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CHARACTERIZATION OF VARIABLY LITHIFIED FELDSPATHIC SANDS IN THE INNER COASTAL PLAIN AND FALL ZONE

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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 Statistical Area (MSA) through the Association of American State Geologists and U.S. Geological Survey (AASG-USGS) STATEMAP Program. The Richmond MSA encompasses 16 counties in the Piedmont and Coastal Plain provinces of central-eastern Virginia and includes the cities of Richmond, Petersburg, Colonial Heights, and Hopewell along interstates I-95, I-64, and I-85 (Figure 1). The goal is to produce and compile detailed 1:24,000-scale geologic maps along the interstates and in other high-growth areas that can be used for regional land-use planning. To date, new geologic mapping has been completed on three quadrangles (Bon Air, Richmond and Seven Pines) and is in progress on two others (Chesterfield and Drewrys Bluff).

New mapping on these five quadrangles has already resulted in several significant contributions over previously published detailed maps (i.e., Daniels, 1974; Goodwin, 1980): 1) major revisions to stratigraphic nomenclature and correlations across the Fall Line[1] (Figures 2 and 3) in this region; and 2) these maps are now populated with hundreds of new structural measurements (particularly joints) in Coastal Plain sediments and basement rocks (Petersburg Granite and Triassic rocks) not shown on earlier maps, which are integral for regional groundwater research and local environmental assessments and remediation (Carter and others, 2005; 2006).

Of particular interest is that during new detailed mapping, a distinctly characteristic Coastal Plain lithology was identified. This lithology – variably lithified pebbly feldspathic sand, or sandstone (heretofore referred to as feldspathic sand) is very similar in appearance to local granite saprolite, but is distinct in that: 1) it contains rounded pebbles, which implies some sort of sedimentary transport and deposition; and 2) the lithology is typically very indurated to lithified. In the Inner Coastal Plain, feldspathic sand locally comprises the basal section of the Pliocene upper Chesapeake Group immediately

[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. In the Richmond area (on the Glen Allen, Richmond, Bon Air, 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 230 to 260 feet above sea level on the Chesterfield and Bon Air quadrangles.

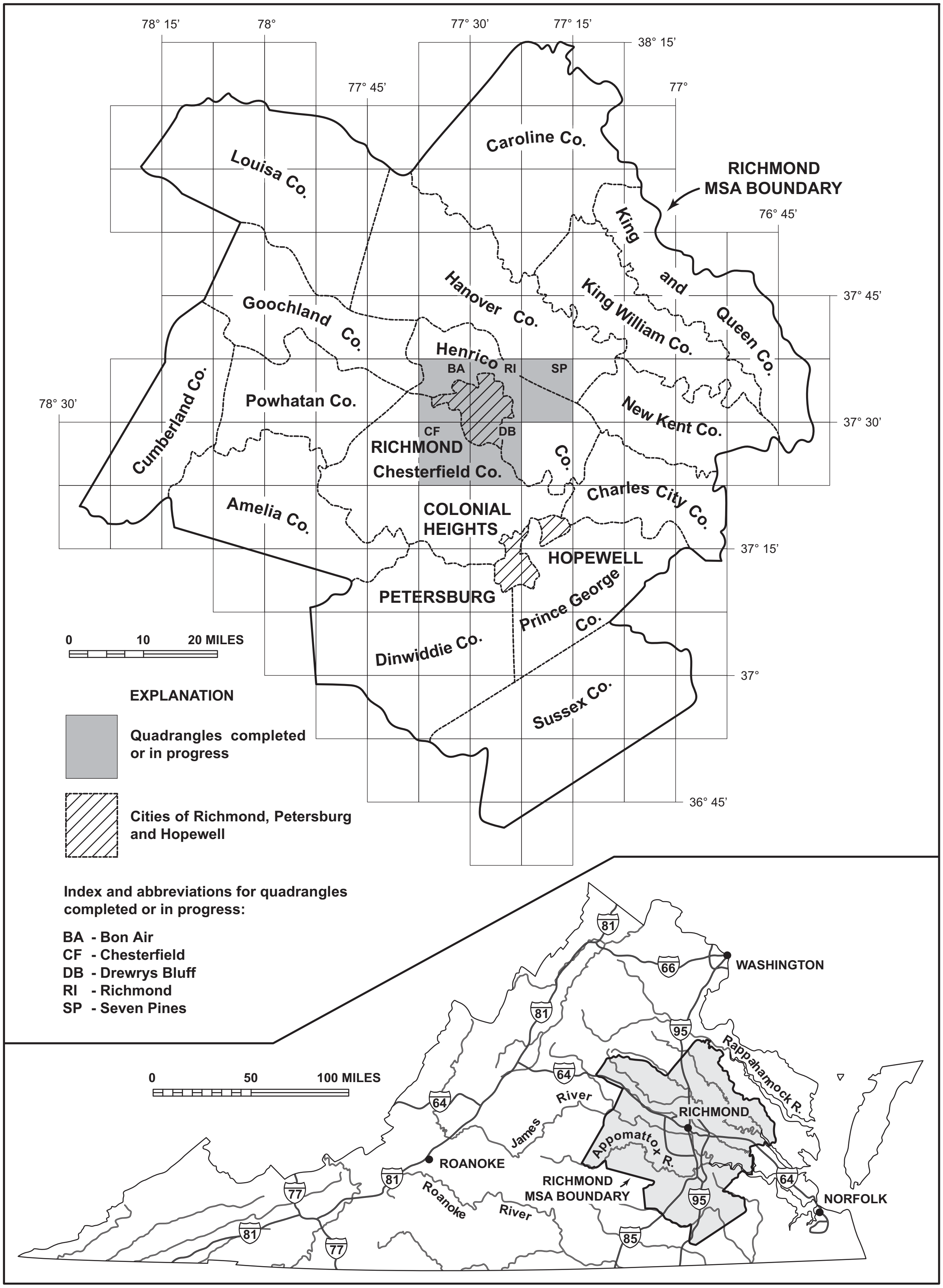


Figure 1. Location of the Richmond Metropolitan Statistical Area. Inset map shows quadrangles completed or in progress as part of the VDMR-AASG-USGS STATEMAP Program.

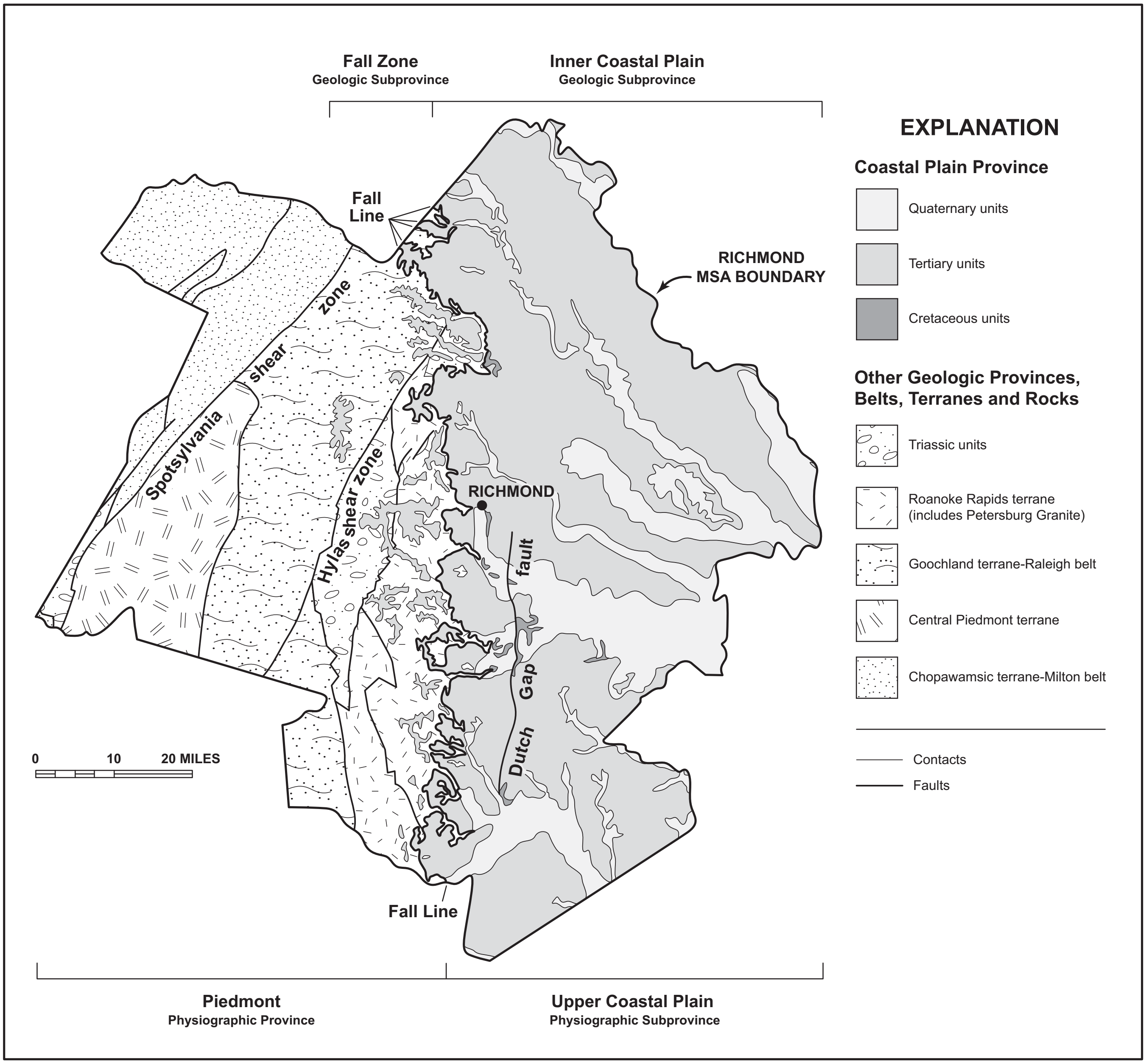


Figure 2. Geology and definitions of geologic and physiographic provinces and subprovinces in the Richmond Metropolitan Area. Geology compiled mostly from the Geologic Map of Virginia (Virginia Division of Mineral Resources, 1993). Other sources include: Bobyarchick and Glover (1979); Horton and others (1991); and Spears and others (2004). 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 Tertiary to Quaternary 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 (of the Coastal Plain physiographic province).

east of the Fall Line. In the Fall Zone, the lithology underlies (i.e., locally comprises the basal sections) high-level (250 to 350 feet above sea level), mid-level (200 to 250 feet above sea level) and low-level (140 to 160 feet above sea level) Tertiary clay, sand and gravel terraces. Feldspathic sand also occurs (as a singular lithology) in Quaternary to Tertiary alluvial and colluvial valley fill (channel fill and side slope) deposits.

Detailed mapping, modal analyses, and collection and compilation of geochemical data are providing a better understanding of this lithology, which is important because feldspathic sand poses particular environmental and land use issues in the Richmond area that should be considered by urban planners.

DESCRIPTION OF VARIABLY LITHIFIED PEBBLY FELDSPATHIC SAND

Regardless of the stratigraphic unit in which feldspathic sand occurs, the lithology is remarkably consistent in meso- and microscopic character and mineralogy. Mesoscopically, feldspathic sand is very light-gray to pinkish-gray fresh, but weathers 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, however, the matrix contains very few mica minerals, contains matrix-supported, sub- to well-rounded pebbles, and is typically very indurated to lithified (Figure 4). Feldspar in the matrix is variably weathered to clay, which, with hematite, carbonate and possibly 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 5). A clast-supported gravel lag deposit, up to about 1foot (0.3 meter) thick, typically occurs at the contact with the underlying granite (Figure 6) and is locally iron cemented. This lithology predominantly overlies Petersburg Granite along unconformable contacts (Figures 7 and 8).

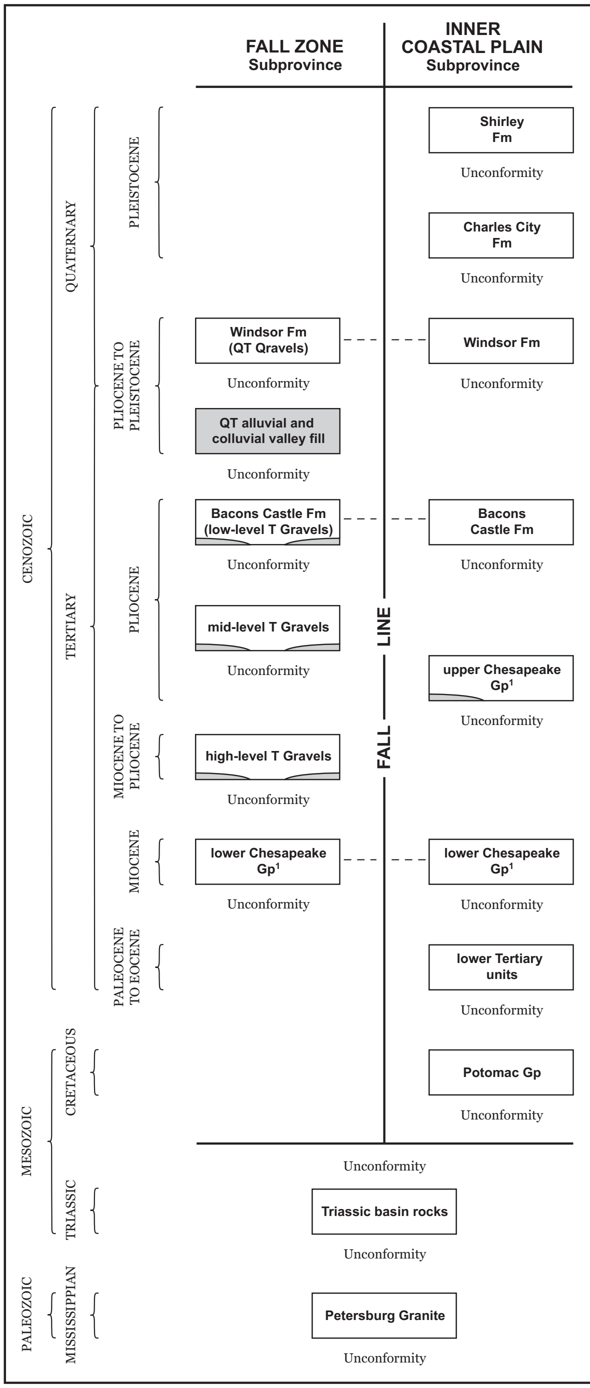
Primary sedimentary features hint at depositional mode – entrained matrix-supported clasts within feldspathic sand suggest high-energy depositional environments. Clast-supported gravel lags are more indicative of fluvial deposition. These observations suggest that pebbly feldspathic sands were deposited as periodic debris flows that mixed granite saprolite with reworked gravels from older or more distal units.

In thin section, a suite of four samples of lithified feldspathic sand averages about 44 percent quartz, 23 percent sericite and clay minerals, 18.5 percent hematite, 9 percent potassium feldspar, 3 percent plagioclase, 2 percent carbonate, and traces of biotite, muscovite (both as detrital grains) and ilmenite/magnetite (Table 1). Angular- to subangular quartz and feldspar grains in the matrix are cemented with clay minerals, hematite, carbonate and possibly authigenic silica. 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 strained quartz and feldspar, 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).

Lithification is a unique attribute of feldspathic sand. Lithification is variable, ranging from moderately- to completely indurated, but no correlation between lithification and stratigraphic position (Figure 3) has been observed. Some exposures show variable lithification within the outcrop (Figure 9), suggesting that induration may be a pedogenic process (i.e., hardpan). Underlying granite saprolite has never been observed to develop a hardpan. Both granite saprolite and feldspathic sand are very clay-rich from the chemical disintegration of feldspar, but lithified feldspathic sand also contains abundant hematite and some carbonate as cementing agents. Much additional work, beyond the scope of basic detailed geologic mapping, is needed to resolve the process of lithification in feldspathic sand.

GEOCHEMISTRY OF FELDSPATHIC SANDS

As part of the detailed geologic mapping regimen in the Richmond Metropolitan Statistical Area, lithologic samples are collected for geochemical analyses. The purpose is two-fold:



	DESCRIPTION OF UNITS
Shirley Fm	sand, gravel, silt and clay; morphology - 20 to 45 feet above sea level.
Charles City Fm	sand, silt and clay; morphology - 50 to 70 feet above sea level.
Windsor Fm	coarse gravel (containing *Skolithos*) and sand; equivalent to QT gravels in Fall Zone; morphology - 70 to 100 feet above sea level.
QT gravels	coarse gravel (containing *Skolithos*) and sand; equivalent to Windsor Fm in Inner Coastal Plain; morphology - 120 to 130 feet above sea level.
QT alluvial and colluvial valley fill	lithified feldspathic sand and gravel; morphology - deposits range from 140 to 290 feet above sea level in Fall Zone.
Bacons Castle Fm	coarse gravel (containing *Skolithos*) and sand; equivalent to low-level T gravels in Fall Zone; morphology - 100 to 170 feet above sea level.
low-level T gravels	coarse gravel (containing *Skolithos*) and sand; lithified feldspathic sand locally at base; equivalent to Bacons Castle Fm in Inner Coastal Plain; morphology - 140 to 160 feet above sea level.
mid-level T gravels	gravel and sand; lithified feldspathic sand locally at base; morphology - 200 to 250 feet above sea level in Fall Zone.
upper Chesapeake Group[1]	pea-gravel, sand and silty sand; lithified feldspathic sand at base along Fall Line; morphology - 100 to 240 feet above sea level.
high-level T gravels	gravel and sand; lithified feldspathic sand locally at base; morphology - 250 to 350 feet above sea level in Fall Zone.
lower Chesapeake Group[1]	silty clay; gravel base in Fall Zone; morphology - 50 to 100 feet above sea level in Inner Coastal Plain; 260 to 270 feet above sea level in Fall Zone.
lower Tertiary units	glauconitic sand and sandy silt; gravel at base; includes Aquia, Marlboro and Namjemoy Fms; morphology - 40 to 50 feet above sea level.
Potomac Gp	feldspathic sand, polymictic gravels and organic silty clay; morphology - below 40 feet above sea level.
Triassic basin rocks	arkosic sandstone, shale and coal.
Petersburg Granite	layered, foliated, porphyritic and subidiomorphic tonalite, granodiorite, granite and alkali-feldspar granite.

EXPLANATION OF SHADED AREAS WITHIN STRATIGRAPHIC COLUMN, ABOVE LEFT

Distribution of lithified pebbly feldspathic sand within regional stratigraphic units of the Fall Zone and Inner Coastal Plain

Figure 3. Stratigraphy, correlation and brief description of Coastal Plain units across the Fall Line (dashed line denotes equivalency of units across the Fall Line). Coastal Plain units rest unconformably above Triassic 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. No detailed sedimentology or paleontologic studies have been conducted to confidently subdivide these lower Chesapeake Group formations in this area.

Figure 4. Lithified pebbly feldspathic sand at the base of the upper Chesapeake Group along a tributary of Reedy Creek, southeastern quadrant of the Bon Air quadrangle (37.5079°N, -77.5162°W, NAD 27). Erosion and entrenching through lithified feldspathic sand creates creeks with steep walls. Shovel is approximately 3.5 feet (1 meter) long.

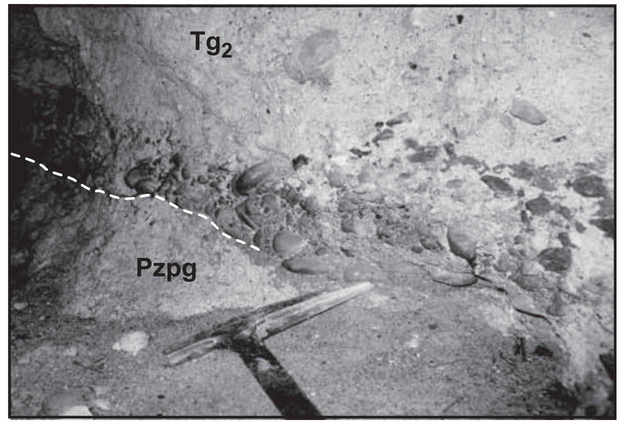

Figure 6. Basal gravel and lithified pebbly feldspathic sand of basal mid-level Tertiary gravels in a tributary of Upham Brook, northeastern quadrant of the Bon Air quadrangle (37.6028°N, -77.5229°W, NAD 27). Petersburg Granite (Pzpg), left and above hammerhead, underlies gravel lag along the contact shown by a thin dashed line. Hammerhead is about 8 inches (20 centimeters) long.

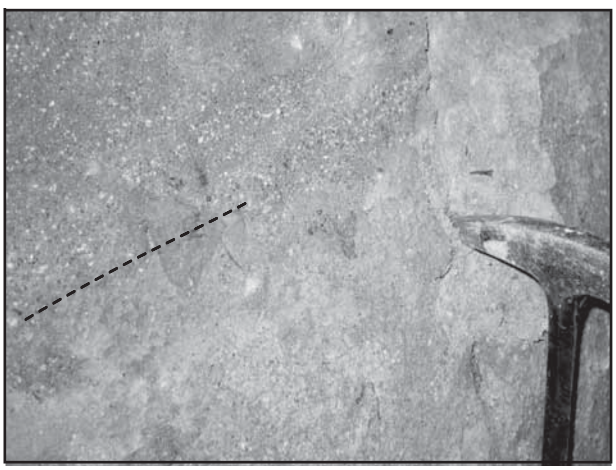

Figure 5. Bedded lithified pebbly feldspathic sand of basal mid-level Tertiary gravels on the campus of the University of Richmond, central quadrant of the Bon Air quadrangle (37.5724°N, -77.5440°W, NAD 27). Bedding is marked by a thin dashed line in the photograph, and dips approximately 11°NW toward the James River. Hammerhead is about 8 inches (20 centimeters) long.

Figure 7. Basal lithified feldspathic sand of low-level Tertiary gravels on the south bank of the James River, central western quadrant of the Bon Air quadrangle (37.5525°N, -77.6134°W, NAD 27). Unconformable contact with underlying Petersburg Granite is buried beneath colluvium in the lower half of the photograph. Visible part of hammer in the photograph is about 8 inches (20 centimeters) long.

1) to populate and compile geochemical signatures of all lithologies from established map units in the region; and 2) to aid geologic mapping by comparing geochemical data from established units with newly identified units or lithologies. These comparisons are not meant to be exhaustive investigations, but rather are simplistic graphical presentations (Harker diagrams and spider graphs) of geochemistry, from which to draw some basic and very general conclusions.

To better understand the characteristics of lithification, geochemistry of hard rock granite, granite saprolite, and feldspathic sand was compared for this project. Geochemistry of several feldspathic sand samples was also compared with Inner

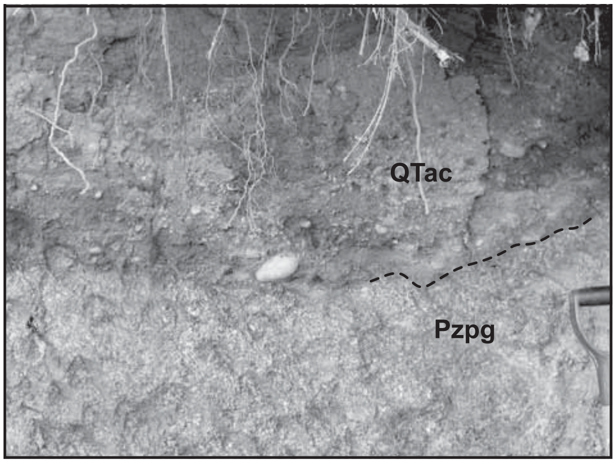

Figure 8. Lithified feldspathic sand and gravel of one of many Quaternary-Tertiary alluvial and colluvial valley fill deposits (QTac), unconformably resting on Petersburg Granite (Pzpg), on the Bon Air and Chesterfield quadrangles. This outcrop is south of the James River in the central quadrant of the Bon Air quadrangle (37.5439°N, -77.5580°W, NAD 27). A thin dashed line in the photograph marks the contact between the units. Visible part of shovel handle in the photograph is about 1 foot (30 centimeters) long.

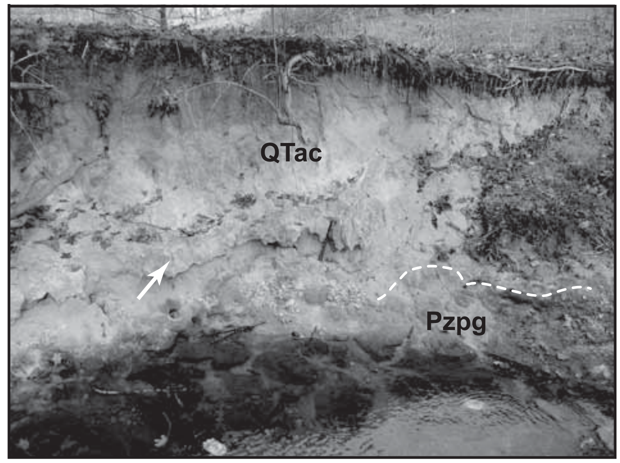

Figure 9. Variably lithified feldspathic sand in a Quaternary-Tertiary alluvial and colluvial valley fill deposit exposed along a tributary of Deep Run, northwestern quadrant of the Bon Air quadrangle (37.6095°N, -77.5858°W, NAD 27). A thin dashed line in the photograph marks the contact between Quaternary-Tertiary alluvium and colluvium (QTac) above Petersburg Granite (Pzpg). Arrow marks a zone of highly lithified feldspathic sand. Hammer is approximately 15 inches (38 centimeters) long.

Coastal Plain sediments and Triassic rocks in the region. Results of this effort are presented in Figures 10-13.

Figure 10 presents comparative geochemical changes between hard rock granite and saprolite. At similar SiO_2 weight percent, saprolite is depleted in soluble Na_2O, CaO and P_2O_5, as expected, but generally enriched in trace and rare earth elements. These data are consistent with published results from geochemical studies of saprolite derived from rock types similar to the Petersburg Granite (Islam and others, 2002; O'Beirne-Ryan and Zentilli, 2006). Figure 11 presents comparative geochemical changes between saprolite and feldspathic sand samples. As SiO_2 weight percent increases, feldspathic sand is depleted in aluminum and other metals (iron, manganese, magnesium, and titanium – presumably these are readily leached out of the system early in the process of physical separation of sand grains from the source material); sodium, calcium and phosphorous remain relatively constant. Feldspathic sand is consistently depleted in trace and rare earth elements.

Figure 12 compares geochemical suites of feldspathic sand from each of the stratigraphic units in which the lithology occurs. Of note is that most Quaternary to Tertiary alluvial and colluvial valley fill deposits (and to a lesser extent feldspathic sand at the base of mid-level Tertiary gravels) are separate from feldspathic sand at the bases of high-level Tertiary gravels and the upper Chesapeake Group near the Fall Line (compare particularly K_2O versus SiO_2 .). These samples also consistently plot nearer to granite saprolite samples, and are presumably closely related. Also, at similar SiO_2 weight percent, feldspathic sand at the base the upper Chesapeake Group near the Fall Line is consistently enriched in metals (iron, manganese, magnesium, and titanium) than other feldspathic sand suites. This may be the result of leaching from sediments higher in the unit into the basal feldspathic sand.

Lastly, comparison of feldspathic sand samples to sediments from regional stratigraphic units reveal additional trends (Figure 13). For example, a limited suite of upper Chesapeake Group samples from the Seven Pines quadrangle, approximately 14 miles (23 kilometers) east of the Fall Line, are consistently more "mature" in major elements (notably aluminum) than feldspathic sand from the base of the upper Chesapeake Group near the Fall Line on the Bon Air quadrangle. This may be attributed to depositional environment. Weathered granite may have contributed abundant immature sediment

Table 1. Modes (calculated from 200 point counts per thin section) of Tertiary to Quaternary lithified feldspathic sand samples. Samples of Triassic and Cretaceous rocks are also provided for comparison. Map unit abbreviations: TRns – Triassic Newark Supergroup; K – Cretaceous; QTac – Quaternary-Tertiary alluvial and colluvial valley fill deposits; Tg_2 – mid-level Tertiary gravels. Latitude/Longitude coordinates in NAD 27.

SAMPLE	MAP UNIT	QUADRANGLE	LATITUDE	LONGTITUDE	Quartz	Plagioclase	K-spar	Biotite	Muscovite	Chlorite	Sericite/ Clay Minerals	Hematite	Zircon	Ilmenite/ Magnetite	Epidote	Carbonate
9970	QTac	Bon Air	37.6100	-77.5861	41.5	3	6				23	22.5		0.5		3.5
9956	Tg_2	Bon Air	37.5791	-77.5585	51	4.5	10.5	trace	trace		30.5	3.5				
9969	Tg_2	Bon Air	37.6230	-77.6121	52	2	6.5	trace			14.5	22.5		trace		2.5
9971	Tg_2	Bon Air	37.5763	-77.6061	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	11.5	trace	trace		
9972	TRns	Bon Air	37.6153	-77.6124	53.5	5.5	17.5	3	Trace	Trace	18.5	Trace	Trace	Trace	1	

SAMPLE	MAP UNIT	THIN SECTION DESCRIPTIONS
9970	QTac	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 quartz-feldspar granite). Few large hematite concretions; cores appear to be mostly clay minerals.
9956	Tg_2	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 appears to be dissaggregated granite.
9969	Tg_2	Subangular to angular grains of quartz (strained) and feldspar, few composite grains (foliated metamorphic quartz and quartz-feldspar granite), 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 show hematitic weathering rind.
9971	Tg_2	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	K	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	TRns	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 and epidote (from feldspar) and chlorite (after biotite) are alteration phases. Very similar to lithified feldspathic sand sections; sample appears to be disaggregated granite.

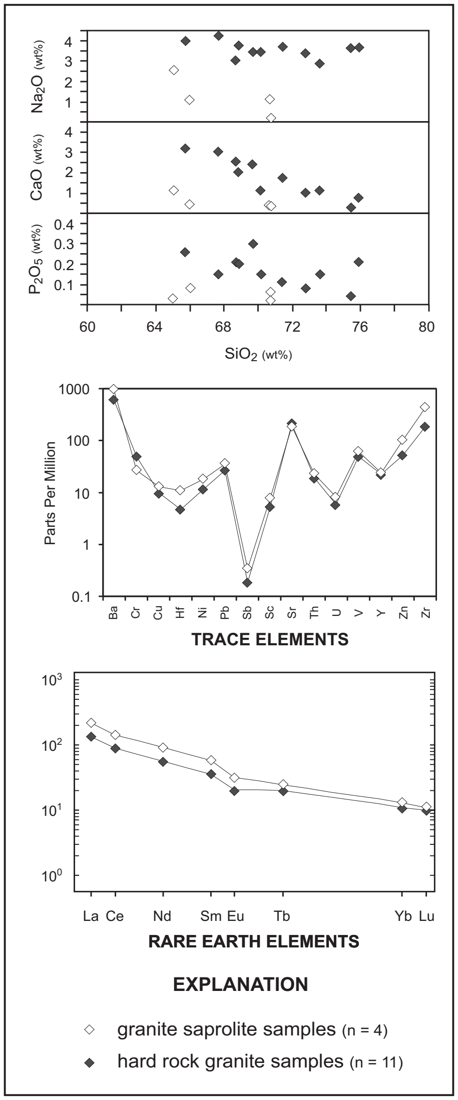

Figure 10. Major and minor element Harker diagrams, and trace and rare earth element spider graphs for samples of hard rock and saprolitic Petersburg Granite, showing geochemical changes between hard rock granite and granite saprolite. Values for trace and rare earth elements in spider graphs are averages; error bars not shown for clarity. 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).

to the thin westernmost edge of the upper Chesapeake Group near the Fall Line, whereas thicker upper Chesapeake Group sediments farther east were multiply reworked (i.e., quartz was concentrated as clays were winnowed out of the sediments) in the shallow marine depositional environment.

Other observed trends include the disparate

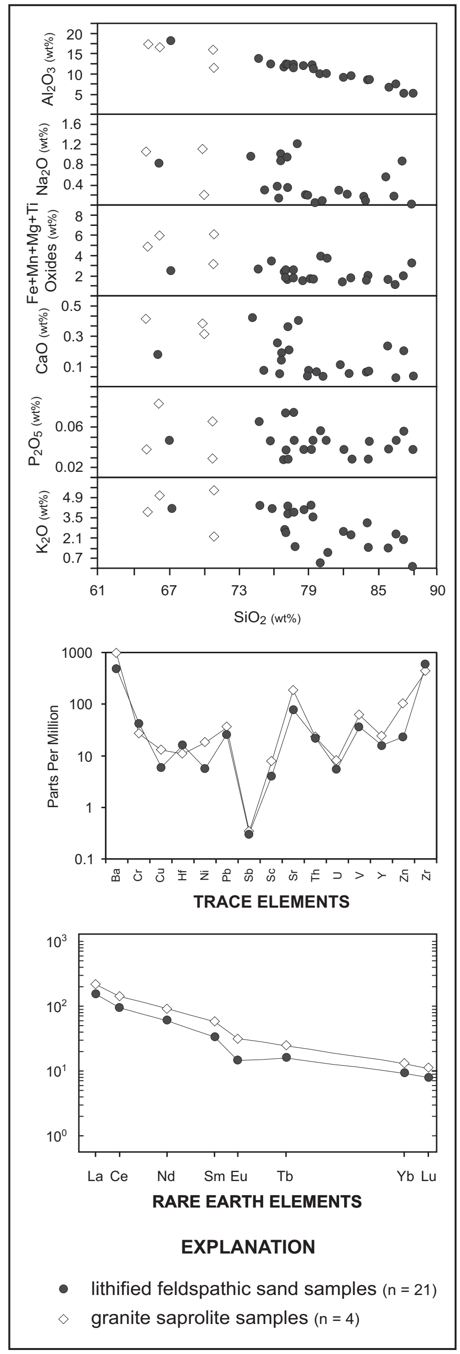

Figure 11. Major and minor element Harker diagrams, and trace and rare earth element spider graphs for Petersburg Granite saprolite and feldspathic sand samples, showing geochemical changes between granite saprolite and feldspathic sand. Values for trace and rare earth elements in spider graphs are averages; error bars not shown for clarity. 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).

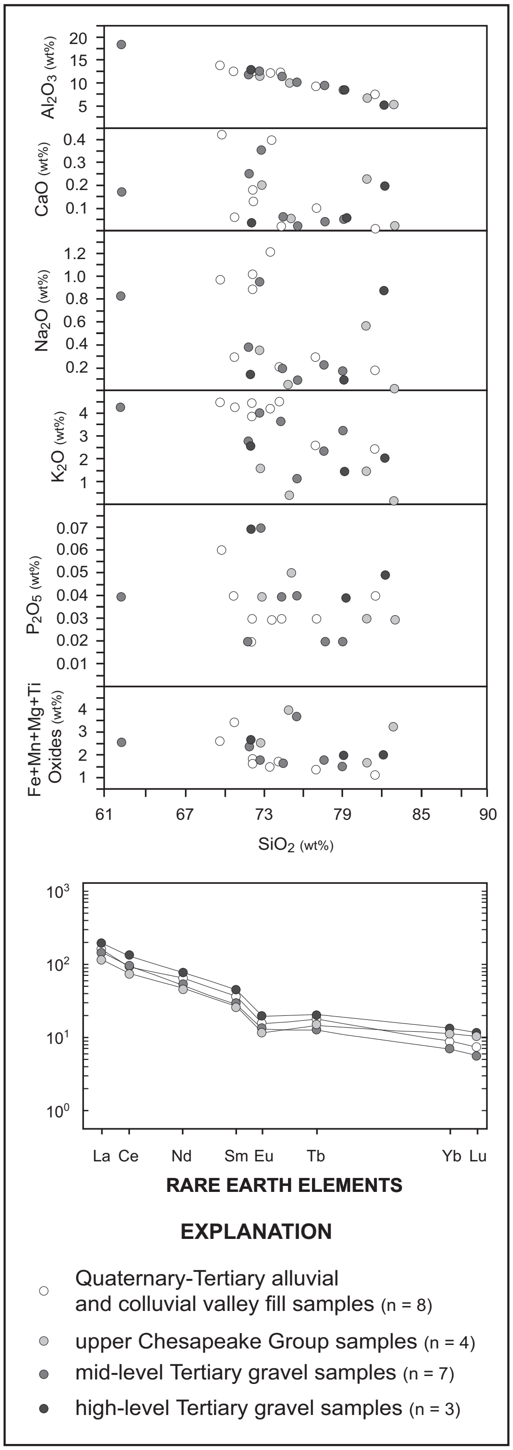

Figure 12. Major and minor element Harker diagrams and rare earth element spider graph for feldspathic sand samples, showing differences in geochemical signatures. Values for rare earth elements in spider graph are averages; error bars not shown for clarity. Spider graph created using PetroGraph, version 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).

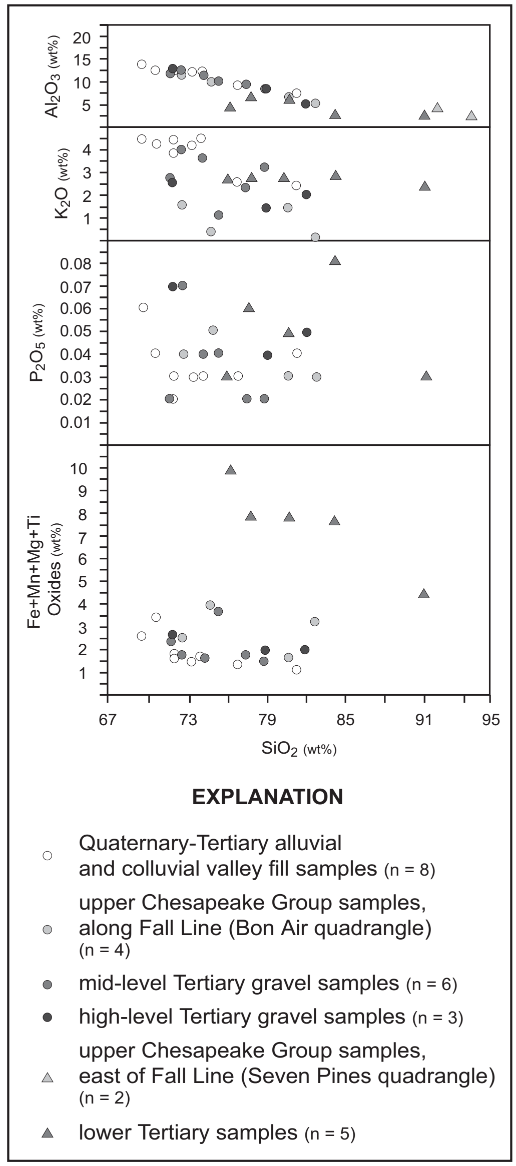

Figure 13. Major and minor element Harker diagrams for samples of feldspathic sand, upper Chesapeake Group sediments east of Fall Line (Seven Pines quadrangle) and lower Tertiary sediments, showing differences in geochemical signatures.

grouping of samples of lower Tertiary sediments (Aquia and Nanjemoy Formations) in aluminum, other metals (iron, manganese, magnesium, and titanium) and phosphorous from feldspathic sand suites. This is likely caused by abundant iron-rich, but aluminum-poor, glauconite and phosphate in lower Tertiary sediments (albeit potassium in these samples shows no such separation).

DISCUSSION

Goodwin (1980, 1981) recognized a gradational sequence from Petersburg Granite to "reworked saprolite" to high-level Tertiary gravels on the Bon Air and Glen Allen quadrangles. He described the transitional lithology as granite saprolite, with a few scattered rounded quartz pebbles.

The U.S. Department of Agriculture, Natural Resources Conservation Service (2004, 2006) also identifies soils developed on this unique lithology. Soils of the Pouncey Series are defined as:

> "grayish brown to light brownish gray sandy loam with few rounded quartz pebbles and gray clay loam, above light to dark gray, extremely hard, weakly cemented sandstone. Pouncey soils occur on upland flats or depressions and along intermittent drainageways. The slopes are generally concave with gradients of 0 to 2 percent and range from about 0 to 4 percent. These soils formed in a 20 to 40 inches thick mantle of fluvial materials over extremely hard sandstone. Although the upper 2 to 4 inches of the material described as sandstone bedrock have some characteristics of a fragipan, the material as a whole is considered to be more geologic in origin than pedogenic. The material designated as sandstone bedrock may rest directly on the underlying granitic rocks, or it may be underlain by sandy and gravelly materials with granitic bedrock at 5 to 10 feet, or by cemented sands and gravels, or by clay with sand and gravel at about 6 feet."

The type location of the Pouncey Soil Series is near the intersection of Pouncey Tract Road (State Route 271) and Shady Grove Road, Glen Allen quadrangle (37.6718°N, -77.6126°W, NAD 27). Goodwin (1981) shows this locality to be at the contact between high-level Tertiary gravels and Petersburg Granite.

Goodwin's "reworked saprolite" and "sandstone" bedrock of the Pouncey Soil Series has been recognized during current work in the Richmond area as variably lithified pebbly feldspathic sand. This lithology is not specific to a single regional stratigraphic map unit. Feldspathic sand has been observed at the base of high-, mid- and low-level Tertiary gravels in the Fall Zone, and within basal sections of upper Chesapeake Group sediments just east of the Fall Line. Feldspathic sand has also been identified as the singular lithology in Quaternary to Tertiary alluvial and colluvial valley fill deposits.

These Quaternary to Tertiary alluvial and colluvial valley fill deposits 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., high-, mid- and low-level Tertiary gravels) or underlying broad, relatively flat topographic surfaces (i.e., upper Chesapeake Group sediments). The paucity of paleontologic data requires that new mapping and analytical methods, notably modal and geochemical comparisons, provide temporal correlations between these deposits with well-defined Tertiary gravel stratigraphy in the Fall Zone and Inner Coastal Plain units to the east.

Variable lithification distinguishes Quaternary to Tertiary alluvial and colluvial valley fill deposits from younger (late Pleistocene to Holocene) surficial alluvium; the deposits are also generally higher in elevation than surficial alluvium. Modal analyses (Table 1) distinguish them from Triassic sandstone, which contains chlorite and epidote as low-grade metamorphic alteration phases. Likewise, clast composition separates them from Cretaceous sediments (cretaceous polymict conglomerates contain volcanic clasts, and the trace fossil *Skolithos* are absent in quartzite clasts, in contrast to arkosic conglomerates, which contain no volcanic clasts, and many *Skolithos*-bearing quartzite clasts). Geochemical comparisons (Figure 12) suggest an association with mid-level Tertiary gravels. Thus, there is reasonable circumstantial evidence to suggest that these deposits are late Tertiary (Pliocene) to Quaternary (early Pleistocene) in age. Continued mapping in the Richmond area will test the hypothesis and should provide additional samples for analysis.

ENVIRONMENTAL AND LAND USE ISSUES

Lithified feldspathic sand contributes to several serious land use and environmental issues in the Richmond area. For example, lithification makes feldspathic sand much more difficult and expensive to excavate than "soft" granite saprolite or unlithified Coastal Plain sediments. Construction in lithified feldspathic sand-bearing units may experience significant time and monetary setbacks if not properly planned for in advance.

Landslides in the Richmond area can cause millions of dollars in property damage and loss of life with each passing tropical storm (Ress, 2004). 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 14). In the western part of the Richmond area, contacts between lithified feldspathic sand and overlying unconsolidated sands and gravels, or feldspathic sand and underlying granite, were the primary locus for small landslides, probably as sands and gravels above the less permeable contacts became oversaturated from the intense rainfalls of the storms (Figure 15). 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 lithified feldspathic sand. Mapping demonstrates that jointing is common in both crystalline rocks of the Petersburg Granite and in lithified feldspathic sand. Although traditionally surmised to be desiccation features, joints in Coastal Plain units in the Richmond area follow distinct trends, some of which parallel sets in the underlying granite (Figure 16). Many streams and other topographic lineaments are similarly oriented to joint sets in lithified feldspathic sand and Petersburg Granite, and likely influenced their morphologic patterns (Carter and others, 2006). Similar joints have been mapped elsewhere in the southern Atlantic Coastal Plain of South Carolina and Georgia (e.g., Wyatt and Temples, 1996). Many of the Isabel- and Gaston-induced landslides throughout the west Richmond area failed along joint and fracture systems parallel to the scarp face (Figure 14). High potential exists for future failures in areas where lithified feldspathic sand-bearing units outcrop along streams and side slopes parallel

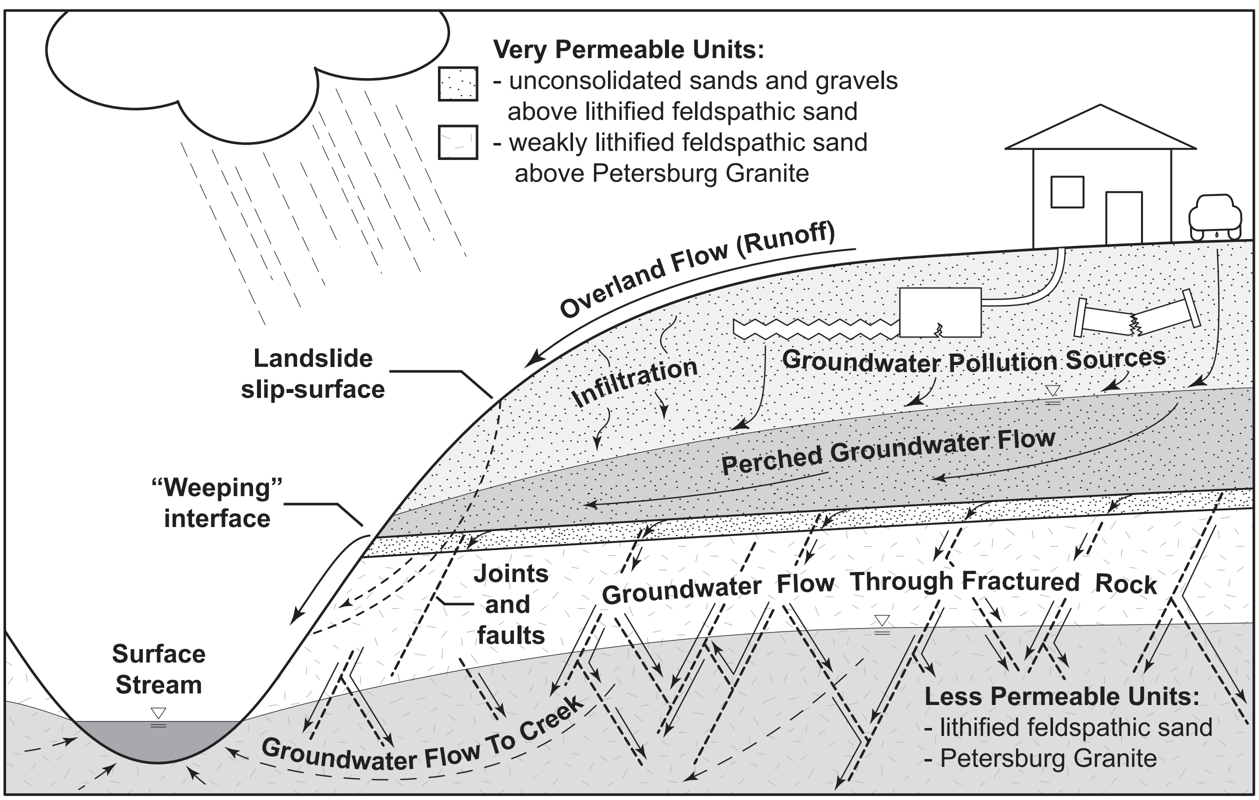

Figure 14. Model for many of the environmental and geologic hazards in the Richmond area. Perched groundwater tables in permeable units become polluted from failing septic systems, broken sewer pipes, surface runoff and other causes, and leak into surface streams along the daylighted interface with underlying 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 within the stratigraphic pile, at or very near this interface.

to these regional joint trends.

The permeability contrast that helped create the landslides during Tropical Depression Gaston may also complicate the shallow groundwater flow system during ordinary time. Based on observations during new mapping, lithified feldspathic sand may act as a local aquitard during normal flow conditions, perching groundwater in recharge areas and increasing the rate of interflow (Figure 14). 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.

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Figure 15. Photograph of a small landslide exposing feldspathic sand at the base of Tertiary low-level gravels along Pocoshock Creek, northwestern quadrant of the Chesterfield quadrangle (37.4945°N, -77.5867°W, NAD 27). Arrow (far right, in the background) marks the contact between bedded feldspathic sand and underlying Petersburg Granite. Continued failure here (notice post-failure colluviation of the scarp face in the foreground) will threaten several homes just up the slope above the scarp (undercutting by the stream during high-flow storm events also contributes to continual failure here). Long edge of field book is about 7.5 inches (19 centimeters) long.

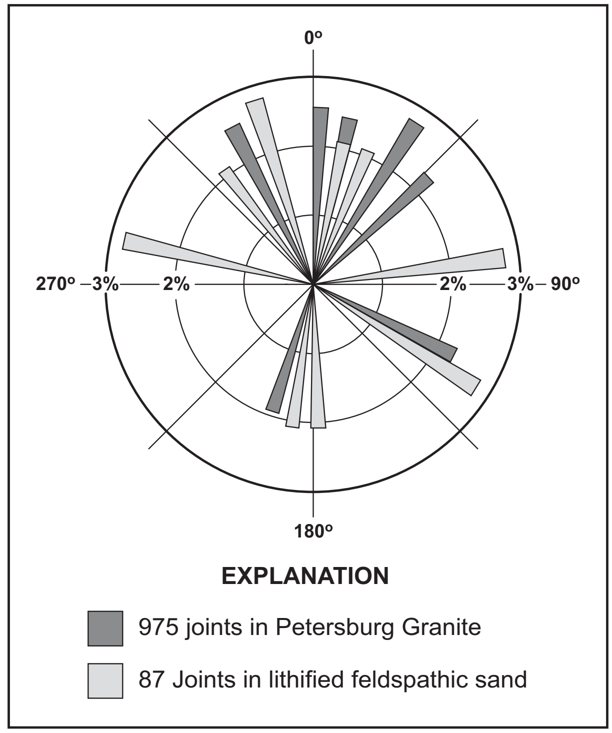

Figure 16. Unidirectional rose diagram of joints in Petersburg Granite and lithified feldspathic sands. The rose diagram was created using Stereonet For Windows, version 1.1.6, by Richard Allmendinger, Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York. Petals are defined by 5-degree increments. Only the largest petals are shown to reduce scatter.

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