GEOCHEMICAL DATABASE WITH GENERALIZED INTERPRETATION FOR IGNEOUS ROCKS FROM THE CENTRAL APPALACHIANS OF VIRGINIA, MARYLAND, AND PENNSYLVANIA

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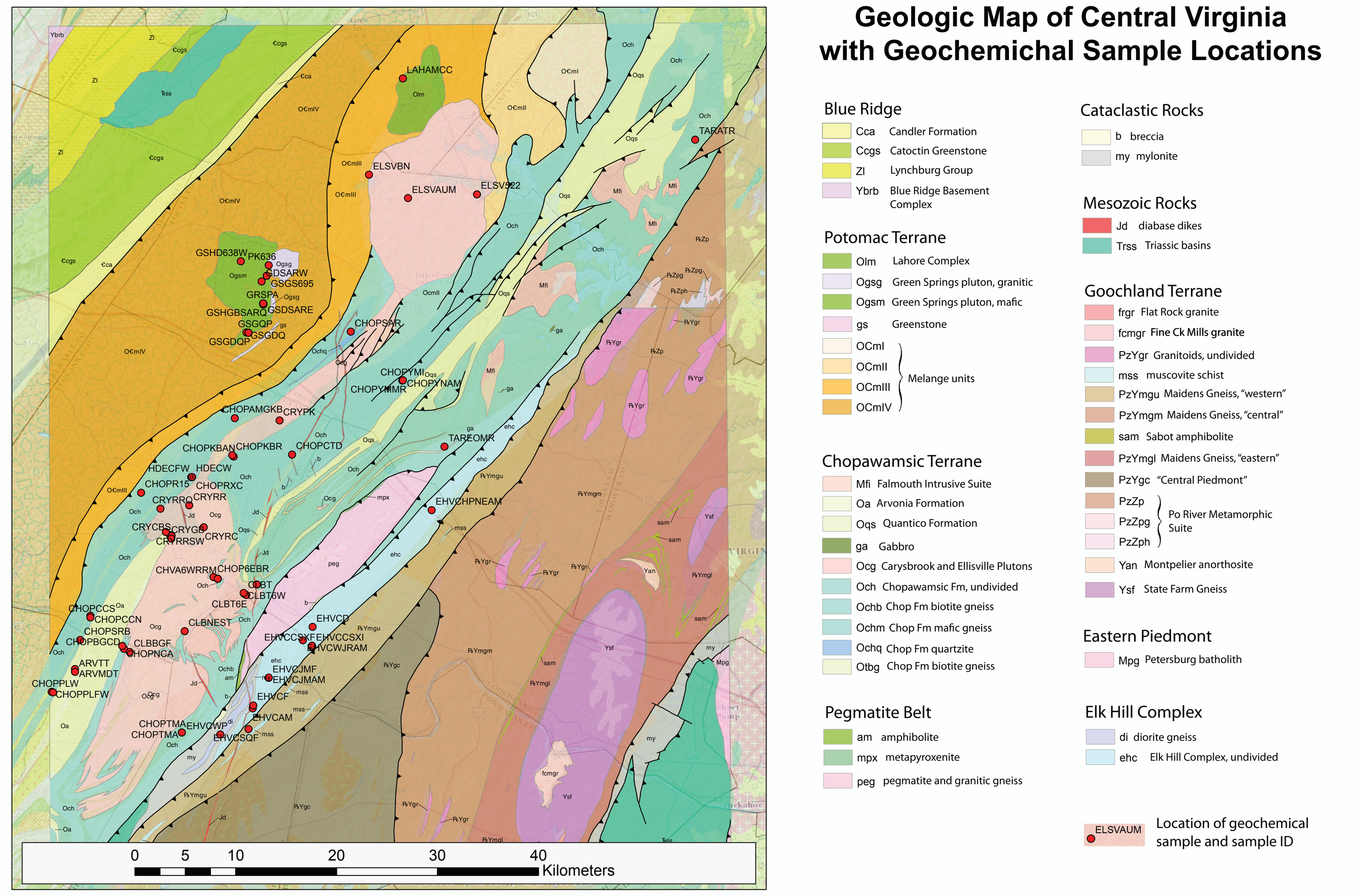
ABSTRACT

When used with field observations, chemical compositions of igneous rocks provide information about the tectonic settings in which the rocks formed. Geochemical analyses of ~120 pristine to metamorphosed plutonic and volcanic rocks from the Central Appalachians are being organized for release by the VA DMME. Much of the sampling was done by the senior author and co-worker Vik W. Skema in search of a plutonic source for glaciogenic cobbles of island arc affinity in the Rockwell Formation of PA, MD, and WV. Units to be included in the release are: Carysbrook (8 samples), Catoctin (1), Chopawamsic (26), Columbia (5), Elk Hill Volcanic Complex (14), Ellisville (4), "Eocene" (8), "Evergreen Church" (2), Gold Vein (1), Lahore (2) Leatherwood (3), Occoquan (1), "Mt. Hermon Pyroclasts" (3), Ordovician pyroclastics (2), Poore Creek (2), Green Springs (7), Milton (3), Mount Rogers (7), Rich Acres (1), Robertson River Igneous Suite (6), Ta River (3), and U.S.G.S. Reference samples (3).

Preliminary observations suggest that the Chopawamsic (CP) of VA and James Run (JR) of MD include a range of compositions from basalt to rhyolite, but that the JR contains fewer mafic rocks. Similarly, no samples of JR contain ≤ 0.05 ppm Ta, but 12 samples of the CP do. Hence, the subduction zone for the JR arcs may have had a more outboard, i.e., oceanic interaction overall despite evidence of local Grenvillian contamination of the CP near its western margin. The Elk Hill Volcanic Complex (EHVC) is more bimodal than the CP or JR, with compositions clustering around basalt and rhyolite. It has an arc signature including both back arc N- and E-OFBs. One 21-cm-wide felsic dike at the type locality crosscuts folded compositional layering. The tightly clustered adakitic Carysbrook granodiorite and more variable Ellisville granite-granodiorite are related. The Columbia granitic gneiss is not adakitic and does not appear to be geochemically related to either the Carysbrook or the Ellisville plutons. The Rowlandsville pluton of MD ranges from granite to diorite and some samples are very similar to the Carysbrook except for the Rowlandsville not being adakitic. However, ongoing studies of the Green Springs-Poore Creek plutons indicate that they are parts of a single differentiation series in which the felsic samples are adakitic, but not the mafic ones.

Geologic Map of Central Virginia with Geochemical Sample Locations

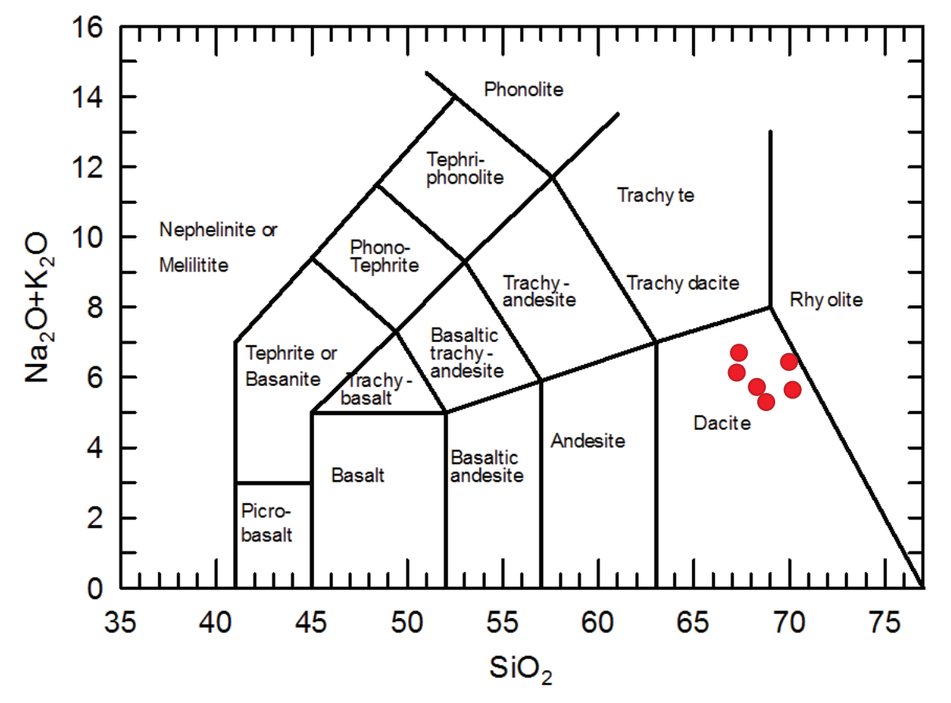


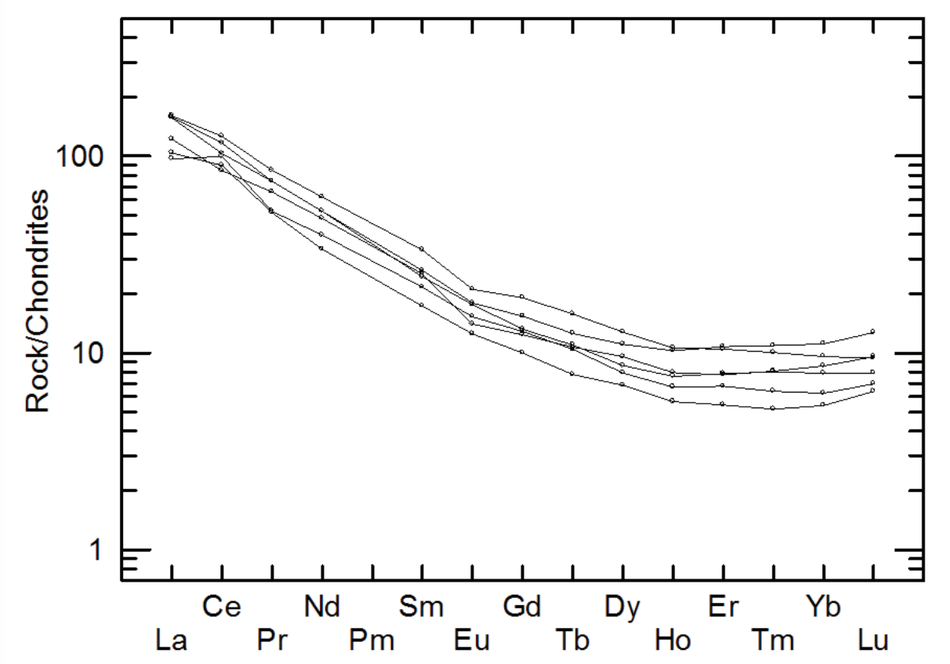
CARYSBROOK GRANODIORITE

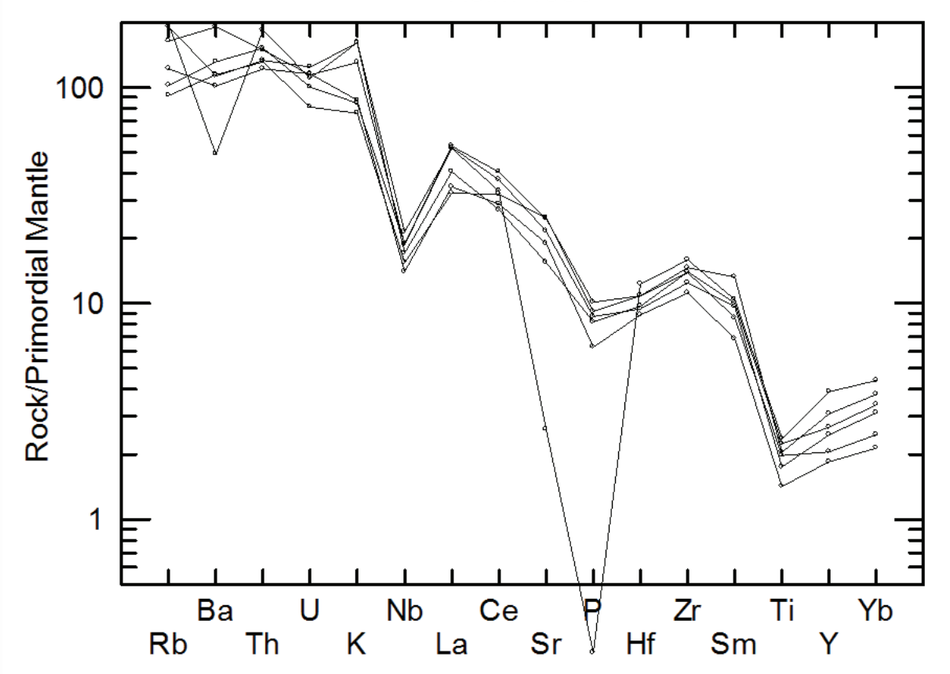
The Carysbrook granodiorite of Stose and Stose (1948) is located in Fluvanna County, VA. It is closely related to the "narrow neck or tail" connecting the Carysbrook Pluton with the Ellisville Pluton proper to the north (Hughes et al., 2013).

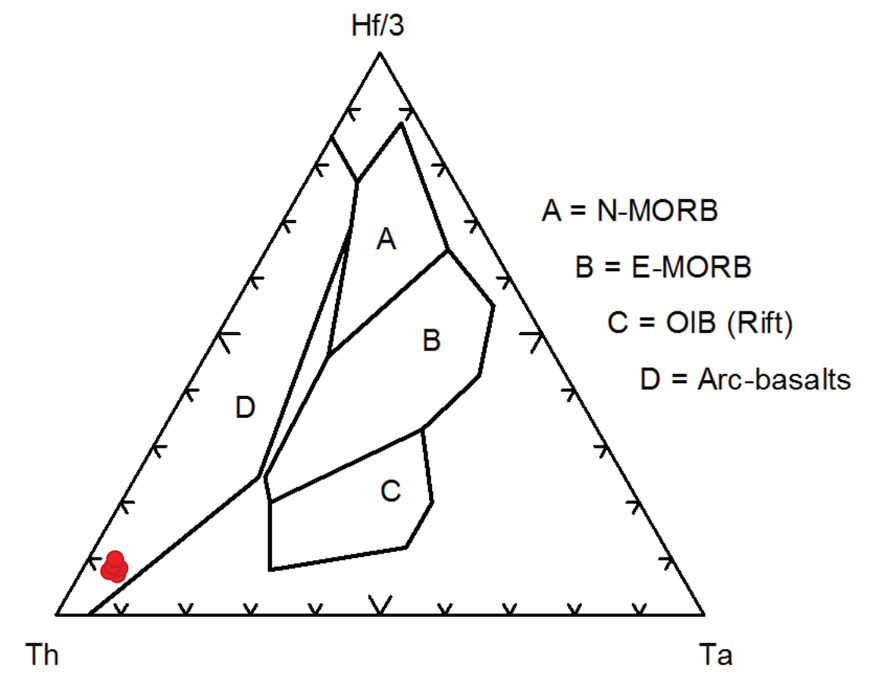
- Typically very uniform felsic granodiorite (dacite) based on Total Alkalies vs. Silica.
- The REE pattern has a negative slope with little or no negative Eu anomaly.
- It is a volcanic arc granite (VAG based on Y + Nb vs. Rb), but slightly closer to SYNCOLLISIONAL than the Columbia Gneiss.
- Five samples are adakitic (Sr/Y vs. Y) and two are not, perhaps due to alteration.
- It is literally connected to the "narrow neck" and more compositionally variable Ellisville Pluton to north (Hughes et al., 2013).
- U-Pb zircon SIMS age of 444 ± 11 Ma (1σ) for Carysbrook Pluton, probably from E. bank Rivanna River near VA 615 bridge (Sinha et al., 2012).
- U-Pb zircon SIMS ages of 444 ± 6 Ma and 440.9 ± 3 Ma (1σ, Wilson, 2001 and Sinha et al., 2010, respectively) for Ellisville Pluton. U-Pb zircon TIMS age of 433, $^{40}Ar/^{39}Ar$ age of 441 ± 2 Ma on amphibole, and 441 ± 8 Ma Rb/Sr isochron (Pavlides 1994). The medium-grained main phase "Narrow Neck" of Ellisville and the fine-grained main body of Ellisville yielded U-Pb zircon TIMS ages of 443.7 ± 4.4 (2σ) and 436.8 ± 4.2 (2σ) respectively (Hughes et al., 2013).
- In the abandoned railroad cut 1km SSW of Carysbrook, Fluvanna County, the upper contact of the Carysbrook is overlain by a 1-pebble thick conglomerate at the base of a 3-m thick sandstone at the base of the Arvonia Formation slate. The Carysbrook here has been depleted of the mobile elements CaO, Na_2O, P_2O_5, Sr, and S, but not of the immobile, incompatible elements. We cannot rule out that at this locality and nearby on VA 672 0.1 km W of US Route 15, it is hypabyssal or even a pyroclastic phase.

Unconformity at the top of the Carysbrook Pluton. Railroad cut 1 km SSW of Carysbrook, VA.







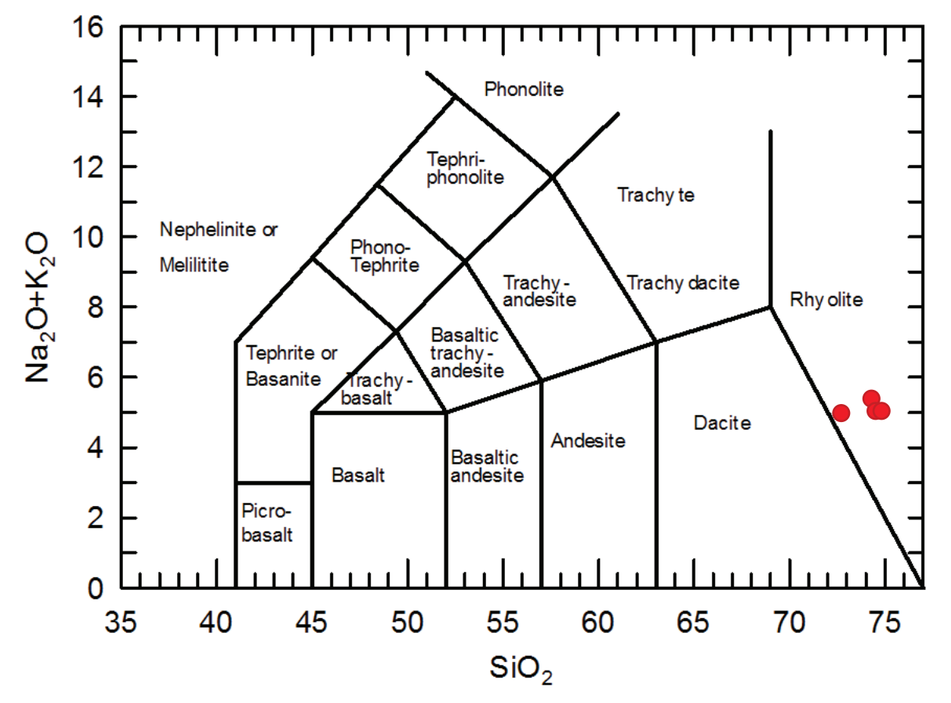


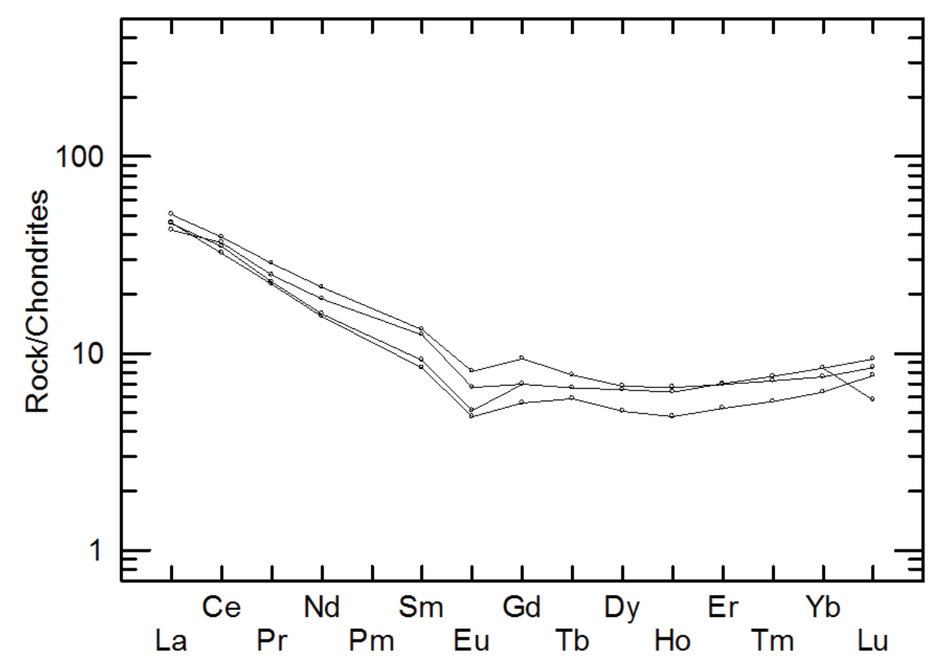
COLUMBIA GRANITIC GNEISS

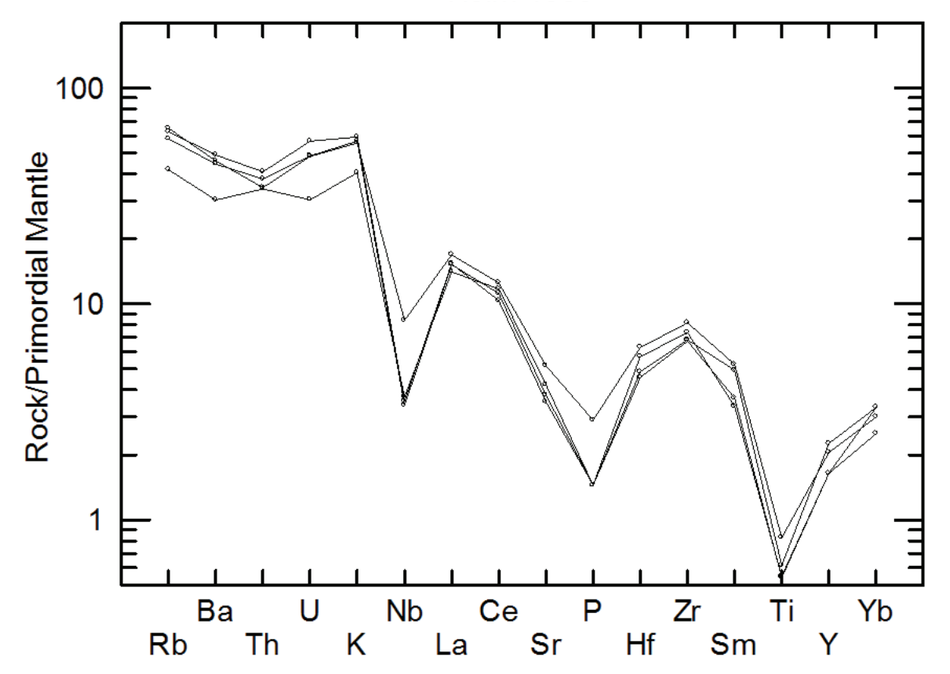
The Columbia Granite of Jonas (1928) has an established type locality, the Cowherd Quarry on the eastern edge of Columbia, Fluvanna and Goochland Counties, VA. The Columbia Granitic Gneiss has been previously conflated with the distinctly adakitic Carysbrook Granodiorite to the west. The Columbia Granitic Gneiss has been metamorphosed and almandine-spessartine dodecahedra are typically visible with a hand lens.

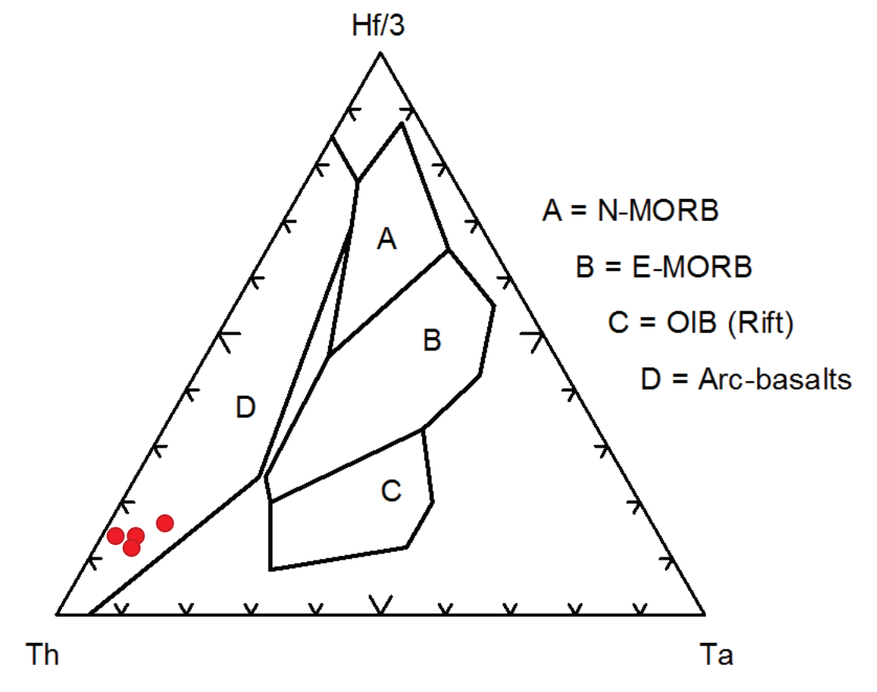
- The Columbia Granitic Gneiss is a moderately uniform granite (rhyolite) composition based on Total Alkalies vs. Silica.
- The REE pattern has a negative slope and a small negative Eu anomaly.
- It is a volcanic arc granite (VAG) based on Y + Nb vs. Rb.
- No samples show an adakitic signature based on Sr/Y vs. Y.
- It is very distinct geochemically from the adakitic Carysbrook Granodiorite and its closely related kin to the north, the connecting "Narrow Neck" and Ellisville Pluton proper of Hughes et al. (2013).
- It is somewhat distinct geochemically from the more alkali-rich "Western Columbia" dimension stone quarries of Mose and Nagel (1982). Sample CLBNEST has a much larger negative Eu anomaly.
- U-Pb zircon SIMS age of 457 ± 7 (1σ) has been reported for the type locality by Wilson (2001).
- It intrudes the Chopawamsic Formation east of New Canton, Buckingham County. An additional sample (CLB6EBR) from 3 km NW of Columbia, Fluvanna County, may be a hybrid between Columbia Granitic Gneiss and Chopawamsic volcanics.

Columbia granitic gneiss at its type locality, Cowherd Quarry, Columbia, VA.





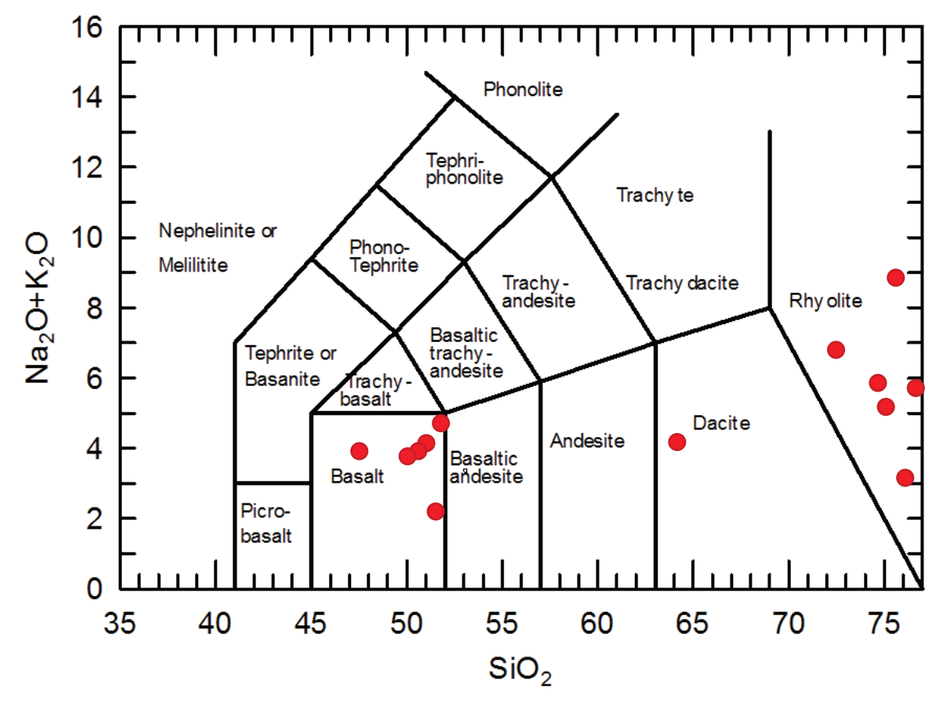


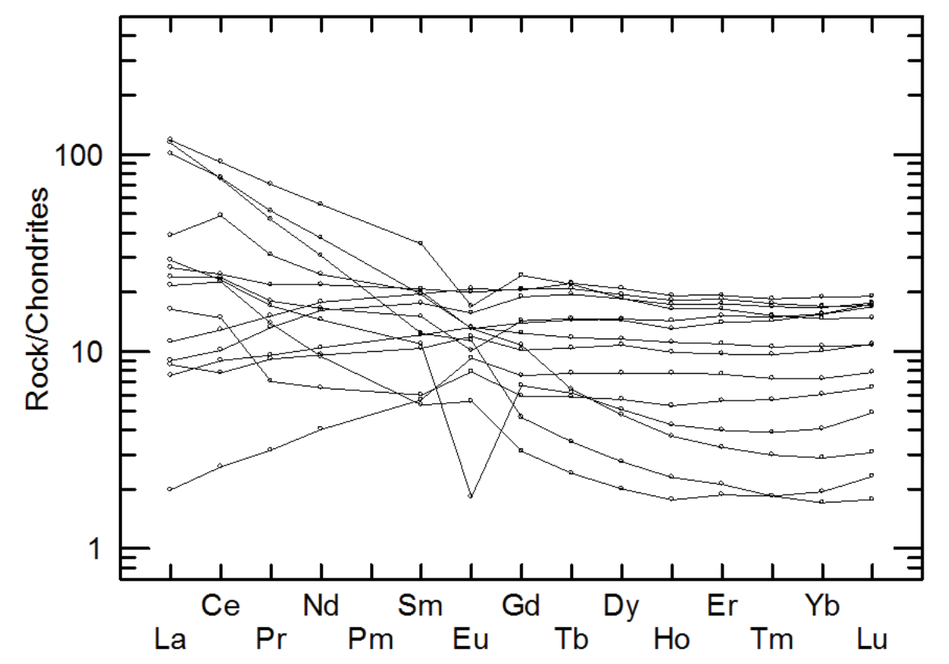


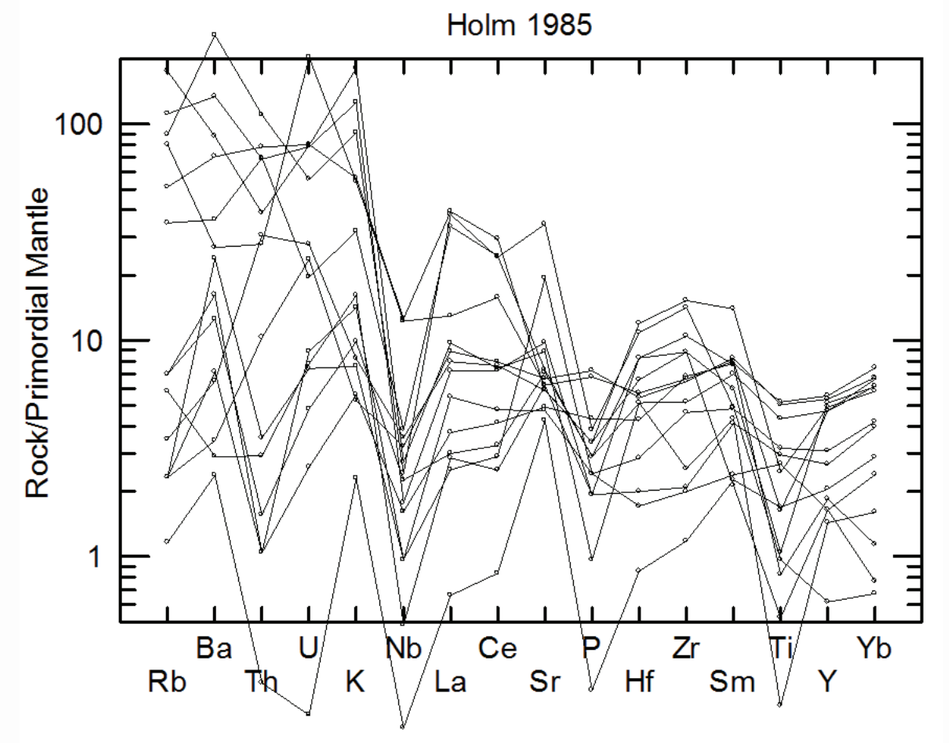
ELK HILL VOLCANIC COMPLEX

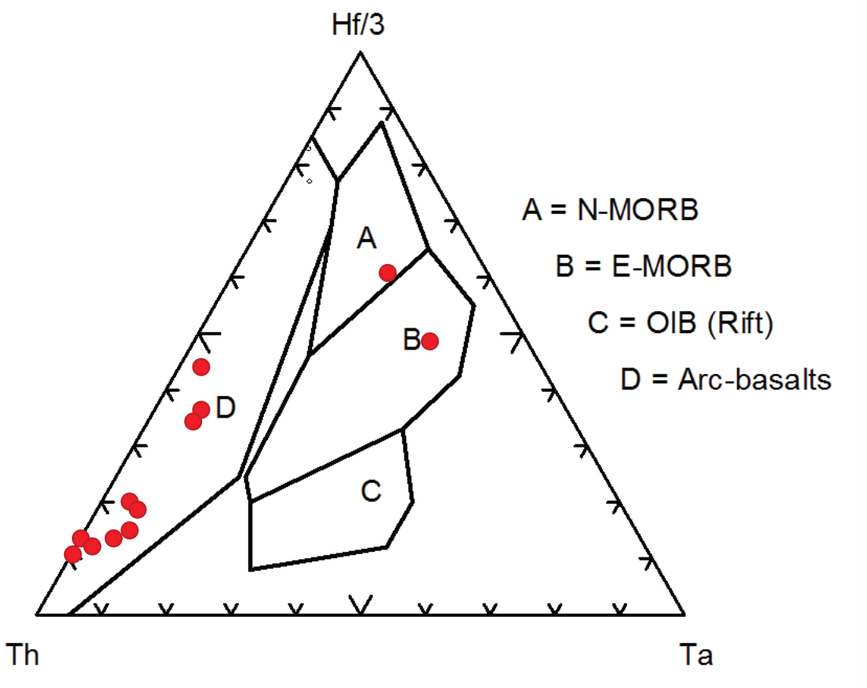
The Elk Hill Complex of Taber (1913) has an established type locality along the CSX right-of way ~2 km S of the hill by that name in Goochland County, VA. Recent workers (e.g., Spears and Bailey, 2002; Spears et al., 2013) recognized the volcanic nature of the Elk Hill and extended it from the type section southwestward to central Cumberland County and northeastward to eastern Louisa County. Although metamorphosed to amphibolite facies, some primary volcanic features such as epidote-filed amygdules are locally recognizable south of the James River. We propose that textural and geochemical evidence warrants recognition as the Elk Hill Volcanic Complex (EHVC). It is bound on the NW by the Lakeside High Strain Zone and on the SE by the Spotsylvania High Strain Zone (Spears, 2011), both of which are Paleozoic transpressional mylonite zones bearing a Mesozoic brittle extensional overprint. The EHVC type section does not include all of the lithologies currently observed within the EHCV. It should be noted that 14 m from the north end of the railroad cut, the type section includes a distinct 21-cm wide dike of granitic composition that crosscuts foliation and appears to be relatively unmetamorphosed. Stringers of such granite could potentially skew crystallization ages of the EHVC toward low estimates. Geochemically, the Elk Hill Volcanic Complex exhibits the following characteristics:

- It is bimodal on Total Alkalies vs. Silica with 6 basalts, 6 granites, 1 basaltic andesite and 1 dacite. This bimodality may suggest a rift or early back arc basin spreading center.
- Five of the basaltic samples have overall flat REE patterns with three of them showing moderate depletion of LREE. All characteristic of N-OFB.
- A spider plot of mafic samples normalized to N-OFB, tends to be flat for the right side of the diagram (LILE = large ion lithophile elements), but is strongly enriched in K and Pb (HFS = high field strength elements possibly enriched by fluids from subducted sediments?) and depleted in Nb and variably depleted in Ti. These latter four deviations from N-OFB suggest an arc environment.
- On a Mn-TiO_2/10-Y*3 diagram, five of the basaltic samples plot in or very near the Island Arc Basalts and none in the MORB field.
- Basaltic rocks are somewhat uniform, but minor differences occur between type locality and other outcrops. On an AFM diagram, the mafic rocks almost define the Tholeiitic vs. Calcalkaline boundary and the more felsic samples are within the calcalkaline field.
- The felsic samples are volcanic arc granites (VAG) based on Y + Nb vs. Rb.
- A few felsic samples have REE patterns and other characteristics for which crustal or recycled crustal metasediments cannot be ruled out. Interpreting zircon dates may be difficult.
- On several diagrams, two of Pavlides (1981) Ta River Amphibolite samples P70-50 from Stafford Quadrangle and P76-78 from Louisa County, resemble EHVC amphibolite samples. A geochemical relationship between the EHVC and Ta River cannot presently be ruled out.







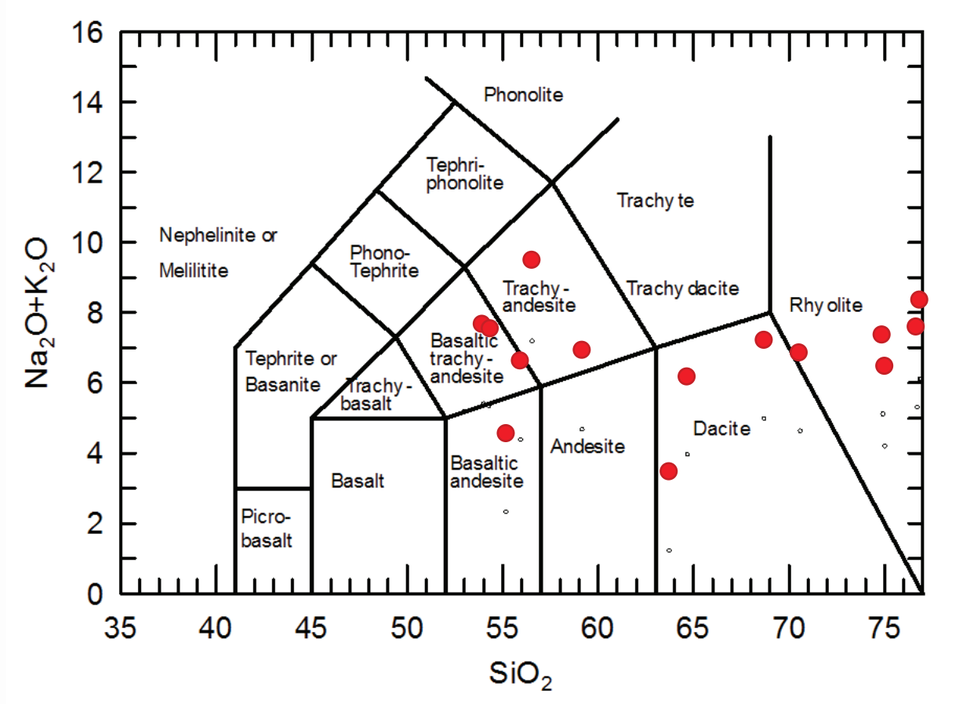


CHOPAWAMSIC FORMATION

The Chopawamsic Formation of Southwick et al. (1971) and Pavlides (1981) has a type section along Chopawamsic Creek, Prince William County, VA. That section was not sampled for the present study. For the Fredericksburg area a bit to the south, Pavlides (1981) notes that the Chopawamsic contains felsic to intermediate volcanic rocks. (As he notes, his keratophyre basaltic samples appear to have lost SiO_2 and gained Na_2O by albitization.) Further difficulties result from conflation of the volcanics in the Chopawamsic Formation with those in the Milton Terrane to the SSW and/or Ta River oceanward. Further, many samples of Chopawamsic volcanics from the Gold-Pyrite belt of Taber (1913) are hydrothermally altered.

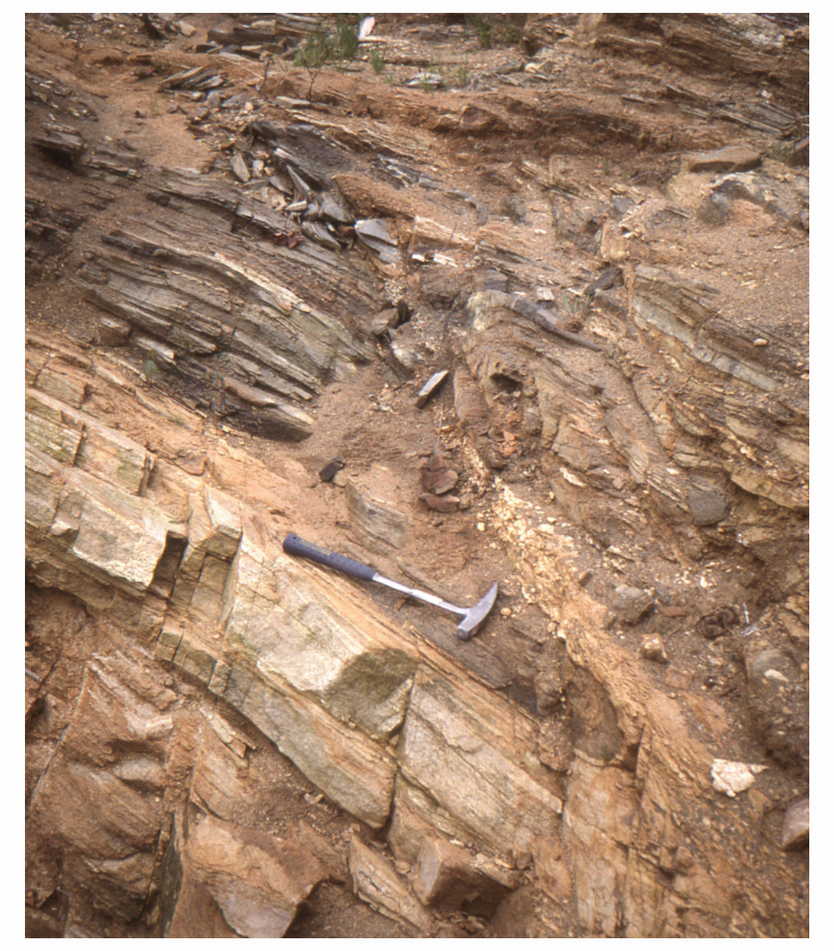
Pavlides divided the Chopawamsic in the Fredericksburg area into three groups based on Nb and rare earth elements and which correlate with geographic location. Nb and Th are potential inverse proxies for how pristine an island arc magma is with respect to crustal contamination and are used to make the tentative subdivisions herein. Note that the Th-Hf/3-Ta trace element diagram (Wood, 1980) utilizes these same tendencies.

- Overall, the Chopawamsic (N = 26) is a highly variable suite with most unaltered samples ranging from Basaltic Andesite to Rhyolite using Total Alkalies vs. Silica.
- Those 9 samples containing > 3.5 ppm Nb and > 3.5 ppm Th are rhyolites, LREE patterns for them have a negative slope, a moderate negative Eu anomally, and somewhat flat HREE. (Note that this group includes one metarhyolite and two felsic pyroclasts from the Milton Terrane which seem to fit in reasonably nicely.) This group of 9 samples probably included a component from Grenvillian crustal source via a west dipping initial subduction zone. They are mostly Volcanic Arc Granites, but a few spill over into the Within Plate and Collisional Granite fields using Y + Nb vs. Rb.
- Those 13 samples containing < 0.1 ppm Ta have flat or nearly flat, OFB like REE pattern with small or no Eu anomalies. Note that this group presently includes three intermediate to mafic samples from the Milton Terrane which seem to fit reasonably well.) The 13 are probably derived from an OFB source from an east-dipping subduction zone, but are themselves mostly intermediate with respect to silica.
- Those 6 samples containing > 0.1 ppm Ta and less than 3.5 ppm Nb are tentatively posited to be transitional from a west dipping to an east dipping subduction source.
- On the Th-Hf/3-Ta diagram (Wood, 1980) one can perhaps see these groupings as bands of samples parallel to the Th-Hf/3 axis.
- Unlike the Chopawamsic, 26 samples of the James Run Formation of MD do not include any samples containing < 0.1 ppm Ta. That is, no samples plot along the Th-Hf/3 axis because the James Run is the product of a west dipping subduction zone. Unlike the Chopawamsic, the James Run does have hypabyssal to plutonic equivalents.
- Overall, it appears that the ca. 480 Ma Wilmington Complex of DE and the ca. 490 Ma Baltimore Mafic Complex of the PA-MD border were the first to impact Laurentia. They were followed by the James Run Volcanic-Port Deposit Tonalite hypabyssal to plutonic rocks. The James Run in turn was followed by the higher Nb and Th portion of the ca. 470 Ma Chopawamsic Formation which through subduction zone polarity flip produced the low Ta portion of the Chopawamsic, the outboard Ta River Amphibolites, and possibly the more mafic volcanics of the Milton Terrane.



Felsic schist with volcanic phenocrysts in the Chopawamsic Formation, near Yanceyville, VA.

Weakly layered felsic gneiss in the Chopawamsic Formation, Mt. Elba Farm, Cumberland County, VA.



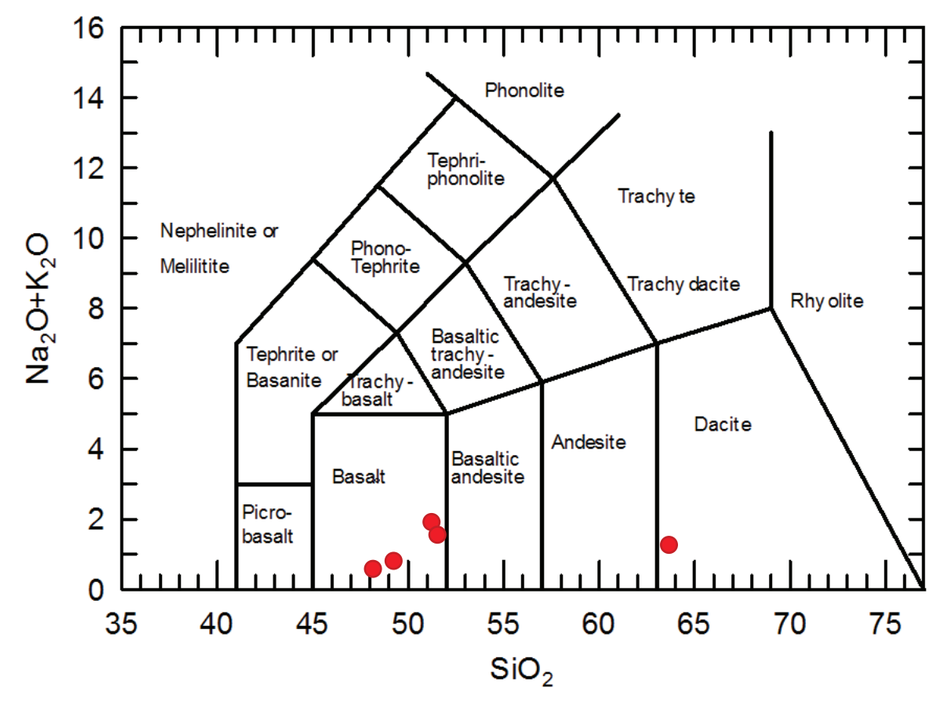
Interlayered felsic and mafic metavolcanic rocks, Elk Hill Complex. Borrow pit on private farm along Boston Branch, Cumberland County, VA.

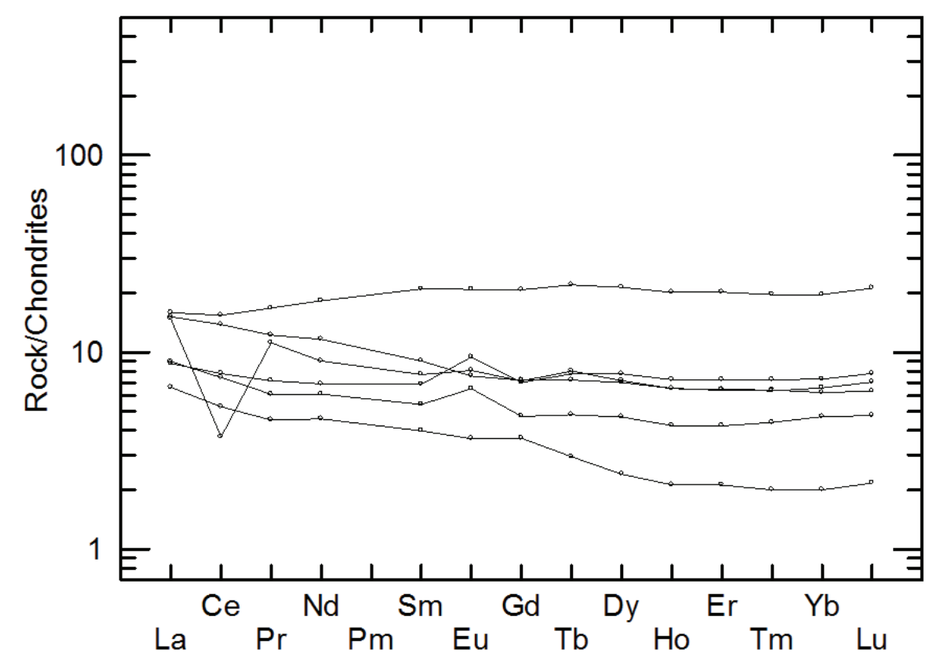
TA RIVER AMPHIBOLITE

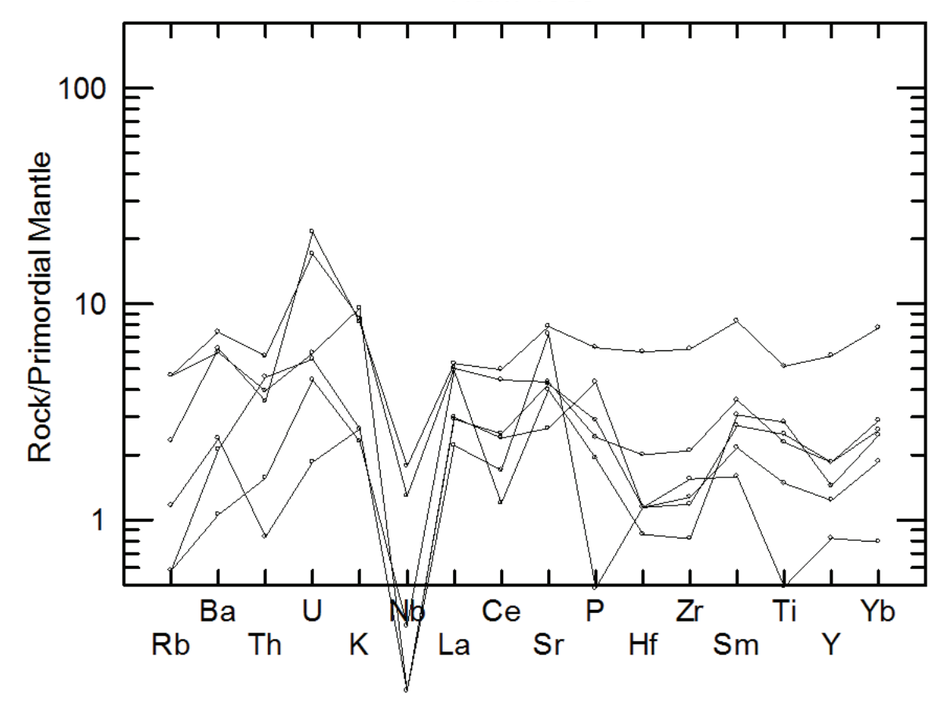
The Ta River Amphibolite is a discrete, field-mappable lithodeme of the Ta River Metamorphic Suite of Pavlides (1980) and has a type locality along the Ta River near Towles Mill Road, Spotsylvania County, VA. As noted by Pavlides (1981), the defining characteristic of the Ta River is the amphibolite, and it appears to be a more oceanic first cousin or sibling to the Chopawamsic Formation. Likely, it formed after the subduction zone polarity flipped oceanward, minimizing mixing of Laurentian crustal derivatives into the mafic melts. This resulted in basaltic composition (based on Total Alkalies vs. Silica) unlike the Chopawamsic Formation and James Run Formation which generally lack unaltered rocks of basaltic composition. The Ta River exhibits exhibits the following characteristics:

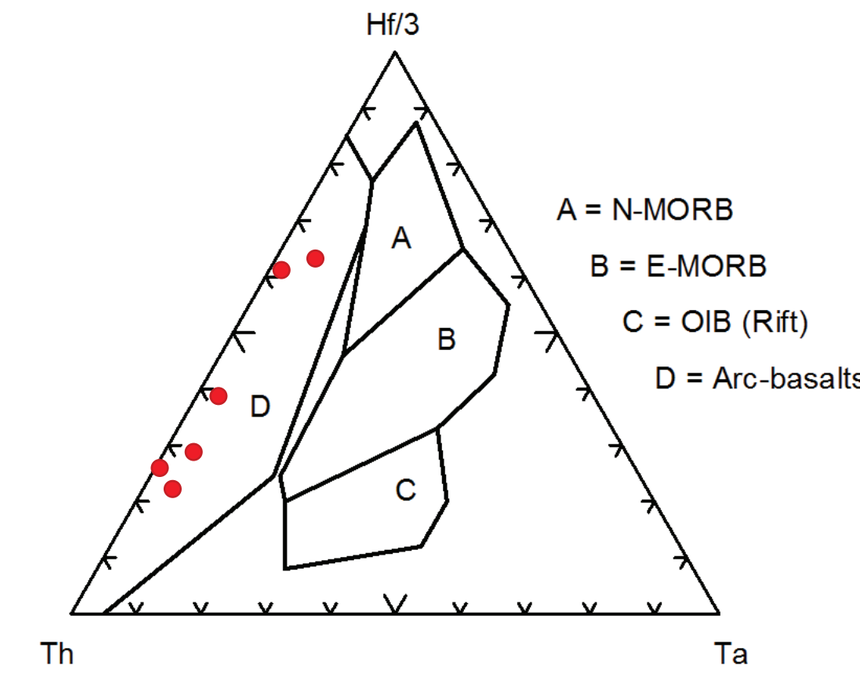
- Flat REE patterns similar to N- to E- Ocean Floor Basalts (N-OFB). Two samples have small positive Eu anomalies.
- Evolving Back Arc Basin (BABB), tholeiitic (from AFM = Alkalies-Fe-Mg diagram) basalts that are transitional from N- to E-OFB from several diagrams.
- Extremely low Ta (< 0.1 ppm) unlike all James Run Formation and some sub-groups of the Chopawamsic Formation. Consistent with polarity of subduction zone being flipped oceanward.
- Relatively uniform field appearance and hence mappable in part because of very high density from ~ 12 % Fe as Fe_2O_3 and pale bluish-gray colored epidote-group mineral. Most samples also high in CaO: 12 to 15 %.
- Undated and unlikely to contain dateable zircons of igneous origin. Presently can only be presumed to be younger than main-stage Chopawamsic Formation.
- Geochemical near match with Pavlides (1981) Ta River samples P70-50 from Stafford County and P76-78 from Louisa County.
- Unexpected, geochemical near match with mafic dacite found on N. side VA Route 6 west of Rivanna River, Fluvanna County. Perhaps a glimpse of transitional polarity flip?
- Unexpected, geochemical near match with a high-Fe, high-Ca amphibolite sample previously presumed to be Chopawamsic from Trenton Mills, Cumberland County.
- Unexpected, geochemical near match of altered picrobasalt from N. shore Occoquan River, Fairfax County. One of northernmost outcrops of "Chopawamsic" in VA.

Ta River amphibolite outcrop along unnamed creek in eastern Pendleton quadrangle, Louisa County, VA.









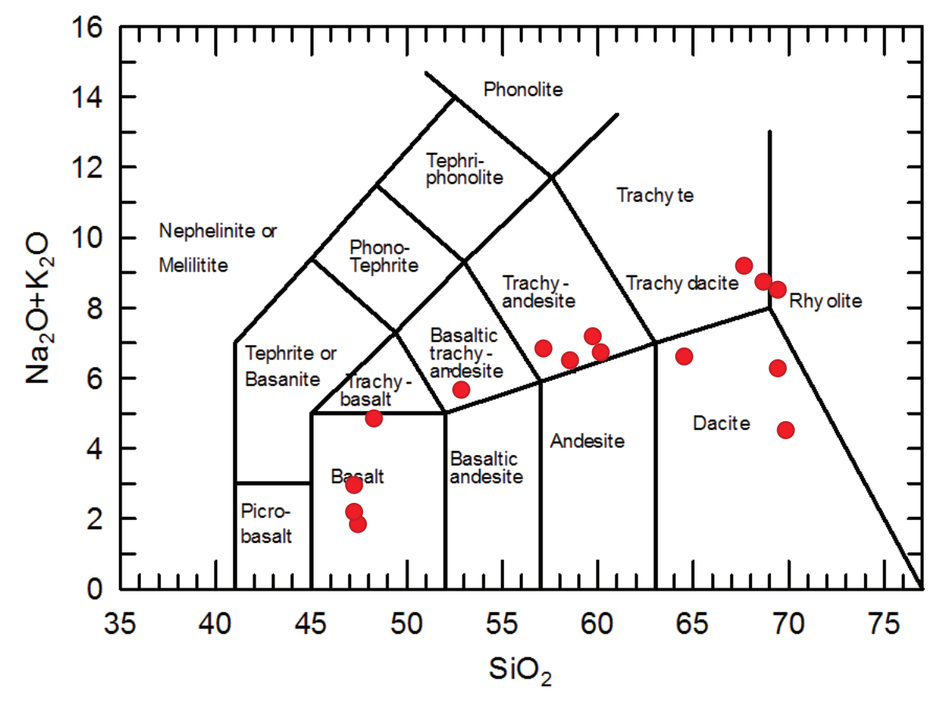
GREEN SPRINGS PLUTON

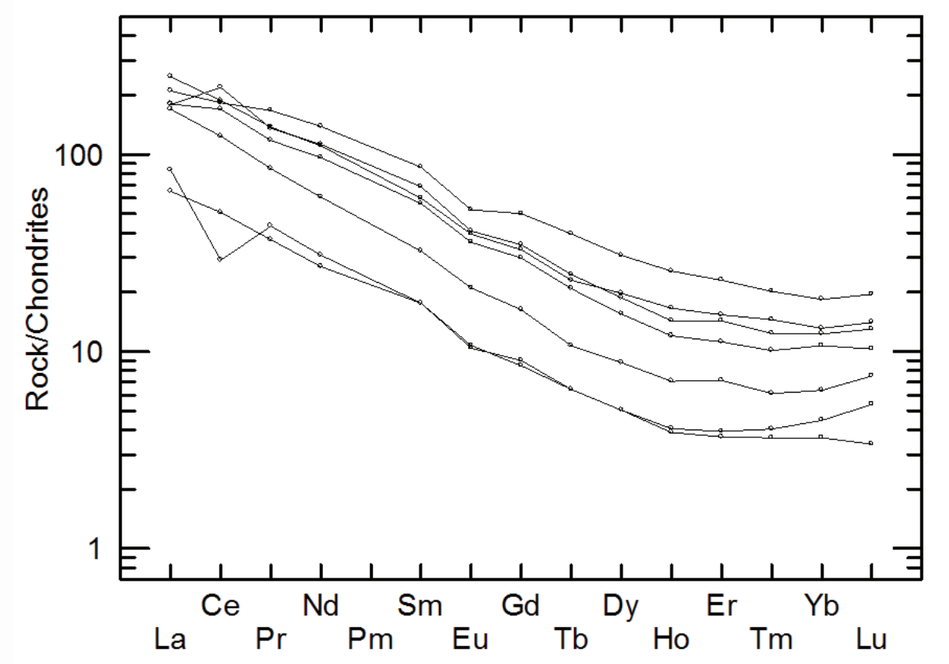
The Green Springs Pluton of Hopkins (1960) has a de facto type locality in a series of outcrops along the ENE side of the South Anna River, about 0.6 km NE of Poindexter, Louisa County, VA. The associated Poore Creek Pluton of Pavlides (1994) is not known to have large outcrops, but is exposed near Poore Creek along Valentine Mill Road about 4 km N of Poindexter, Louisa County, VA. The Green Springs and Poore Creek are believed to be phases of one and the same differentiated pluton. D. L. Rossman (1991) mapped the Boswells Tavern 7 ½' quadrangle where most of the Green Springs Pluton and Poore Creek are located and appears to have done the most work on them. He divided the Green Springs Pluton into three phases: a felsic granodiorite to granite (= ~ The Poore Creek of others), an intermediate diorite, and a mafic hornblendite. Wilson (2001) provided major and minor oxide analyses and SIMS estimates for both the Green Springs and Poore Creek phases. The first two of our diagrams include data from Rossman (1991) and Wilson (2001).

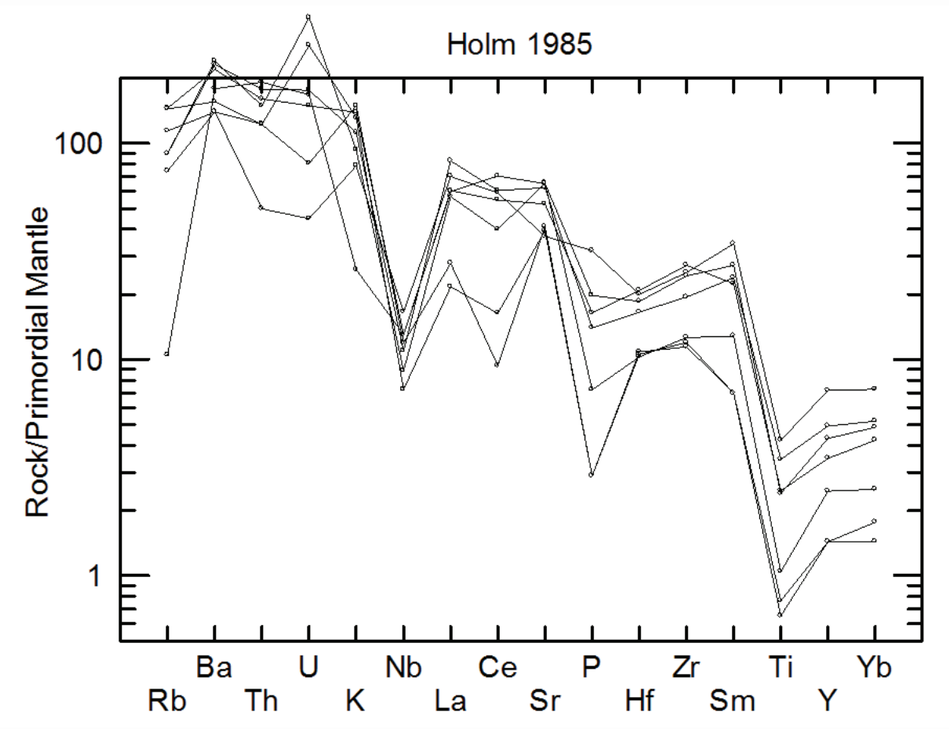
The Green Springs Pluton and Poore Creek felsic phase are currently being studied by Hughes et al. (2017) and described in more detail in the adjacent poster.

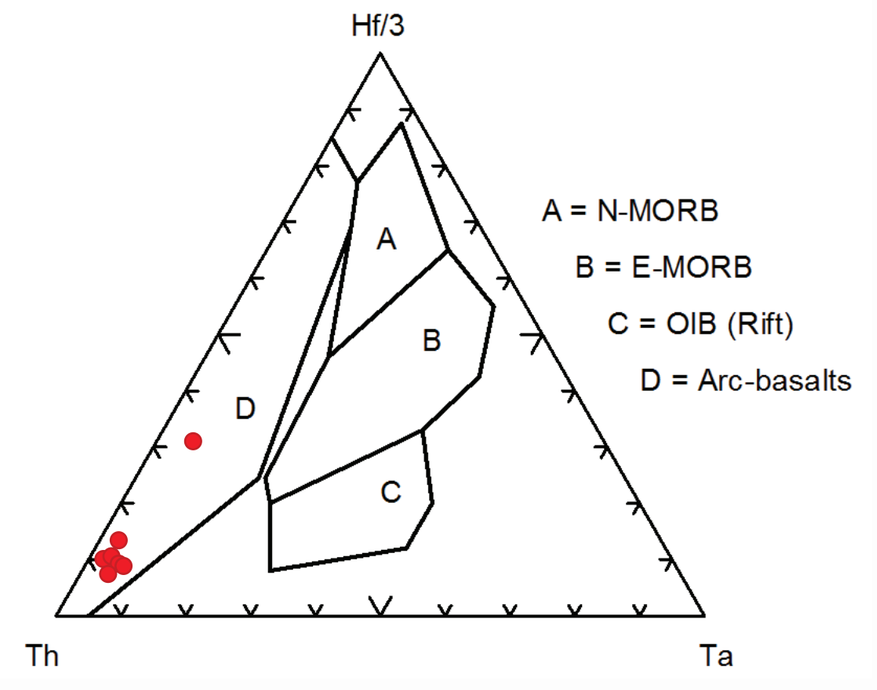
- Compositions range widely from basalt to rhyolite and are all moderately alkali-rich, straddling the border with their trachy-counterparts based on Total Alkalies vs. Silica Diagram.
- Plots of MgO, CaO, TiO_2, MnO, P_2O_5, Co, Ge, Sc, Y, and exclusively trivalent lanthanides against SiO_2 suggest a single differentiation series so far, but 5 additional samples will be analyzed.
- SEE ADJACENT POSTER BY HUGHES ET AL.!

Coarse-grained diorite with dark mafic dikes or xenoliths in the Green Springs Pluton near Green Springs, Louisa County, VA. Photo credit: Nick Evans.









CONCLUSIONS

1) Pavlides was probably right about the Ta River being outboard of the Chopawamsic. Type Ta River is different from other rocks mapped as Ta River, but all could be from the same general oceanic environment, probably with less of a Laurentian source than the Chopawamsic. When we say "Laurentian," we can't necessarily rule out a microcontinent.

2) Columbia does not equal Carysbrook. Within their type areas, they are field recognizable. As Hughes et al. (2013) noted, the Carysbrook "narrow neck" and Ellisville are closely related. Therefore, Ellisville is not related to Columbia.

3) The Chopawamsic is moderately variable, probably due to the degree of Laurentian input. When describing Chopawamsic, one needs to specify if the term is being used includes Milton Terrane, the Ta River, etc. There are some significant geochemical differences between the Chopawamsic and the traditionally conflated James Run of MD. We should not include generalizations from James Run into Chopawamsic. In the field, intermediate Chopawamsic samples look more mafic than they turn out to be based on analytical geochemistry. Mafic does not always = basaltic. Amphibolites of Chopawamsic tend to = Ta River geochemically. Field-mapping friendly definitions are needed.

4) The EHVC type locality cannot and should not be changed, but the EHVC across the James to the WSW is moderately different, containing moderately deformed volcanic rocks. We cannot rule out some tectonic mongrelization within the EHVC belt. The EHVC is crosscut by a small amount of later granitic rock at the type locality. This might interfere with dating techniques. We can't rule out that our one EHVC medium grained dacite is a later intrusion. Otherwise, the EHVC is bimodal.

5) The bimodal EHVC is not like bona fide Chopawamsic, which ranges from basaltic andesite to rhyolite - a range characteristic of arc volcanics.

6) Geochemistry is a powerful tool to verify the integrity of map units and interpret their origin and relationships to one another. Careful geologic mapping is another important tool. Careful age-dating of petrographically and geochemically well-defined samples, especially from type localities, can also prove to be a powerful tool.

Acknowledgements

As noted below, Smith is grateful to many who assisted with sampling and/or suggesting field sampling sites. In particular, he wishes to thank his wife, Gloria J. Smith, for supporting numerous mini-vacations to central VA which included a day or more each of her assisting with the sampling and her agreement to utilize limited family funds for such travel and resulting analytical expenses.

Under the direction of former State Geologist, George Love, the Pennsylvania Geological Survey allowed Smith to use their sample preparation facilities. Also, under Donald M. Hoskins, a second, former State Geologist, the Pennsylvania Survey supported analytical costs for the Robertson River Igneous Suite and Mount Rogers Metarhyolite to permit comparison with the Rittenhouse Gap Felsite Dikes of Berks County, Pennsylvania (Smith, 2003). VADMME/ USGS GSMAP supported about half of the analyses in 2015 and 2016 – especially those in areas of their active geologic mapping.

Wright Horton, U.S. Geological Survey, provide suggestions for sampling the Metadacite Tuff in the Quantico Slate, and confirmed several localities that he and John N. Aleinikoff had previously sampled. James P. Hibbard, North Carolina State University, Raleigh, provided location data for the Prospect Granite, Old Mill Granitic Gneiss, and Milton Terrane Metarhyolite. Those units were sampled with much help from Viktoras W. Skema, Pennsylvania Geological Survey, retired. Skema also assisted with finding and sampling some localities each in the Carysbrook Pluton, Elk Hills Volcanic Complex, and Green Springs Pluton. Bill S. Henika assisted Spears and Smith with a day of sampling of the Elk Hill Volcanic Complex. The locations for the Arvonia Metatuff (precise location for Taber's Tuff, 1913), Goldvein Pluton, Pleasant View Farm Chopawamsic Metarhyolite outcrop, and Beach Nut Drive Ellisville Pluton outcrop were provided by Jim Hibbard's then graduate student K. Stephen Hughes. Some of Hughes' other sampling sites in the Ellisville and Carysbrook Adakitic Granitic Gneiss were "rediscovered" by Smith and he always found evidence of Hughes' prior hammering to be reassuring. Stephen also provided precise location data for Taber's (1913) Metatuff in the Arvonia Slate which was sampled by the authors. Mapping by William S. Henika, Virginia Tech, was used in southern VA. Anne B. Witt of the VA Geological Survey assisted David Spears with a day of sampling at the Elk Hill Volcanic Complex type locality. Locations for the Robertson River Igneous Series were taken from the published work, maps, and field trips led by Richard P. Tollo of George Washington University. Locations for the Mount Rogers Metarhyolite were adapted from the maps and work of Douglas W. Rankin, U.S. Geological Survey, and applied to more recent roadcuts. Logistical assistance in collecting the Mount Rogers Formation in roadcuts of Grayson Highland State Park was provided by acting manager, Harvey N. Thompson. Consulting geologist Ray Lambert provided a drill core section of the Mount Rogers Metabasalt. Sampling of the Lahore Pluton and Ta River type locality were based on the work of Louis Pavlides, U. S. Geological Survey. The Mesozoic nepheline syenite and the Eocene Mole Hill locations were shown to Smith on a circa 1968 field trip led by Charles P. Thornton of the Pennsylvania State University. Other locations of Eocene volcanics in VA benefited from communications and field trips led by Jonathan Tso, Radnford University, and Ronald R. McDowell, West Virginia Geological Survey. The enigmatic Arvonia Metadacite Tuff was sampled from an outcrop personally identified by Nick Evans on the 26th Industrial Mineral Forum Field trip (1990). Although Smith located "new" outcrops, many other locations were "mined" from geologic mapping done by others in the U.S. Geological Survey and the VA DMME.

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