched water tables are common above discontinuous ferricrete, ironstone, or clay-rich layers, and where the unit is underlain by clayey silt of the lower Chesapeake Group or Petersburg Granite. Thicker deposits should pose little or no problems for surface excavations, but discontinuous layers and lenses of sand and gravel within the unit may cause heavy loads (i.e., building foundations) to differentially settle.

CLAYEY SILT OF THE LOWER CHESAPEAKE GROUP

Clayey silt of the lower Chesapeake Group contributes to poorly drained, clay-rich soils. At depth, the unit is nearly impermeable, except along joints and fractures. Seasonal perched water tables in high-level Tertiary gravel deposits above the unit are common, and should be considered in regional hydrogeologic frameworks.

Disseminated iron sulfides in clayey silt and other units on the quadrangle (Figure 34) also pose serious environmental problems. Naturally weathered outcrops tend to be stable, but, when disturbed by construction, sulfides oxidize and hydrate to sulfates, releasing sulfuric acid to the soil and severely diminishing water quality from surface runoff. Near Fredericksburg, Virginia, sediments equivalent to Miocene clayey silt of the Bon Air quadrangle produced over 370 acres (1.5 square kilometers) of ultra acidic (pH less than 3.5) soils during construction of a regional airport in 2000 (Fanning and others, 2004). The post-construction landscape remained completely barren before intensive (and expensive) remediation measures were initiated in 2002. Care should be taken when excavating clayey silt on the quadrangle to avoid acid drainage.

SILICIFIED CATACLASITE

Quartz-rich (and thus nutrient-poor) soils above silicified cataclasite are very sandy and rocky. These highly permeable soils drain quickly and are also very shallow, so they do not hold water for extended periods. Silicified cataclasite is resistant to weathering and erosion. These rocks may be encountered at much shallower depths than surrounding saprolitized granite or Triassic sedimentary rocks during excavation, and will require blasting and heavy equipment to remove. Although jointing within the rock is common, silicified cataclasite may impede lateral flow of shallow groundwater through surrounding saprolite (Figure 35). However, the limited distribution of silicified cataclasite on the quadrangle reduces impacts on regional urban development.

INTRUSIVE ROCKS

Very shallow, swelling, clay-rich soils with poor drainage and low permeability characterize weathered Jurassic diabase. Dense spheroidal boulders of diabase within the soil may also be difficult and expensive to excavate. Weathered aplite produces a shallow, clay-rich soil with poor drainage and low permeability, whereas pegmatite produces a shallow, sandy soil with moderate drainage and moderately high permeability. Additionally, diabase (and to a lesser degree, aplite and pegmatite) is more resistant to weathering and erosion than surrounding saprolitized granite, and may be encountered at much shallower depths during excavations. These rocks may also impede lateral flow of shallow groundwater through surrounding saprolite (Figure 35). All require blasting and heavy equipment for excavation. Fortunately, the limited distribution of aplite, pegmatite, and diabase dikes on the quadrangle reduces impacts on regional urban development.

TRIASSIC ROCKS OF THE RICHMOND BASIN

Environmental and land use factors vary with the lithology of Triassic rocks – sandstone, shale, and coal – in the Tuckahoe sub-basin. Weathered sandstone produces shallow to very shallow, clayey to sandy soil and saprolite, with locally poor drainage and moderate

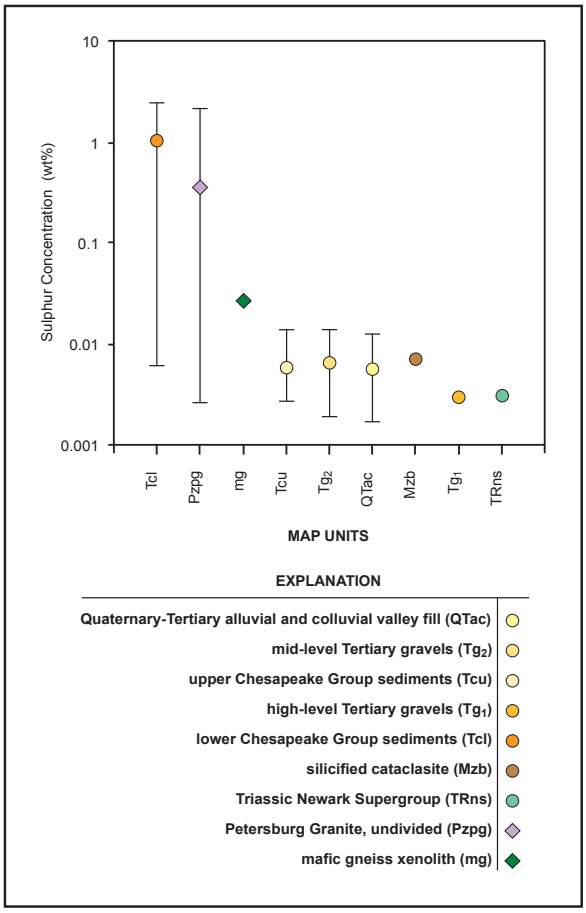

Figure 34. Logarithmic graph comparing sulfur concentrations in map units on the Bon Air quadrangle from whole-rock geochemical analysis. Clayey silt of the lower Chesapeake Group and Petersburg Granite show the highest concentrations of sulfur; high-level Tertiary gravels and Triassic Newark Supergroup sandstone have the lowest. Bars, where present, represent minimum and maximum range of data; points represent the average. Mafic gneiss, silicified cataclasite, high-level Tertiary gravels, and Triassic Newark Supergroup are represented by single samples. Rock unit abbreviations: QTac – Quaternary-Tertiary alluvial and colluvial valley fill; Tg_2 – mid-level Tertiary gravels; Tcu – upper Chesapeake Group; Tg_1 – high-level Tertiary gravels; Tcl – lower Chesapeake Group; TRns – Triassic Newark Supergroup; Mzb – Mesozoic silicified cataclasite; Pzpg –Paleozoic Petersburg Granite, undivided; mg – mafic gneiss. Data for diagram are provided in the Appendix.

permeability. Weathered shale produces deep, swelling clay-rich soil and saprolite with poor drainage and low permeability. Both rock types require blasting and heavy equipment for excavation below saprolite. Collapses of abandoned coal mines, shafts, and pits in the Richmond area pose significant risks to public safety (i.e., Sundquist, 1988; Hankins, 1990; Crawford-Squires, 1991). Although only one coal prospect pit is approximately located on

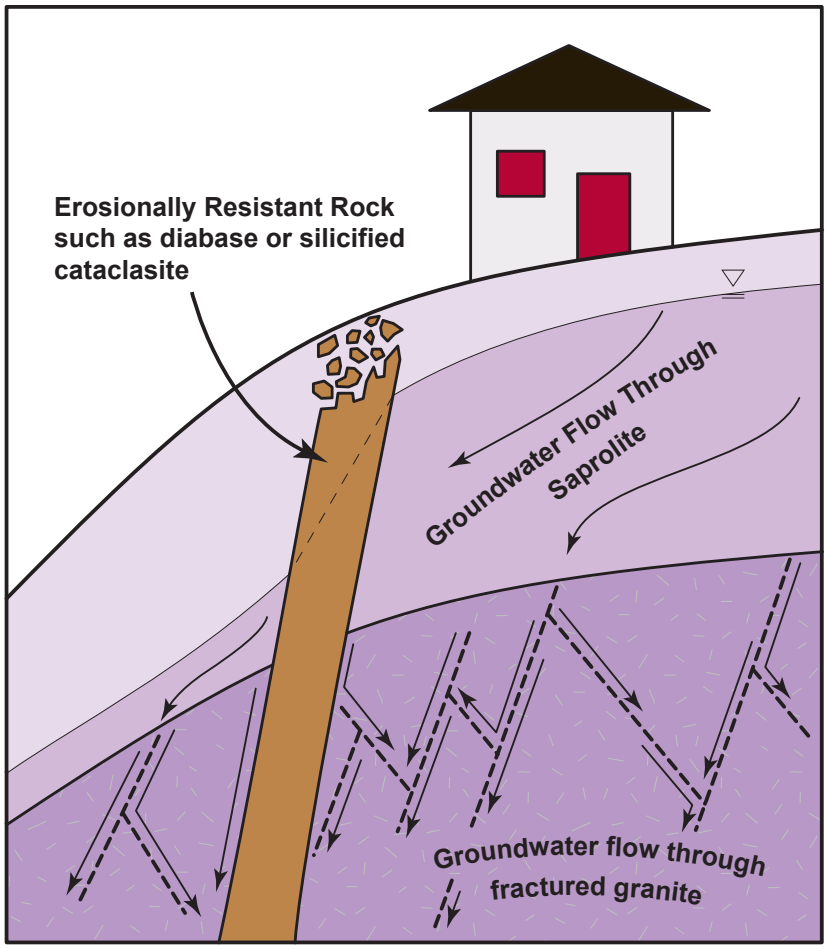

Figure 35. A model for the potential effect of erosion-resistant rocks (such as silicified cataclasites or diabase dikes) on lateral groundwater flow through surrounding saprolite or fractured granite. These rocks may act as "dams" to pond shallow groundwater.

the quadrangle (Shaler and Woodworth, 1899), there is the potential for other abandoned pits and shafts, now completely covered by urban development, to exist in the area.

PETERSBURG GRANITE

All phases of Petersburg Granite weather to deep, well-drained soils and saprolite, with moderate to high permeability. Swelling clays are more likely in soils and saprolite developed from layered granite gneiss and foliated granite. Saprolite is difficult to compact, and susceptible to sediment and erosion problems during excavation. Thickness of saprolite above granite bedrock (i.e., depth to bedrock) is highly variable and ranges from several feet (about 1 meter) to tens of feet (several meters). Bedrock, which requires blasting and heavy equipment for excavation, is nearly impermeable except along joints and fractures.

Radon gas in the Petersburg Granite, derived from the decay of radium, thorium, uranium, and other radioactive elements and isotopes, poses potential public health risks. Radon gas is a significant indoor air contaminant that reportedly causes 21,000 lung cancer deaths per year (U.S. Environmental Protection Agency, Centers for Disease Control, 2005). An initial assessment of geochemical data (Appendix) suggests radon gas emissions may vary amongst the four phases of the Petersburg Granite in the Richmond area (Figure 36). Subidiomorphic granite shows the highest concentrations of trace elements with radioactive isotopes, and layered granite gneiss has the lowest. However, many homes and businesses are shielded from gas buildup by Coastal Plain sediments that cover much of the Petersburg Granite on the Bon Air quadrangle.

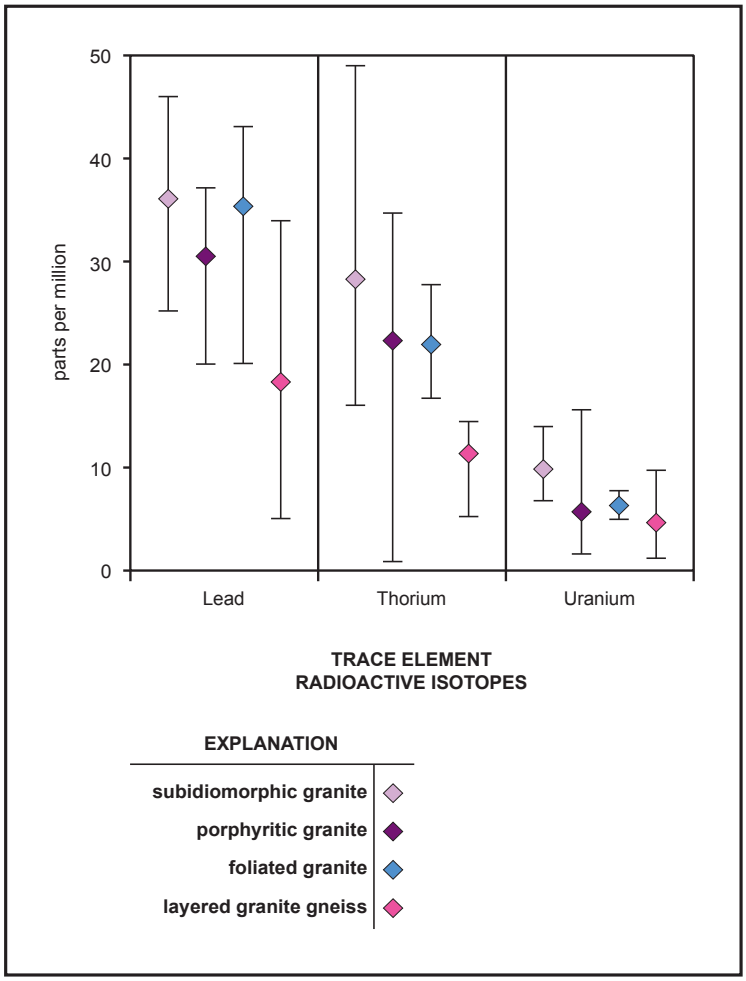

Figure 36. Graph comparing concentrations of trace elements with radioactive isotopes (lead, thorium, and uranium) in the four phases of Petersburg Granite, from whole-rock geochemical analysis. Bars represent minimum and maximum range of data; points represent the average. Data for graph are provided in the Appendix.

XENOLITHS WITHIN PETERSBURG GRANITE

The varying mineral composition of xenolithic felsic and mafic metamorphic rocks within Petersburg Granite contributes to these lithologies having slightly different environmental properties. Weathered felsic gneiss produces deep to very deep, well-drained soils and saprolite, with moderate to high permeability. Weathered mafic gneiss also produces deep soils and saprolite, but is rich in swelling clays, and has low permeability. Saprolite derived from both lithologies is difficult to compact, potentially yields under loads, and is susceptible to sediment and erosion problems during excavation. Thickness of saprolite above bedrock is highly variable, and ranges from several feet (about 1 meter) to tens of feet (several meters). Bedrock, which requires blasting and heavy equipment for excavation, is nearly impermeable, except along joints and fractures. The limited distribution of these rocks on the quadrangle reduces impacts on regional urban development.

LANDSLIDES

Landslides in the Richmond area can cause millions of dollars in property damage and loss of life with each passing tropical storm (Ress, 2004). For example, Hurricane Isabel in September 2003 and Tropical Depression Gaston in August 2004 wreaked havoc in the Richmond area, leaving hundreds, if not thousands of landslides in their wake (Carter and Berquist, 2005).

New detailed mapping has highlighted many of the causative geologic factors involved in landslide formation. Failures typically occur at the daylighted contacts between permeable and less permeable boundaries (Figure 37). In the Bon Air quadrangle, contacts between Quaternary to Tertiary sand and gravel units and the underlying granite were the primary locus for small landslides (Figure 38), probably as sands and gravels above the less permeable units became oversaturated from the intense rainfalls of the storms. Undercutting along the base of the slope at creek level also likely contributed to many of the failures. Failures also typically occur along joints or fractures within indurated to lithified Coastal Plain units. Mapping demonstrates that jointing is common not only in crystalline rocks of the Petersburg Granite, but also in clayey silt of the lower Chesapeake Group and lithified pebbly feldspathic sand in several Coastal Plain units. Many of the Isabel- and Gaston-induced landslides throughout the west Richmond area failed along joint and fracture systems parallel to the scarp face. High potential exists for future failures in areas where jointed Coastal Plain units crop out along streams and side slopes parallel to these regional joint trends.

SURFACE WATER POLLUTION FROM PERCHED WATER TABLES

The permeability contrast that helped create the landslides during Hurricane Isabel and Tropical Depression Gaston may also complicate the shallow groundwater flow system during ordinary time. Many lithostratigraphic units act as aquitards to create perched water tables (Figure 37) throughout the Richmond area (Daniels and Onuschack, 1974). Based on

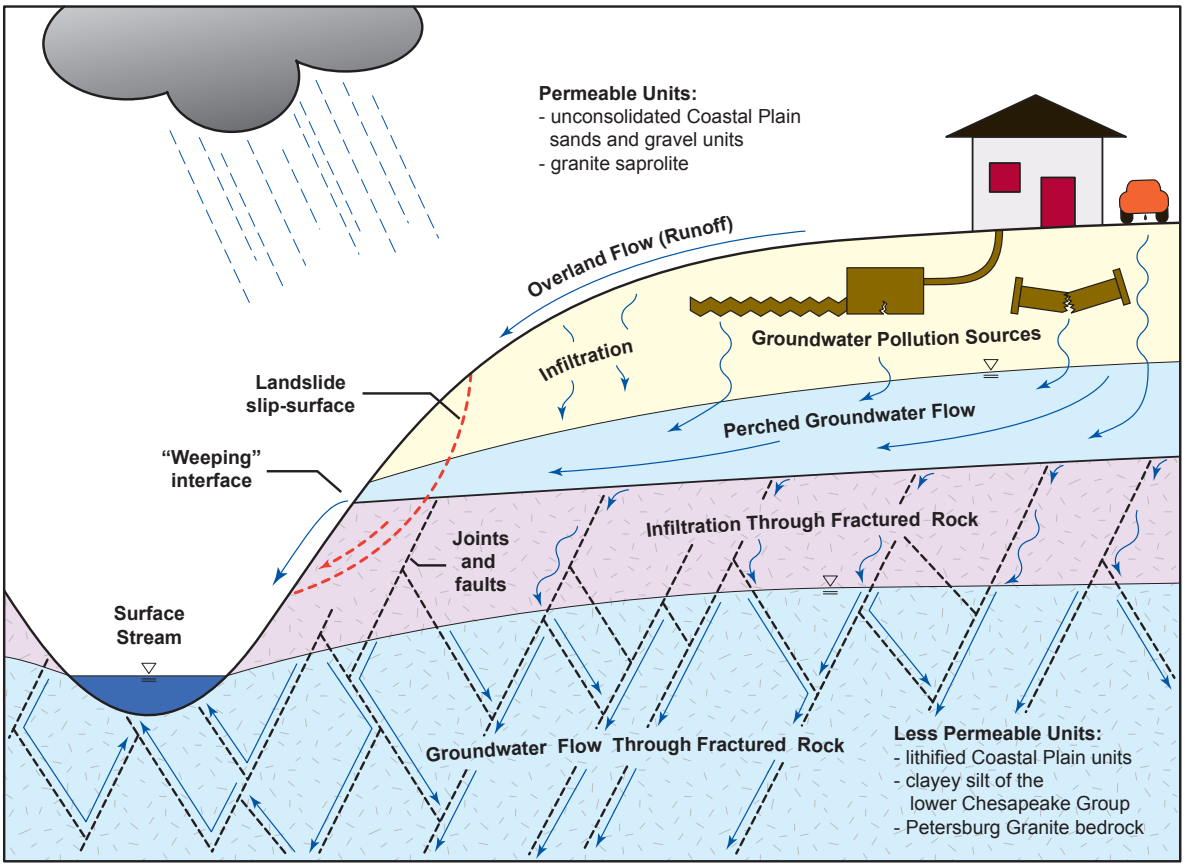

Figure 37. Model for many of the environmental and geologic hazards in the Richmond area. Perched groundwater tables in permeable units become polluted from failing septic systems, broken sewer pipes, surface runoff, and other causes, and leak into surface streams along the daylighted interface with underlying less permeable units. During major rain events such as the passing of hurricanes and tropical storms, pore pressure within these perched aquifers significantly increases, causing slope failure along joints and faults at or very near this interface.

observations during new mapping, many units and intraformational lithologies on the Bon Air quadrangle act as local aquitards during normal flow conditions, perching groundwater in recharge areas and increasing the rate of interflow. This results in quicker discharge of groundwater to surface streams. As a result, streams in these areas are more susceptible to contamination from polluted groundwater, especially in urbanized areas (Figure 39).

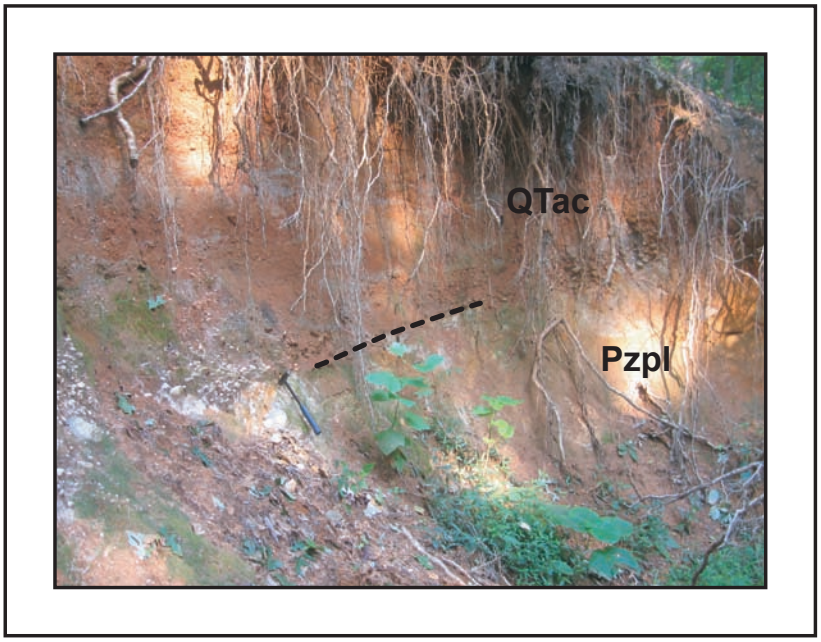

Figure 38. Small landslide at the contact between layered granite gneiss of the Petersburg Granite (Pzpl) and Quaternary-Tertiary alluvial and colluvial valley fill (QTac). The landslide is located in a tributary of Powhite Creek near Mt. Nebo, in the central-southern part of the quadrangle. The hammer, which is approximately 15 inches (38 centimeters) long, rests at the contact (marked by a dashed line) between the two units. Outcrop coordinates – 37.51312°N, 77.57419°W, NAD 27.

SUMMARY OF SIGNIFICANT RESULTS

Results of new mapping on the Bon Air quadrangle, in conjunction with comparison mapping in the Richmond area, all through the STATEMAP program, include:

- Four phases of Petersburg Granite – subidiomorphic granite, porphyritic granite, foliated granite, and layered granite gneiss – were recognized and delineated on the geologic map. These subdivisions challenge the validity of a single geochronometric date for the entire outcrop belt of Petersburg Granite. Foliations in Petersburg Granite, traditionally interpreted to be of igneous-flow origin, may be tectonic; alignment of biotite defines most foliations, with some biotite altered to low-grade metamorphic assemblages (e.g., chlorite). Geochemical analyses support Bobyarchick and Glover's (1979) proposal for syntectonic emplacement of the granite.
- Petersburg Granite was used extensively by the building stone industry during the late 1800's and early 1900's for construction of numerous public buildings in Richmond and Washington, DC, and for curbing stone, paving stone, and monuments. All of these quarries on the Bon Air quadrangle are now catalogued and compiled.

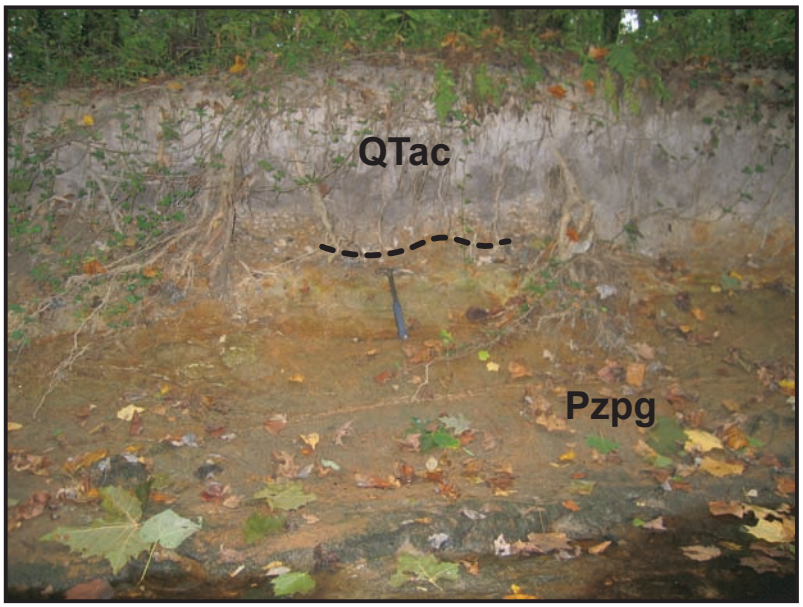

Figure 39. Iron-stained water from a seasonal perched groundwater table leaches out at the contact between Petersburg Granite (Pzpg) and Quaternary-Tertiary alluvial and colluvial valley fill (QTac), in a tributary of Upham Brook near Shaaf Pond, in the northeastern part of the quadrangle. Hammer, which is approximately 15 inches (38 centimeters) long, rests at the contact (indicated by a dashed line) between the two units. Notice the iron staining on the granite pavement just above creek-level. Outcrop coordinates – 37.59664°N, 77.60727°W, NAD 27.

- Several new Coastal Plain units were recognized and delineated on the geologic map. Low-level Tertiary gravels cap hills and mantle slopes at elevations ranging from 130 to 200 feet above present sea level along both banks of James River, Powhite Creek, and Upham Brook. On the Drewrys Bluff quadrangle to the southeast, these gravels are mapped at the same elevation and laterally grade into upper Pliocene Bacons Castle Formation along Falling and Kingsland creeks (Carter and others, 2007b), establishing an absolute correlation between fall zone Coastal Plain units on the Bon Air quadrangle with well-defined Inner Coastal Plain stratigraphy to the east. Quaternary-Tertiary gravels cap hills at an elevation of about 120 feet above present sea level in the vicinity of Willow Oaks Country Club, south of James River. Their morphology and lithology are consistent with the lower Pleistocene to upper Pliocene Windsor Formation downstream along James River. Quaternary-Tertiary alluvial and colluvial valley fill deposits occur as isolated channel fill and mantle side slopes throughout the quadrangle. Sedimentary characterists indicate that these deposits likely originated as periodic debris flows, which may have been generated by Cenozoic faulting.

- As part of the procedure for systematic detailed geologic mapping in the Richmond area, samples of major map units and constituent lithologies were collected for modal and geochemical analyses. The purpose is to compile modal and geochemical signatures of all lithologies from established map units in the region, which aids geologic mapping by allowing comparisons from these established units with newly identified units or lithologies. For example, geochemical comparisons between samples from the Bon Air quadrangle and a suite east of the Fall Line suggest that clayey silt beneath high-level Tertiary gravels correlates with Miocene lower Chesapeake Group Formations on the Richmond, Seven Pines, and Drewrys Bluff quadrangles (likely equivalent to the middle to lower Miocene Choptank and/or Calvert Formations). Similarly, geochemical comparisons between high-level Tertiary gravel samples from the Bon Air quadrangle and Inner Coastal Plain units suggests a close association with Pliocene upper Chesapeake Group and Bacons Castle Formation sediments. These comparisons demonstrate that geochemistry can be used to constrain temporal correlations between map-scale units, and possibly distinguish constituent formations within regional stratigraphic groups in the Richmond area.
- New mapping shows that Pliocene upper Chesapeake Group sediments on the quadrangle overlie high-level Tertiary gravel at several localities along the Chippenham scarp, and are overlain locally by mid-level Tertiary gravels, which are much more extensive than previously reported. These relationships suggest possible correlation between high-level and mid-level Tertiary gravels on the Bon Air quadrangle with a well-defined measured section of upper Chesapeake Group strata on the Richmond quadrangle to the east.
- Identification of Carolina Bays not only above high-level Tertiary gravels on the Midlothian upland, but also above upper Chesapeake Group and Bacons Castle Formation sediments on the Richmond and Norge uplands, suggests that these features are no older than lower Pleistocene to upper Pliocene (rather than possibly older than late Tertiary as speculated by Goodwin and Johnson, 1970) if all the bays formed contemporaneously, or that there were multiple periods and ages of their formation in the Richmond area.
- Regional joint sets within several Coastal Plain units were recognized and appear to parallel sets in underlying Petersburg Granite basement. The map is now populated with hundreds of new joint measurements in Coastal Plain sediments and basement rocks (Petersburg Granite and Triassic Newark Supergroup rocks), which are integral for regional groundwater research and local environmental assessments and remediation.
- The role of Mesozoic and Cenozoic faulting in this area is clarified. Faults occur throughout the quadrangle and some appear to offset units as young as Pliocene. Silicified cataclasites, which cut Petersburg Granite and juxtapose Triassic Newark Supergroup rocks in the northwestern part of the quadrangle, are clearly Mesozoic in age. En echelon faults, represented by silicified cataclasites, strike from about N0ºE to N55ºE, dip between 30º and 70º either to the east-southeast or west-northwest, and

show either reverse or normal kinematics. Several silicified cataclasite fault zones appear to have been reactivated in the Cenozoic. Deposits of mid-level Tertiary gravel and Quaternary-Tertiary alluvial and colluvial valley fill are truncated by silicified cataclasites. Offsets in the basal elevations of lower Chesapeake Group clayey silt, high- and mid-level Tertiary gravels, and upper Chesapeake Group sediments hint at faults that generally strike from N0ºW to N60ºW and which are now covered beneath colluvium and urban development. Regionally, the Chippenham scarp also appears to be broadly tilted about an east-west axis. These Cenozoic faults throughout the Richmond area are likely reactived Mesozoic structures, and are probably not related to the Eocene Chesapeake Bay impact crater farther east.

- All map units on the Bon Air quadrangle exhibit geologic properties and characteristics that should be considered by regional urban planners, and many of the units pose serious environmental threats. For example, high concentrations of disseminated iron sulfides in clayey silt of the lower Chesapeake Group will produce ultra acidic soils and surface water runoff if exposed during construction. Radon gas is derived from the decay of radium, thorium, uranium, and other radioactive elements and isotopes in Petersburg Granite (particularly the subiodmorphic phase of the granite) and poses potential public health risks in air-tight structures built directly over granite. Swelling clays are common in soils and saprolite above many rock types on the quadrangle, including biotite- and hornblende-rich mafic gneiss xenoliths within Petersburg Granite and Triassic shale. Silicified cataclasite zones and igneous dikes (aplites, pegmatites and diabase) may impede lateral flow of shallow groundwater through surrounding saprolite, and shallow perched groundwater aquifers within Coastal Plain units are particularly susceptible to pollution. High potential exists for landslide failures throughout the quadrangle, especially along streams and side slopes where jointed Coastal Plain units overlying Petersburg Granite crop out.

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APPENDIX

Whole-rock geochemistry of samples collected on the Bon Air and other quadrangles in the Richmond metropolitan area (samples from others quadrangles are labeled in the table). Rock unit abbreviations: QTac – Quaternary-Tertiary alluvial and colluvial valley fill; Tbc – Pliocene Bacons Castle Formation; Tg_2 – mid-level Tertiary gravels; Tcu – Pliocene upper Chesapeake Group; Tg_1 – high-level Tertiary gravels; Tcl – Miocene lower Chesapeake Group; Tl – lower Tertiary units; K – Cretaceous Potomac Group; Mzb – Mesozoic silicified cataclasite; TRns – Triassic Newark Supergroup; Pzpg – subidiomorphic phase, Paleozoic Petersburg Granite; Pzpp – porphyritic phase, Petersburg Granite; Pzpf – foliated phase, Petersburg Granite; Pzpl – layered granite gneiss phase, Petersburg Granite; mg – mafic gneiss. Latitude/Longitude coordinates in NAD 27. Samples analyzed by Activation Laboratories Ltd., Ancaster, Ontario, using FUS-ICP method.

SAMPLE	ROCK UNIT	QUADRANGLE	LATITUDE/ LONGITUDE	SiO_2%	Al_2O_3%	Fe_2O_3(T)%	MnO%	MgO%	CaO%	Na_2O%	K_2O%	TiO_2%	P_2O_5%	LOI%	TOTAL%
9949	QTac	Bon Air	37.6077/ -77.5430	81.89	9.21	0.91	0.011	0.1	0.1	0.3	2.58	0.33	0.03	3.045	98.51
9953	QTac	Bon Air	37.5456/ -77.5454	74.6	13.84	1.48	0.022	0.29	0.42	0.97	4.45	0.78	0.06	3.642	100.5
9954	QTac	Bon Air	37.5553/ -77.5320	78.47	12.2	1.01	0.013	0.16	0.4	1.22	4.14	0.289	0.03	2.701	100.6
9955	QTac	Bon Air	37.544/ -77.5581	75.68	12.65	2.13	0.031	0.45	0.06	0.3	4.2	0.807	0.04	3.88	100.2
9965	QTac	Bon Air	37.6108/ -77.5756	77.03	12.28	1.01	0.01	0.18	0.13	1.02	4.42	0.4	0.03	3.31	99.82
9970	QTac	Bon Air	37.6100/ -77.5861	77.1	12.66	1.09	0.011	0.14	0.18	0.89	3.85	0.55	0.02	3.71	100.2
9978	QTac	Bon Air	37.6192/ -77.5574	86.45	7.55	0.68	0.009	0.03	0.01	0.18	2.39	0.378	0.04	2.031	99.76
9942	Tg_2	Bon Air	37.6028/ -77.5229	79.21	12.28	1.03	0.013	0.08	0.02	0.21	4.47	0.529	0.03	2.311	100.2
9948	Tg_2	Bon Air	37.5326/ -77.5274	77.61	12.56	1.04	0.019	0.09	0.36	0.95	3.95	0.619	0.07	3.145	100.4
9950	Tg_2	Bon Air	37.5299/ -77.5340	82.6	9.56	1.09	0.013	0.09	0.04	0.22	2.35	0.563	0.02	3.205	99.75
9951	Tg_2	Bon Air	37.5724/ -77.5441	79.35	11.41	1.09	0.017	0.15	0.06	0.2	3.61	0.374	0.04	3.494	99.79
9952	Tg_2	Bon Air	37.5095/ -77.5571	80.52	10.13	2.89	0.014	0.12	0.02	0.09	1.09	0.629	0.04	4.594	100.1
9956	Tg_2	Bon Air	37.5791/ -77.5585	84.02	8.58	1.1	0.013	0.07	0.05	0.17	3.2	0.315	0.02	2.471	100
9969	Tg_2	Bon Air	37.6230/ -77.6121	76.75	11.86	1.61	0.012	0.18	0.25	0.38	2.72	0.563	0.02	4.77	99.11
9971	Tg_2	Bon Air	37.5763/ -77.6061	67.03	18.39	1.92	0.011	0.2	0.17	0.83	4.24	0.407	0.04	5.98	99.21
9943	Tcu	Bon Air	37.6243/ -77.5056	85.9	6.57	0.76	0.011	0.1	0.23	0.56	1.41	0.747	0.03	2.348	98.66
9944	Tcu	Bon Air	37.5906/ -77.5158	77.72	11.42	1.45	0.011	0.3	0.2	0.35	1.54	0.753	0.04	5.536	99.32
9945	Tcu	Bon Air	37.5079/ -77.5163	87.98	5.13	2.06	0.007	0.09	0.02	0.02	0.12	1.027	0.03	3.051	99.52
9947	Tcu	Bon Air	37.5002/ -77.5220	79.99	10.02	2.61	0.012	0.16	0.05	0.05	0.36	1.134	0.05	5.052	99.49
9977	Tg_1	Bon Air	37.5405/ -77.5579	76.91	12.9	1.57	0.016	0.34	0.04	0.15	2.55	0.739	0.07	4.586	99.87
9946	Tg_1	Bon Air	37.6235/ -77.5192	84.13	8.83	1.18	0.015	0.12	0.06	0.11	1.49	0.712	0.04	3.368	100.1
9975	Tcl	Bon Air	37.5214/ -77.5713	68.38	14.81	5.86	0.012	0.33	0.01	0.14	2.54	0.742	0.16	6.641	99.62
9962	Tcl	Bon Air	37.5133/ -77.6012	61.73	13.69	6.63	0.031	1.48	0.87	0.75	2.39	0.982	0.23	11.09	99.87
9968	Tcl	Bon Air	37.5299/ -77.5875	50.43	21.04	12.11	0.111	0.81	3.23	0.25	0.56	1.245	0.04	9.86	99.68
9974	Tcl	Bon Air	37.5068/ -77.5745	60.69	13.65	4.73	0.022	1.01	0.13	0.18	1.84	0.788	0.08	17.24	100.4
9972	TRns	Bon Air	37.6153/ -77.6124	77.3	10.09	3.79	0.071	0.43	0.36	1.06	3.18	0.179	0.05	2.84	99.34
9967	Mzb	Bon Air	37.53677/ -77.61371	91.57	4.47	1.19	0.013	0.25	0.11	0.1	0.27	0.237	0.05	2.14	100.4
9966	Pzpg	Bon Air	37.5541/ -77.5930	72.75	14.26	1.65	0.031	0.45	0.99	3.37	5.19	0.216	0.08	0.94	99.92
9958	Pzpp	Bon Air	37.5456/ -77.5628	69.7	14.41	3.55	0.072	1.02	2.37	3.45	4.24	0.734	0.3	0.57	100.4
9960	Pzpp	Bon Air	37.6149/ -77.5390	70.14	15.27	2.67	0.033	0.58	1.08	3.43	5.46	0.455	0.15	1.26	100.5
9961	Pzpp (saprolite)	Bon Air	37.5502/ -77.5616	70.71	16.06	2.07	0.048	0.46	0.36	1.12	5.48	0.534	0.02	3.56	100.4
10172	Pzpp (saprolite)	Bon Air	37.5440/ -77.5581	66.05	16.63	4.09	0.051	1	0.42	1.06	5.16	0.822	0.08	4.36	99.73
9959	Pzpf (saprolite)	Bon Air	37.5244/ -77.5346	65.09	17.48	3.6	0.021	0.66	1.08	2.52	3.93	0.556	0.03	4.03	99.01
9963	Pzpl (saprolite)	Bon Air	37.5540/ -77.5925	70.73	11.53	4.39	0.025	0.77	0.31	0.19	2.22	0.939	0.06	9.14	100.3
9964	mg	Bon Air	37.5540/ -77.5925	38.62	5.01	13.67	0.24	31.05	3.46	0.34	0.05	0.264	0.03	6.85	99.6

SAMPLE	Au (ppb)	Ag (ppm)	As (ppm)	Ba (ppm)	Be (ppm)	Bi (ppm)	Br (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cs (ppm)	Cu (ppm)	Hf (ppm)	Hg (ppm)	Ir (ppb)	Mo (ppm)	Ni (ppm)	Pb (ppm)	Rb (ppm)	Sb (ppm)	S (%)
9949	< 1	< 0.5	< 1	360	2	< 2	< 0.5	< 0.5	1.6	81	6.5	6	5.9	< 1	< 1	< 2	4	24	140	0.2	0.002
9953	< 1	< 0.5	< 1	917	3	< 2	1.1	< 0.5	3.2	51.3	5	7	16.8	< 1	< 1	< 2	5	34	170	0.2	0.003
9954	< 1	< 0.5	< 1	753	2	< 2	1.4	< 0.5	2.7	12.6	4	5	5.8	< 1	< 1	< 2	6	31	170	0.2	0.003
9955	< 1	< 0.5	1	901	2	< 2	1.4	< 0.5	4.9	20.1	6.8	8	20.5	< 1	< 1	< 2	7	34	180	0.3	0.008
9965	< 1	0.8	< 1	630	3	< 2	2.4	< 0.5	2.3	17.7	5.2	8	7.7	< 1	< 1	< 2	5	32	220	0.2	0.008
9970	< 1	0.6	< 1	690	2	< 2	1.5	< 0.5	2.3	17.4	4.3	6	10	< 1	< 1	< 2	4	27	140	0.3	0.011
9978	< 1	< 0.5	2	197	1	< 2	1	< 0.5	< 0.1	55.7	4.1	3	10.2	< 1	< 1	< 2	2	23	130	0.2	0.003
9942	< 1	< 0.5	< 1	429	1	< 2	1	< 0.5	1.3	50.4	4.9	8	11.9	< 1	< 1	< 2	2	24	120	0.2	0.003
9948	< 1	< 0.5	< 1	988	2	< 2	0.9	< 0.5	2	11.3	3.3	5	15.3	< 1	< 1	< 2	3	34	110	0.2	0.002
9950	< 1	< 0.5	1	517	1	< 2	1	< 0.5	1.8	18.5	3.5	4	15.8	< 1	< 1	< 2	4	21	90	0.2	0.006
9951	< 1	< 0.5	1	596	1	< 2	1.5	< 0.5	2.8	53.1	7.2	7	6	< 1	< 1	< 2	6	32	170	0.4	0.007
9952	< 1	< 0.5	4	180	1	< 2	17	< 0.5	2.4	22.2	4.8	5	12.9	< 1	< 1	< 2	8	21	60	0.4	0.009
9956	2	< 0.5	1	468	1	< 2	1.2	< 0.5	1.6	70.9	7	4	6.4	< 1	< 1	< 2	3	27	170	0.2	0.003
9969	< 1	< 0.5	2	488	1	< 2	2	< 0.5	4.3	16.1	4	8	7	< 1	< 1	< 2	5	19	130	0.3	0.007
9971	< 1	0.9	2	806	2	< 2	1.8	< 0.5	5.5	16.1	4.2	14	6.7	< 1	< 1	< 2	8	40	170	0.4	0.013
9943	1	< 0.5	2	303	1	< 2	1.2	< 0.5	2.9	23.1	2.8	2	35	< 1	< 1	3	4	20	70	0.3	0.003
9944	< 1	< 0.5	3	321	2	< 2	2.3	< 0.5	3.4	37.2	5.3	6	20.2	< 1	< 1	< 2	12	27	80	0.5	0.003
9945	1	< 0.5	4	48	< 1	< 2	1.9	< 0.5	1.2	42.1	1.4	2	31	< 1	< 1	< 2	4	13	< 10	0.5	0.005
9947	2	< 0.5	6	102	< 1	< 2	2	< 0.5	3.5	66.2	3.5	4	41.2	< 1	< 1	< 2	14	26	30	0.7	0.012
9977	2	< 0.5	2	700	2	< 2	1.4	< 0.5	2.6	58.3	5.2	10	16.3	< 1	< 1	< 2	8	31	120	0.3	0.003
9946	< 1	< 0.5	< 1	302	1	< 2	1.1	< 0.5	1.5	64.3	4.1	4	23.1	< 1	< 1	< 2	5	22	80	0.3	0.003
9975	1	< 0.5	17	438	2	< 2	3	< 0.5	2.3	80.9	9.5	21	13.4	< 1	< 1	19	8	27	90	0.9	0.007
9962	< 1	< 0.5	13	469	4	< 2	7.8	1.1	23.9	80.4	8.1	29	9.3	< 1	< 1	5	48	20	120	0.6	2.04
9968	< 1	< 0.5	< 1	300	3	4	< 0.5	< 0.5	32.6	113	2.9	10	4.4	< 1	< 1	< 2	138	15	30	0.3	0.009
9974	< 1	< 0.5	8	294	3	< 2	8.3	20.5	29.7	76.1	11.3	15	7.7	< 1	< 1	9	65	27	100	0.6	2.06
9972	< 1	< 0.5	2	666	3	< 2	< 0.5	< 0.5	8.5	88.9	6.1	8	2.2	< 1	< 1	6	16	24	140	< 0.1	0.003
9967	< 1	1.7	3	100	2	5	0.7	< 0.5	3.9	97.5	2	14	1.2	< 1	< 1	4	19	120	20	0.3	0.007
9966	< 1	0.7	2	750	4	< 2	< 0.5	< 0.5	3.8	57.1	3.5	5	5.2	< 1	< 1	5	10	37	250	0.2	0.003
9958	< 1	< 0.5	< 1	937	5	< 2	< 0.5	< 0.5	6.8	44	4.5	13	7.3	< 1	< 1	< 2	5	31	200	0.2	0.004
9960	3	< 0.5	1	1008	3	< 2	< 0.5	< 0.5	4.5	6.9	3.6	9	8.1	< 1	< 1	< 2	3	32	190	< 0.1	< 0.001
9961	< 1	< 0.5	< 1	907	4	< 2	1.2	< 0.5	3.2	8.8	6.9	4	8.1	< 1	< 1	< 2	3	36	280	0.2	< 0.001
10172	< 1	< 0.5	< 1	1257	4	< 2	< 0.5	< 0.5	12.6	9	6.9	12	11.2	< 1	< 1	< 2	5	37	270	< 0.1	0.003
9959	< 1	< 0.5	1	1122	3	< 2	1.4	< 0.5	5.1	18.8	5.6	16	8.6	< 1	< 1	< 2	9	43	180	0.2	0.003
9963	4	0.9	12	483	3	< 2	6.1	7.5	23.7	65.5	5.5	20	16.6	< 1	< 1	9	54	22	90	0.6	1.81
9964	< 1	< 0.5	2	188	1	7	1.1	0.7	132	4340	< 0.2	11	0.5	< 1	< 1	< 2	1200	10	20	< 0.1	0.026

SAMPLE	Sc (ppm)	Se (ppm)	Sr (ppm)	Ta (ppm)	Th (ppm)	U (ppm)	V (ppm)	W (ppm)	Y (ppm)	Zn (ppm)	Zr (ppm)	La (ppm)	Ce (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Tb (ppm)	Yb (ppm)	Lu (ppm)	Mass (g)
9949	3.64	< 0.5	51	2.4	32	7.2	22	< 1	13	28	195	57.8	94	40	6.52	0.8	0.7	1.22	0.18	1.109
9953	5.18	< 0.5	161	2.4	18.2	7.6	42	< 1	17	45	649	42.8	72	31	5.62	1.18	0.8	1.86	0.26	1.328
9954	2.99	< 0.5	128	0.7	14.2	3	22	< 1	7	22	190	28.9	43	18	2.67	0.8	0.4	0.76	0.11	1.281
9955	6.42	1.4	131	3.3	20	9	55	< 1	33	55	734	80.3	90	81	14	2.52	1.6	3.77	0.52	1.106
9965	3.98	0.6	85	1.8	36.8	8.5	24	< 1	19	25	272	62.5	91	33	6.48	0.88	0.8	2.13	0.29	1.251
9970	3.63	< 0.5	102	< 0.3	17	4.1	29	< 1	14	20	352	41.5	68	24	4.24	0.83	0.6	1.4	0.21	1.256
9978	2.18	< 0.5	30	3	44.3	4.8	14	< 1	16	11	288	74.7	123	61	8.83	0.69	1.1	1.55	0.23	1.1
9942	2.18	< 0.5	51	1.9	18.6	4.3	15	< 1	11	16	412	35.1	69	25	4.64	0.69	0.6	1.4	0.21	1.164
9948	2.87	< 0.5	164	1.4	10.9	5.9	26	< 1	14	22	517	95.9	193	55	8.81	1.65	0.8	1.37	0.2	1.3
9950	3.22	< 0.5	71	1.1	11.9	3.3	33	< 1	6	16	533	19.3	30	13	2.21	0.52	0.4	1.26	0.19	1.337
9951	3.83	< 0.5	74	1.6	24.9	6.2	23	< 1	13	26	183	39	66	28	4.48	0.72	0.6	1.24	0.18	1.209
9952	4.82	< 0.5	33	1.6	25.2	5.7	46	2	12	20	461	43.8	83	32	5.2	0.74	0.5	1.16	0.16	1.161
9956	2.2	< 0.5	61	1.9	23.8	3.4	15	1	10	13	189	33.9	57	24	4.26	0.51	0.5	1.07	0.15	1.056
9969	3.81	< 0.5	68	1.7	12.5	4.7	42	< 1	7	22	255	18.2	29	10	1.9	0.44	0.3	1.09	0.17	1.131
9971	5.12	< 0.5	106	< 0.3	39.1	6.6	45	< 1	28	36	231	85.1	130	55	8.5	1.7	1	2.35	0.3	1.097
9943	4.25	1.5	58	2.7	15.4	4.7	30	< 1	16	13	1321	34	59	27	4.55	0.91	0.6	2.08	0.3	1.278
9944	7.17	< 0.5	51	1.8	38.6	9.8	61	3	25	29	762	84.8	143	63	10.3	1.36	1.2	2.81	0.42	1.26
9945	4.15	< 0.5	12	1.3	7.2	2.5	51	2	10	8	1050	9.92	16	7	1.21	0.2	0.3	1.69	0.3	1.434
9947	6.13	< 0.5	29	1.4	13.1	3.9	77	2	16	22	1670	25.9	48	16	3.08	0.75	0.6	2.4	0.38	1.387
9977	6.58	0.9	111	1.9	21	5.6	48	< 1	21	45	686	71.7	137	57	10.1	1.96	0.9	2.2	0.29	1.21
9946	4.09	1.2	46	2.3	17.8	4.3	32	< 1	12	20	859	44.2	81	34	5.49	0.88	0.8	1.57	0.24	1.434
9975	9.99	< 0.5	63	1	13.9	10.1	89	< 1	16	32	469	35.1	64	27	5.1	1.04	0.7	1.93	0.31	1.148
9962	15.4	< 0.5	88	1.4	10.5	4.1	104	< 1	56	169	373	63.6	109	46	10.5	2.48	1.5	5.88	0.88	1.142
9968	38.4	< 0.5	65	0.5	3.9	1.1	260	3	16	67	132	9.14	21	10	2.32	0.85	0.5	2.47	0.37	1.492
9974	11.9	< 0.5	51	1	9.2	3.5	100	< 1	82	147	223	77.6	158	80	17.8	5.47	3.1	8.15	1.16	1.684
9972	3.12	< 0.5	85	0.8	8.9	5.2	23	2	2	55	79	21	40	18	2.68	0.75	0.4	1.43	0.25	1.036
9967	3.71	< 0.5	53	< 0.3	5.1	2.8	33	7	4	11	37	19.2	25	12	2.27	0.66	0.3	0.54	0.09	1.05
9966	2.54	< 0.5	140	1.8	48.9	8.6	18	< 1	7	51	169	45.2	74	29	4.19	0.98	0.4	0.74	0.11	1.136
9958	5.4	< 0.5	410	1.6	16.2	4.1	54	< 1	21	83	316	58.6	110	37	7.44	1.57	1.2	1.84	0.25	1.306
9960	3.67	< 0.5	271	1.3	34.3	2.5	31	< 1	9	63	301	81.4	128	50	7.83	1.25	0.6	0.69	0.11	1.299
9961	6.83	< 0.5	168	1.6	33.4	15.8	40	< 1	6	57	269	48	47	22	4.15	0.95	0.4	0.67	0.1	1.067
10172	6.76	< 0.5	236	2.6	24.7	7.1	76	< 1	34	97	433	128	235	102	16.9	2.69	1.7	3.46	0.47	1.026
9959	6.32	< 0.5	289	2.2	21.6	6.5	56	< 1	11	79	319	52.3	81	30	5.71	1.27	0.6	1.03	0.16	1.032
9963	11	< 0.5	69	1.1	11	4.1	78	< 1	45	184	691	61.1	131	69	15.1	3.81	1.9	5.3	0.74	1.299
9964	14.4	< 0.5	28	< 0.3	0.5	< 0.1	81	6	6	105	14	3.98	7	5	1.18	0.31	0.2	0.55	0.08	1.264

Whole-rock geochemistry of samples collected on the Bon Air and other quadrangles in the Richmond metropolitan area (samples from others quadrangles are labeled in the table). Rock unit abbreviations: QTac – Quaternary-Tertiary alluvial and colluvial valley fill; Tbc – Pliocene Bacons Castle Formation; Tg_2 – mid-level Tertiary gravels; Tcu – Pliocene upper Chesapeake Group; Tg_1 – high-level Tertiary gravels; Tcl – Miocene lower Chesapeake Group; Tl – lower Tertiary units; K – Cretaceous Potomac Group; Mzb – Mesozoic silicified cataclasite; TRns – Triassic Newark Supergroup; Pzpg – subidiomorphic phase, Paleozoic Petersburg Granite; Pzpp – porphyritic phase, Petersburg Granite; Pzpf – foliated phase, Petersburg Granite; Pzpl – layered granite gneiss phase, Petersburg Granite; mg – mafic gneiss. Latitude/Longitude coordinates in NAD 27. Samples analyzed by Activation Laboratories Ltd., Ancaster, Ontario, using FUS-ICP method.

SAMPLE	ROCK UNIT	QUADRANGLE	LATITUDE/ LONGITUDE	SiO_2%	Al_2O_3%	Fe_2O_3(T)%	MnO%	MgO%	CaO%	Na_2O%	K_2O%	TiO_2%	P_2O_2%	LOI%	TOTAL%
10101	Tbc	Seven Pines	37.5507/ -77.3174	73.66	11.06	7.57	0.014	0.21	0.03	0.1	0.65	1.048	0.05	6.23	100.6
10102	Tbc	Seven Pines	37.5300/ -77.3035	88.48	4.52	3.24	0.029	0.1	0.01	0.15	0.37	1.046	0.06	2.03	100
10090	Tcu	Seven Pines	37.5996/ -77.2779	91.39	4.14	1.77	0.016	0.12	0.02	0.08	0.32	0.526	0.03	1.74	100.1
10097	Tcu	Seven Pines	37.6130/ -77.2949	93.65	2.52	0.97	0.011	0.07	0.01	0.16	0.4	0.457	0.04	0.93	99.22
10151	Tg_1	Glen Allen	37.6575/ -77.6137	87.12	5.43	0.92	0.011	0.11	0.2	0.89	2.06	0.988	0.05	1.03	98.81
10098	Tcl	Seven Pines	37.6081/ -77.3637	76.24	7.91	3.65	0.037	0.72	1.16	1.12	1.89	0.999	0.07	5.24	99.04
10100	Tcl	Seven Pines	37.5447/ -77.2829	79.5	7.27	2.89	0.024	0.53	0.47	0.71	1.64	0.809	0.06	4.73	98.63
10129	Tcl	Seven Pines	37.5996/ -77.27786	81.79	7.97	2.63	0.016	0.37	0.06	0.21	1.63	1.017	0.04	4.37	100.1
10099	Tcl	Drewrys Bluff	37.4450/ -77.4027	56.98	21.41	2.97	0.008	1.12	0.13	0.16	2.13	1.289	0.08	12.2	98.48
10142	Tl	Yellow Tavern	37.6852/ -77.4553	76.34	10.23	2.55	0.025	0.81	0.28	0.71	2.65	0.698	0.91	5.116	100.3
10164	Tl	Richmond	37.615/ -77.4579	90.57	2.7	2.88	0.027	0.31	0.05	0.18	0.88	1.254	0.03	1.633	100.5
10103	Tl	Drewrys Bluff	37.4450/ -77.4027	84.26	2.8	4.63	0.06	0.45	0.08	0.19	0.94	2.525	0.08	2.52	98.55
10104	Tl	Drewrys Bluff	37.4311/ -77.4369	76.85	4.11	6.23	0.073	0.66	0.06	0.18	1.37	2.967	0.03	6.7	99.24
10105	Tl	Drewrys Bluff	37.4868/ -77.4139	78.39	6.81	4.74	0.055	0.56	0.03	0.23	1.21	2.486	0.06	4.17	98.74
10106	Tl	Drewrys Bluff	37.4868/ -77.4139	81.06	6.16	4.83	0.048	0.67	0.04	0.25	1.62	2.27	0.05	3.79	100.8
10133	K	Dutch Gap	37.3838/ -77.3157	86.45	5.99	0.66	0.01	0.1	0.25	0.45	2.37	0.131	0.08	1.96	98.44
10136	K	Ashland	37.7807/ -77.4059	80.85	10.14	1.42	0.015	0.21	0.3	0.74	2.84	0.397	0.06	3.042	100
10149	K	Chester	37.2832/ -77.4115	80.67	11.14	1.05	0.004	0.18	0.04	0.21	2.62	0.34	0.03	4.156	100.4
10131	K	Drewrys Bluff	37.4199/ -77.3964	80.7	11.54	0.85	0.007	0.11	0.04	0.14	2.73	0.4	0.02	3.674	100.2
10057	Pzpg	Chesterfield	37.4921/ -77.6243	75.38	13.91	0.88	0.009	0.08	0.3	3.62	5.68	0.055	0.04	0.55	100.5
10157	Pzpg	Drewrys Bluff	37.4898/ -77.4278	71.38	14.51	2.17	0.045	0.54	1.75	3.68	4.64	0.28	0.11	0.53	99.61
10055	Pzpp	Chesterfield	37.459/ -77.6179	68.88	15.23	3.15	0.058	0.85	1.97	3.77	4.97	0.518	0.2	0.64	100.2
10161	Pzpf	Drewrys Bluff	37.4388/ -77.4365	68.7	14.42	3.43	0.047	0.95	2.57	3.04	4.86	1.522	0.21	1.2	101
10054	Pzpl (saprolite)	Chesterfield	37.4641/ -77.6083	61.23	19.25	5.42	0.074	2.48	0.02	0.05	2	0.7	0.03	7.97	99.22
10056	Pzpl	Chesterfield	37.4415/ -77.5788	67.71	15.77	4.89	0.098	1.65	3.05	4.26	1.75	0.628	0.15	0.8	100.8
10159	Pzpl	Drewrys Bluff	37.4898/ -77.4278	65.74	16.26	3.99	0.062	1.53	3.2	4.01	3.42	0.524	0.26	0.56	99.56
10163	Pzpl	Richmond	37.5232/ -77.421	80.78	11.16	1.14	0.011	0.26	0.84	4.17	1.86	0.115	0.03	0.54	100.9

SAMPLE	Au (ppb)	Ag (ppm)	As (ppm)	Ba (ppm)	Be (ppm)	Bi (ppm)	Br (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cs (ppm)	Cu (ppm)	Hf (ppm)	Hg (ppm)	Ir (ppb)	Mo (ppm)	Ni (ppm)	Pb (ppm)	Rb (ppm)	Sb (ppm)	S (%)
10101	< 1	< 0.5	11	124	1	< 2	2.9	< 0.5	3.6	112	3.4	9	10.6	< 1	< 1	3	11	16	30	0.9	0.012
10102	< 1	0.7	7	86	< 1	< 2	1.3	< 0.5	3.1	39.8	0.8	13	14.9	< 1	< 1	3	11	19	20	0.4	0.008
10090	< 1	< 0.5	2	84	< 1	< 2	0.9	< 0.5	2.2	54.8	0.8	11	6.1	< 1	< 1	< 2	10	17	< 10	0.3	0.005
10097	< 1	< 0.5	2	150	< 1	< 2	1	< 0.5	1.2	149	< 0.2	7	6.5	< 1	< 1	11	6	7	10	0.2	0.004
10151	< 1	1	< 1	337	1	< 2	< 0.5	< 0.5	2.4	114	1.1	8	29.7	< 1	< 1	< 2	6	21	70	0.4	0.014
10098	< 1	0.6	8	480	1	< 2	3.2	< 0.5	4.5	63	2.7	11	21.3	< 1	< 1	7	10	16	70	0.5	0.536
10100	< 1	< 0.5	8	390	1	< 2	4.4	< 0.5	5	64	3.1	10	14.4	< 1	< 1	4	15	17	60	0.3	0.411
10129	< 1	0.6	9	344	1	2	3.8	0.5	11.9	43	2.6	15	16.2	< 1	< 1	3	21	13	50	0.3	0.951
10099	4	0.7	12	374	2	< 2	2	< 0.5	6.5	107	9.1	26	6.3	< 1	< 1	3	33	21	110	0.7	0.006
10142	2	< 0.5	6	460	2	< 2	2.1	< 0.5	2.8	162	5.9	6	21	< 1	< 1	< 2	5	19	100	0.5	0.008
10164	< 1	< 0.5	11	113	1	< 2	1.5	< 0.5	1.6	74.3	0.9	2	21.7	< 1	< 1	3	2	8	30	0.6	0.004
10103	< 1	< 0.5	4	102	< 1	< 2	0.9	< 0.5	3.6	160	1.3	5	30.4	< 1	< 1	11	8	8	40	0.3	0.159
10104	< 1	< 0.5	14	134	2	< 2	2	< 0.5	5.7	95.9	1.9	16	35.7	< 1	< 1	9	15	12	50	0.5	0.986
10105	< 1	< 0.5	13	181	2	< 2	3	< 0.5	3.6	157	2.5	6	29.8	< 1	< 1	12	10	12	40	0.6	0.011
10106	< 1	< 0.5	14	183	2	< 2	4	< 0.5	3	116	2.7	5	31.3	< 1	< 1	12	7	11	50	0.4	0.006
10133	< 1	< 0.5	< 1	523	1	< 2	< 0.5	< 0.5	2.3	25.8	0.8	7	1.9	< 1	< 1	< 2	7	16	60	0.1	0.038
10136	< 1	< 0.5	< 1	673	1	< 2	0.6	< 0.5	4.9	12.8	2	4	4.8	< 1	< 1	< 2	5	17	60	0.1	0.002
10149	4	< 0.5	< 1	640	1	< 2	1.7	< 0.5	2	20	4	8	4.1	< 1	< 1	< 2	6	25	70	0.3	0.007
10131	< 1	< 0.5	< 1	638	1	< 2	0.7	< 0.5	2.3	20.7	1	3	5	< 1	< 1	< 2	4	18	60	0.2	0.006
10057	4	< 0.5	1	258	5	< 2	< 0.5	< 0.5	1.8	48.8	7.1	5	1.5	< 1	< 1	5	2	46	310	< 0.1	< 0.001
10157	< 1	0.5	< 1	643	5	< 2	< 0.5	< 0.5	6.8	9.5	8.2	20	4.6	< 1	< 1	< 2	57	25	190	0.1	0.069
10055	2	< 0.5	< 1	> 1000	4	< 2	< 0.5	< 0.5	5	45.5	5	11	6.6	< 1	< 1	4	5	27	190	< 0.1	0.004
10161	< 1	< 0.5	< 1	1087	4	< 2	< 0.5	< 0.5	7.7	87.6	1.6	23	8.2	< 1	< 1	5	13	20	140	< 0.1	0.016
10054	< 1	< 0.5	< 1	353	4	< 2	1.3	< 0.5	13.4	84.2	21.5	6	5.3	< 1	< 1	< 2	31	16	290	0.3	0.006
10056	< 1	< 0.5	3	169	5	< 2	< 0.5	< 0.5	9.9	59.3	9.4	16	3.7	< 1	< 1	< 2	7	34	170	0.2	0.009
10159	< 1	< 0.5	< 1	554	7	< 2	< 0.5	< 0.5	9	21.2	2.3	9	3.8	< 1	< 1	< 2	12	15	90	< 0.1	0.015
10163	< 1	< 0.5	< 1	434	< 1	< 2	< 0.5	< 0.5	0.9	< 0.5	1.2	5	4.6	< 1	< 1	< 2	1	5	20	< 0.1	0.005

SAMPLE	Sc (ppm)	Se (ppm)	Sr (ppm)	Ta (ppm)	Th (ppm)	U (ppm)	V (ppm)	W (ppm)	Y (ppm)	Zn (ppm)	Zr (ppm)	La (ppm)	Ce (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Tb (ppm)	Yb (ppm)	Lu (ppm)	Mass (g)
10101	10.3	< 0.5	23	1.2	11	3.8	112	3	16	21	607	31	58	23	3.71	0.9	0.5	2.13	0.32	1.272
10102	4.78	< 0.5	14	1.1	4.7	2.2	43	3	10	33	656	15.4	33	14	2.56	0.67	0.3	1.27	0.2	1.289
10090	3.1	< 0.5	10	0.7	3.2	1.1	23	4	4	16	248	9.6	41	9	1.39	0.49	0.2	0.61	0.09	1.127
10097	1.79	< 0.5	28	0.4	2.7	1	15	< 1	6	12	291	11.5	24	11	1.98	0.78	0.3	0.5	0.07	1.101
10151	3.25	3.5	77	2.5	32	6.9	27	1	34	11	1125	74.7	126	48	8.74	1.18	1.2	4.17	0.66	1.327
10098	7.4	< 0.5	134	1.5	7.3	1.9	65	3	14	44	995	23.8	45	18	3.42	1.34	0.5	2.1	0.32	1.312
10100	7.04	< 0.5	86	1.7	5.9	2.1	68	3	22	56	580	31.7	57	26	4.82	1.36	0.7	2.35	0.35	1.273
10129	8.11	< 0.5	43	0.7	7.9	3.4	74	< 1	20	50	747	26.6	47	24	5.01	1.21	0.8	2.11	0.32	1.629
10099	19.4	6.9	69	1.1	17.8	6.5	169	< 1	31	81	285	59.2	104	40	7.47	1.77	1	4.16	0.71	1.038
10142	9.63	< 0.5	74	1.1	9.8	20.8	70	2	44	17	772	38.3	110	52	12.8	3.44	2.2	4.53	0.67	1.13
10164	3.52	< 0.5	19	1.4	6.6	2	60	2	16	17	876	18.9	39	14	3.33	0.6	0.5	2.17	0.34	1.559
10103	4.66	5.4	35	2.8	13.2	4.1	70	3	21	39	1479	37	81	38	6.61	1.12	0.9	3.02	0.48	1.386
10104	7	11.9	21	3.2	18	7.1	87	5	28	49	1672	47.4	96	41	7.6	1.27	1.2	4.57	0.83	1.329
10105	8.58	9.5	25	2.3	17.4	5.7	94	4	29	40	1369	47.7	93	45	7.88	1.48	1.1	4.72	0.84	1.29
10106	8.07	< 0.5	27	2.1	18.6	7.4	95	5	31	34	1441	46.9	90	41	7.15	1.25	1	4.15	0.76	1.273
10133	2.12	< 0.5	110	< 0.3	27	0.9	40	< 1	5	7	57	6.44	12	5	1.04	0.37	0.2	0.63	0.09	1.141
10136	4.57	< 0.5	128	< 0.3	3.1	1.6	24	< 1	7	14	150	15.9	32	12	2.66	0.82	0.4	0.94	0.13	1.358
10149	4.75	< 0.5	109	0.3	5.8	2	47	< 1	7	16	137	12.1	25	9	1.77	0.48	0.3	0.76	0.11	1.252
10131	4.72	< 0.5	79	0.5	3.2	1	28	< 1	9	12	170	11.9	21	7	1.58	0.54	0.3	1.23	0.19	1.248
10057	2.07	< 0.5	82	1.5	16.1	13.9	< 5	< 1	39	15	39	12.1	22	10	2.69	0.51	0.6	4.44	0.77	1.07
10157	3.71	< 0.5	247	1.4	20	6.7	33	< 1	16	55	168	36	60	23	4.49	0.86	0.7	1.26	0.2	1.301
10055	4.61	< 0.5	433	3	22.7	4.5	41	< 1	24	68	257	80	144	52	7.27	1.86	1	2.58	0.4	1.129
10161	6.11	< 0.5	381	7.3	27.6	8.1	60	< 1	65	51	340	101	216	114	23.9	4.31	2.7	5.68	0.76	1.149
10054	13.3	< 0.5	4	1.9	19.1	9.6	83	3	36	104	200	49.8	97	50	10.7	3.76	1.8	3.73	0.62	1.131
10056	10.5	< 0.5	239	< 0.3	14.4	6.7	87	2	13	86	125	20.2	38	18	3.5	0.73	0.6	1.07	0.15	1.39
10159	6.68	< 0.5	294	< 0.3	5.1	1.2	63	< 1	10	64	167	32.5	52	20	3.97	1.13	0.5	0.62	0.09	1.386
10163	4.34	< 0.5	52	< 0.3	6.2	1.5	< 5	< 1	39	12	116	19.8	34	16	3.14	0.67	0.7	4	0.63	1.246

VIRGINIA DIVISION OF GEOLOGY AND MINERAL RESOURCES – OPEN-FILE REPORT 07-03 – SUMMARY OF THE GEOLOGY OF THE BON AIR QUADRANGLE: A SUPPLEMENT TO THE GEOLOGIC MAP OF THE BON AIR QUADRANGLE, VIRGINIA